Sustainable Resource Management: A Methodology for Analysis

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Abstract

A resource endowment, represented by an index of quality, is placed into a dynamic production model to determine how resource use adjusts to meet sustainability objectives and how production input use changes with fluctuations in resource quality. Impacts of various sustainability objectives and the time path of resource quality are identified and evaluated using substitution, reversibility and uncertainty criteria.

Introduction

When attempting to sustain natural resources, we find ourselves in a predicament: we want to attain it but cannot agree on what "sustainability" is or how to achieve it. This dilemma is not trivial, for society has a fixed endowment of natural resources and the consequences of miscalculations to current and future generations could be severe. Here we explore the optimal use of a non-renewable natural resource given alternative assumptions about what sustainability means.

There are several dimensions of optimal resource use to consider. Resources provide multiple goods and services, both market and nonmarket. Resource quality may vary by region, by firm, and by year. Finally, resource contribution may not be independent from other inputs. That is, some resources can be replaced in production by substitutes. We intend to develop a framework to address these issues and apply it to an empirical example using an index of resource quality.

Our objective is to examine three criteria cited in literature, reversibility, uncertainty and substitution, and three sustainability definitions, constant consumption, constant stock, and intergenerational equity. Many have examined these criteria/definitions (Arrow, et al., 1995; Kaufmann, 1995; Pearce and Atkinson, 1993, 1995) but actual empirical studies tend to focus on one or two facets (Abler and Shortle, 1995; Arce-Diaz et al., 1993; Stockle et al., 1994).We provide new insights by looking at a single, comprehensive empirical example. Our framework falls short of a true representation of a "system" but it is designed to address our objectives in an integrated manner.

In this paper, we proceed with a discussion about sustainability concepts and a description of our proposed framework. An empirical example follows. Finally, we conclude with a summary of key findings to address several concerns about the sustainability of resource use. Our aim is not to replace previous research but rather to broaden the understanding of how resource quality contributes to and is affected by production decisions in a sustainable environment.

A Brief Review of Sustainability Concepts and Criteria

Advocates have long debated the meaning of sustainability. Most definitions include economic, environmental or social concerns. Hartwick (1978) and Solow(1974) defined sustainability economically as the ability to maintain constant consumption (or productivity) by substituting between natural resources and manmade capital in production. Pearce and Atkinson(1993, 1995) define it environmentally by stating that natural and manmade capital complement each other in a production process and as natural capital is the limiting factor of production, it must be preserved. Finally, a more general definition states that social welfare must be maintained across present and future generations (WCED, 1987). This definition imposes neither substitutability nor complementary relationships but requires some undefined measure of intergenerational equity to be fulfilled.

Three criteria my be used to evaluate these interpretations of sustainability: substitutability, reversibility and uncertainty. Substitutability can be described through technical interdependence (*TI*) (Beattie and Taylor, 1985). *TI* denotes how well an input may substitute for another when prices change or when one or more inputs become constrained. If inputs are competitive, an input might substitute for another without necessarily reducing output. But if inputs are complementary, substitution cannot maintain a given level of output. *TI* is most relevant when inputs are (or are becoming) scarce. If substitutes exist, sustainability may not require conservation. However, complementarity between natural resources and other inputs implies that resource depreciation will likely reduce output.

Certain functions dictate the relationships among inputs. All inputs in a Cobb Douglas function, for example, are complementary. The Quadratic allows any <u>one</u> type of relationship to exist. The Transcendental permits both substitution and complementary relationships among inputs and allows that relationship to change along an isoquant.

Reversibility is the ability of a firm to revert back to a former input mix once it has chosen others. Uncertainty refers to any unforeseen circumstances that may either follow as a consequence of, or impact, production. Uncertainty arises with respect to all prices, input and output supply, profits and other impacts. As a manager depletes his resource base in favor of one or more substitute inputs he has limited his set of possible input mix combinations. If use of these substitutes leads to unforeseen consequences, he may not be able to readjust his mix because either reversal is costly, difficult and time consuming, or impossible as in the case of resource depletion. In many cases irreversibility and uncertainty impacts do not limit themselves to the production process but affect the broader economy or the environment. In addition, these impacts may themselves be irreversible.

Framework

We examine what the three sustainability definitions imply for management of a resource in a production setting. A framework is presented and then applied in an empirical example. For illustrative purposes it is assumed that: 1) producers are endowed with a resource quality, 2) suppliers of inputs and outputs face perfectly competitive markets, 3) firms are profit maximizers, and 4) the production function is strictly concave.

We assume that a firm may use either or both of two factor inputs to produce an output. Production is also a function of the firm's endowment of a natural productivity, resource quality, *rq*. The *rq* is a special input because producers cannot control their initial endowment of *rq* nor, can they immediately change it. This *rq* contributes to the effectiveness of the added inputs and, therefore, has implications for the choice of input mix and the sustainability of production. How *rq* enters the production function will determine its relationship with inputs and its impact on the optimal input mix and output but, in general, producers prefer more *rq* to less *rq* to enhance production.

An endowment of *rq* changes over time. It may deteriorate naturally. Humans may also influence the rate of *rq* change by using inputs that slow or accelerate the deterioration process. Inputs that accelerate *rq* depreciation may positively impact profits and production today but could have negative future impacts by depleting what may be an important input to production.

As *rq* changes over time, firms will adjust their input mix to maintain economic viability, while meeting other personal and social objectives. This may increase, maintain or reduce production. Their ability to sustain production will be highly influenced by the path of degradation for *rq*. A firm must decide whether it is better to preserve its resource base as long as possible, or whether it is better to substitute it away. The first case sustains the resource, the second case does not. However, either may sustain income. If case 2 sustains a higher income and production is not threatened by a loss of *rq*, economic sustainability and environmental sustainability may be at odds.

Managing Soil Stocks

Soil quality in rain fed agricultural production was chosen for the first empirical application as it matches our framework well. In addition, data for soils are abundant and a list of measurable soil characteristics exists which can be placed in an index to describe the quality of a particular soil.

Our framework can be applied to soils as follows. In agriculture, production of any rain fed crop, is a function of precipitation and added inputs such as tillage, applied nitrogen, and sprayed pesticides. In addition, the farmer has an endowment of soil quality (*sq*). *Sq* is a function of its important characteristics including available water capacity, bulk density, pH and organic matter[1].

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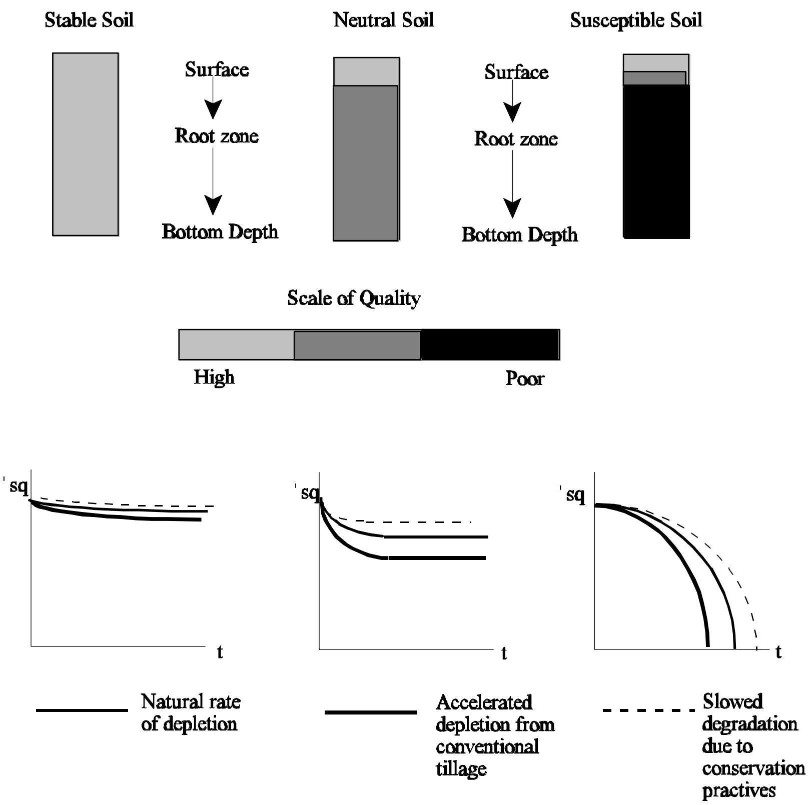
[1] Based on work by Bowman and Petersen(1996), Pierce et al. (1983) and Pieri (1995) the *sq* index was constructed as a function of the sufficiencies of available water capacity, bulk density, ph, and organic matter in each soil layer down to rooting depth, and a weighting factor for each layer. See Popp (1997) for details.

Figure 1 Three types of soils and their possible paths of quality degradation

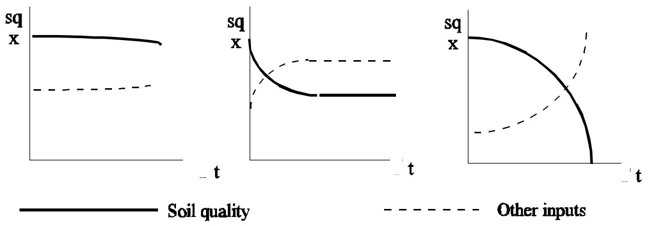


Soils are subject to a natural rate of degeneration caused by erosion. Erosion removes soil from the surface and exposes the subsurface layers. Soil quality degradation will depend on how much change erosion can bring compared to its natural rate of regeneration. Pierce et al. (1983) showed that potential change is determined in part by the rate at which top soil is removed and the quality of the topsoil compared to the quality of the lower layers (Figure 1).

Soils whose subsurface layers have a similar quality as the top soil can be called *stable soils* because as the soil erodes, the quality stays relatively unchanged. In neutral soils all the lower layers have similar quality levels but they are less than that of the top layer. These soils stabilize after a period of degradation. Susceptible soils have a poor soil beneath a thin good quality top layer. With erosion, the quality of the soil declines continuously until it (asymptotically or actually) reaches zero.

Humans can influence *sq* degradation. Conventional tillage equipment, such as a moldboard plow, that loosens soils makes it easier for *sq* to erode and may accelerate depreciation. Conservation practices, such as reduced tillage intensities or terraces, can slow *sq* depreciation.

Figure 2 Tradeoffs between *sq* and other inputs



As *sq* changes, a producer will attempt to adjust the input mix to maintain economic viability and meet societal regulations. If substitutes exist as *sq* decreases, the use of these other inputs may follow one of the paths in Figure 2. If a producer depreciates *sq* in favor of a substitute, yields may be maintained but unforeseen consequences may ensue. Increased demand for a compensating input could cause input price fluctuations across sectors. Large degradations in *sq* could reduce the soil's ability to hold nutrients and lead to leaching. In these or other cases the producer may want to change his input mix to include more *sq*. This may not be possible if *sq* use has followed a path of irreversible use (panel III). In short, sustainability is dependent upon substitutability which depends on the form of the production function and the characteristics of soil quality. In addition, what is sustainable today may not be sustainable tomorrow due to reversibility and uncertainty.

Dynamic Optimization

The framework is used to develop a dynamic model of production based on innovations by Bowman and Petersen (1996), Burt (1981), Clark and Furtan (1983), Hoag (1998), McConnell (1983), Pierce et al.(1983), Pieri (1995) and Saliba (1985).

Based on the information provided above, the producer's dynamic problem is to maximize over time the discounted profits of production subject to the availability of soil quality, and the level of the environmental byproducts (soil nitrogen and leaching) of production:

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

$$subject\ to: SQ_t = h(SQ_{t-1,} L_t, SC_t) \qquad (2)$$

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

$$LCH_t = n(SN_t, N_t, L_t, W_t, Y_t) \qquad (4)$$

where *L* is tillage, *SN* is soil nitrogen, *N* is applied nitrogen, *P* is pesticides, *W* is precipitation, *SC* is soil conservation, *Y* is yield, *LCH* is leaching, P_y is output price, the u_i are prices for the management practices, and *r* is the discount rate. A producer's decisions influence not only the level of crop production in any year but have economic, environmental and social consequences as well. Social considerations are captured by tracing the paths of the economic and environmental impacts over time, thus allowing us to use this model to examine the concepts of *sq* and sustainability.

The problem was empirically estimated on three susceptible, three neutral and three stable soils used for non-irrigated corn production in Missouri, Minnesota and Iowa. 100 years of data pertaining to soil characteristics, crop production, weather, economic and environmental indicator variables were simulated in the EPIC model. Using data for the *sq* characteristics listed earlier, an index of soil quality was calculated for each soil. The fixed effect regression technique was applied to the *sq* index and to a subset of the remaining simulated panel data to estimate equations 1-4. All equations were tested and corrected for problems associated with panel data (Hsaio, 1991; Madalla, 1993). The production process was fitted to the transcendental function, thereby implying the existence of both complementary and substitution relationships among inputs that may change over the level of inputs used. The adjusted R^2 values ranged from 0.729 for 0.999 for all functions.

Once estimated, the equations were placed into GAMS. A baseline scenario was created for each of the nine soils to track the paths of *sq* degradation. These paths mirrored those found in

Figure 1. From the baseline, new scenarios were created for each soil to target the conditions for the following sustainability objectives:

> *Sustainability as constant consumption*– yield *in any year* must be at least 90 percent 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 production period.
>
> *Sustainability as intergenerational equity*- leaching over the 100 year period must be at least 10 percent less than overall leaching in the baseline scenario.

These conditions represented one interpretation found in the literature for each of the three sustainability definitions selected. We recorded the economic, environmental and social impacts and the path of *sq* degradation associated with each sustainability objective. We further evaluated the management decisions using substitution, reversibility and uncertainty criteria.

Key Findings for Managing a Soil Endowment

Results show that economic, environmental and social impacts, and the ability to meet objectives, are highly dependent on soil type and on how sustainability is defined. In some cases, one optimal input mix can fulfill all sustainability objectives but in others, the objectives are at odds. In general, the deeper/better the soil, the more obvious/consistent was the approach to sustainability. Lower quality soil types require more complex approaches. These results are discussed below.

Different strategies are needed for different soil types

For a given objective, different soils required a different input mix. On stable soils, *sq* was an important input and conservation practices were consistently used to maintain quality. On lesser quality soils, *sq* was often substituted away in favor of increased fertilizer or tillage intensities. While soil conservation was occasionally applied to neutral soils, conservation costs outweighed benefits (except under constant stock) on susceptible soils and was rarely included in management decisions.

Sustainability conflicts are exacerbated by poor resource quality

When *sq* was high and abundant, all three definitions were achieved under the same optimal input mix. Production, profit and soil quality were positively impacted while negative environmental byproducts, such as leaching, were minimized. But when the optimal mix was dominated by inputs other than *sq*, impacts of attaining each objective put the sustainability definitions at odds. For example, increased fertilizer and tillage use needed to attain constant per capita consumption levels on some soils often resulted in *sq* depletion and leaching. In these cases, striving for constant consumption eliminated the possibility of simultaneously attaining constant stock and intergenerational objectives. Moreover, since inputs were imperfect substitutes, added inputs could not compensate completely for the loss of more and more *sq*. Therefore, as *sq* is further decreased the negative impacts to production, soil stocks and environmental byproducts associated with losses in *sq*, could increase many fold and render one or more interpretations of sustainability unattainable. On two susceptible soils, added inputs could not compensate for *sq*'s contribution to yield over time and as a result, sustainability defined by this interpretation of constant consumption was not attainable on these soils.

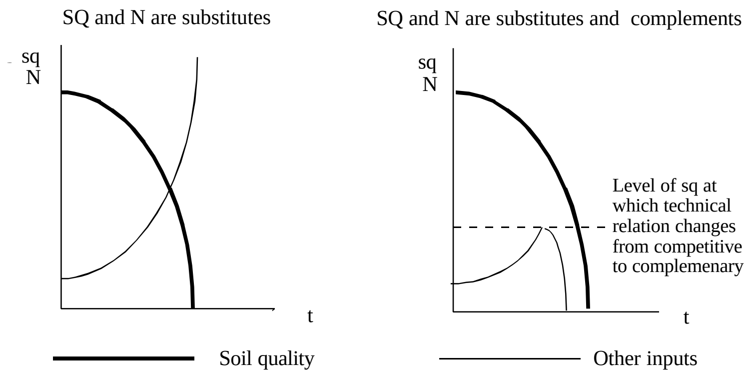
Once a substitute does not always make a substitute

There are two reasons why susceptible soils could not meet all the objectives over the full 100 year period. The inability of other inputs to perfectly substitute for decreases in the availability of good *sq* is one reason. Changes in the *TI* relationships over different levels of input use is the other.

The production function was estimated as a transcendental $Y = Ax_1^{a_1} e^{b_1 x_1} x_2^{a_2} e^{b_2 x_2}$ (5)

The estimated function described predominantly imperfect technically competitive relationships

Figure 3 Tradeoffs between *sq* and applied nitrogen under different technically interdependent relationships



between *sq* and other inputs when the quality of the soil was good. On stable and neutral soils, where quality stabilized at high levels (as seen in Figure 1) other inputs were able to compensate for the modest loss in *sq* over time to meet sustainability objectives. But at low levels of *sq*, the imperfect substitute relationship between *sq* and other inputs often turned complementary. Thus, on susceptible soils, as *sq* was increasingly degraded, substitution efforts became less and less effective until the relationship between *sq* and most other inputs turned complementary. As shown in Figure 3, once complementarity was established, the optimal use of a compensating input (such as fertilizer) which had been increasing through time, started to decrease. As both the compensating input and *sq* were less productive, yields fell and the constant consumption conditions could not be fulfilled on susceptible soils.

Once sustainable not always sustainable

All three objectives were met easily and simultaneously on stable soils. Neutral soils attained the three objectives with three different optimal input mixes. Even susceptible soils attained most objectives. But are these decisions optimal when reversibility and uncertainty are considered? That depends upon how easy it is to reverse input use decisions when an unforeseen circumstance arises.

On stable and neutral soils, when *sq* reached a steady state, the input mix also stabilized. These optimal mixes are easy to reverse because as seen in Figure 2 both *sq* and added inputs (insomuch as they have only been used in small quantities relative to *sq*) are plentiful. Therefore, as long as competitive input relationships exist, should any internal or external shock develop, the optimal input mix can be adjusted easily to reduce the input associated with/impacted by the shock and to increase the use of another in its place. However when *sq* is gravely degraded below any steady state level, a producer cannot reverse his input mix when a shock occurs. In this case not only will negative consequences persist but they may increase at increasing rates over time. In this case, management decisions once thought to be sustainable may not truly be sustainable when managers who have followed an irreversible use of *sq* encounter a negative unexpected event.

Conclusions

To summarize, we have developed a framework to examine endowments of resource quality used in a production process. Soil quality used for agricultural production purposes was applied to our framework in an empirical example to better understand three interpretations of three definitions of sustainability and three criteria used to evaluate them.

We demonstrated in our framework that different endowments of a resource quality can change over time in different ways. When this endowment is used in a production setting, competitive inputs will respond differently to different changes in resource quality when targeting a given objective of sustainability.

In our empirical example we learned that when soil quality is good and abundant, it will be preserved so that multiple sustainability objectives can be fulfilled simultaneously with little worry of irreversibility or uncertainty. But when soil quality is depreciated and substituted away in favor of other inputs, sustainability objectives will likely compete with each other. Losses in soil quality can result in negative economic, environmental and/or social impacts, depending on which sustainability objective is targeted. Furthermore, when soil quality is depreciated, changing technically interdependent relationships and potential irreversibility and uncertainty conditions can render sustainability objectives unattainable.

While this research is the first step in uncovering the relationship between the path of change for a unique natural resource endowment and its use in production processes, the results may be used to: 1) help determine which soils need to be protected, 2) identify tradeoffs between conservation and nitrate leaching as erosion occurs, 3) show how risk and uncertainty (as defined here) affect soil quality conservation and 4)provide other information helpful to policy makers dealing with soil management. For example, a related implication of these results is that because producers have no economic incentive to conserve poor soils, government intervention may be necessary if society targets sustainability objectives on these soils.

Finally, the concepts that were demonstrated by this example may serve as a guide for addressing other interpretations of sustainability (that is other interpretations of constant consumption, constant stock and intergenerational equity) and/or other endowments of resource quality. It may eventually be extended to more complex issues such as concurrent management of multiple natural resources, such as water, forests, and fisheries. The important characteristics that influence an endowment of another resource can be included in a quality representation and then placed in models to simulate scenarios to examine a number of concerns, including those addressed here.

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