Finessing Productivity as an Indicator of Agricultural Sustainability

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NR385: Theory of Ecological Economics
December 17, 2003

ABSTRACT

Despite a near universal acceptance of the importance of sustainability in agriculture as well as a relative convergence of ideas and definitions regarding the concept, agricultural sustainability has remained an elusive concept to operationalize. Indeed, while various indicators of sustainability abound, none have been adopted on a wide scale or applied to a significant number of agricultural operations. Yet, the development of a readily measurable indicator of on-farm sustainability would be an extremely useful guide to farmers and policy makers seeking to increase the sustainability of current production systems as well as to consumers who wish to purchase products from farms that are not simply organic, but actually pursuing a highly sustainable course of production.

After an overview of various frameworks for defining sustainability and the crafting of related indicators, I shall examine the ways in which productivity can be used as a measure of sustainability. Productivity is a term that carries a lot of baggage amongst those in the environmental movement. However, a farm is first and foremost a system of production, and therefore, productivity must remain a focus when analyzing the health and sustainability of an agricultural operation. Further, by viewing productivity through various lenses, I believe it is a concept that can be finessed to reveal significant information regarding the sustainability of a farm system. I shall discuss various ways of approaching productivity, the advantages and disadvantages of using it as an indicator of sustainability, and ways that it might be operationalized to feasibly provide much needed data regarding a farm's ability to persist into the desirable future.

1. Introduction

"The appellation of the word 'sustainable' to a farming system remains a matter of opinion. Most farmers and agricultural professionals have a 'feel' for what 'sustainable' is, in the way it is currently applied to agricultural systems." (Smith, 1994:4) Although this quote is nearing ten years old, it still captures the state-of-the-art in our ability to determine whether or not a farming system is sustainable. This is true despite the fact that, as Rodale pointed out some years back, being sustainable is like being pregnant--either you are or you aren't. (Hansen, 1996:135) Although the definitions of sustainability are legion, ranging from the mundane to the cryptic, the difficulty with developing a litmus test for agricultural sustainability is more a reflection of the inherent complexity of a farming system than it is of our inability to reach consensus regarding a specific wording that encapsulates what we mean by a sustainable agricultural system.

Attempts have been made to assess the sustainability of a variety of agriculture-related systems at numerous scales. Food sustainability has been analyzed at the individual farm scale (e.g. Gomez et al., 1996, and Rigby et al., 2001), as well as the production system scale (e.g. Gerber-Leenes et al., 2003 and Dutilh and Kramer, 2001). Geographic scope has ranged from the individual farm to the village level (e.g. Di Pietro 2001) to the regional (Giupponi, 1998) to the global (e.g. Tilman et al., 2002 and Penning DeVries et al., 1995). The significant majority of definitions of sustainability used reduce, at least in essence, to that given by the Food and Agriculture Organization of the United Nations: "A sustainable agriculture is one that, over the long-term, enhances environmental quality and the resource base on which agriculture depends; provides for basic human food and fiber needs; is economically viable and enhances the quality of life for farmers and society as a whole." (FAO, 1989)

The need to guarantee the sustainability of our food system is obvious, and the foundation of the modern human food system is agricultural production. To most, it is equally clear that current agricultural practices are not sustainable, given the trends of the past one hundred years, and certainly when projecting into the future when world population is expected to grow another 50% and dietary demands by an even greater rate as a significant portion of humanity shifts their caloric intake from subsistence toward a more affluent diet heavy in meats and other energy-intensive comestibles. (Tilman, et al., 2002) Large scale soil erosion, groundwater depletion, salinization of soils, phosphorous and nitrogen run-off into surface waters, environmental contamination by the persistent toxins found in pesticides and herbicides, loss of habitat, and an extreme reliance on diminishing fossil fuels for energy and fertility maintenance are some of the major issues confronting modern agriculture as it seeks to adapt to the reality of food production on a world of limited resources and a finite capacity to absorb our wastes.

It is precisely the dire impacts of current agriculture that lead to the "feel for sustainability" referred to at the opening of the article. Clearly, a sustainable agriculture would not deplete groundwater resources, would not irreparably contaminate soils or allow topsoil to erode away, would have a plan for life beyond fossil fuels—all this while at the same time maintaining a sufficient level of production and providing a viable economic existence for the people involved. Yet despite such a readily available "sense" of what sustainability means, the concept has proven to be quite difficult to operationalize. As noted by Izac and Swift (1994:106), the intuitive definitions "…are attractively holistic, but too vague and ambiguous to lead to clear cut measurements of the sustainability of specific agroecosystems."

2. Characterizations of sustainability (Hansen, 1996)

A single farm system, be it a large scale monoculture or a highly diverse vegetable operation, is a multilayer, hierarchical system whose complexity rivals that of a national economy. Scientists are just beginning to understand the linkages and interactions between different components, within and across scales, and a thorough understanding of the behavior of such a system is still far beyond our reach. This is further compounded by the fact that the attempts of the last 60 years to greatly simplify agricultural systems—by replacing complex biological interactions with simple nutrient flows and taking extreme measures to eradicate all life forms except for the anointed crop—have led to a dramatic decrease in sustainability. It seems clear that efforts to increase sustainability will generally lead to increased complexity and diversity within agroecosystems making reductionist modeling and analysis even more difficult.

Despite such complexity, there are certain behaviors and characteristics of agricultural systems that have come to be deemed desirable and gathered under the rubric of sustainable agriculture. Hansen (1996), based on an exhaustive review of attempts to characterize agricultural sustainability, identified four frameworks in which researchers are approaching the concept of a sustainable farm system.

2.a. Sustainable agriculture as an ideology or philosophy

Sustainable agriculture as an ideology focuses on a set of values that it believes should be embodied in the production of food. Such values are often juxtaposed to those deemed inherent to conventional agriculture. A partial list of such values would include diversity, self-sufficiency, respect for nature, decentralization, and equity. Examples of defined approaches to farming that hold themselves to be sustainable include organic farming, biodynamic farming, and permaculture. Hansen (1996) and others point out that such a definition of sustainability is often developed as a reaction to “conventional agriculture”, a somewhat artificial concept which has been stretched to the edges of caricature and is not necessarily representative of the majority of modern farmers.

2.b. Sustainable agriculture as a set of strategies

Under this characterization, a variety of practices are delineated that are seen as conducive to sustainable food production. Farms that confine their practices to this set of strategies are deemed to be sustainable. Practices are chosen by their ability to maintain production while limiting environmental impact. As with sustainability as an ideology, strategies are often developed in reaction to conventional methods that have proven to be destructive. Such strategies include organically-derived pesticides and soil amendments and low stocking rates for animals. Other practices are developed based on an ecological analysis of farm systems. These included integrated pest management, crop rotations, rotational grazing, and a maintenance of a high level of soil organic matter.

This second concept of sustainability readily lends itself to the development of indicators. Rigby et al. (2001) evaluated 237 farms in the United Kingdom using an aggregate measure based on practices used. Strategies that fell within an approved set were given a weighted, positive score while those that were deemed detrimental were given negative scores. The final indicator was the summation over all practices yielding a continuous rather than binary evaluation of sustainability. Taylor et al. (1993) followed a similar tact though in a greatly restricted context. Narrowing the focus to a specific crop within a particular regional enabled their measurements to be more refined.

Such indicators beg the support of later empirical analyses of sustainability. For, as Hansen states (1996:126): "If strategies are identified as sustainable based on their effect on agricultural systems, and agricultural systems are then judged to be sustainable based on their implementation of sustainable strategies, ...a form of circular logic results." Just as an example, prior to the development of the methods that now characterize conventional agriculture, there were still farms that were ecologically unsustainable despite their de facto avoidance of "the bad.".

Hansen also notes (1996:125) that any characterization of sustainability as an approach ignores the potential contextuality of the prescribed methods. Sustainability in the wealthy expanses of the United States, where food and resource surpluses are a given, must have a different operational meaning from resource poor areas where reductions in production generally mean an increase in malnutrition and starvation.

2.c. The ability to satisfy a diverse set of goals

Here again we see a response to "conventional agriculture", this time questioning the ends more than the means. The green revolution has epitomized the myopic focus of modern agriculture upon one goal—the maximization of productivity. The successes achieved in attaining this goal are undeniable with yields/hectare having tripled while calories/person in developing countries have increased by 50%. (Conway,1997) But the documented environmental and social costs are devastating and threaten the stability of the entire system. This has led to a characterization of sustainability as the ability to maintain production while at the same time maintaining or improving the natural environment and revitalizing rural cultures and families. Other goals are also put forward. It is within this framework that the FAO definition given earlier was developed.

2.d. The ability to continue or persist

This seems the most intuitive application of the traditional idea of sustainability. It certainly stands as a prerequisite to all other definitions since the farm that perishes prematurely cannot be seen as having the ability to sustain itself or the broader human system. This is the framework within which I will work to analyze the ways in which productivity can act as an indicator of sustainability.

This conception of sustainability is presented in a broader context by Patten and Costanza (1995) who state: "*a sustainable system is one which survives or persists*." (p.193) They note that this immediately raises two specific questions that must be answered if an operational definition is to be had: (1) What system should persist? (2) For how long? In particular, they point out that no system persists forever, and the reasonable and healthy life span of a given system is dependent on its scale and function within the larger hierarchy of a metasystem. (p.195)

These are important questions when deciding how to assess agricultural sustainability. According to Lynam and Herdt (1989:383): "Much of the confusion in the discussion of sustainability reflects a mixing of systems levels, namely the lack of recognition that a plant photosynthetic system is embedded in a plant system which is embedded in a cropping system which is part of a farming system, which lies within the international market system." Each level has a different expected life span as well as different characteristics that pertain to its ability to persist. For my purposes, the answers to these questions are as follows. The system I am concerned about is the farm as an economic and ecological entity. It should persist for as long as its existence is useful to and desired by the family that manages it and the community it serves.

It is important to note that it is arguable whether sustainability is a property that can be assessed at the farm system scale because of the extreme openness between it and the larger metasystem. As Lynam and Herdt note, this depends on the level of dependency within the hierarchy. "Openness creates the very difficult problem of determining when sustainability is an inherent property of the defined system, dependent on endogenous relationships..., or when sustainability is so dependent on external forces that the system level should be upgraded in order to define sustainability accurately." (1989:383) While a resolution to this issue is elusive, I believe it is quite clear that individual farms have an expected life span that is desirable, from an ecological and from a social perspective. It is the ability of a farm to persist in production to the end of this expected life span that we are seeking to measure.

3. Indicators of agricultural sustainability

If the goal is to increase the sustainability of farms and food systems, a characterization of sustainability is an impotent concept if it does not lead to feasible methods of measuring the extent to which a farming system matches a given characterization. Such operationalizing of the concept of sustainability is critical to the ability of researchers to analyze given systems and offer prescriptions to farmers and policy makers to increase sustainability at multiple scales. Inherent in this is the idea that the internal workings of an indicator should be sufficiently transparent as to enable identification of potential areas of improvement.

Hansen (1996:134) states that any useful indicator "…should be based on a *literal* interpretation of sustainability," as well as be system oriented, quantitative, predictive, stochastic, and diagnostic. Rigby et al. (2001) also note the need for an indicator to be readily measurable if it is to have practical application. However, feasibility is difficult to assess without clearly stated goals and boundaries of application. Productivity as an indicator will visibly demonstrate the trade-offs between reliability and cost of assessment regarding agricultural indicators.

3.a. Indicators as predictions

According to Costanza and Patten(1995:194), "What passes as *definitions* of sustainability are often *predictions* of actions taken today that one hopes will lead to sustainability." This characterization certainly holds true for attempts at defining, or at least operationalizing, agricultural sustainability, and I would add that the effect is aggravated by the inherent complexity of agricultural systems. While there is a general consensus that certain desirable characteristics at the farm level should lead to a maintenance of production in the future, these characteristics do not define *sustainability*. Rather, we believe them to be reliable *predictors* of sustainable production. It is far from guaranteed that a farm whose internal characteristics meet certain criteria will indeed persist into the future.

To examine this issue further, I believe it useful to divide indicators into two classes, holistic versus reductionist, depending on whether they predict sustainability based on measurements taken of different internal components of the system or on measurements taken at a systems level. There are multiple examples of each kind.

3.b. Reductionist Indicators

A reductionist indicator begins with a predetermined list of components of an agricultural system that it has deemed integral to achieving sustainability. In the indicator developed by Rigby et al. (2001), they give five components they base measurement upon: seed sourcing, soil fertility, pest/disease control, weed control, and crop management. Bockstaller et al. (1997) look at nitrogen and phosphorous flows, pesticide use, irrigation, organic matter, energy, crop diversity, soil structure, soil cover, and ecological structures. Of course, within each of these components, there is also the possibility for much greater differentiation. The Natural Resources Conservation Service (SSSA,1996:395) gives the following indicators merely for the physical condition of the soil: "topsoil depth, bulk density, porosity, aggregate stability, texture, crusting, and compaction."

The assessed state of the selected components is what is used to predict sustainability. This can happen in two ways. First, and ideally, direct measurements can be taken. Soil organic matter, chemical residues in soils and water, levels of biodiversity at different scales, or system energy consumption can all be measured directly and used to assess the health of the agroecosystem. The probability of future sustainability is than derived. An indicator calculated in this manner I will call a primary predictor because it relies on primary data to make its prediction.

Less ideal but more common (Rigby et al., 2001; Taylor et al., 1993; and Bockstaller et al., 1997) is to assess the health of various farm components by looking at the practices used. Since no direct measurements are taken, another level of prediction must take place—that of the impact of various practices upon certain farm components. For this reason, I call indicators calculated in this fashion secondary indicators. For example, a lack of continuous field cover is predicted to lead to soil erosion, and soil erosion has a measurable impact on productivity. The approaches to sustainable agriculture described by Hansen as being based on a set of strategies lie in parallel to secondary predictor indicators. Such approaches, organic farming being one example, will evaluate as sustainable under certain indicators merely because of the components chosen for indication and the attendant predictions based on specific practices.

Secondary predictors, by ignoring systems interactions, have limited relaibility. The application of a synthetic nitrogenous fertilizer does indeed risk contaminating nearby groundwater, but the level of risk and of potential contamination do not lie in a simple Boolean state. Amount and method of application, tillage methods, and weather patterns all affect the flow of the soluble nitrogen. Indeed, it cannot be assumed that such usage will automatically lead to greater nitrogen run-off than the spreading of manure, an approved organic method. This is reflected in the arguments of several writers who have pointed out that at least one methods approach, that of certified organic farming, should not be assumed to be a subset of sustainable farming techniques. (Rigby and Caceres, 2001; Ikerd, 1993)

Secondary predictors also often fail to take context into consideration. Local geological, hydrological, and ecological characteristics are all factors in determining the impacts of different tillage, pest control, and fertility maintenance practices upon the future productivity of a farm. Regarding impacts upon the broader system, the specific location of a farm within a region is quite important in determining the effects of the farm and its practices upon water quality, air quality and local biodiversity as demonstrated by Giupponi (1998:81).

3.c. Holistic Indicators

In contrast to reductionist indicators, a holistic indicator looks at systems level phenomenon in order to form predictions of sustainability. Two such indicators are a non-negative time trend in output (Lynam and Herdt,1989) and total factor productivity. Similarly, Conway (1997:174) describes three systems level properties that are pertinent to sustainability as the ability to exist. (His fourth property, equity, lies outside the scope of this paper.) A sustainable system should maintain a high level of productivity, should feature relatively stable production, and should be highly resilient. This last property in particular has become more dominant in the literature, in part due to its greater predictive ability.

Note that systems level indicators do not escape the fact that they are merely predictors of sustainability. Sustainability cannot truly be measured until sometime in the future. (Costanza and Patten, 1995) Also, Conway (1997) has demonstrated that complex systems may be degrading internally without signs of degradation at a systems level until a collapse is precipitated in a relatively short period. However, systems that have demonstrated a high level of resilience are less likely to be hiding internal degradation.

4. Productivity as an indicator of sustainability

In one manner or another, every framework of sustainability and every indicator examined has dealt with the productivity of a farming system. Several incorporate it outright by defining stable and/or high levels of production to be goals of a sustainable system. For others, it is an implied goal within the measure (e.g. soil health is considered crucial to sustainability because soil health is crucial to production).

Indeed, it is meaningless to discuss the sustainability of a farm system without discussing productivity because: *A farm or agroecosystem is first and foremost a* <u>*system of production*</u>*.* It is for this reason that several researchers take a non-decreasing time trend of productivity as *the* defining element of a sustainable system. (Lynam and Herdt, 1989) While an agroecosystem may provide other amenities and have other goals, both social and environmental, its primary function is to take inputs and convert them into humanly desired outputs. Any system that fails to continue to do this in an efficient manner cannot be considered a sustainable agroecosystem.

In particular, I will argue that a nuanced assessment of productivity as it relates to Conway's three conditions will give significant information regarding the sustainability of a farm system. In particular, when examining productivity, it is necessary to consider multiple components of production and to analyze its trend over time. Following Conway, that trend should be non-decreasing, display relative stability, and where appropriate, demonstrate a high level of resilience. The time frame necessary for conducting such an analysis is not obvious, but according to Lynam and Herdt (1989) is likely to be between 5 and 20 years. It should also be born in mind that a time trend analysis implies an intrafarm comparison, not interfarm. Where appropriate, certain forms of productivity should be analyzed relative to other farms. But using simple economic productivity as an indicator of sustainability between farms can have the negative effect of encouraging unsustainable levels of production.

4.a. The theoretical model

In essence, the health of an agroecosystem is intimately connected to its ability to efficiently convert inputs into outputs. If an agroecosystem fails to do this, it cannot be considered a healthy farm system. Somewhere, there is a damaged or improperly functioning component within the system—whether it be soil structure, farmer management, genetic diversity, or an altered environment—that ultimately threatens the farm's ability to persist, either economically or ecologically. Conversely, if a farm system is performing well in terms of production, it is difficult to suggest that it has shortcomings that might impair its sustainability. Certainly this cannot be a foolproof assessment, but then neither is any indicator.

The crux of the issue revolves around how to conceive productivity. The term rankles the feathers of ecological economists precisely because historically it has been narrowly defined, not just in agriculture but in all systems of economic production. To conceive of productivity merely as the ability to maintain a high profit margin is to do a great disservice to a valuable concept. While I shall argue that such an economic conception is one important facet of productivity, it is not the only one, nor the most important[1].

To be precise, productivity will be defined as *a* ratio of outputs to inputs. It need not be all inputs or all outputs, and the method of measuring either category can take various forms. Indeed, it is precisely the different ways in which we can assess inputs, outputs, and their ratio that leads to a wealth of information. But regardless of the particular form, there is a single principle that guides the analysis—<u>what you get out compared to what you put in is the determinant of the health of a system of production</u>.

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[1] As an example, Herman Daly's definition of economic efficiency as Utility/Throughput is really a form of productivity.

4.b. General arguments against productivity as an indicator

Without elaborating on specific ways of assessing productivity, there are some general reasons to be suspicious of its efficacy as an indicator. Such critiques at the systems level must be born in mind as I attempt to finesse critical information from an assessment of productivity.

4.b.1. Weak assumption of sustainability

By assessing the health of a system based on its productivity and thereby ignoring qualitative and quantitative measurements of the types of capital that make up a farm system, I am allowing for substitutions to take place between types of capital without necessarily impacting sustainability. In general, the condition of maintaining a total level of capital is considered a weak condition for sustainability. This is contraposed with a strong condition of sustainability as described by Costanza and Daly (1992) in which stocks of natural capital in particular must be maintained. They and other ecological economists have rightly argued that as regards stocks of natural capital, the precautionary principle dictates a far more conservative strategy than has driven economic decision making. "While a lower stock of natural capital may be sustainable, society can allow no further decline in natural capital given the large uncertainty and the dire consequences of guessing wrong." (1992:1)

However, on the farm scale, I would contrast this with the following statement from Izac and Swift (1994:110): "The farmer will be concerned with the overall performance of the farm as much as with individual fields. It may be perfectly acceptable for one part of the farm to be degrading during a particular time period, as long as the overall trend is positive." Due to fluctuations in the physical or economic climate, the farmer may have to adjust methods in different seasons, sometimes favoring the development of some components to the detriment of others.

Natural capital within a farm system is vital to its productivity. But an agroecosystem is a complex system that is constantly developing. Farmers, in order to adapt to exogenous forces, often alter their practices in ways that affect stocks of natural capital. Such adaptations are at times critical to remaining viable. In assessing the sustainability of the system, I believe a strong sustainability assumption is not necessarily appropriate at that scale. However, at the same time, we want to guard against optimistically assessing a farm operation that is replacing healthy soils with fossil-based fertilizers.

4.b.2. Hidden internal degradation may lead to catastrophic shift

"Unsustainability can express itself either as a gradual change or as an abrupt collapse." (Hansen 1996:131) Internal degradation within a system may not be evident until a system transitions to a new state through a process of catastrophic shift. Models of different ecosystems have shown that there can be multiple states of equilibrium for the same set of current conditions (hysteresis). The basin of attraction is determined by the previous state, and once a transition occurs, recovery can be difficult or impossible. Desertification is an example of such a process. Once sufficient land cover is lost, recovery is impossible, even with a restoration of previous conditions that once were productive.

Theoretically, such a transition could take place within an agroecosystem that, based on aggregate measurements, appeared quite stable. Internal degradation could precipitate a sudden collapse without prior warning at the systems level. This would imply a need for periodic monitoring of internal conditions despite relative signs of health in terms of productivity.

However, it is arguable that catastrophic collapse must be preceded by at least some decline in systems level health and productivity. Scheffer et al. (2001) present a discussion of hysteresis and describe the s-shaped curve that leads to a bifurcation in states. Their models clearly show a decline in the ecosystem state prior to collapse. The question is not so much about whether degradation can be hidden, but about the degree of degradation relative to systems level behavior. This is the case with desertification, and arguably the case with agroecosystems.

4.b.3 Farm productivity ignores impacts on metasystem.

A narrow focus on the internal productivity of a farm ignores the possibility of negative impacts of the farm operation upon the broader systems that contain and sustain the farm. Certainly a strictly economic analysis ignores such externalities. In particular, a farm can affect the sustainability of the larger metasystem. An agricultural operation might:

- Contaminate surface waters by pesticide and fertilizer run-off leading to increased toxicity for aquatic life and algal blooms;
- Contribute to global warming through a strong dependency on fossil fuels to power machinery and produce synthetic fertilizers;
- Impair human health by impacting groundwater via chemical leaching;
- Impair local ecosystems services by reducing habitat or fouling the air with animal odors;
- Provide significant amenities through multiple uses such as tourism and education.

As noted by Izac and Swift, "Because these processes transcend farm boundaries, study at [a higher] level is necessary in order to account for the external effects of farming practices, which are by definition ignored at the crop- and farm-system scale." (1994:112) Elements of a farming operation that impact the sustainability of the broader metasystem are not typically captured by an economic productivity analysis because they are elements whose true economic cost (or benefit) is undervalued because they are external to the market mechanism. This leads to suboptimal decision making on the part of farmers, policy makers, and consumers.

An analysis of productivity, however, need not remain within the bounds of a flawed system. As a system of production, a farm serves to take in inputs and convert them to outputs that hopefully have value to society. Outputs that have a negative impact on society should be part of the productivity analysis, at least at certain levels. Similar, unvalued benefits of agricultural production, such as habitat preservation for song birds or carbon sequestration, should also be incorporated. The key is to select an appropriate lens.

4.b.4 Incommensurability of inputs and outputs

When calculating agricultural productivity and conducting interseason comparisons, an immediate difficulty encountered is how to measure both input and output in a commensurate fashion. If the same exact inputs were used each season to produce a certain yield of the same crop, calculating productivity for purposes of comparison would be quite easy, even if commensurability was never attained between the numerator and the denominator. But clearly inputs change from year to year, not just in quantity, but often in substance as well. Further, it is clear that many farms produce more than one crop in a given season, and many more change and diversify their operations from year to year.

It is precisely what components of input and output we choose to examine and the ratio formed between them that enables productivity analysis to lead to a suite of indicators regarding the sustainability of an operation. When dealing with a complex system whose goal is the production of a variety of good and services, commensurability is a crucial issue that should not be seen as an obstacle, but rather as an opportunity to derive significant and diverse pieces of information about the system.

4.c. General arguments for productivity as an indicator of sustainability

It is well worth presenting some sound theoretical arguments for why productivity can be the basis of a reasonable sustainability indicator given the role it has played in the development of a highly unsustainable agricultural system. Economics and yield have been the battle cries of agroeconomists and international aid agencies as they have devastated rural economies the globe over. The logical response by many has been to disconnect productivity from sustainability. To do so, however, not only shuns a valuable empirical tool, but has also created barriers between environmentalists and farmers, two groups that by all sane reasoning should be valuable allies to each other!

4.c.1 Necessary condition for sustainability

No matter which framework is used to examine productivity, it is clear that a stable and appropriately high level of productivity is a necessary condition for a farm operation to persist. Farms that are economically inefficient will not be able to compete and, no matter the laudability of their ecological design, will not remain around. Similarly, those that squander biological resources will eventually lose out to those that use their natural capital effectively. This is especially true as temporary fixes such as fossil-based fertilizers and pesticides become more expensive and regulated.

Any indicator that can deem a farm sustainable when in reality that farm is on the brink of economic collapse is an inappropriate indicator. The struggle to make agriculture more sustainable must begin with economics. Farmers more than any other constituency wish to preserve and protect the natural and social systems underlying agriculture. The structure of federal policies, guided by the agrochemical industries, has forced farmers to choose between survival and sustainability. At the farm scale, there is no long term without a short term, and sustainability analysis needs to recognize this.

4.c.2 Addresses complexity of farm system

At the farm level, the numerous elements that make it a system of biological production form a web of interaction far more complex than any other system of economic production. A preliminary examination of just the soil components that affect productivity demonstrates clearly the degree of complexity involved. Populations of soil microbes, nematodes and macroinvertebrates, weed seed counts, levels of macro and micronutrients, salinity, pH, organic matter, etc. all combine (and interact) with various other elements to give the farm an inherent level of potential productivity. When manipulated by the farmer and combined with various inputs such as seed, fertilizer, labor etc., this potential productivity results in an actual harvest. However, I believe that the inherent complexity of the system is such that it is impossible to select any one component, examine the variation within it, and thereby develop any reliable prediction of the impact upon future viability.

At best, changes at lower scales can be classified as either positive or negative, though even this is not always a safe venture in a complex agroecosystem. A measured change in soil structure that increases root penetration most likely will lead to greater production. However, under certain cultivation methods and weather conditions, it is quite possible that the same change in soil structure will also lead to greater soil erosion and an eventual decrease in production. The interaction of the various components, especially given the great variety of contexts in which agriculture occurs and the array of technologies used, indicate that it is only at higher levels of the system that a true analysis of sustainability can occur.

4.c.3 Micro-level freedom with macro-level control: Farmers as adaptive managers

"...considerable evidence suggests that in many circumstances, the overall costs to society of reaching a given target are higher under regulation than under mechanisms that allow a maximum of micro-level freedom...subject to macro-level control." (Daly and Farley, 2003:385) This is a relevant design goal of ecological economics. Regarding the sustainability of agriculture, the dominant goal is the ability to maintain production indefinitely, particularly at the national and global levels. For our purposes, the macro-level goal is for a farm to be able to maintain production for as long as such production is desired by the family managing the farm and by the community served. Relevant analysis of other systems of economic production suggests that the best way to do this is set systems level goals while at the same time enabling micro-level actors to innovate and use their knowledge to craft the most efficient means.

Another way to interpret this is to view farmers as adaptive managers of the farm systems they operate. The interactions between a farmer and the system he or she manages are far too intricate to evaluate on a component by component scale. In order for modern agriculture to transition to a sustainable mode of production, it is critical that the knowledge possessed by individual farmers be given full reign to address the unique problems faced by each farm in its particular context. Indeed, farmers are constantly developing unique, small-scale technologies, such as new cultivation or irrigation methods, or locally-adapted seed varieties, that enable them to remain productive in the face of exogenous changes such as an altered political, economic, or climatic environment. (Lynam and Herdt, 1989:386) Productivity details how successful a farmer is in this endeavor far better than any measure that seeks to pass judgment on individual practices separate from their role in the entire system.

5. Finessing productivity as an indicator

5.a. General analysis

Regardless of what form productivity takes, there are some general rules regarding its basic structure and what characteristics are measurable and desirable with regards to predicting sustainability.

- Productivity is always measured as a ratio of outputs to inputs.
- Inputs and outputs can be measured in direct physical units (e.g. weight, acres) or in derived units (e.g. calories, dollars, etc.)
- The trend in productivity over time is the relevant topic of analysis where a minimum time-frame of several season is expected.

Drawing on Conway's analysis (1997:174), four characteristics of productivity can be assessed.

Relative level of productivity:

Relative to the given context and goals of production, does the farm achieve an acceptable level of production? This requires a judgment pertaining to appropriate levels of productivity and is the least pertinent of the four characteristics to sustainability. If a farm has persisted for twenty years at a given level of productivity, it would seem that it is operating at a sustainable level regardless of its relevance to other goals. However, some categories naturally suggest thresholds of acceptable productivity. For example, when measuring the ratio of total energy of outputs to inputs, a level below one strongly implies unsustainable production.

Time trend of productivity:

Productivity should show a non-negative trend over time (Lynam and Herdt, 1989). This is the most pertinent of the four characteristics. A decline in the ratio of outputs to input, especially when measured in physical terms, implies a decline in the capital of the system. If such a decline persists over time, it predicts that the farm system will eventually cease to meet the needs of either the family that manages it or the community it serves.

Stability:

All measures of productivity should be relatively stable. A high degree of variability implies a strong potential for failure in meeting economic goals and a likelihood of dropping below certain ecological thresholds. It also implies a greater sensitivity to conditions and therefor a greater likelihood for the termination of the operation due to exogenous pressures. Stability can be measured by the coefficient of variation.

Resilience:

An agroecosystem should have the ability to maintain productivity when subjected to a stress or shock. When a system with low resilience is perturbed, it either settles into a lower state of productivity or collapses. A highly resilient system should quickly return to former levels of productivity. Potential shocks could include price swings, droughts, a lifting of trade barriers or subsidies, or a personal crisis for the farm family. Resilience, a concept drawn from ecology, is a potent indicator of sustainability. However, it cannot be measured in the absence of a perturbation, and local perturbations may require more research than is feasible.

5.b. Frameworks for assessing productivity

Five frameworks are presented for assessing productivity. Each one focuses on a different component of agricultural production and presents its own requirements in terms of data collection. The distinguishing characteristic of each is what elements of the input and output are focused on and what units are selected for measurement.

5.b.1. A physical assessment - energy productivity

To calculate energy productivity, inputs and outputs must be assessed for caloric content. Inputs incorporated into the calculations include all consumed fuels, all amendments, and any draft animal power used. Human labor can be included but generally is an insignificant component. Each element including machinery, seeds, fertilizers, and pesticides is measured based on a lifecycle analysis. Transportation energy requirements to bring products to market should also be included. Among outputs, only desired products are included in calculations.

In Food, Energy, and Society (1996), Pimental and Pimental conduct an energy productivity assessment at a national scale for numerous agricultural products and nations. Their work clearly demonstrates the reduction in energy efficiency that accompanies greater industrialization and intensification. Energy productivity for rice production in the Philippines using carabao is 3.29, topping efficiency in Japan (2.80) and California (2.1). (1996:121-123).

It seems somewhat obvious that an energy productivity of at least 1 is crucial to sustainability. This is certainly the case when assessing crops for use in producing biodiesel or ethanol for fuel consumption. It is also clear that to be sustainable, a farm should have a non-declining trend in energy productivity. But judgments should not necessarily be based on absolute values. Spinach (energy productivity of .23) and other nigh-nutrient crops often have negative returns on energy but remain vital components of a sustainable food system because of their dense loading of nutrients.

5.b.2. A chemical assessment - nutrient productivity

Calculations of inputs and outputs can be done for a number of different chemical nutrients, most notably nitrogen, phosphorous, and potassium. Information can be gained not only regarding productive efficiency, but also impacts upon the larger system. Nitrogen and phosphorous in particular are significant sources of pollution in ground and surface waters. If outputs are restricted to harvested crops for purposes of calculations, then conservation of matter requires that any chemical nutrient deficiencies between outputs and inputs must be somewhere else. While it is more difficult to assess nitrogen which can escape to the atmosphere, excess phosphorous must either build up in the soil or leach into surrounding waters. Since there is a limit to what the soil can hold, continual deficiencies must eventually make their way out of the system as pollutants.

Nutrient efficiency is also an important factor to assess. One of the primary arguments against the feasibility of organic production on a global scale is the projected demand for nitrogen as a soil amendment. Extrapolated requirements of compost and manure are technologically infeasible, and yet clearly natural gas and petroleum as sources of urea are also limited. For this reason, efficient use of nitrogen is a key indicator of future sustainability.

5.b.3. A biological assessment - biomass yield

Biomass production per hectare is another possible assessment of productivity. It is a crude assessment in the context of agriculture and is more suited to the analysis of forests or ecosystems. Yet intuitively, the concept of biological productivity seems to be at the heart of agricultural production which is after all a subset of biological production. This is particularly true in contexts where quantity of production is more important than what is produced, for example in the production of biomass for conversion to ethanol or biogas.

Since biomass is an insignificant input to most agricultural systems, it seems infeasible to have a true biomass productivity[2]. Yet, by only focusing on land area as an input, biomass yield allows for a great deal of substitution between natural and manufactured capital. Degradations in the agroecosystem can be masked by replacing damaged soils with synthetic fertilizers, reduced biodiversity with pesticides, and inherently reduced yields by the use of higher producing varieties.

However, it is possible to make adjustments to glean more knowledge from biomass yields. Adjustments can be made for improved varieties in much the same way that prices over time are adjusted for inflation. It is also possible to do a total factor productivity analysis using biomass as the dependent variable and land, fertilizer, and agrochemical use as the dependent variables. In some contexts with limited resources, capital substitution is simply not an option making biomass yield a more effective indicator.

5.b.4. An economic assessment - financial productivity

When assessing total productivity, it quickly becomes important to be able to aggregate diverse inputs. None of the previous measures of productivity are able to accomplish this, including energy analysis which completely ignores land as an input. This is one of the primary advantages of an economic productivity analysis. In particular, within this framework, all inputs and outputs are evaluating according to market prices and given a value per unit in dollars. Traditional accounting practices are used to determine what essentially is profit margin.

Despite the relative ease of calculation and the convenience of commensurability amongst inputs and outputs, this is the measure that creates the most rancor amongst ecologists and environmentalists. The market is indeed a fickle and unreliable assessor of value. However, there are some advantages to this measure that beg appreciation. First, as noted earlier but worthy of repetition, a positive level of economic productivity is a necessary condition for sustainability. Until economic systems reflect a higher level of ecological wisdom, no farm will survive unless it is financially solvent. Second, economic productivity directly relates to a major component of most concepts of sustainability—the wellbeing of the farm family. Too many farmers are paying for greater ecological sustainability with their sanity and the wellbeing of their families. Too great a cost in terms of human capital will eventually affect the ability of the farm to persist.

Finally, it is important to bear in mind that agriculture is an anthropocentric endeavor with humanly defined goals. Production of an farm system cannot be fully evaluated without incorporating somehow the utility that production has for human communities. Since very few farm operations, CSAs being a notable example, have direct consumer input in their production decisions, the dollar value of their products is the best proxy we have of the utility these products provide to people. An increase in economic productivity could very well reflect a greater contribution to human welfare at a reduced cost.

It should be noted that because of the extensive affect of policy upon the agricultural market place, economic productivity can be calculated in two ways: within the current policy

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[2] This will change as farms become more dependent on inputs of raw organic matter and less upon refined fertilizers.

framework including subsidies, taxes, price supports, cost-shares etc., or in a policy-neutral framework that assumes no intervention by the government. Given the unreliable and contextual nature of agricultural policy, for the purposes of predicting sustainability it probably makes the most sense to calculate economic productivity in a policy-neutral framework.

5.b.5. An ecological economic assessment - Pigouvian productivity

The most obvious flaw with using financial productivity as a method of analysis is the inability of the market to capture externalities. Elements of a farming operation that impact the sustainability of the broader metasystem but are not measured via a purely economic analysis are typically elements whose true economic cost is undervalued because they are external to the market mechanism. Similarly, there are several undervalued amenities that a farm provides that also fail to make their way into an economic analysis. This failure, however, is not an inherent flaw in productivity as a measure but rather lies in the reliance upon the market to place values on inputs and outputs.

Productivity can be finessed to incorporate values external to the market through the application of theoretical Pigouvian taxes and subsidies. Such taxes traditionally have been used to (1) attempt to recoup some of the external costs associated with a commodity or production process, and (2) attempt to create a market optimal price for the commodity or process that reflects its true costs and/or benefits to the general welfare. The goal is to address the problem of externalities with the least amount of interference in the market.

Such levies are often referred to as "sin taxes" in the popular media, but this appellation poorly colors their application to agricultural practices. The use of a synthetic, nitrogenous fertilizer that leads to a significant increase in production certainly has benefits to the greater community in the form of a more secure and less costly food supply. To label such methods "sinful", which the environmental movement sometimes appears to do, is inappropriate and hindering in its polarizing effect upon much-needed debate. However, we must be equally frank in acknowledging the costs in terms of greater nitrogen run-off than would result from more stable organic forms of nitrogen. These costs are not reflected in the current market price of urea or any other synthetic agricultural amendment.

The externalities associated with farming, be they part of conventional or alternative agricultural methods, have not, by and large, been addressed through legislation or regulation (due in no small part to the significant lobbying power of the agrochemical industries.) However, it is still the case that an expert judgment can be ascertained regarding what level of Pigouvian taxes might be suitable regarding a particular practice. It is precisely the application of Pigouvian taxes based upon expert judgment to an economic analysis of productivity that allows the calculation of an indicator of ecological economic productivity, what I shall call Pigouvian productivity..

To achieve this, theoretical prices must be established for at least the most common of agricultural inputs and outputs. Methods such as contingent valuation, willingness to pay, and willingness to accept can be used to assess externalities associated with fertilizer, pesticide, and herbicide use, loss of habitat, fossil fuel consumption, expected levels of soil erosion, and groundwater use. Numerous beneficial outputs that are normally ignored should also be reassessed including preservation of certain forms of habitat, the development of natural capital, and the vital role agriculture plays in the preservation of rural communities.

It is important to be frank regarding the nature of this task. While market optimal prices theoretically exist for commodities that currently incur external costs (and/or benefits), it is clear that their precise calculation is beyond current economic technology and will be for some time to come. Some have argued that it is an impossible quest with precise values beyond the ken of scientific analysis. (Sunstein, 1994) However, it is possible to apply an “effective” tax upon products with negative externalities in order to use market forces to encourage innovations that eventually remove or reduce the negative elements. The more expensive toxic pesticides are, the greater the incentive to use Integrated Pest Management techniques. A subsidy upon compost would expand the market for compost, thereby increasing production, eventually leading to greater competitiveness with synthetic fertilizers because of economies of scale. As a starting place, it would seem reasonable to apply a combination of taxes and subsidies to achieve the result of making “sustainable” methods competitive with “unsustainable” methods. Indeed, such market-driven remedies to environmental dilemmas are strongly advocated by economists such as Paul Hawken (1993).

Other goals pertinent to sustainability can be addressed in this manner as well including the preservation of natural capital at higher scales. Ecological economist Herman Daly has long argued that the use of non-renewable resources should not outpace the development of renewable alternatives. A Pigouvian tax on fossil fuels that was inversely proportional to remaining stocks would reduce their rate of consumption at the same time that it encouraged the development of renewable alternatives. A similar approach should be taken with irrigation and water consumption. A higher price for water would quickly result in significant efficiency gains. While such taxes and subsidies have not been widely applied, we can effectively determine appropriate levels and use them to determine a new level of cost for inputs as well as a reassessed value for outputs.

The resulting measure of productivity will most likely be quite different from a purely economic assessment. Pigouvian productivity will hopefully indicate whether or not the value of a farm’s production outweighs the costs to society and to the ecosystem upon which society depends. An economically successful operation could have a Pigouvian productivity below 1. Indeed, discrepancy between it and financial productivity can function as a strong indicator to policy makers regarding the economic challenges faced by farmers as they seek out more ecologically sustainable methods.

A time trend of Pigouvian productivity for a given farm would serve as a significant indicator of how successfully a farm is moving toward reducing its impact upon the metasystem. Farms that are able to successfully switch out higher taxed elements for lower taxed or even subsidized elements will see measured improvement in their Pigouvian productivity. Such a measure would provide greater flexibility in addressing farms that are neither 100% organic nor 100% conventional in their methods. A farm may find that it achieves a greater degree of sustainable production by incorporating synthetic elements when deemed prudent. This measure, by looking at the value of output as well as the adjusted value of input, should be able to give a more subtle evaluation of a farm’s performance as it tries to achieve a maximum level of sustainability.

Most importantly, this is the first and only modification of productivity that assesses a full spectrum of impacts upon the larger systems that contain and sustain the farm system. The first three assessments, by examining the efficiency with which a farm system converts inputs to outputs, certainly achieve some measure of its value to society. The economic evaluation provides an even broader scope of assessment for determining the benefits of a farm system. But it is not until we account for the pervasive effect of externalities that we achieve a true measure of the overall effect of a farm upon society and upon the ecosystems that society depends on. As noted, such cost-benefit analysis is not the determining factor regarding the sustainability of a particular farm, but as regards the sustainability of local, national, and global food systems it provides significant information.

6. Discussion

Does productivity, with all its various facets, capture the essence of system health? Clearly, the next step is to carry out some empirical data collection from various farms to examine the trends over time regarding productivity. Ideal analysis would look at twenty years of data from a variety of farm systems including farms that are no longer in operation contrary to the wishes of the farm family. Such an analysis would at the least give an indication of how well productivity functions as an indicator for farm sustainability. It would also provide significant information pertinent to sustainability at higher scales.

Moving to the step of application raises the issue of how difficult productivity would be to operationalize as an indicator. This is a crucial question regarding its practicability. As

Rigby et al. (2001) note, a good indicator should be readily measurable with a reasonable amount of data collection required. This issue haunts any reductionist indicator that is a primary predictor. On-site data collection and analysis of such factors as soil composition, tilth, soil biodiversity, and erosion is time-consuming and expensive with the necessary input of resources per farm staying constant. Secondary predictors, by focusing on practices used, avoid this problem. Secondary predictors can generally be assessed via surveys which are relatively quick and easy to process. Cost in time and resources per farm decreases as more farms are studied. However, the real price is paid in reliability as significant issues such as context and internal systems relations are ignored.

Each version of productivity presented would present a considerable challenge in terms of calculations. This is especially true of Pigouvian productivity. However, one common factor overcomes a significant portion of the barrier to operationalizing this indicator. All forms of productivity analysis require the exact same data—a record of inputs and outputs for each farm. Each indicator is essentially a ratio of linear functions where the input variables are simple the standard inputs and outputs most farms already currently record. The calculation of the necessary functions is a significant task, but it is one time work. Coefficients can be amended and updated as improved methods and data become available, but once a given set of coefficients have been determined, calculations for a variety of farms should be as feasible as the calculations required for any secondary predictor such as that proposed by Rigby et al. (2001).

This issue aside, there are four issues I see that remain to be addressed when using productivity as a method of analysis:

What about unsustainable inputs?

Given the current economic framework, a significant portion of agricultural inputs rely on non-renewable resources. Productivity as an indicator could easily imply the sustainability of a farm because for over twenty years it has performed well as an efficient transformer of inputs into desired outputs. However, if fossil fuels form a critical component of those inputs, how can a farm be deemed sustainable?

It is important to bear in mind the applicable scale when assessing sustainability at the farm level. A farm may eventually cease to exist because of unsustainable dynamics that exist at higher scales. An assessment restricted to the farm scale clearly ignores the possibility of instability at larger scales. National and global food systems might collapse for a variety of reasons including political and economic instability brought about by the demise of the fossil fuel era. A farm-based indicator primarily seeks to address the sustainability of a farm within a given metasystem. This is not to say that analysis at the farm level might not provide information regarding sustainability at higher scales. Certainly a disparity between economic productivity and Pigouvian productivity suggests problems at the agroeconomic level. But assessment at the farm scale is within the context of the current metasystem. Farms that rely on nonrenewable inputs that are more local and have a shorter timeframe for depletion should, however, show signs of unsustainability.

Discount rate

Within economics, the discount rate is an important element in calculating values. Future pay-offs are reduced by a set annual rate to reflect current rates of growth of capital as well as certain levels of risk. On a more intuitive level, people have a stronger preference for what they can have today versus what they might get in a year. Such thinking has led economists to question the idea of intergenerational equity. The propose value of what might be around in twenty or a hundred years is diminished to almost nil when a discount rate is applied. By assuming that all value is constantly increasing, it makes no sense to set aside until later what can be consumed today.

This issue is pertinent to calculating productivity. Purely economic productivity, based on revealed preferences in the market, would be expected to display the effects of a discount rate. The need to conserve natural capital for the future arguably would be negated by current benefits derived from depleting it today. However, Pigouvian productivity should be structured in such a way as to incorporate the utility of future generations. This certainly warrants greater consideration.

Social productivity

How are the social returns to agricultural production to be measured? Is this only possible through Pigouvian productivity where capturing social values in terms of taxes and subsidies seems somehow inappropriate? It is true that surveys can capture people's willingness to pay to maintain the farms in their area or preserve "the rural feel" of their community. But significant social investments are made on the part of farm families, and it seems there should be some way to examine the social returns from agriculture which seem abundant. It is also essential to explore the relevance of social productivity to sustainability. Are all forms of efficiency relevant to a farms ability to persist?

The next step of empirical data collection should help resolve at least this last question. By statistically comparing the time trends in productivity for farms that have succeeded and farms that have failed, much is to be learned about the factors that determine a farm's ability to persist.

Interfarm vs. Intrafarm comparisons

Finally, it is relevant to revisit the issue of interfarm vs. intrafarm comparisons. For determining a farm's ability to persist, I maintain that intrafarm comparisons hold the greatest relevance, particular if a farm has been in operation for a number of seasons. What the exact time threshold should be is not determined here, but it seems clear that if a farm's productivity trends are all non-negative over a period of twenty years, that farm has demonstrated obvious staying power. Economically and ecologically it has been able to adapt to a variety of changing conditions and maintain itself as a viable operation. This is regardless of how it may compare to other farms.

However, there is much to be learned from certain interfarm comparisons, particularly with regard to assessing sustainability at higher scales. Farms that perform poorly with regards to an energy, chemical, or Pigouvian assessment and yet are thriving economically should stand as bellwethers to agricultural policy makers. Similarly, farmers that are struggling economically but achieve high levels of productivity in other areas deserve the support of consumers and communities. But such assessments are primarily relative to other farms. It is a worthy goal to rank farms based on energy, biological, or Pigouvian efficiency.

7. Conclusion

Despite its supposed antithetical nature to sustainability, I believe productivity deserves a position within the realm of indicators of agricultural sustainability. Productivity:

- Fits within a common framework with other indicators;
- Assesses sustainability at a systems level;
- Acknowledges the fact that an agricultural system is first and foremost a system of production;
- Is a necessary condition for a system to persist into the future;
- Leads to a suite of indicators that reveal significant information regarding the health and value of a system;
- Is readily measurable after a significant investment of one-time work.

Productivity should not be taken as the only indicator of sustainability but instead should be viewed as a valuable analysis tool. This value will be boosted by an empirical assessment of the role of productivity in the ability to persist of a variety of farms.

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