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Sustainable Soil Management: A Framework for Analysis

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ABSTRACT

Sustainable resource management is one of the most complex concerns today. Society has spent billions on conserving productive and marginal soils in cultivation yet it is unclear whether these efforts buy sustainability. Further study about which soils need conservation merits consideration.

We propose a framework to examine the sustainability of resource management in objective, measurable ways. A resource endowment, represented by a quality index, is placed into a dynamic model to determine how resource use adjusts to meet sustainability objectives and how production input use changes with fluctuations in resource quality. Impacts of sustainability objectives and the time path of resource quality are evaluated using substitution, reversibility, and uncertainty criteria.

To assess the impact of conservation, data for soils and corn production inputs were evaluated in a three-step simulation, regression, and optimization analysis. Results show that the decisions to use or conserve soil and the impacts of these decisions are highly dependent upon soil type and on how sustainability is defined. In general, while conservation slowed degradation on marginal soils in production, conservation was most effective on the productive soils. In addition, the better the soil, the more likely soil conservation easily and consistently met the requirements of sustainability.

INTRODUCTION

Since the 1930s, the United States has enacted an array of policies to address the adverse effects of soil erosion. Some policies remove lands from production (either temporarily or permanently). Others provide conservation opportunities on lands, even marginal soils that are actively cultivated. Should we support all types of U.S. soils in production? Are these policies economically efficient? Are they sustainable? Our research intends to offer new insights into these questions.

We developed a general framework to examine the sustainability of resource management in objective, measurable ways. This framework is flexible enough to be applied to different sustainability definitions and to address alternative resource management strategies for endowments that differ across time and space. Yet, it is definitive enough to provide concrete results about sustainability. Through it, we aim to broaden the understanding of how resource quality contributes to, and is affected by, production decisions in a sustainable environment.

In the framework, a resource endowment, such as soil, is modeled as an index of quality. This index is comprised of resource characteristics important for a given production process. The index is placed into a dynamic model to ascertain: 1) how resource use adjusts to meet the requirements of different sustainability definitions and 2) how management decisions change with fluctuations in resource quality. The path of resource change over time is evaluated with respect to sustainability criteria. In addition, the economic and environmental impacts associated with management decisions are identified. While this framework may be applied to any resource, we purposely chose to limit our scope to soil resources. In essence, the framework is used here to identify the conditions where soil conservation is efficient and under what definitions of sustainability conservation practices are sustainable.

Sustainability Definitions and Criteria

The literature suggests three criteria which can be used to evaluate the sustainability of a production process: substitutability, reversibility, and uncertainty (Arrow et al., 1995; Kaufmann, 1995; Pan, 1994; Pearce and Atkinson, 1995). *Substitutability* denotes how well one input may substitute for another when prices change or when inputs become constrained. Inputs have a relationship that is independent, complementary or competitive. If inputs are complementary or independent, substitution cannot maintain a given level of output. Thus to maintain production, the *stock* of the resource quality must be preserved. If inputs are competitive, one input might substitute for another without necessarily reducing output and thus the *flows* of the resource may be used to enhance production.

Competitive relationships alone do not justify the depletion of a resource endowment. The decision must also be evaluated against *uncertainty* and *reversibility* criteria. Production is plagued by uncertainty. Sudden increased use of a competitive input, or declines in a resource could impose unexpected negative impacts on production or on society. Output may be dependent on a minimum resource level, making substitution beyond some threshold ineffective. Sustainability requires that the input mix be adjusted in response to all unexpected occurrences. That is, a manager must be able to reverse his choice of inputs used. His ability to adjust depends upon his endowment and the flexibility that remains in his input decisions.

Sustainability has been defined in many ways (see

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Pezzey, 1992). Many definitions, however, include economic or environmental objectives related to the sustainability criteria mentioned above. Sustainability may simply be defined as the ability to maintain a profit over time. Two seemingly opposing definitions are often cited in the literature. The *constant consumption* definition states that sustainability is the capacity to maintain a constant stream of per capita consumption and as such, natural capital and manmade capital may substitute for each other in the production process (Hartwick, 1977; Solow, 1974). The *constant stock* definition states that natural capital (which is not reproducible and not easily substituted) is the limiting factor of production and therefore must be preserved over time in order for the production process to be sustainable (Pearce and Atkinson, 1995).

As stated above, many have discussed sustainability but actual empirical studies tend to focus on one or two facets (e.g. Abler and Shortle, 1995; Arce-Diaz et al., 1993; Farmer, 2000; Reynolds, 1999) and, therefore, have been unable to provide persuasive conclusions based on the interaction of these three sustainability criteria together. In our framework, the sustainability of soil conservation practices is assessed using all criteria and definitions stated above.

Building a Framework for the Management of US Soils in Production

The quality of a resource is one of many factors that contribute to economic and environmental production processes. For example, the availability of safe drinking water is related to water quality as well as to purification technologies, water storage and water transportation. Similarly, the ability of a soil endowment to contribute to agricultural production depends upon the characteristics of the soil as well as the availability of other inputs such as fertilizer, tillage and soil conservation practices. Therefore, to truly appreciate a manager's ability to maintain a production process, one must examine how a resource interacts with other inputs in a production setting.

In this framework, a firm may use a number of added inputs to produce a given output. Production is also a function of a firm's endowment of natural productivity called resource quality, *rq*. Unlike other inputs, the initial resource endowment cannot be controlled nor initially changed. For example, yield on a non-irrigated crop is a function of precipitation and inputs such as tillage, fertilizer and pesticides. In addition, the producer has an endowment of soil quality, *sq*. A resource endowment is not constant, it changes over time. The case of a decreasing endowment poses interesting questions for sustainability. A resource may depreciate through two means. It can change through the normal operations of the environment and through anthropogenic means. While there are many paths of change an endowment can take, many of these paths can be placed into one of three categories: stable, neutral or susceptible. *Stable* endowments are those who maintain their quality over time. *Neutral* endowments initially succumb to change, but eventually reach a steady state. *Susceptible* endowments succumb to change until the quality is depleted.

Soils are degraded naturally by erosion. How *sq* changes depends upon how much net change erosion brings. Three types of soil endowments in Figure 1 described by Pierce et al. (1983) match the three categories offered in the framework. *Stable* soils, whose subsurface layers qualities are similar to that of the topsoil, stay relatively unchanged as erosion occurs. *Neutral* soils, whose sub-layer qualities are similar but less than that of the top layer, stabilize after a period of degradation. *Susceptible* soils succumb to erosion because beneath a thin layer of good topsoil is a poor quality soil. Quality may fall until it asymptotically or actually reaches zero.

Humans may influence *sq* by choosing inputs that alter the erosion rate. Conventional tillage, which churns soil making it easier to erode, is a *soil using* input. Sprayed fertilizers and other inputs that do not impact erosion rates are *soil neutral* inputs. *Soil conserving* inputs, such as contouring or terracing, slow erosion to preserve quality longer but may or may not impact current production.

As an endowment changes over time, producers will adjust their input mix to maintain economic viability and target sustainability (if society desires it). This may result in increased, maintained, or reduced levels of output and resource quality. These results are highly individualized based upon the type of resource endowment, the path of degradation followed, and the evaluation of management options using three known sustainability criteria.

As *sq* changes over time, it is expected that the use of *sq* and substitute inputs (when they exist) will follow paths similar to those in Figure 2. If a producer chooses to extensively depreciate *sq* in favor of a substitute, yields may be maintained temporarily, but unforeseen consequences may ensue. Increased demand for a substitute may cause price fluctuations or shortages. Extensive *sq* degradation could reduce the soil's ability to perform environmental functions such as nutrient holding. In such circumstances, a producer may want to reverse his input mix to include more *sq*. This may not be possible if *sq* has followed a path of irreversible decline, as in panel III. In short, sustainability is dependent upon substitutability. In addition, what is sustainable today may not be sustainable tomorrow due to reversibility and uncertainty.

General Guidelines for Managing Heterogeneous Soil Endowments

Part of the Story

Our research examines conditions under which it may or may not be acceptable to substitute away a resource endowment and still maintain production potential. These observations derived from the framework above can be summarized for soils in four guidelines. First, conservation is important on neutral and susceptible soils when *sq* shares an independent or complementary relationship with other inputs. Second, for stable soils, production may be maintained without conservation if degradation from anthropogenic sources is not excessive. Third, when substitutes are present, production may allow the degradation of stable and neutral endowments. Finally, given the risks associated with irreversibility and uncertainty, it

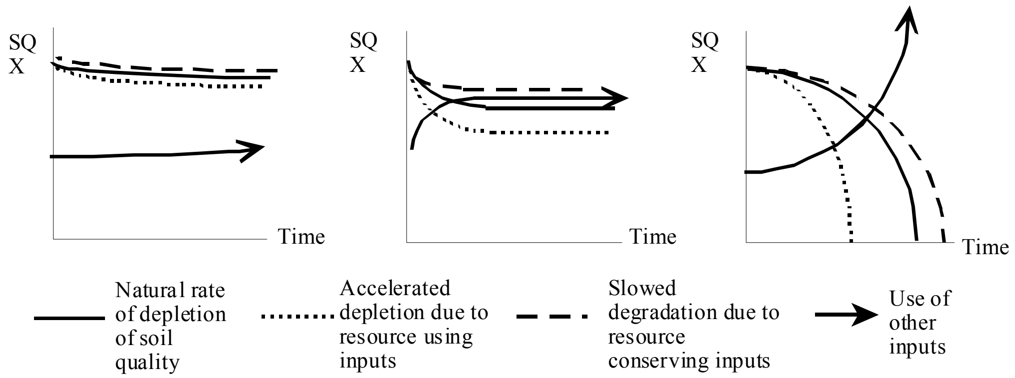

Figure 1: Time paths of input use and degeneration rates for three soils.

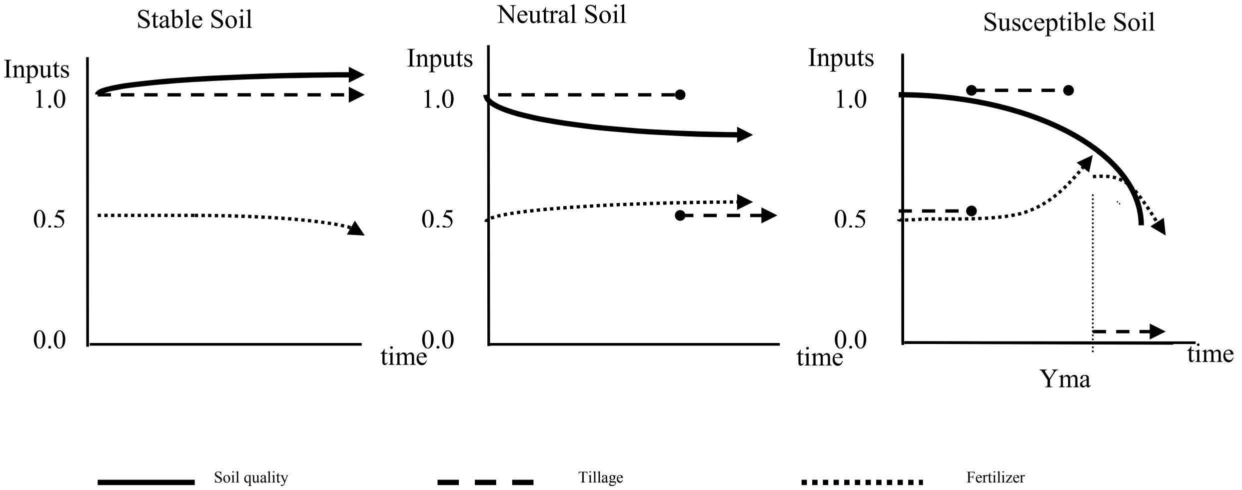

Figure 2: Profit Maximization: Average resulting normalized soil stock (resource quality) and input use time paths scale on stable, neutral and susceptible soil resources.

may be best to conserve susceptible soils even when substitutes exist.

These guidelines seem to justify the use of government supported cost share opportunities for conservation practices to maintain susceptible (or marginal) lands in production. Some may even interpret these guidelines as suggesting that conservation policy might focus efforts on marginal soils as productivity may be maintained on other soils through substitute inputs. However, we suggest that these guidelines present only part of the story for the following reasons. First, sustainability does not always focus on production objectives; it is defined in many ways. Second, we find no indication that current conservation practices can efficiently maintain production on all lands indefinitely. Therefore, we have conducted an empirical investigation to examine these issues and present another side of the story.

Dynamic Model of Agricultural Production

Based on the framework, a dynamic model was built for non-irrigated corn production. Soil management is evaluated on the three soil types under general profit maximizing conditions and two interpretations of sustainability: constant consumption (maintenance of a minimum production level) and constant resource stock (maintenance of a maximum soil quality level). The choice of crop and soils are based upon earlier work by Pierce et al. (1983). The choice of sustainability definitions is based on the literature review.

The producer's problem was to maximize over time the discounted profits subject to the availability of *sq* and the level of the environmental byproducts of production[1]:

$$\max \Pi = \sum_{t=0}^{T} (1+r)^{-t} \{ P_y f(SQ_t, L_t, SN_t, N_t, P_t, W_t) - u_1 L - u_2 N - u_3 P - u_4 SC \} \quad (1)$$

subject to:

$$SQ = h(SQ_{t-1}, L_t, SC_t) \quad (2)$$

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[1] Environmental byproducts were included in the model in order to study other definitions of sustainability not presented here. See Popp (1997) for details.

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

$$LCH_t = m(SN_t, N_t, L_t, W_t, Y_t) \tag{4}$$

Equation 1 shows that discounted profit over period T is a function of soil quality, *SQ*, precipitation, *W*, soil using inputs such as tillage, *L* and soil neutral inputs such as soil nitrogen, *SN*, applied nitrogen, *N*, and sprayed pesticides, P. Associated prices consist of the output price, P_y and management practice costs, u_i. *SC* is a soil conservation practice and *r* is the discount rate. Equation 2 explains that current *sq* is determined by past *sq* and current management decisions to use or preserve *sq*. Equations 3 and 4 state that a producer's decisions influence not only the level of current crop production, *Y*, but have environmental consequences (such as changes in *SN* and leaching*, LCH*, levels over time) as well.

An index was used to represent soil quality in this model. A review of the literature suggests a growing consensus as to which soil characteristics are important to agricultural production (e.g., Jaenicke and Lengnick, 1999; Karlen et al., 1997; Larson and Pearce, 1994). Building upon work by Bowman and Petersen (1996), Pieri (1995), and Pierce et al. (1983), a soil quality index was constructed as a function of available water capacity, AWC, bulk density, BD, organic matter, OM, and pH, PH (Popp, 1997):

$$SQ = g(AWC, BD, OM, PH) \tag{5}$$

Empirical Estimation

The producer's problem was empirically estimated on three susceptible, three neutral and three stable soils used in non-irrigated corn production in Iowa, Missouri and Minnesota. Soil characteristics, crop production (including input use decisions), weather, and economic and environmental indicator variables data were simulated for 100 years in the EPIC (Environmental Policy Integrated Climate) model (Mitchell et al., 1995). An index for each of the nine soils was calculated using data for the *sq* characteristics in equation 5. The fixed effects regression technique was applied to the *sq* index variable and other simulation panel data to estimate equations 1 through 4. All functions were tested and corrected for problems associated with panel data (Hsiao, 1991). The adjusted R^2 values and functional forms for equations 1 through 4 were 0.729 (transcendental), 0.986 (linear), 0.999 (linear) and 0.737 (logarithmic), respectively.

Once estimated, the equations were placed into GAMS (General Algebraic Modeling System) (Brooke, Kendrick, and Meeraus, 1992) to study the contribution of soil conservation in attaining sustainability objectives. The model chose the optimal management strategy from the following inputs. There were three annual tillage options: conventional, conservation, or no-till. Annual nitrogen fertilizer application rates could range between 0 and 210 lbs/acre. The annual pesticide application could range between 0 and 100% of recommendations. The soil conservation option was a decision to apply or not to apply the relevant conservation practice that year. The relevant practice varied by soil type and were chosen based on those most frequently encountered on these soils in these areas (Beeler and Green, personal communication 1997). Inexpensive and highly effective residue management and contouring practices were chosen for stable soils. Terracing techniques were chosen for neutral and susceptible soils. These practices were more expensive and assumed to be only 75 percent effective in controlling erosion (Beeler and Green, personal communication 1997). Details concerning soil conservation modeling and effectiveness can be found in Popp (1997).

A profit maximization scenario was created to track the natural paths of *sq* degradation over time. These paths mirrored those in Figure 1. New scenarios were created so that agricultural producers had to manage *sq* to target one of two other sustainability objectives over the 100 year period: 1) maintain at least a minimum level of crop production (based on historical yields) or 2) preserve *sq* through continual soil conservation over time.

Empirical Results

Results of this investigation included observations on environmental and sq changes, stability of the input mix, profit levels and output levels. Specific results for each soil are enumerated in Popp (1997). Here, we focus on the ability of different soils to meet sustainability objectives, and the contribution of soil conservation in attaining those objectives. In general, while conservation on susceptible soils helped attain some sustainability ideals for some time frame, soil conservation was found to be more efficient in preserving quality and attaining sustainability goals on other soil types.

Profit Maximization

In the first scenario, sustainability was defined as maximizing profits based on equations 1 through 4. Figure 2 shows the normalized time paths of input use over the 100 year period. The optimization model chose conservation measures on all of the stable soils for the full 100 years, and soil quality was improved over the initial state (from 0.80 to 0.811 on average). Conservation measures were also effective on all neutral soils, but because of differences in input, output and conservation practice prices across regions, the point in time and the level at which soil quality reached a steady state varied by soil type. Conservation practices were not introduced on neutral and susceptible soils until late in the planning horizon as the benefits did not outweigh the costs until soil quality had degraded for some time.

Profit maximizing producers used conservation on the richer endowments, but let other endowments erode partially, as in the case of the neutral soil, or fully, as in the case of a susceptible soil. Only in the case of two susceptible soils did natural capital become a complement to other capital. As shown in Figure 2, the use of other inputs was as presented in Figure 1, except for susceptible soils. Fertilizer and tillage use did rise and at an increasing rate as soil quality fell. However, other input use crashed when soil quality and fertilizer became complementary, as shown at Ymax in Figure 2. When these input levels fell, production

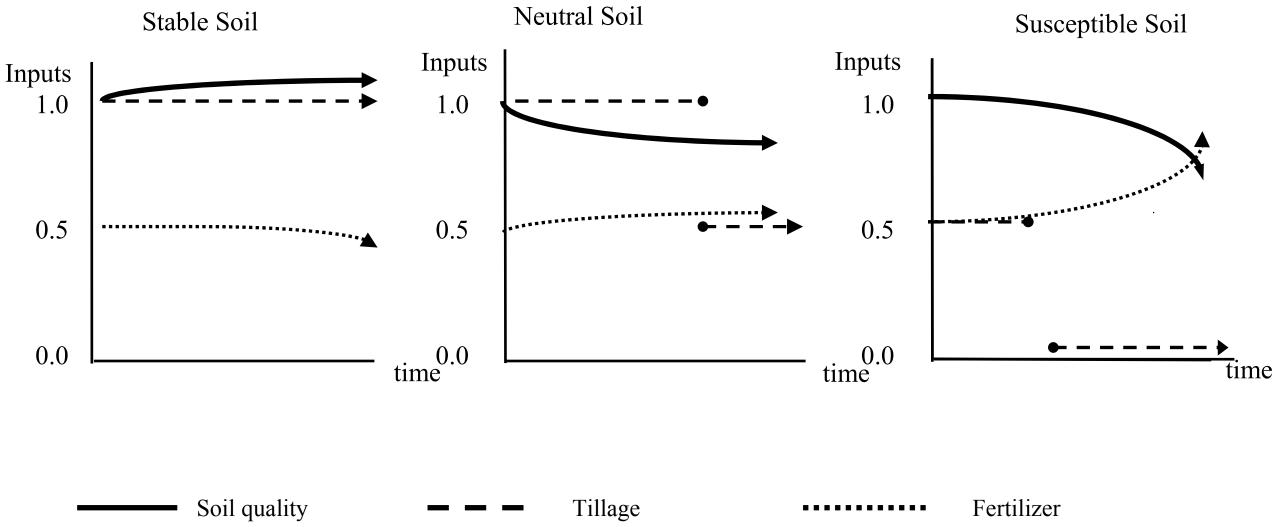

Figure 3: Constant Consumption: Average resulting normalized soil stock (resource quality) and input use time paths scale on stable, neutral and susceptible soil resources

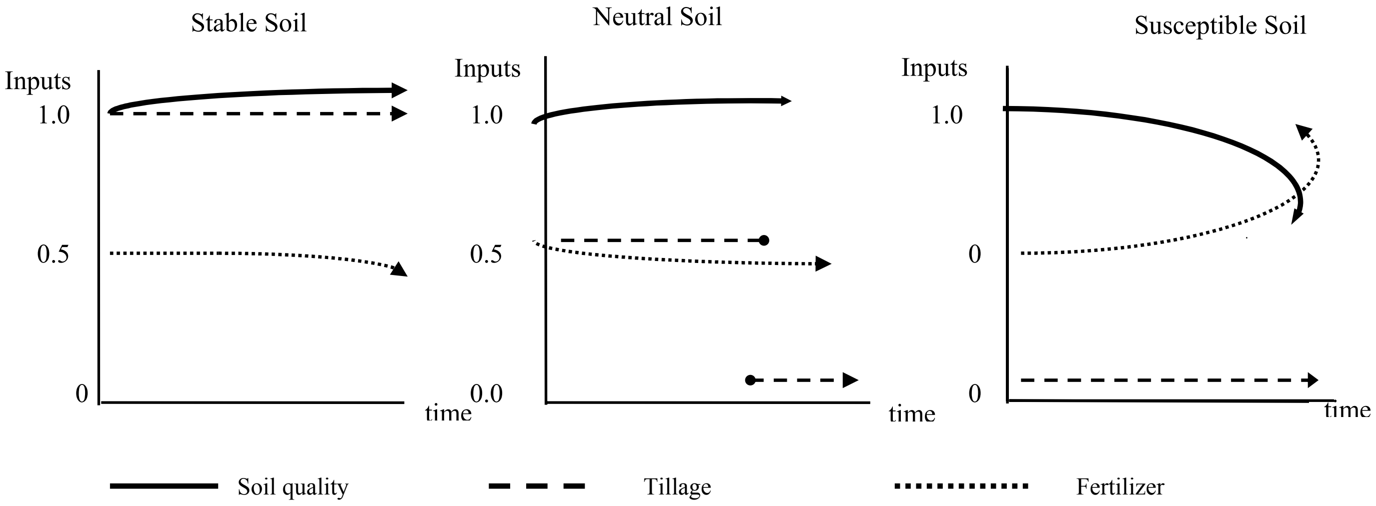

Figure 4: Constant Stock: Average resulting normalized soil stock (resource quality) and input use time paths on stable, neutral and susceptible soil resources

levels fell by about half (on average from 120 bushels to 60bushels) on all susceptible soils.

Constant Consumption

To quantify the impacts of constant consumption a condition based on Bellon (1995) was included that annual yields for the 100 year period could not fall below 90 percent of the yield attained in the first year of the baseline scenario. The average results for stable and neutral soils are presented in Figure 3. Interestingly, for the stable and neutral soils, the best solution to this scenario was also the solution to the first scenario. That is, conservation measures were implemented for the full 100 years of the planning horizon, conventional tillage levels were used throughout the planning horizon. Profits were relatively high and both soil quality and yields increased over time. On neutral soils, conservation measures were implemented but at different rates. Soil quality decreased over time, but steady states were reached on all three soils. Losses in annual yield over time were held below eight percent. High levels of profit were attained, but less than those that accrued on stable soils.

As shown in Figure 3, in an attempt to fulfill the sustainability requirement on one susceptible soil, soil quality depletion was greatly slowed by implementing soil conservation for 70 years, and reducing tillage intensity from conservation tillage to no till. As soil quality fell, fertilizer levels increased and minimum yields were attained. However, for the other two susceptible soils, there was no optimal path of input mix that could maintain annual yields throughout the entire planning horizon. Presumably, this is because conservation practices were ineffective in keeping soil quality at the levels needed to maintain production. Tillage intensity was reduced from conservation to no till.

Fertilizer levels were also adjusted as fertilizer, tillage and soil quality changed competitive to complementary inputs through time. Even when conservation methods were fully implemented over the planning horizon, annual yields could only be maintained at 83 and 85 percent, respectively.

Constant Stock

In this study, sustainability is examined in a production setting. Therefore, constant resource stock definition of sustainability requires conservation measures (whether it be contouring, residue management or terraces depending on soil type) to be fully implemented every year of the planning horizon. Results are illustrated in Figure 4. As soil conservation practices were already fully implemented on the stable soils in the profit maximization and constant output scenarios, this same soil management plan, also fulfilled the constant stock requirement. Profits were maximized and the input mix was steady (fertilizer, pesticide and tillage levels changed very little). Moreover, both soil quality and production increased over time. Although the constant stock and constant consumption definitions are often cited as having competing objectives, these objectives are compatible on stable soils. On neutral soils, soil quality increased over time, fertilizer use fell, optimal tillage fluctuated, and costs increased. As a result, profit levels were lower than in previous scenarios.

Even when the initial endowment of soil quality was 0.78 or 0.79, no till and conservation practices were unable to bring susceptible soils into a steady state with continuous cropping over a 100 year period. They did, however, greatly slow the erosion process, such that soil quality on average was only reduced to 0.63 as compared to an average of 0.25 in previous scenarios. Fertilizer levels increased to substitute for the loss in soil quality. Annual yields still fell over time, but were greatly improved over the profit maximization scenario. However, the high cost of conservation needed to improve soil quality and output greatly reduced the profit level when compared to the constant consumption and profit maximization scenarios.

CONCLUSIONS

Managing Heterogeneous Soil Endowments - More of the Story

This paper reports on the development of a framework for evaluating resource management decisions in a production setting. The framework demonstrates that different resource endowments can change over time in different ways. Evaluating changes using substitution, reversibility and uncertainty criteria has produced some general guidelines for managing a resource in a single production process. However, these guidelines should be evaluated individually based on the intended management objective.

Current U.S. soil conservation policy provides support for conservation practices on all lands under cultivation. This coincides with the general guideline that for production sustainability, stable (productive) soils can be eroded as long as substitutes exist, but susceptible (marginal) soils should be conserved. The empirical study shows that soil conservation practices may be useful in slowing *sq* loss and thus help to maintain the productive capacity of susceptible soils over some time. However, conservation, was often found to be inefficient or even undesirable on susceptible soils because they were too costly and/or incapable of maintaining *sq* at high enough levels over an extended period of time. On the other hand, conservation was found to be instrumental in meeting not only production objectives, but also sustainability targets defined by profit and resource preservation motivations on the stable soils. In general, soil conservation seemed to be more important and economically efficient, the better the initial quality of the soil.

Does this mean that US policy makers should abandon support for conservation of marginal lands? We suggest not. Instead, further research might be conducted to develop new conservation technologies that are beneficial and economically efficient in meeting different sustainability objectives. In the meantime, the benefits of soil conservation on “good” soils might be promoted from environmental (quality preservation) and economic (profit) perspectives so that even while society continues to debate the notion of a true meaning of sustainability we know that soil conservation practices will ultimately help us achieve those goals.

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