Indicators of Natural Resource Scarcity:

Review, Synthesis, and Application to U.S. Agriculture

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1. Introduction

An increase in natural resource scarcity is defined as a reduction in economic well-being due to a decline in the quality, availability, or productivity of natural resources. Simple in concept, the measurement of natural resource scarcity is the subject of significant debate about which of the alternative indicators of scarcity, such as unit costs, prices, rents, elasticities of substitution, and energy costs is superior (e.g. Brown and Field, 1979; Fisher, 1979; Hall and Hall, 1984; Cairns, 1990; Cleveland and Stern, 1993). Most neoclassical economists argue that, in theory, price is the ideal measure of scarcity (e.g. Fisher, 1979) though some argue in favor of rents (Brown and Field, 1979; Farzin, 1995). Barnett and Morse (1963) developed the unit cost indicator from their reading of Ricardo as an alternative to the neoclassical indicators. Some ecological economists favor a biophysical model of scarcity and derive energy-based indicators (e.g. Cleveland et al., 1984; Hall et al., 1986; Cleveland, 1991a, 1992; Ruth, 1995).

The scarcity of agricultural products has received considerable attention due to the obvious importance of food production and the very vocal argument that degradation is undermining the bioproductivity of the agricultural resource base. A number of analysts argue that soil erosion, groundwater depletion, reduced genetic diversity, and other forms of resource degradation are severe threats to the long run productivity of U.S. agriculture (Brown, 1984, 1994; Ehrlich and Ehrlich, 1991; Pimentel, 1993. These claims seem to be supported by the results of field experiments and statistical analyses by agronomists and agricultural engineers who find significantly reduced crop yields on eroded land relative to non-eroded land (American Society of Agricultural Engineers, 1985; Follett and Stewart, 1985). Resource degradation in agriculture is a key driving force in the dynamic models of the U.S. (Gever *et al.,* 1986) and world economy (Meadows *et al,* 1992), and in conceptual models of agricultural development in the tropics (Hall and Hall, 1993). In various ways, these models project increasing scarcity of food in the future.

Other analysts argue that while degradation is important, there is little evidence to indicate it is undermining the future of US agriculture. Crosson (1995) finds that the on-farm costs of degradation over the next 100 years are small. Every analysis of multi- and total factor productivity in the US shows a substantial overall increase since the 1940s (Trueblood and Ruttan, 1995), suggesting that the US agricultural resource base has not undergone pervasive, irreversible, long-term damage, and/or that technical change and factor substitution have more than offset any effects of degradation (Ball et al., 1995). These conclusions are buoyed by the 24% decline in sheet and rill erosion in the US from 1982 to 1992 (USDA, 1994).

The purpose of this chapter is to review the different methods used to analyze resource scarcity, including their underlying theories, methodologies, and principal empirical results. We attempt to put the issue in perspective by stepping back and asking the question, "what do we actually mean by scarcity," a question rarely addressed in the literature, and answer it in the context of the various approaches. We propose the terms *use scarcity* and *exchange scarcity* to distinguish between two broad approaches to measuring scarcity. These terms relate to the classical concepts of use and exchange value. Definitions of use and exchange value have varied among different economic paradigms, but broadly speaking use value is the value derived from consumption of a good while exchange value is the value of goods or money that can be obtained in exchange for the good in an actual or potential market. Our usage of use value is not the same as some environmental economists, who use it to describe value derived from active use of the resource in consumption or production as juxtaposed to "non-use values" of environmental resources that contribute to utility through, for example, knowledge of their existence.

As proposed in this chapter, exchange scarcity is commonly measured by price or rent depending on whether the scarcity of resource commodities or in situ natural resources is being measured. Use scarcity refers to the ability of natural resources to generate use value and is typically measured in terms of the balance between the productivity and availability of the resource base and the level of technology (Cleveland and Stern, 1993). We call the most general indicator of the latter type generalized unit cost (GUC). Barnett and Morse's (1963) unit cost is a special case of this indicator. However, it is possible to decompose such indicators into more fundamental components that reflect the driving forces behind changes in scarcity. We develop this decomposition and apply it using econometric estimation of a demand system for the U.S. agricultural sector between 1950 and 1993.

2. The **Classical Model of Scarcity**

Ricardo and Marx argued that the labor cost of production is a common unit of measurement of the use value of commodities, and that use value, rather than exchange value, was the "real" measurement of value. Ricardo viewed nature not as a factor of production, but as a force resisting the efforts of labor to produce use value (Commons, 1934). The poorer the quality of the resource base, the more it resists the efforts of labor. Thus, interpreters of the classical model such as Barnett and Morse (1963) define an increase in scarcity as an increase in the resistance of nature to the efforts of people to produce resource commodities. The classic example is Ricardo's case of the declining fertility of land at the extensive margin. From this perspective the appropriate measure of scarcity is the labor required to produce a unit of the commodity. Rising resistance or rising scarcity means that more labor is required. This is the source of the unit cost measure which in its simplest form is the inverse of labor productivity. The term unit cost is somewhat unfortunate. Some analysts (e.g. Farzin, 1995; Uri and Boyd, 1995) erroneously assume that unit cost is the average cost of extraction. Barnett and Morse also combine the Ricardian model with a neoclassical production function to derive a more comprehensive measure of scarcity that accounts for capital inputs.[1] In this case unit cost is the inverse of multi-factor productivity defined with respect to labor and capital. Hall *et al.* (1988) expanded the definition to include energy inputs.

Barnett and Morse (1963) defined unit cost as:

$$UC_t = \frac{\alpha_t \left(L_t / L_b \right) + \beta_t \left(K_t / K_b \right)}{Q_t / Q_b} \qquad (1)$$

where:

UC_t = unit cost of extraction at time t

Q_t = net output (value added) in constant dollars

L_t = labor cost measured as number of persons employed

K_t = capital cost measured as net fixed capital stock in constant dollars

Q_b, L_b, K_b = output, labor and capital inputs in the base year b

α_t = $I^L_t \,/\, I^T_t$ where I^L is total labor compensation and I^T is value added originating in the industry in question (other indexation procedures such as Divisia aggregation can be used).

The classical model from which Barnett and Morse derive the unit cost index assumes that resources are used in order of descending quality. With unchanging technology, cumulative extraction will be associated with an increase in the quantity of labor and capital required to extract a unit of the resource. Technological innovations work in the opposite direction, reducing required labor and capital inputs per unit output. In real world cases, where resources are not used in strict order of quality, new discoveries of higher quality resources can also lower unit cost. Barnett and Morse argued that unit cost reflects the net effect of these opposing forces, and thus measures the long run productivity of the resource base. As we show below, the overall quantity of resource stock under exploitation also affects unit cost. Using more natural capital with given inputs of capital and labor will normally raise the productivity of the latter inputs.

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[1] Throughout, capital refers to manufactured capital, although occasionally we use the term "natural capital" which can be understood as referring to the resource stock or resource base. Natural capital emphasizes the active contribution resource stocks play in production - e.g. pressure in oil reservoirs forces oil to the surface.

Empirical Results of the Classical Model

Barnett and Morse calculated the unit cost index for aggregate resource industries (agriculture, forestry, fisheries, mining) and individual resource commodities in the U.S. from 1870 to 1957. They found an almost universal decline in unit cost, which they viewed as a rejection of the classical school's "iron law of diminishing returns." The lone exception was the forest products sector which showed an overall increase in labor cost per unit output.

Johnson et al. (1980) used regression analysis to update Barnett and Morse through 1966, and used a dummy variable to test for a significant change in the trend in scarcity after 1957. They found that the cost of aggregate agricultural and mineral commodities fell at a *faster* rate from 1957 to 1966 compared to the period before 1957. Johnson et al. also found an overall increase in the cost of forestry products from 1870 to 1970, although costs generally declined after 1957. This trend was confirmed by Cleveland and Stern (1993) for the subsequent years to 1990 as well.

Hall and Hall (1984) updated the unit cost analysis for a number of resources, and used regression analysis to test for a significant change in scarcity between 1960 and 1980, and for the possible effects of the energy price shocks on unit cost. They found that the unit cost of petroleum and coal began to increase in the 1970's, but not for agriculture, electricity and metals. The authors emphasized that costs turned upward prior to the energy price increases, indicating that the actions of the OPEC cartel were not the principal cause of the increase in cost.

The cost of oil resources in the U.S. has attracted considerable attention. Cleveland (1993) calculated the unit cost index for petroleum (oil and gas) extraction in the U.S. from 1880 to 1990. He found a precipitous decline in cost through the 1960's, followed by a sharp increase in cost through 1990. Like the Hall and Hall results, costs turned upward prior to the energy price shocks. Cleveland (1991b) also calculates the average (not unit) cost of oil discovery and production in the U.S. from 1936 to 1988. He finds that the time path for both are consistent with Slade's (1982) U shaped time path for scarcity. The cost of oil discovery has increased steadily since the 1930's, while the cost of production began to increase in the 1960's. Like Hall and Hall (1984), Cleveland's econometric analysis indicates that the actions of the OPEC cartel accelerated, but did cause, the cost increase.

Critique of the Classical Model

Barnett and Morse argued for the use of unit costs and against the use of rents as a scarcity indicator because changes in rent may be due to "changes in interest rates, relative demand, and expectations concerning future resource availability" (p. 225) - in other words, forces that obscure the issue of productivity. As Smith (1980) stated "Their objective would seem to call for measuring resource scarcity without judging the legitimacy of society's ends...Thus [Barnett and Morse] implicitly accepted the notion that there was an objective measure of scarcity independent of consumer preferences" (p. 261). Neoclassical economists criticize Barnett and Morse's unit cost measure because, *inter alia*, "Whether a resource is becoming scarce or not, for example, ought to depend in part on expectations about future supplies" (Brown and Field, 1979, p. 230). In other words, an indicator that excludes any factor that determines exchange value is inadmissible.

One significant shortcoming is that unit cost excludes all inputs other than capital and labor and output is measured in value added terms. Fuel, water, and other purchased inputs are excluded, though this problem is addressed by Hall *et al.* (1988) and is not a fundamental problem. The most serious computational issue is that unit cost is a constructed index, which requires assumptions about the best way to measure output, inputs, and the weighting factors (Brown and Field, 1978; Howe, 1979). Particularly troublesome is the measurement of capital input and how the capital stock is depreciated over time. The weighting factors also are problematic because the return to capital is typically unobserved and combined with the compensation for land in a single measure of total profit.

Brown and Field (1979) showed that labor only unit cost would rise in the face of an increase in the price of the resource stock relative to wages. But, they argued, the impact would be greater the greater the ease of substitution between resources and labor in producing resource commodities. This relationship stands to reason, as the optimal ratio of labor use to resource use will shift more the easier substitution is. Innovations that make it easier to substitute away from the resources base will accelerate the rate of increase in unit cost. This, they state, is perverse.

The more general point is that, contrary to Barnett and Morse's assertions, unit cost does depend on factor and output prices and all the variables that drive those prices. As discussed in the next section, similar problems affect the biophysical indicators. It is, however possible to calculate a unit cost indicator that is more independent of price movements. The generalized unit cost indicator that we develop in section 6 is relatively free of such distortions.

3. The **Neoclassical Model of Scarcity**

The neoclassical view of scarcity begins with the theory of optimal depletion (Hotelling, 1931) in which resource owners are assumed to maximize the discounted profits from the extraction and sale of the resource. Solution of the model suggests two possible scarcity indicators: price and rent. Fisher (1979) demonstrates this with a simple optimal control problem for nonrenewable resource extraction in which the private profit-maximizing resource owner faces the following problem:

$$\text{Maximize} \int_0^\infty [PY - WE]e^{-rt}dt$$

subject to:

$$dX/dt = -Y$$

$$Y = f(E,X,t) \qquad (2)$$

where P is market price, W is the price of hiring a unit of effort E, Y is the quantity of the resource commodity produced from the stock X, and f() is the production function. In equilibrium the following condition is met:

$$P = W/(\partial Y/\partial E) + q \qquad (3)$$

where q is the costate variable attached to the constraint in the Hamiltonian. Market price, therefore, has the attractive feature of capturing the sum of direct sacrifices such as the cost of hiring labor, and indirect sacrifices such as the change in the net present value of future profits caused by reducing the size of the remaining resource stock. The quantity q is known as the shadow price of the stock, user cost, or rent. If we are only interested in the direct and indirect sacrifices associated with depleting the stock, rather than producing the commodity, q is a better indicator. Therefore, market prices are the appropriate scarcity indicator for resource commodities and rents for resource stocks.

Several authors have developed theoretical time paths for rent and price as a resource is depleted (e.g. Hotelling, 1931; Fisher, 1979; Lyon, 1981; Sedjo and Lyon, 1990; Slade, 1982; Farzin, 1992, 1995). In Hotelling's simple model both price and rent rise monotonically at the rate of interest. In Fisher's model price still rises monotonically but rent may follow a non-monotonic path. Slade (1982) developed a more complex model where the path of prices over time may follow a U shape, implying that declining prices may be a misleading signal for long-run scarcity. Farzin (1992, 1995) derives a variety of time paths under varying assumptions. The theoretical literature indicates that for sufficiently general models, any time path may be possible. Lyon (1981) and Sedjo and Lyon (1990) derived specific models for forest products. The resulting time path is an S-curve, a path which both rents and prices follow remarkably closely in the US in the last couple of centuries (Cleveland and Stern, 1993).

Empirical Results of the Neoclassical Model

The empirical analysis of price and rent is characterized by applying more sophisticated econometric tools to time series data. Barnett and Morse's (1963) visual inspection of prices from

1870 to 1957 led them to reject the hypothesis of increasing scarcity for agriculture and minerals (metals, nonmetals, and fuels), and accept it in forestry. The trend for fisheries was indeterminate.

Smith (1979) uses Brown-Durbin CUSUM (Cumulative Sum of Squares) and Quandt log-likelihood tests to examine the stability of the coefficients from a simple linear regression of real prices as a function of time for four broad industry groups from 1900 to 1973. He finds significant instability, and concludes that any judgments as to a consistent pattern of change in the price series would be "hazardous."

Devarajan and Fisher (1982) develop a two-period model of optimal depletion which indicates that marginal discovery cost is a close proxy of rent. They found that the average cost of oil discovery in the U.S. showed a statistically significant increase from 1946 to 1971, indicating a clear increase in scarcity.

Slade (1982, 1985) develops a model of optimal depletion in which the long run path of price is U-shaped due to changes in the effects of depletion and technical change. She tested the U-shape model by estimating a quadratic time trend model for 12 nonrenewable resources in the U.S. from 1870 to 1978. She found significant U-shapes for 11 of the 12 resources, and noted that all had passed the minimum points on their fitted U-shaped curves, indicating growing scarcity.

Ozdemiroglu (1993) updated Slade's (1982) analysis by fitting a quadratic model to time series price data for 39 resources in five categories from a number of developed and developing nations. Of the nine resources that have significant trend coefficients, five show an inverted U-shape, contrary to Slade's finding of a pervasive U-shape for the U.S. extractive sector. Ozdemiroglu's series are much shorter (as short as 12 years in the case of coal) than those used by Slade. Given that Slade's hypothesis is about long run trends, it is doubtful that his analysis really tests Slade's hypothesis.

Hall and Hall (1984) estimated a time trend model for 14 resource commodities in the U.S from 1960 to 1980, and tested for the possible effects of the energy price shocks on price. They found that the real price of fuels and electricity increased in the 1970's, and the actions of the OPEC cartel accelerated~but did not cause-the observed increase in price.

Forest products in the U.S. have received considerable attention. Brown and Field (1979) found the rental value of Douglas fir (as measured by its stumpage price) relative to its lumber price increased significantly from 1930 to 1970. They noted that this increase occurred at the same time that the unit cost of forest products (L/Q) declined. Brown and Field also found that the stumpage price of Douglas fir relative to a quality adjusted wage rate increased from 1920 to 1970. Cleveland and Stern (1993) test econometrically for trends in lumber prices from 1800 to 1990 and for trends in stumpage prices from 1910 and 1989 in the U.S. They find that both series are explained by a logistic function. Prices for lumber products and rental rates for timberland are much higher today than in the past, but have leveled off in recent decades.

An issue ignored in most studies of scarcity indicator trends, whether classical, neoclassical, or biophysical, is the time series properties of the series in question. Recently Uri and Boyd (1995) and Berck and Roberts (1996) have addressed this question. Berck and Roberts (1996) revisit Slade's (1982) results. They find that most of the series are difference stationary rather than trend stationary, i.e. they can be represented by unit root processes. This result was confirmed by Uri and Boyd (1995) for the average cost of extraction and real resource price series for a group of metals. Berck and Roberts (1996) find that forecasting 1991 prices using an AREMA model estimated on 1940 to 1976 data generates more accurate predictions than Slade's quadratic model for all commodities except copper. The prices forecast by the AREVIA model are also lower for all commodities except copper. Using the quadratic model to predict 2000 prices from a 1991 base, the quadratic model gives a probability of an increase in price of more than 75% for every commodity and a mean probability of 87%. The ARIMA model has a mean probability of increase of 57% with only one commodity having a probability of less than 50%. So while price rises are seen to be less likely when a more appropriate model is fitted, the odds are still above even for an increase in prices in the future.

Critique of the Neoclassical Model

Price has a number of practical advantages relative to unit cost (Cleveland, 1993). First, the prices of most natural resources are readily observable, and that avoids the pitfalls of having to construct an index from secondary data. Second, the joint effects of the physical, technological, and market factors that influence scarcity are subsumed in a single index. Third, price is not hampered by the joint product problem in industries such as oil and gas extraction which complicates measurement of unit cost. Natural gas and crude oil have separate and distinct market prices. Rent does not, however, have many of these advantages.

There also are numerous caveats to the theoretical properties of price and rent. Most importantly, market prices and rents only indicate *private* scarcity (Fisher, 1979). In the presence of market imperfections or market failure, social indicators of scarcity will diverge from the private indicators.

The arguments for price are based on highly simplified models of optimal resource depletion that rest on restrictive assumptions about market structure, technical change, uncertainty about future cost and market conditions, and other factors that determine price. In the real world there are many practical problems with price that negate some of its theoretical advantages. The price of natural resources are determined in markets that are far more complex than those described in many of the theoretical models. Furthermore, the trend in scarcity suggested by price is sensitive to the benchmark that nominal prices are compared to (Brown and Field, 1979).

Rent faces similar problems as a scarcity indicator. Mattey (1990) shows that stumpage prices, the resource rent in the forestry sector, are influenced more by government policy and economic forecasts than by changes in the difficulty of production. Fisher (1979) describes the possibility of rent falling to zero as a low grade backstop resource was substituted for a depleted higher quality resource, and thus sending perverse signals about the impact on social well-being.

Norgaard (1990) presented what he argued was a logical fallacy in the empirical scarcity literature. The argument boils down to two points: imperfect information means that price or rent is not an accurate scarcity indicator for a resource owner, and that, in addition, imperfect or non-existent markets mean that price or rent are not indicators of social scarcity. Neither of these points is new, and they are explicit in earlier studies (e.g., Barnett and Morse 1963; Fisher, 1979). Norgaard also argues that if resource owners actually did have perfect information about resource scarcity then economists could ask them directly for this information. Yet economists generally prefer to use market data to investigate people's preferences rather than asking them directly. Stated preference methods such as contingent valuation are normally only used in the absence of markets for the resource. So even if resource owners had perfect information, it might be useful to exploit market data where available.

4. The **Biophysical Model Of Scarcity**

The biophysical approach begins by redrawing the conventional boundaries of the economic system. The economic process is a work process and as such it is sustained by a flow of low entropy energy and matter from the environment. As materials and energy are transformed in production and consumption, higher entropy waste heat and matter ultimately are released to, and assimilated by, the environment. Analysis of exchange in markets, which grabs the limelight in conventional economic analysis, is given less attention and is seen as an intermediate step in the process of fulfilling human needs and desires by the flow of energy and materials from resources to production, pollution, and environmental assimilation.

The biophysical approach defines the resource transformation process as one that uses energy to upgrade the organization of matter to a more useful state (Ayres, 1978; Cook, 1976; Gever et al., 1986; Hall et al, 1986; Cleveland, 1991a; Ruth, 1993). In their natural state resources are not useful inputs to the production process. They must be located, extracted, refined, transported, and upgraded in other ways to useful raw materials or products. By definition, lower quality resources require more energy to upgrade to a given state. The same fundamental relationship exists for renewable and nonrenewable natural resources (Hall et al., 1986). Just as more energy is required to isolate copper metal from a lower grade ore, more energy is required to pump oil from deeper and smaller fields, harvest food from less fertile soil, and catch fish from smaller and more remote areas.

A second tenet of the biophysical model emphasizes the role that energy plays in implementing technical innovations in the extractive sector. Technical improvements have tended to be energy-using and labor-saving, achieved through the use of more powerful energy converters (Georgescu-Roegen, 1975). Empirical research demonstrates a significant relationship between labor productivity, the quantity of installed horsepower (Maddala, 1965) and fuel use (Hall et al., 1986) per worker in the U.S. extractive sector. Energy converters also have evolved towards the use of higher quality forms of energy. Animate energy converters such as human labor and draft animals were replaced by inanimate energy converters burning wood and coal, then oil and natural gas, and eventually electricity.

The energy used to extract a resource is mirrored by the additional use of renewable resources and ecosystem services, such as clean water and air, and the land used to support the extraction process. The increase in throughput of energy and materials also increases the generation of wastes which, in turn, increases the use of natural capital in various forms for waste assimilation. The increase in the overall scale of extraction that accompanies the cumulative depletion of a resource increases the demand for natural capital inputs because that expansion often diverts larger portions of the landscape to extraction activities. Changes in the quality of the resource base affect all of these costs just as they affect the energy cost of extraction. For example, the decline in quality of the U.S. oil resource base has increased the energy cost of oil extraction. In turn, this has increased the amount of CO_2 released by the fuel burned to extract the oil, and the amount of water used per barrel of oil (Kaufmann and Cleveland, 1991; Cleveland, 1993). In surface metal and coal mines, a decline in resource quality increases the stripping ratio and hence the amount of waste produced per unit of the product (Gelb, 1984).

Empirical Results of the Biophysical Model

The energy cost of extracting a unit of resource in the U.S. shows some important differences relative to the trends in unit cost and price. The most thoroughly examined resources are fossil fuels (Cleveland et al., 1984; Hall et al., 1986; Gever et al., 1986; Cleveland, 1991; Cleveland, 1992; Cleveland, 1993). The energy cost of extracting oil and gas increased by 40 percent from 1970 to the 1990's, indicating a significant increase in scarcity. The energy cost of coal extraction increased by a similar magnitude.

The energy cost of agricultural output increased steadily from 1910 through the late 1970's as the direct and indirect use of fossil fuels replaced labor and draft animals (Cleveland, 1991; Cleveland, 1995a, 1995b). Since the second energy price shock energy costs have declined due to reduction in the rate of energy use per hectare, a reduction in the number of harvested hectares, and larger farms. Cleveland (1995a) finds no evidence that resource degradation has diminished the productivity of energy use in U.S. agriculture.

The energy cost of metals such as silver, bauxite, and iron show increasing scarcity in the U.S., while copper, lead, and zinc show stable or decreasing scarcity (Cleveland, 1991). Most nonmetals show no signs of increasing scarcity measured by their energy cost.

Cleveland and Stern (1993) develop an index of energy cost of forest products in the U.S. that adjusts for energy quality by using a Divisia index to aggregate energy inputs. Unit energy costs of forest products showed a decrease in scarcity since 1947.

Critique of the Biophysical Model

Stern (1994) argues that a biophysical theory of production need not reduce to an energy theory of production. Low entropy energy and matter are not the only nonreproducible inputs to production.[2] According to Stern, information could be seen in an analogous way to energy as a nonreproducible input. This information is accumulated as knowledge. Technology consists of the designs for the products to be manufactured, the ideas for which come in part come from human imagination and the techniques used in producing those products. These techniques consist purely of the application of the knowledge of physical laws and the chemical and biological properties of resources to the production process, though of course the techniques used at any one time are contingent on the path of knowledge accumulation to that date. This latter knowledge is the result of the extraction of information from the environment. Capital, labor, and energy are required to extract that knowledge from the environment and render it into an economically useful form. Capital, labor, and other reproducible goods are produced within the economy by applying the two nonreproducible factors of production low entropy energy and knowledge to matter. From

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[2] Biophysical analysts have often argued that energy is the primary factor of production and labor and capital are intermediate factors of production, while neoclassical economists are said to hold the opposing view. This is not a very good use of terminology. Capital stocks and labor are primary factors of production in the static production context because they are not produced within the production period. In most applications (with the exception of population economics and some recent endogenous growth theory), however, capital is treated as a reproducible factor and labor as a nonreproducible factor. However, the only truly nonreproducible factors are energy (energy vectors - fuels - are intermediate factors) and as we argue here information.

the perspective of Ricardo and Marx the use value of the products is not a function of energy alone, but also of the knowledge employed. For example, knowledge is embodied in the physical arrangement of capital, e.g., the shape and design of machines. From a more neoclassical perspective, knowledge can be used either in an embodied form in the capital and labor inputs or in the combination of the factors of production in the production process. The implication is that the economic value of capital and labor is not a linear function of the energy used in their production alone, even if we ignore the fact that two different products embodying the same energy and knowledge may have different values in their use by people.

Stern (1996) shows that unless we subscribe to an energy theory of value where the productivity of non-energy inputs is a linear function of the energy used in their manufacture, energy cost could be a misleading indicator of scarcity. In particular, for most reasonable estimates of the elasticity of substitution of energy for capital and labor, energy cost could rise even though no change has occurred in the productivity of the resource base or in the state of technology. This finding is suggested by empirical studies (Cleveland, 1995a; Mitchell and Cleveland, 1993) that show rising energy cost as the relative price of energy to capital and labor declined.

That productivity is not a function of energy alone is clear from the issue of varying energy quality (Berndt, 1978; Kaufmann, 1994). Petroleum is considered to be a higher quality fuel than coal because of the accompanying physical and chemical properties of the fuel vector and the technologies available for using the fuels. This difference cannot be explained purely in terms of the embodied environmental energy in the fuels i.e. petroleum has not undergone considerably more processing in the environment than has coal. This problem can be addressed by using quality-weighted indices of energy inputs (Cleveland, 1993; Cleveland and Stern, 1993; Stern, 1993) typically the relative prices of the fuels. This is only a partial solution which implies certain separability conditions on the production function.

5. Towards a Synthesis: Use and Exchange Scarcity

Much of the debate about the strengths and weaknesses of various scarcity indicators ignores a fundamental point: different indicators measure different types of scarcity. We elaborate this point below using the concepts of *use scarcity* and *exchange scarcity.*

The two fundamental concepts of value in economics are use value and exchange value. The exchange value of a commodity is identical with its price. For an individual wishing to acquire a resource commodity, market price is a valid indicator of exchange value. A resource becomes more scarce if its exchange value increases or the sacrifices required to obtain it increase. It is this meaning of scarcity that we term exchange scarcity. Note that these sacrifices do not necessarily relate to changes in the difficulty of obtaining the resource from the environment itself, although the two obviously may be related.

Use value was always a problematic concept because either it was impossible to measure or the units of measurement were unclear. Ricardo and Marx's labor theories of value were intended to solve this problem but created as many difficulties as they cleared up. In the neoclassical view, use value is represented by some indicator of total utility such as consumer surplus, while exchange value represents marginal utility.

Commons (1934) paralleled the concepts of exchange and use value by his categories of "scarcity" and "efficiency." Efficiency is a measure of productivity and is defined as the rate of production of use value by the factors of production, or output per unit input. The inverse of this output/input ratio is unit cost. When there are several factors of production, it is impossible to identify *a priori* the contribution of each to use value. But if the input/output ratio is calculated omitting one of the factors i.e. land, a rise in the ratio implies, *ceteris paribus,* a decline in the use value produced by the omitted factor and an increase in what we call use scarcity. The parallel exchange value concept is the revenue/cost ratio, the rate of revenue generation per unit of expenditure on inputs, or the profit markup rate. If only land is omitted from the calculation of expenditure on inputs, then the profit markup rate is $M = 1 + rR/C = pQ/C$ where r is the rental rate, R is land, C is cost of all other inputs, p is the output price, and Q the output quantity. Thus unit cost is a use value indicator of natural resource scarcity and rent, prices, and average costs are related components of Common's own scarcity measure, M.

Commons (1934) defined use value in terms of quantities of commodities, though he recognized that use value did change with what we would now call changes in preferences, in household production functions, or in capital stocks associated with household production (Stigler and Becker, 1977), so a "commodity theory of value" was not really satisfactory. In the neoclassical view, unless utility functions are linear in commodities, use value also is a function of the quantities of other commodities consumed. Calculation of the utility of consumers derived from natural resources also needs to take into account the efficiency of production downstream from the resource sector. The unit cost indicator is an "upstream indicator" of use scarcity. The prices of resource commodities do not necessarily move in the same direction as rent (Fisher, 1979), and downstream use scarcity does not necessarily move in the same direction as unit cost. To our knowledge no-one has attempted to construct a "downstream indicator" of use scarcity.

Now we can explain Fisher's (1979) comments on the inadequacy of rent as a scarcity indicator. Rent falls to zero as a stock of minerals of variable quality is depleted. The average use value of the remaining mineral deposits declines, but so does their exchange value. In the extreme case, nobody wants to buy useless rocks and therefore their rent declines to zero. The scarcity of use value embodied in the minerals has increased sharply and this will be correctly reflected in the rise in unit cost noted by Fisher. Society is indeed much worse off - its ability to produce use value Is much diminished. In order to obtain a full picture of the scarcity of natural resources in both its dimensions we must examine both exchange value and use value, exchange scarcity and use scarcity.

6. Beyond Scarcity Indicators: Generalized Technical Change

The problem with all natural resource scarcity indicators is that we can only look at the historic time path of the indicator and guess what the trend will be in the future. Without a clear understanding of the forces that drive the changes in the indicator this can be little more than a guess or extrapolation. The recent literature on the time paths of prices and rent (Farzin, 1992) indicates that many time paths are possible, and assuming that the trend will continue is problematic. In order to develop more effective forecasts of future resource scarcity we need to look beyond the crude indicators to the production technologies, natural resource bases, and market structures that determine the indicators. Though no one could accurately forecast any of these variables it should be possible to constrain the possible changes to a greater degree, through additional research efforts, than is possible for the indicator itself in the absence of this knowledge. Most analyses of scarcity assume that the net result of these opposing forces is reflected in the historical trend of the indicator, and they do not explicitly measure the effects of depletion and innovation. One exception is the analysis of the cost of oil extraction in the U.S., for which sufficient data are available to describe or proxy depletion and innovation (Norgaard, 1975; Cleveland, 1991).

We propose here a generalized unit cost indicator. As we describe below, one advantage is that it directly decomposes into a number of more fundamental trends, such as the effects of depletion, technical change, and resource availability. Barnett and Morse (1963) attempted a simple version of this decomposition with their index of relative unit cost - the ratio of unit cost in the extractive sector to unit cost in the non-extractive sector. The idea was to remove the overall technical change trend in the economy from the use scarcity indicator so that it more accurately reflected the results of depletion alone.

The starting point is a production function for a resource commodity Q:

$$Q = f(A_1X_1, \ldots, A_nX_n, A_RR, S) \tag{4}$$

where Q is gross output, R is the resource base from which the resource is extracted, and S is a vector of additional uncontrolled natural resource inputs such as rainfall and temperature. The X_i are other factors of production controlled by the extractor, and the A_i are augmentation factors associated with the respective factors of production. A_R is the augmentation (or depletion) index of the resource base. In theory we could also allow the effective units per crude unit of S to vary, though in most applications it will be assumed that the augmentation index is constant. Equation (4) can be obviously generalized to multiple outputs and multiple resource inputs. A useful simplifying assumption is that the production function exhibits constant returns to scale in all inputs including the resource inputs. Again, generalizations can be made. Note that if S is measured in terms of rainfall, temperature etc., rather than water, heat etc., the relevant constant returns relates to the expansion of X and R, but not S.

Taking the time derivative of lnQ yields:

$$\dot{Q} = \Sigma \sigma_i \dot{A}_i + \sigma_R \dot{A}_R + \Sigma \sigma_i \dot{X}_i + \Sigma \sigma_j \dot{S}_j + \sigma_R \dot{R} \qquad (5)$$

where the σ_i are the output elasticities of the various inputs. A dot on a variable indicates the derivative of the logarithm with respect to time. We define multifactor productivity as:

$$\dot{\mathrm{MFP}} = \dot{Q} - \Sigma \sigma_i \dot{X}_i = -\dot{\mathrm{GUC}} \qquad (6)$$

where GUC is a generalized unit cost indicator. Typically the change in ln MFP will be calculated using a Divisia index of input where σ_i is replaced with the relevant revenue share. In equilibrium $\Sigma \sigma_i = C/V$ where C is cost and V is revenue. The remaining profit is distributed as rent to the resource owners. The traditional definition of unit cost, (1), differs by the premultiplication of $\Sigma \sigma_i \dot{X}_i$ by V/C.[3] This difference in equation (6) renders our indicator much more independent from distortions due to change in relative factor prices. From (5) and (6) we find that the change in the logarithm of generalized unit cost (GUC) can be alternatively defined as:

$$\dot{\mathrm{GUC}} = -\Sigma \sigma_i \dot{A}_i - \sigma_R \dot{A}_R - \Sigma \sigma_j \dot{S}_j - \sigma_R \dot{R} \qquad (7)$$

Thus, changes in GUC are the sum of the four terms in (7), respectively:

1. Technical change

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[3] Conventional measures of multifactor productivity are computed in the same way as "traditional unit cost." Under constant returns to scale, the change in the logarithm of a conventional total factor productivity indicator that divides an output index by an index of all inputs including the resource stocks is equal to $-\dot{U} - \sigma_R \dot{R}$.

2. Resource depletion or augmentation
3. Change in uncontrolled natural resource inputs such as rainfall and heat
4. Change in the dimension of the resource base.

These components seem to cover the dynamics that unit cost proponents have tried to capture without distortions caused by shifts in input or output prices. Traditional unit cost has an additional term on the RHS of (7) which is a weighted sum of variable factor inputs. Factor prices still affect our indicator because, in general, the output elasticities will be functions of input quantities. For the special case of the Cobb-Douglas production function the indicator is completely independent of prices. Given suitable data, the subcomponents of (7) can be estimated econometrically. In the following section we develop and estimate such a model for the US agricultural sector.

An interesting corollary of (7) is that all previous studies of biased technical change in the extractive sector of the economy aggregate technical change, resource depletion, and resource availability. For example some studies (Abt, 1987; Constantino and Haley, 1988; Merrifield and Haynes, 1985) of the forest products industry indicate that technical change has tended to be wood-using. This has been taken to indicate that wood is relatively less scarce than the other factors of production (Stier and Bengston, 1992). However, the finding of a wood-using bias could indicate that the quality of the resource base declined, and a wood-saving bias could indicate an improvement in the quality of the resource base. In general, the bias of "technological change" in an extractive industry does not provide useful information on the scarcity of the natural resources in question unless further information is available which allows the researcher to separate the effects of depletion from the effects of technological change.

7. Application to U.S. Agriculture

Generalized Unit Cost

We calculated GUC for the US agricultural sector between 1948 and 1993 using Divisia aggregation and revenue shares. The index of input included all variable controlled inputs and the capital stock. The data set is described in Ball *et al.* (1995). We aggregated the Ball *et al.* data into the following indices:

1. Livestock output
2. Crop output
3. Labor input

4. Fertilizer input
5. Pesticide input
6. Energy input
7. Land input - not including structures - the Ball *et al.* index of land is adjusted for the changing coverage of land types in the cultivated area over time.
8. Capital stock - durable equipment, structures, and inventory.
9. Other intermediate inputs - lime, feed; seed, and livestock; agricultural services, miscellaneous.

This numbering of the inputs will be used throughout the following discussion. The revenue share of the capital stock is derived using the approach of Berndt *et al.* (1993). The total service flow of land and capital is derived using service prices and capital quantities from the Ball *et al.* data set. The share of capital in this potential service flow is calculated from that data. Actual profit is calculated as gross operating surplus, i.e., revenue minus the cost of the five variable inputs above. The return to capital is the calculated capital share multiplied by the actual profit. The share in revenue is the negative of the return to capital divided by revenue. The generalized unit cost index is shown in Figure 1. The figure shows a steady decline in generalized unit cost over time.

Econometric Method

In this case the change in the logarithm of generalized unit cost, GUC, is explained by:

$$\dot{GUC} = - \Sigma \sigma_i \dot{A}_i - \sigma_R \dot{A}_R - \Sigma \sigma_j \dot{S}_j - \sigma_R \dot{R} \qquad (8)$$

where the inputs *i* include the variable inputs and the capital stock. The vector S consists of temperature and rainfall, and R is agricultural land. Rainfall and temperature data are from Tiegen and Thomas (1995).

The parameters in (8) are estimated by applying maximum likelihood to a system of demand and supply equations for six of the inputs and outputs, the profit function, and an equation relating the share of land in the capital service flow to the profit elasticity with respect to land. This system is derived as follows. Farmers are assumed to maximize variable profits given the quasi-fixed inputs, the uncontrolled inputs, the price vector, and the state of technology:

$$\Pi_t = \sum_{i=1}^{2} p_{Qit} Q_{it} - \sum_{j=1}^{5} p_{Xjt} X_{jt} \qquad (9)$$

subject to the transformation frontier:

$$0 = f(Q_{1t}, Q_{2t}; X_{1t} A_{X1t}, \ldots, X_{5t} A_{X5t}; K_t A_{Kt}, \ldots, R_t A_{Rt}; S_{1t}, S_{2t}; \beta) \tag{10}$$

where there are two outputs Q_i (crops and livestock), with prices p_{Qit}, and are 5 variable inputs X_j (labor, fertilizer, pesticides, energy, miscellaneous) with prices p_{Xj} and augmentation factors A_{Xj}. The manufactured capital stock K has an augmentation factor A_K; R is land with augmentation index A_R. There are two uncontrolled resource inputs S_j - temperature and rainfall. The augmentation factors are approximated by exponential trends:

$$A_{it} = \exp(\delta_i t) \tag{11}$$

Assuming competitive input and output markets and under certain regularity conditions (Diewert, 1973), a profit function can be derived that defines the maximum profit attainable given the quasi-fixed inputs, the uncontrolled inputs, the price vector, and the state of technology. We use a translog profit function which is the most flexible form of commonly used specifications for this application (Lopez, 1985):

$$\ln\Pi_t = \gamma_0 + \sum_{n=1}^{11} \gamma_n \ln Z_{nt} + \frac{1}{2} \sum_{n=1}^{11} \sum_{m=1}^{11} \Gamma_{nm} \ln Z_{nt} \ln Z_{mt} + \varepsilon_{\Pi t}$$

$$Z_t' = [p_{Q1t}, p_{Q2t}; p_{X1t}/A_{X1t}, \ldots, p_{X5t}/A_{X5t}; R_t A_{Rt}; K_t A_{Kt}; S_{1t}, S_{2t}] \tag{12}$$

where $\varepsilon_{\Pi t}$ is a random error term. The logarithms of all variables are normalized by subtracting the mean of the logarithm of each from the series in order to obtain parameter estimates invariant to the measurement units (Stern, 1995). We impose symmetry of Γ, homogeneity of the first degree in the price vector, constant returns to scale in the quasi-fixed inputs, and the convexity-concavity conditions implied by the theory of profit maximization (Varian, 1992). Profit is convex in the price vector but concave in the quasi-fixed inputs and the uncontrolled inputs. The latter are imposed only at the point at which all variables are equal to unity (and their logarithms are equal to zero). This normalization is applied by subtracting the mean of the logarithm from the logarithm of each variable as proposed by Stern (1995). First order homogeneity in prices is imposed by dividing all prices and profit by the price of the other input category. All prices and profit are multiplied by the appropriate augmentation index. Homogeneity of profit with respect to the fixed inputs is imposed by dividing land and profit by capital's augmentation index.[4] Land and profit are divided by their augmentation indices. We transform the variables so that normalized profit is

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[4] We could just as well divide profit by land and capital by land (Barten, 1969).

convex in all variables. This is achieved by substituting the reciprocal of all the non-price variables into the profit function. Profit is homogenous of degree minus one in the transformed quasi-fixed inputs, i.e. the capital/land ratio. Convexity is then imposed using a procedure developed by Lau (1978). The Γ_{mn} parameters in (12) are not estimated directly. Instead, we estimate the parameters contained in a lower triangular 9×9 matrix (C). $\Phi = CC'$ therefore is a positive semidefinite matrix. This matrix is the hessian of the profit function at the point of normalization. Γ is derived as follows:

$$\Gamma_{ii} = \Phi_{ii} - \gamma_i(\gamma_i - 1) \qquad i = 1, \ldots, 9$$

$$\Gamma_{mn} = \Phi_{mn} - \gamma_m \gamma_n \qquad m, n = 1, \ldots, 9 \qquad (13)$$

The transformed profit function is given by:

$$\ln\Pi_t - \ln R_t = \gamma_0 + - \delta_{X5}t + \delta_R t + \sum_{n=1}^{9} \gamma_n \ln Z_{nt} + \frac{1}{2}\sum_{n=1}^{9}\sum_{m=1}^{9} \Gamma_{nm} \ln Z_{nt} \ln Z_{mt} + \varepsilon_{\Pi t}$$

$$Z_t' = [A_{X5\,t}\,p_{Q1t} / p_{X5\,t}, A_{X5\,t}\,p_{Q2t} / p_{X5\,t}; A_{X5\,t}\,p_{X1t} / (p_{X5\,t}A_{X1t}), \ldots, A_{X5\,t}\,p_{X4\,t} / (p_{X5\,t}A_{X4\,t}); A_{Kt}K_t / (R_t A_{Rt}); S_{1t} / (R_t A_{Rt}), S_{2t} / (R_t A_{Rt})] \qquad (12')$$

Supply and demand equilibria are derived via Hotelling's lemma - output supplies and factor demands equal the respective derivatives of the profit function:

$$\frac{p_{Qit}Q_{it}}{\Pi_t} = \gamma_{Qi} + \sum_{j=1}^{9} \Gamma_{ij}[\ln Z_{jt}] + \varepsilon_{Qit} \qquad i = 1, 2 \qquad (14)$$

$$\frac{p_{Xit}X_{it}}{\Pi_t} = \gamma_{Xi} + \sum_{j=1}^{9} \Gamma_{i+2j}[\ln Z_{jt}] + \varepsilon_{Xit} \qquad i = 1, 4 \qquad (15)$$

The derivatives of the profit function with respect to capital and land are the ex-ante shadow prices of these two quasi-fixed inputs. Following Berndt *et al.* (1993), we assume that the relevant elasticities are equal to the shares of the two factors in the estimated service flow from capital. Then:

$$\frac{\rho_{Rt}R_t}{\rho_{Rt}R_t + \rho_{Kt}K_t} = -\gamma_R - \sum_{j=1}^{9} \Gamma_{7j}[\ln Z_{jt}] + \varepsilon_{Rt} \qquad (16)$$

where the ρ_i's are the estimated service prices of each asset. The negative sign is required because the estimated parameters define the elasticity of 1/R rather than R itself.

We estimate the system of equations defined by 12' through 16. The model is a nonlinear seemingly unrelated regressions model (Harvey, 1990; Amemiya, 1985). The concentrated likelihood function, L^*, is defined as:

$$\ln L^* = -0.5\, T \ln \left| \frac{1}{T} \sum_t \varepsilon_t \varepsilon_t' \right| + c \qquad (17)$$

where c is a constant, T is the number of observations, ε_t' indicates the transpose of the estimated 8×1 residual vector in period t, and |...| is the determinant of the relevant matrix. The likelihood function is maximized using the Davidon-Fletcher-Powell algorithm (Hamilton, 1994) using a procedure we wrote in RATS 4.02.

Econometric Results

The econometric estimation is applied to the data from 1950 to 1993.[5] We do not provide all the estimated parameters because many of the estimated parameters such as those in the matrix C have no direct economic meaning. Table 1 presents diagnostic statistics for the 8 equations of the model. Table 2 presents the estimate of 5. Table 3 presents the mean of the profit elasticities, one of the building blocks of the decomposition of MFP. Only the elasticities of temperature and rainfall are estimated - the other elasticities are the observed mean profit shares.

The residual diagnostics generally show that the model is an adequate representation of the data. The Durbin Watson statistics shows a lack of first order serial correlation with the exception of the residuals of the land share equation. Interpreted as a cointegration test statistic (Engle and Granger, 1987) it shows that all the equations could be interpreted as long-run cointegration equilibria. The Box-Pierce Q statistic generally shows a lack of higher order serial correlation except in the first and last equations. The Phillips-Ouliaris (1990) cointegration test statistic indicates cointegration in most cases though tabulated values are not available for a model with nine or more regressors. The land share equation again is fairly poor. As land is a quasi-fixed input we expect that equilibrium between the service price and shadow price is not regained as fast as the other variable input equilibria. In fact, the disequilibrium between the total estimated service flow and gross operating surplus typically persists for a large number of periods, though equilibrium is

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[5] The 1948 and 1949 price and quantity data were unusable because of lack of comparable data on weather conditions.

eventually regained.

The augmentation rates of all factors with the exception of land and pesticides are positive. Pesticides show a very rapid decline in effectiveness over time. This result is consistent with the increasing genetic resistance in insect pests in U.S. agriculture (Pimentel *et al.,* 1991). Land also shows a decline in effective units per crude unit, although a slower one than pesticides. This result is consistent with the hypothesis that erosion and other forms of soil degradation have had a demonstrable effect on productivity (Pimentel *et al,* 1993; Troeh, et al., 1991). However, the overall decline in GUC shows that technical change has augmented other factors faster than pesticide effectiveness has fallen, land quality has fallen, and harvested land area has declined (see next section). This result is consistent with previous productivity work which finds a significant and positive rate of input-augmenting technical change (Trueblood and Ruttan, 1995). The mean rainfall elasticity represents a problem with the model as this would not expected to be negative.

Combining the information in Tables 2 and 3, the biggest positive component of technical change countervailing land degradation and area decline is rising labor efficiency, followed by increasing capital efficiency. There is no strong trend in temperature or rainfall so these variables do not make a big contribution to changes in GUC.

Decomposition of MFP

Table 4 gives the breakdown of MFP (l/GUC)in terms of the mean contributions to its growth rate during the period under consideration. MFP grew at a mean annual rate of 1.76%. The residual unexplained variation in MFP is about .14% per annum. The estimates are long-run trend estimates of MFP and measured MFP is above trend for most of the last decade and below trend at the beginning of the period, which biased the growth rate upwards. Growth in labor quality, skills etc. contributed about 78% of this rise or 1.37% per annum. The next most important factor is other inputs, followed by capital. If only the positive components of technical change were present the MFP growth rate would be 2.17% per annum. The declining effectiveness of pesticide lowers this to 2.04% and the remaining changes in resource factors are all negative.

Land "depletion" contributes a negative 0.29% a year to MFP growth while land quantity contributes less than negative 0.1% per annum. Rainfall and temperature contribute small negative amounts. In the absence of positive technical change and assuming that the pesticide effect is largely due to "natural causes", the "natural" factors would lead to MFP declining at 0.55% per annum and the US's food market outlook would be quite different.

8. Conclusions

One of the fundamental challenges in the analysis of sustainability is the quantification and measurement of the balance between the productivity and availability of the resource base and the level of technology. We propose an indicator of this type called generalized unit cost (GUC). Our application of GUC indicates that when the requisite data are available, the method provides separate estimates of changes in the quality or the effective units per crude unit of the natural resource base as well as the degree to which technology increased the effectiveness of other inputs. The results indicate that the effectiveness of the land and pesticide input declined in the US between 1950 and 1993, but that technology increased the effectiveness of other inputs to the extent that GUC declined significantly throughout the period. We anticipate extending this approach to other natural resource sectors.

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Table 1 Residual Diagnostics

Equation	R^2	DW	Q(11)	Phillips-Ouliaris
S_{CROPS}	0.73277	1.796833	25.589823 (0.0075)	-5.89489
$S_{LIVESTOCK}$	0.59922	1.846939	16.337694 (0.1290)	-6.11174
S_{LABOR}	0.81161	1.528185	27.465315 (0.0039)	-5.06614
$S_{FERTILIZER}$	0.60971	1.426318	21.724709 (0.0266)	-4.86108
$S_{PESTICIDE}$	0.80447	1.742793	18.133813 (0.07852)	-5.71087
S_{ENERGY}	0.61187	1.734605	16.914396 (0.1104)	-5.96780
$\ln\Pi$	0.67354	1.474471	17.562484 (0.0923)	-5.17955
S_{LAND}	0.79787	0.826185	29.199833 (0.0021)	-3.11720

Notes : significance levels in parentheses.

Tests are as follows :

DW : Durbin Watson test for first order serial correlation

Q(8) : Box Pierce Q test for general serial correlation / nonstationarity

Phillips-Ouliaris : Phillips-Ouliaris cointegration test

Table 2 Augmentation Rates

Variable	Labor	Fertilizer	Pesticide	Energy	Land	Capital	Other
5	0.05137	0.02020	-0.07124	0.01613	-0.02144	0.01621	0.01197

Table 3 Mean Profit Elasticities

Variable	Labor	Fertilizer	Pesticide	Energy	Land	Capital	Other	Temperature	Rainfall
$\partial \ln \Pi / \partial \ln y$	-1.1966	-0.1843	-0.07385	-0.2314	0.4445	0.5555	-1.6857	2.6376	-0.3101

Table 4 Decomposition of MFP

Source	Contributions to Growth Rate of MFP	Percent of Total
Augmentation Trends		
Labor	0.013673	77.9%
Fertilizer	0.000855	4.9%
Pesticide	-0.00125	-7.1%
Energy	0.000846	4.8%
Other inputs	0.00457	12.6%
Land	-0.00285	-1.6%
Capital	0.001733	9.8%
Uncontrolled Factors		
Rain	-0.00021	-1.2%
Temperature	-0.00042	-2.4%
Land Quantity	-0.00075	-4.3%
Estimated MFP	0.0162	92.3%
Residual	0.001355	7.7%
Actual MFP	0.017555	100%

Figure 1. Generalized unit cost (GUC).