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THE THEORY OF NATURAL RESOURCE SCARCITY INDICATORS: TOWARDS A SYNTHESIS

by

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ABSTRACT

I review the literature on natural resource scarcity indicators further developing my previous work on this issue (Cleveland and Stern, 1993). Scarcity indicators can be classified by what is being measured eg. in situ value, commodity value etc. and by the mode of valuation considered: exchange value and use value. Prices and rents are common measures of exchange value or indicators of "exchange scarcity" and unit costs can be seen as use value indicators or indicators of "use scarcity". "Use scarcity" supersedes the term "productive scarcity" used in our previous paper. One of the major aims of this paper is to demonstrate the links between productivity indicators like unit costs and the classical concept of use value. The two classes of indicator relate to the Hotelling or Ricardian scarcity models, Commons' discussions of scarcity and efficiency, and a non-marginal vs. a marginal approach to value and scarcity. Inverse MFP is a generalized version of unit cost which can be decomposed into the basic determinants of use scarcity. I review the critiques from Norgaard, Darwin, and Farzin which argue that none of these indicators captures all the dimensions of social scarcity. I continue to show that unit cost or inverse MFP is a more general use scarcity indicator than indicators derived using energy analysis. However, energy analysis has a role in examining limits to technical change in mitigating resource scarcity. Finally I suggest that the way forward will be in the empirical study of models of resource supply and demand and the building of scenarios regarding possible future trends in resource scarcity rather than in a search for a perfect indicator.

Keywords: Scarcity, sustainability, indicators, theory, review

JEL Topics: Q20 Q30 Q32

I. INTRODUCTION

Cleveland and Stern (1993) presented a new classification of the various indicators of natural resource scarcity that differentiates between the concepts of "exchange scarcity" and "productive scarcity". In this paper I develop that analysis and suggest further improvements in the search for useful scarcity indicators. I also discuss a number of critiques of the use of various scarcity indicators.

As defined by Cleveland and Stern (1993) exchange scarcity is commonly measured by price or rent and applies to both scarcity in factor markets and scarcity in output markets. Productive scarcity or use scarcity refers to the difficulty of producing a natural resource commodity in terms of the balance between the productivity and availability of the resource base and the level of technology. Improvements in technology can counter a decline in the quality or availability of the resource base. Also if a decline in resource quality is offset by increased availability there is no problem of increasing scarcity. Use scarcity is conventionally measured by the quantity of non-resource factors required to produce a unit of output. The inverse of multifactor productivity approximates the ideal indicator.

The second section of the paper reviews the literature on scarcity indicators, develops a synthesis in terms of exchange and use scarcity and discusses how the use scarcity indicators can be decomposed into subcomponents that reflect technical change, changes in resource quality and changes in resource availability. The literature review argues that though we need to be precise by what we mean by scarcity in order to know how to measure it, the literature has rarely been very clear on this point. The synthesis redefines our classification and discussion of scarcity indicators. The result is a more consistent and insightful system. I suggest the adoption of the term "use scarcity" to either replace or supplement our previous somewhat clumsy "productive scarcity". The decomposition of the use scarcity indicators can be carried out using econometric methods. We are attempting to estimate such decompositions in a number of studies (Perrings and Stern, 1995; Stern, *et al*., 1995).

The third section of the paper presents critiques of exchange scarcity indicators, use scarcity indicators, and biophysical, or energy analysis, indicators. Norgaard (1990) argued that all empirical studies of resource scarcity indicators are philosophically flawed. His critique appears to apply to the use of market prices and rents to measure social exchange scarcity. Darwin (1992) and Farzin (1995) both argue that some technical improvements in resource use result in increased extraction and potentially faster depletion and more environmental degradation. This critique

applies most relevantly to the use scarcity indicators. An alternative to the standard price and unit cost indicators is provided by energy analysis or the biophysical approach to resource scarcity (Hall *et al*., 1986). This approach has come in for strong criticism. I argue that the biophysical literature fails because it ignores the importance of information and knowledge in the economic process. However, energy analysis does tell us some important things about long run resource scarcity in a heuristically informative manner.

Though some methods of estimating exchange and use scarcity are conceptually better than others all individual indicators of scarcity have limitations. In my concluding comments I argue in favor of a pluralistic approach to assessing resource scarcity. Some form of measurement of resource availability is necessary but this should be part of a more general approach that also examines the role of resources in production and institutional frameworks for resource use.

II. THE THEORY OF SCARCITY INDICATORS

A. LITERATURE REVIEW

A major issue in the literature on the measurement of natural resource scarcity is which of the alternative indicators of scarcity, such as unit costs, prices, rents, elasticities of substitution, and energy costs is superior (eg. 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 (eg. 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 (eg. Cook, 1976; Chapman and Roberts, 1983; Cleveland *et al*., 1984; Gever *et al*., 1986; Hall *et al*., 1986; Cleveland, 1988, 1991, 1992).

I argue that the various neoclassical, Ricardian, and biophysical indicators measure different aspects of scarcity. First, different indicators measure the scarcity of different types of resources. For instance rents might be a measure of the scarcity of in situ resources while prices are a measure of the scarcity of extracted resource commodities (Fisher, 1979). Part of the discussion of whether rents or prices are the best scarcity indicator ignores this issue (eg. Brown and Field, 1979). Second, there are two different interpretations of the meaning of natural resource scarcity in the literature. Cleveland and Stern (1993) designate these exchange scarcity and productive scarcity, though as will be explained below I now prefer the term "use scarcity". The underlying concept of

exchange scarcity is the opportunity cost of using the resource for a particular use. As Fisher (1979) stated, a natural resource scarcity indicator "should summarize the sacrifices, direct and indirect, made to obtain a unit of the resource" (p. 252). Prices and rents are typical indicators of this type of scarcity.

Unit cost and related indicators measure changes in the productivity of the resource base over time. Neoclassical economists argue that unit cost omits many important costs. It is perhaps unfortunate that Barnett and Morse chose to name their indicator 'unit cost', because it implied to many that they measured the more common average total cost of resource extraction (eg. Farzin, 1995). In fact, unit cost is the ratio of an input index to an output index. In Barnett and Morse's work the inputs considered are capital and labor alone or only labor in some cases, so that in the latter case unit cost is simply the reciprocal of labor productivity. Hall *et al*. (1981) expanded the definition to also include materials. Generalized unit cost is identical with the inverse of multifactor productivity (Inverse MFP).[1] Barnett and Morse and others argued that unit cost reflects the long-run productivity of the resource base, measuring the net effect of resource depletion and technological change on the required factor input per unit output. Energy intensity or energy cost is also a potential indicator of use scarcity. Some resource economists (eg. Howe, 1979; Brown and Field, 1979) have argued that resource rents are a measure of scarcity that could be used to monitor the productivity of the resource base. However, Mattey (1990) has shown that stumpage prices, the resource rent in the forestry sector, are much more influenced by government policy and economic forecasts than by changes in the difficulty of production. It seems that rental rates are more appropriately considered to be a measure of exchange scarcity in the factor markets.

In discussions of the usefulness of alternative measures or indicators of natural resource scarcity, much of the debate appears to stem from these two different concepts of 'scarcity' (Barnett and Morse, 1963; Brown and Field, 1979; Fisher, 1979; Howe, 1979; Smith, 1980). The classical authors and Barnett and Morse view scarcity as an issue of the productivity of natural resources. They criticize rents because changes in this indicator may also be due to "changes in interest rates, relative demand, and expectations concerning future resource availability" (p. 225) - in other words, anything that obscures the issue of productivity.[2] 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. Part of the problem is that these authors often do not define what they mean by scarcity. Smith (1978) uses two implicit definitions of scarcity in his paper *Measuring Natural Resource Scarcity: Theory and Practice*. When he discusses the comparative statics of a general equilibrium model he implicitly defines scarcity in terms of relative price "... real unit costs will move in the opposite direction to our relative price measures and thus be consistent with movements in rents and natural resource commodity prices relative to wages and non-resource commodity prices, respectively, only when technical change is assumed absent ... thus ... a relative price measure is a superior index of scarcity." (157). If one defines scarcity by real unit costs then the same logic will lead one to decide that real unit costs are a superior measure of scarcity. But in a dynamic context, Smith (1978) agrees with Fisher's statement "... price is preferred, always increasing (decreasing) as a stock is depleted (augmented) over time." (Fisher, 1979, 31). In this case price is not the fundamental definition of scarcity but rather the remaining effective stock of the *in situ* resource appears to be the implicit definition of the scarcity of that resource.

So even within the neoclassical literature two meanings of scarcity are entertained. The clearest statement of the meaning of exchange scarcity is given in Fisher (1979). Fisher sets up a simple optimal control problem for resource extraction. The scarcity indicator is defined by the relevant price of the resource in the optimal control problem. This price reflects "the sacrifices, direct and indirect, made to obtain a unit of the resource". In Fisher's example the private profit-maximizing resource owner faces the following problem:

$$\text{Max} \int_0^\infty [Pf(E,X,t) - WE]e^{-rt}$$

$$\text{s.t.} \quad dX/dt = -Y \qquad (1)$$

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 will be met:

$$P = W/(\partial Y/\partial E) + q \qquad (2)$$

where q is the costate variable attached to the constraint in the Hamiltonian. Market price, therefore represents the sum of direct sacrifices ie. hiring effort, and indirect sacrifices ie. the change in the net present value of future profits caused by reducing the size of the remaining resource stock. The latter quantity q is also known as the shadow price of the stock, the user cost, or rent. However, 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 will be the appropriate scarcity indicator for resource commodities and rents for resource stocks. Appropriate indicators for other resource problems can be derived by appropriate formulation of the dynamic optimization problem.

The first, important, caveat raised by Fisher is that market prices and rents are only appropriate indicators of private scarcity. In the presence of market imperfections or market failure social indicators of scarcity will diverge from the private indicators. For example, declining market prices (as found by Barnett and Morse, 1963, for most resources) would not necessarily mean that social scarcity was declining unless there was no environmental disruption associated with resource extraction or zero social value was placed on that disruption.

Second, Fisher raises doubts about the adequacy of rent as a measure of scarcity. This is shown by two theoretical models of resource depletion. In the first there is a finite stock of constant quality resources. In the second the stock is of variable quality and extraction of the best quality resources first means that the average quality of the stock declines over time. In the first case the effective units per crude unit are constant but ceteris paribus the marginal product and therefore the rent is rising because less resource stock is being used with the same quantity of capital etc. The price of the resource stock is rising as its quantity declines and therefore the value of the marginal product, the rent, is rising over time as the quantity of the resource is depleted. In the second case in the absence of technical change and increases in the use of capital, labor etc the physical marginal product and the rent of the resource will decline as its quality is depleted. Fisher argues that it will eventually decline to zero. For example if all the above average concentrations of a mineral are exhausted, the remaining resource base would be very large but of extremely low quality.

The latter case appears to worry Fisher because now it seems that society is much worse off than previously but the rent indicator shows that the scarcity of the stock has declined. The indicator does, however, show accurately that resource stocks are not very scarce for those who wish to purchase the rights to their use. There is little contest to buy these low quality stocks. Price will have risen steeply reflecting the fact that private purchasers of resource commodities will have to make great sacrifices to obtain them. Therefore, Fisher argues that prices are a better indicator, despite the fact that they do not reflect social scarcity except under ideal circumstances. Fisher also notes that unit costs will move in the opposite direction to rent in these two cases. The difficulty of extraction does not increase in the first case while it rises in the second case.

The use scarcity indicators were first developed by Barnett and Morse (1963) who used the

writings of Malthus and Ricardo, and particularly Ricardo, as a starting point for their theoretical discussion of of natural resource scarcity. Ricardo, together with Marx, argued that the labor cost of production could be used as a common unit of measurement of the use value of commodities and that use value, rather than exchange value, was the more important or "real" measurement of value.[3] Ricardo also saw nature not as a factor of production but rather 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. Barnett and Morse take the meaning of increased scarcity to be an increase in the resistance of nature to the efforts of people to produce resource commodities; for example Ricardo's classic case of declining fertility of land at the extensive margin. Therefore, naturally we measure such scarcity by 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. Barnett and Morse also combine Ricardo with a neoclassical production function to derive more comprehensive measures of use scarcity that account for the capital employed. Hall and Hall (1984) extend unit cost to cover materials and below I generalize this to inverse multi-factor productivity.

B. TOWARDS A SYNTHESIS

In this section I attempt to synthesize the various observations raised in the previous section regarding alternative scarcity indicators. I rely to a great extent on the concepts of scarcity and efficiency discussed by Commons (1934).

The two fundamental concepts of value in economics are use value and exchange value. For a private person wishing to acquire a resource commodity, market price is a valid indicator of exchange value, though for owners of resources or society the shadow prices of commodities or resources will diverge from their market prices except under unrealistic conditions. Under such conditions prices will " summarize the sacrifices, direct and indirect, made to obtain a unit of the resource" (Fisher, 1979, 252). It is this meaning of scarcity that I term exchange scarcity.

Use value was always a problematic concept because either it was impossible to measure or the units of measurement were unclear. For Smith use value was utility - the happiness or satisfaction derived from using a commodity. The classical economists did not conceive of this utility as declining with increasing consumption. Therefore there was no relation between use value per unit and the abundance or consumption of the commodity. 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; Stern, 1996). The use value of a particular material object would also decline through wear and tear over time. Because even in the classical usage changes in preferences etc. affect the use value of a good, Commons' suggestion to measure use value in physical units is not wholly satisfactory.

Ricardo and Marx tried to find a unit of measurement for use value which would allow aggregation. One common denominator was the amount of labor used to produce the various use values. This was the second version of the classical labor theory of value. Smith had used labor as the numeraire commodity because he had no other method of adjusting for inflation (Commons, 1934). As such, Smith's labor theory of value was a theory of exchange value while Ricardo and Marx's theory was one of use value. Even assuming that labor is the only primary factor and preferences etc. are irrelevant this latter labor theory fails because: labor can be used to do useless things - just because something is difficult to produce does not mean it has to be useful; the efficiency of labor in producing use values changes over time due to technical change; and *in situ* natural resources require no labor in their production and therefore according to Marx and Ricardo have no value. Marx avoided the first problem by declaring that "if the thing is useless, so is that labor contained in it; the labor does not count as labor, and therefore creates no value" (Marx, 1867, 48). He got around the second problem by measuring capital not just in terms of the direct labor used in its production but also in terms of the labor embodied in the creation of the knowledge needed to produce it - so called social labor power (Commons, 1934). However, the former is a case of circular reasoning and the latter difficult to measure.

Commons (1934) paralleled the concepts of exchange and use value by his categories of "scarcity" and "efficiency." Efficiency is a measure of productivity determined by the technical relations of production 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 (or inverse MFP). When there are several factors of production instead of just labor it is impossible to a priori identify the contribution of each to use value. Even in Ricardo's theory of growth there are two factors of production: labor and land, though, as mentioned above he only considered the former to be a factor of production. Now if the input/output ratio is calculated omitting one of the factors ie. land, a rise in the ratio implies a decline in the use value produced by the omitted factor. This may be due to either a decrease in the quantity of the omitted factor, a decline in its quality or effective units per gross unit, or a decline in the efficiency with which the factors are combined. Thus this factor productivity index is a measure of the use value produced by the omitted factor and unit cost is a measure of what I have called above the use-scarcity of the natural capital employed. We can derive the same measure from within Ricardo's paradigm by arguing that the input/output ratio measures

the resistance of nature to human action. Either an increase in nature's innate resistance or a decline in human skill would mean that use-scarcity increases.

Commons contrasts technical efficiency and its role in the production of use value with "scarcity" and its role in the production of exchange value and documents the relationship of the scarcity and efficiency concepts throughout the history of economics. A commodity has exchange value because it is in short supply relative to demand or is scarce. Scarcity is ultimately determined by institutional relations while efficiency is determined by technical relations. In a competitive market, improvements in technical efficiency always increase use values but reduce scarcity, lower prices, and if demand is inelastic lower total revenues, reducing exchange value. The exchange value concepts that parallel input and output are expenditure (on factors) and revenue. The revenue / expenditure ratio is the rate of markup of profit. If only land is omitted from the calculation of expenditure on inputs, then the profit markup rate is $M = 1 + rR/C$ where r is the rental rate, R is land, and C is cost. Thus unit cost is a use value indicator of natural resource scarcity and rent is an exchange value indicator of natural resource scarcity.

Now we can understand Fisher's (1979) comments on the inadequacy of rent as a scarcity indicator in the case of the depletion of a stock of variable quality. The average use value of the remaining mineral deposits declines radically but so does their exchange value. 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.

As we have seen, exchange scarcity indicators are derived from the Hotelling model of resource depletion and use scarcity indicators from the Ricardian model. Neoclassical economists tend to focus more on exchange value while Ricardo was primarily interested in use value. But both schools of thought do recognize the other mode of valuation. Therefore, all the arguments in the literature for and against unit cost as a measure of scarcity are misplaced because the various proponents do not recognize that it is intended to measure a different dimension of scarcity than is price.

As noted above, changes in preferences etc. affect use value. Therefore, even within the classical model unit cost is not a totally adequate indicator of use scarcity. Further complications enter when we look at neoclassical measures of use scarcity rather than the classical measure we have

examined up till now. Whereas the classical measure does not decrease with abundance, neoclassical economists assume that in most cases average use value will decline with increasing consumption. The standard neoclassical interpretation of use value is consumer surplus plus the exchange value (Samuelson, 1980, Hirshleifer, 1984).[4] As demand functions are assumed to decline for normal commodities the average use value of the commodity will decline as consumption rises ie. marginal utility declines. This neoclassical use value also declines with degradation of the commodity or changes in preferences etc. which lower the utility of and hence demand for the product. Demand for a good will also decline if the price of a substitute declines. This is because utility in consumption of a good depends on consumption of its substitutes (and complements). The greater (lesser) the consumption of the substitute (complement) the less (more) the utility derived from consumption of the good.

Unit cost or inverse MFP is, therefore, only an accurate measure of use-scarcity under the assumption that utility functions are linear in commodities and income and that there is no change in preferences over time. The method could be improved by measuring outputs in terms of total utility. In the neoclassical model use-scarcity is a measure of the generation of total utility by natural capital and exchange-scarcity is a measure of the marginal contribution to utility of the resource stock. 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. Therefore, inverse MFP is also only an accurate indicator of use scarcity if the technology of manufacturing processes that employ resource commodities does not change over time.[5] Assuming that technical change is neutral, if net technical progress is faster in the non-resource sector, then the demand for resources per unit output will be declining. Therefore, the faster that technical progress occurs in the non-resource sector relative to that in the resource sector the faster scarcity will be declining.

Why is use scarcity important? The primary reason why economists and others (eg. Malthus, 1778; Ricardo, 1817; Barnett and Morse, 1963; Meadows *et al.*, 1972; Gever *et al.*, 1986) have been concerned with natural resource scarcity is because they thought that the limited availability of natural resources might cause economic development to be unsustainable. Development is defined in terms of the determinants of well-being and a neoclassical definition of sustainable development is: "non-declining utility of a representative member of society for millennia into the future" (Pezzey, 1992, 323). By definition utility refers to use value and not exchange value and therefore use-scarcity is the most immediately relevant measure of scarcity in sustainability analysis. For commodities with inelastic demand, a decline in the quantity of the commodity available will cause the total exchange value to increase but use value to decline. A commodity that has few substitutes or is difficult to replace with substitutes will have inelastic demand. This problem is ignored in

most standard sustainability models (Stern, 1997).

Many authors argue that a necessary condition for the achievement of sustainability is the maintenance of a constant level of capital stock or capital services, both natural and human-made (Page, 1977b; Pearce *et al.*, 1989; Victor, 1991). There are problems in defining the relevant capital stocks and in aggregating them (Norgaard, 1991; Karshenas, 1992; Common, 1993, 1995; Stern, 1997). However, a sufficient condition for the achievement of the constant capital stock condition would be if each individual capital stock was maintained. This condition is neither necessary nor sufficient for sustainability defined as non-declining per capita income except under some strong assumptions. It is, however, a criterion of intertemporal fairness in the sense of giving future generations the same opportunities that we received from previous generations. This means that productive scarcity is concerned with the concept of the sustainability of resource production defined in terms of a non-declining effective resource stock (Page, 1977a; Howe, 1979; Pezzey, 1989). It is also compatible with the precautionary principle given our lack of knowledge about relevant elasticities of substitution (Stiglitz, 1979).

The constant capital stock condition can be defined in terms of use-scarcity. The total use value of the stock should be kept constant. This means multiplying the size of the stock by its average use value. If use-scarcity rises then we need to increase the size of the stock to compensate, while if use-scarcity is falling, for example through technological improvements, development of substitutes, or changes in preferences, we can reduce the size of the stock. This addresses Fisher's (1979) concern, mentioned above, that unit cost will not rise as a constant quality stock of minerals is depleted. The use value per unit will not increase but the total use value represented by the stock will decline. Depending on demand elasticities the total exchange value might rise so that using the exchange value of the stock as an indicator of a constant capital stock could be a dangerous mistake.

C. DECOMPOSING INVERSE MFP

Emerging from the discussion in the previous section is a view that we need to look at many dimensions of scarcity simultaneously. At a minimum we need to look at exchange and use scarcity from private and social perspectives and also to look at the size of capital stocks in addition to their marginal or average value. Though indicators of this sort and historical assessment of sustainability performance may be useful, I argue (Stern, 1997) that building scenarios or modeling the future economy will probably be the most effective way of incorporating sustainability options into the policy debate. It may be important to know if we have been or are unsustainable but it will be most

useful to know what the effects of our current actions may be on the future development of the economy and environment. To that end, this section looks at more disaggregated indicators of use scarcity that might be useful in developing scenarios which are more sophisticated than simply assuming that the scarcity indicators such as unit cost will continue their current trend. These more disaggregated indicators are developed through a decomposition of inverse MFP.

Barnett and Morse (1963) attempted a primitive 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.

As in Barnett and Morse (1963), the starting point is the production function for a resource commodity Q:

$$Q = f(A_1, ..., A_{n-1}, A_R, X_1, ..., X_{n-1}, R, S) \qquad (3)$$

where R is the resource base from which the resource is extracted, and S is a vector of additional uncontrolled natural resource inputs. For example when we look at the scarcity of agricultural land, changes in rainfall and temperature also enter the picture. The X_i are variable 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 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 (3) can be obviously generalized to multiple outputs and multiple resource inputs.

Taking the time derivative of lnQ yields:

$$\dot{Q} = \dot{RTS} \ln Q \, RTS^{-1} + \Sigma \sigma_i \dot{A}_i + \sigma_R \dot{A}_R + \Sigma \sigma_i \dot{X}_i + \Sigma \sigma_i \dot{S}_i + \sigma_R \dot{R} \qquad (4)$$

where the σ_i are the output elasticities of the various inputs. We define multifactor productivity as:

$$\dot{MFP} = \dot{Q} - RTS^{-1} \Sigma \sigma_i \dot{X}_i \qquad (5)$$

Typically the change in log MFP will be calculated using a Divisia index of input where $RTS^{-1} \sigma_i$ is replaced with the relevant revenue share.[6] The change in inverse MFP, I, is simply the negative of the LHS of (5). From (4) and (5) the change in the logarithm of inverse MFP is given by:

$$\dot{I} = -\dot{RTS}\ \ln Q\ RTS^{-1} - \Sigma\,\sigma_i\,\dot{A}_i - \sigma_R\,\dot{A}_R - (1 - RTS^{-1})\ \Sigma\,\sigma_i\,\dot{X}_i - \Sigma\,\sigma_i\,\dot{S}_i - \sigma_R\,\dot{R} \qquad (6)$$

Thus moves in the indicator of use scarcity are the sum of the six terms in (6):

1. Change in returns to scale
2. Technical change
3. Resource depletion or augmentation
4. Change in factor inputs (for non constant returns to scale functions only)
5. Change in uncontrolled natural resource inputs such as rainfall and heat
6. Change in the dimension of the resource base.

The subcomponents of inverse MFP could be estimated directly if we have a means of estimating the size of the resource base directly. The most appropriate technique is the joint estimation of the production function (or profit function) and producer behavior equations. The number of equations estimated must be at least equal to the number of augmentation trends in order to ensure identification. The estimated technical change trends could be assumed to be deterministic or stochastic. In the former case the non-linear seemingly unrelated regression can be employed (eg. Berndt *et al*., 1993; Stern *et al*., 1995). In the latter case they can be estimated by the Kalman filter (eg. Slade, 1989; Stern, 1994). More sophisticated models could seek to endogenize technical change.

An interesting corollary of equation (6) is that all previous studies of biased technical change in the extractive sector of the economy fudge together 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. Poorer wood inputs mean that more will be used per unit of finished product. 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.

Equation (6) also reveals a shortcoming of Barnett and Morse's unit cost index. The simple labor only unit cost is defined by:

$$\dot{I} = -\dot{RTS}\ \ln Q\ RTS^{-1} - \Sigma\, \sigma_i \dot{A}_i - \sigma_R \dot{A}_R - (1 - RTS^{-1})\ \Sigma\, \sigma_i \dot{X}_i - \Sigma\, \sigma_i \dot{S}_i - \sigma_R \dot{R}$$
$$- \sigma_E \dot{E} - \sigma_M \dot{M} - \sigma_K \dot{K} + (1 - \sigma_L)\, \dot{L} \qquad (7)$$

where K is capital, E is energy, and M is materials (assuming a KLEM type specification of the production function such as in Berndt and Wood (1975)). The equation demonstrates that substitution of energy (or capital and materials) for labor reduces unit cost. This was the major criticism of unit cost by energy analysts. Results for a labor and capital unit cost are very similar. Inverse MFP (6) does not suffer from this problem. Future trends in use scarcity might be better understood if we could estimate each of these components separately. Most analyses of use 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).

III. PROBLEMS WITH SCARCITY INDICATORS

A. NORGAARD'S CRITIQUE

Norgaard (1990) argued that the principal theoretical models of scarcity require that resources be scarce and that resource allocators are fully informed of that scarcity in order for economic indicators to be good measures of scarcity. In the realistic case where resource allocators do not have this perfect knowledge there is no information about scarcity in the economic indicators. He goes further to state that if resource allocators were informed about scarcity we should ask them whether resources are scarce rather than attempting to analyze market data to determine this fact. This latter point is less persuasive as in many other areas researchers prefer to examine revealed preferences rather than stated preferences (eg. contingent valuation of environmental resources), if data is available, because of the methodological difficulties in obtaining accurate measurements of the latter. I argue that Norgaard's discussion has some semantic confusion and in any case it applies more to some indicators of resource scarcity than to others.

The semantic confusion is Norgaard's use of the term "scarce". Resources that have a positive price are by definition scarce whatever resource allocators know or do not know. Instead,

Norgaard should have said that the empirical literature is attempting to find out "whether resources are becoming more scarce over time and whether current actions are making the resource more scarce in the future". For a private individual or firm that wishes to purchase units of the resource commodity or hire resource stocks, the market price or rental rate, respectively, is the perfect measure of scarcity, irrespective of what they do or do not know about trends in resource availability. So for this dimension of scarcity, Norgaard's criticism is not valid. His comments are much more valid when we contemplate the use of market prices to evaluate scarcity for either a resource stock owner or society as a whole.

For the resource owner market prices may fail to capture the true indicator of scarcity for two principal reasons. First is an information problem - the resource owner has limited knowledge of the future in terms of future demand, input prices, and extraction technologies and may also have limited knowledge about the true dimensions and quality of the resource stock in his possession. Second is a problem of market imperfections and in particular problems of asymmetric power which prevent resource owners from capturing the full intertemporal rent (see Brower, 1987; Tilton, 1992; Stern, 1995). For society the problems are well known and in addition to the problems facing the resource owner include externalities due to environmental degradation resulting from resource extraction and use.

Norgaard's criticism does not seem to be relevant to the use scarcity indicators. The dimension of scarcity that they reflect does not depend on property rights. Under assumptions about future trends in technology and resource quality, data on use scarcity could be used to generate scenarios about future scarcity. This forward-looking property is, of course, sensitive to changes in the rate and bias of technological change, and to the future discovery of more productive resources (the "Mayflower Problem" in Norgaard's terminology).

In conclusion, I believe that Norgaard (with a little reinterpretation) does make valid points about some uses of empirical scarcity indicators. Obviously market prices will not be accurate reflections of social scarcity except under unrealistic conditions. However, if we are careful to avoid such sweeping generalizations and adopt a more disaggregated modeling strategy as described in the previous section I think that empirical analysis can make a contribution to our knowledge about the future scarcity of natural resources and the implications of those trends for sustainability. It is preferable to develop some knowledge, however imperfect, than to avoid discussion of the issue just because it is impossible to produce a perfect aggregate indicator of social exchange scarcity.

B. DARWIN AND FARZIN

No single indicator of resource scarcity is complete. A recent critique by Darwin (1992) of technical change studies relates to my concept of use scarcity. Most studies of technical change are carried out in the Hicksian framework of input demand functions. That is, the output quantity is taken as given and input prices vary. Darwin uses as his example the lumber industry in the Pacific Northwest of the USA. Even assuming that demand for lumber is totally inelastic, so that demanded output is the same at any price, a technical change that reduces the input requirements of sawlogs would not reduce demand for sawlogs by sawmills by quite as much. The shadow price of sawlogs would fall relative to that of capital and labor and therefore the quantities of capital and labor employed would decrease as sawlogs were substituted for them eg. lumber companies would use less highly skilled workers to determine the optimal cutting pattern, no longer being so concerned with wasting wood. This effect may, however, be accentuated when we take into account changing output quantities in a Marshallian demand and supply framework (ie functions derived from the profit function rather than the cost function). Reduced input costs per unit of production mean that supply will increase at any given price. Taking into account the interaction of supply and demand, price will fall and output increase. This increased output will further increase the demand for sawlogs, and it is possible that the total increase will outweigh the initial decrease in sawlog requirements. Econometric analysis shows that this indeed seems to have been the case in the Pacific Northwest.

This is a clear illustration of the fact that though use scarcity may have decreased, scarcity of trees and forests for non-manufacturing purposes may have increased as more lumber is cut. Productive scarcity is no more a catch-all indicator than is price. It only measures one aspect of overall scarcity.

A similar argument is presented by Farzin (1995) in the context of the effects of technical change on the possible time paths of price and rent indicators. Farzin distinguishes between extraction biased technical change ie. technological improvements that reduce the marginal cost of extraction; and depletion biased technical change ie. technological improvements that reduce the marginal increase in costs due to a reduction in the resource stock. Improvements that reduce marginal extraction costs tend to speed up the rate of depletion and hence the rate of increase in price, though in the short-run they will lower prices. Improvements that reduce marginal depletion costs extend the life of the resource and hence reduce the rate of price increase. Both have the same effects on inverse MSP. In this case though use scarcity declines in the short-run due to the reduction in extraction costs the rate of depletion of the natural resource is accelerated which may accentuate

negative environmental impacts and less remains for use by future generations.

C. CRITIQUE OF THE BIOPHYSICAL APPROACH

The energy analysis, or biophysical, approach to resource scarcity suggests that energy cost is a superior indicator of scarcity to unit cost (eg. Cook, 1976; Chapman and Roberts, 1983; Cleveland *et al*., 1984; Gever *et al*., 1986; Hall *et al*., 1986; Cleveland, 1988, 1991, 1992). This argument is based on the fundamental relationship between energy use and resource quality: lower quality resources have a lower degree of organization and therefore require more energy to upgrade to a given level of organization. This energy cost includes both the energy used in direct fuel use and the energy used indirectly in the production of other inputs. Energy inputs may also be aggregated into quality-weighted indices to reflect variations in productivity among different fuel types (see Berndt, 1978; Cleveland, 1992; Cleveland and Stern, 1993). Another theme in the biophysical literature is that the quantity of energy used in resource extraction represents a cost to society in terms of the non-availability of that energy for other uses. This is the motivation underpinning the concept of energy return on investment (EROI) (see Hall *et al.*, 1986). However, the literature does not clearly differentiate between these two themes. Recently energy analysis has been extended to analyze the relationship between the waste generated per unit of resources extracted and resource quality (eg. Kaufmann and Cleveland, 1991). Lower quality resources require more energy to extract and therefore more pollution is produced.

The biophysical approach seeks to redefine the system boundaries of the economy as compared to the neoclassical approach. The only true external inputs to the system are low entropy energy and highly organized matter (Hall *et al*., 1986). Both capital, as is recognized by neoclassical economists,[7] and labor are produced within the system. I argue in the following that this system boundary is also incorrect because it assumes that the productive capacity of technology is purely a linear function of the energy used to create and implement that technology. In order to demonstrate this I first need to digress in a discussion of production theory.

i. Production Theory

Accounting for capital and labor in terms of their energy cost alone, as is done in energy analysis, ignores those aspects of these factors that contribute to production but do not vary linearly with their energy cost. A biophysical theory of production need not reduce to an energy theory of production. Information is also a primary input to production in the sense that it is not manufactured inside the economic system. Any organized structure contains information [8] that can

be extracted and converted into economically useful knowledge. Technology consists of the designs for the products to be manufactured, the ideas for which come in part 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.

In a finite universe, with a fixed set of physical laws, useful knowledge must ultimately be limited in extent. It seems therefore that as in the extraction of energy from the environment there are diminishing returns to the extraction of knowledge. Anecdotal evidence shows this to be true. One only has to compare the process of innovation in the 19th century with that of today to see that vastly greater resources are employed to obtain a given advance in technology. Particle physics is a clear case of diminishing returns in science.[9] This hypothesis is not new. Marshall stated: "Improvements in production must themselves gradually show a diminishing return" (cited in Barnett and Morse, 1963). Unextracted information behaves, therefore, just like any other nonrenewable natural resource.

However, the role of knowledge in production does not directly parallel that of energy. Chen (1994) discusses this issue in detail. He points out that information as such is immaterial and not directly quantifiable despite the claims of information theorists to the contrary. Its fundamental difference from energy is illustrated by the fact that it is not destroyed by use and it is non-rival in use (Romer, 1994).[10] This implies that it is not a limiting factor on the expansion of the scale of production - there can be constant returns to scale even if the stock of knowledge is held constant - and that there are non-diminishing returns to an increase in the accumulation of knowledge. Like energy, knowledge can be used directly through the means of combining the other factors of production or indirectly through incorporating information in factors of production (Chen, 1994). Capital clearly embodies knowledge about means of production. Labor also does, though here it is a case of information stored in the brain which is used to carry out production tasks. Chen argues that secondary forms of energy such as electricity also embody technical knowledge. Information is also employed through the set of techniques of production. Knowledge is embodied in the minds of the workforce and in the structure of capital. The way in which energy is employed in production, and therefore its productivity, also depends on the employment of knowledge. Without an adequate way of measuring knowledge we must in many cases treat capital and labor as proxy variables for the true primary factor, knowledge. To some extent what is considered technology

and what a factor of production depends on our theory of production. In the neo-Ricardian paradigm, only one technique exists at any one time. Any changes between techniques are considered as technological change (eg. Perrings, 1987). In the neo-classical paradigm changes in the efficiency of production are considered to be technological change while an infinite number of possible techniques may coexist. Disembodied information therefore plays a larger role in the neoclassical theory - if there is only one way to make something most of the knowledge can be incorporated in the capital but when production is more flexible management is more important.

Highly organized matter is not a primary factor of production in the same sense as low entropy energy or knowledge. This is because energy can be used to improve the organization of matter. This of course entails an increase in the entropy of the universe in accordance with the second law of thermodynamics, but does not necessarily entail an increase in the entropy of the open or closed local system. Georgescu-Roegen (1971) asserted that complete recycling of matter was impossible and that in a closed system there exists a material entropy which continues to increase until all matter becomes unavailable - the fourth law. Bianciardi *et al*. (1993) show that this is not the case and that if it was then the second law of thermodynamics would be untrue. The limitation is posed by insufficient supplies of low cost energy inputs with which to process matter into more organized states. Though organized matter per se is not primary, certain aspects of organized matter are primary, at least at the present time. The two most important of these are the chemical properties of the elements (Perrings, 1987) and the genetic characteristics of organisms. Knowledge of these properties is the kind of information that I am including in the knowledge factor of production.

Given that knowledge is also a scarce primary factor, the fact that low entropy energy is primary in this sense no longer is the crucial distinction regarding the economic process, as vast quantities of energy are available on Earth, whether as deuterium in sea-water or as photons in the solar energy flux. The constraints exist in the means of harnessing this energy to economically useful ends.

ii. Implications for Biophysical Indicators

From equation (4) and (7) the change in the logarithm of energy cost is given by (assuming constant returns to scale for simplicity):

$$\dot{I} = -\Sigma\, \sigma_i \dot{A}_i - \sigma_K \dot{K} - \sigma_L \dot{L} - \sigma_M \dot{M} + (1 - \sigma_E)\dot{E} - \Sigma\, \sigma_i \dot{S}_i - \sigma_R \dot{R} + \dot{\varepsilon} \qquad (8)$$

where $\dot{\varepsilon}$ is the change in the logarithm of the ratio of total energy use to direct energy use (U + E) / E. The problem with this indicator is that a rise in direct energy use raises energy cost *ceteris paribus* unless indirect energy use is very large relative to direct energy use:

$$\frac{\partial \ln I}{\partial \ln E} = 1 - \sigma_E - \frac{U}{(U + E)} \qquad (9)$$

where U is indirect energy use. $\sigma_E < 1$ and therefore the derivative is positive unless U is very large relative to E. For example, in Berndt and Wood's (1975) study of US manufacturing $\sigma_E \cong 0.045$ and so if we set (9) equal to zero we find that U has to be at 21 times greater than E in order for the derivative to be zero. Increases in indirect energy use tend to have the opposite effect on the indicator. Assume a uniform one percent increase in capital, labor, and materials, and assume that the additional units of these factors of production are just as energy intensive as those previously employed. Also for simplicity assume that no energy is required to extract the direct energy used so that its embodied energy is zero. In this case the increase in the factors tends to lower energy cost by $100(\sigma_K + \sigma_L + \sigma_M)$ percent. The one percent increase in indirect energy use raises energy cost by 100 E / (E+U) percent. For resource extraction industries the return to R might be quite large in which case E would not have to be that much bigger than U in order for the derivative to be non-negative. For example if the return to land is 20% of the total and the return to energy 5% of the total then direct energy must be 3 times greater than indirect energy.

The implication of this discussion is that substituting energy for capital, labor, and materials will in most circumstances result in rising energy cost. Again assume that $\sigma_E = 0.05$ and $\sigma_R = 0.2$ and that the elasticity of substitution is unity. For a 1% decrease in capital, labor, and materials maintaining output means that direct energy use must be increased by 15%. If direct energy use is equal to indirect energy use, energy cost rises by 6.5%. This substitution may simply reflect a lower relative price for energy. By contrast greater energy use has no effect on inverse MFP (6) and lowers unit cost (7). The results of Cleveland's (1995) study of an energy cost indicator for US agriculture illustrate this result. Energy cost rose steeply until 1979 as real energy prices declined and was reversed after 1979. Cleveland (1995) attributes this result to "diminishing returns to energy". The result is probably partly due to decreasing returns as all factors except land are increased and partly due to substitution of energy for capital and particularly labor along the isoquant.

Mitchell and Cleveland's (1993) analysis of trends in energy cost indicators of fish caught by the fishing industry in New Bedford, Massachusetts also illustrates this weakness of the energy

analysis approach. Energy cost increased during the time period under consideration. The authors discovered that large federal government subsidies began to be paid to fishermen during the sample period in order to purchase new fishing boats, to help maintain the industry in this chronically depressed city. The reduced cost of capital meant that fishermen bought larger ships that consumed more energy in construction and operation than they would otherwise have done. Here a reduced price of capital relative to labor resulted in the substitution of heavily energy intensive capital for less energy intensive labor. Capital and direct energy use are complements in this case and so direct energy use also increased. This behavior caused an increase in the energy use per fish caught that was directly unrelated to changes in technology or resource quality. Part of the increase in energy cost was also due to resource depletion offset to an unknown degree by technological change.

These problems would disappear under the assumption that the output elasticities are proportional to their share of total embodied and direct energy:

$$\sigma_i = (U_i + E_i) / (U + E) \qquad (10)$$

where U_i is the embodied energy of factor i or the indirect energy used in its manufacture and E_i is the direct energy associated with it. The latter quantity is zero for all inputs except direct energy itself. This assumption implies that there are constant returns to total energy use holding land and other resource inputs (R and S) constant. In this case (8) is identical to (6) where the returns to scale are given by :

$$RTS = 1 + \Sigma \sigma_i + \sigma_R \qquad (11)$$

Equation (10) is a form of the energy theory of value. It is not a strict version of the energy theory of value in that the natural resources R and S contribute toward the production of use value. But it is an energy theory of value in that the productive powers of capital, labor, and materials are purely a linear function of their embodied energy. It is also rather unreasonable in that there are constant returns to applying energy to give quantity of natural capital. Assuming constant returns to all factors instead yields:

$$\dot{I} = - \Sigma \sigma_i \dot{A}_i - \Sigma \sigma_i \dot{S}_i - \sigma_R \dot{R} + (\Sigma \sigma_i + \sigma_R) \dot{\varepsilon} \qquad (12)$$

so that increased direct or indirect energy use has the same impact on increasing energy cost. We can avoid this problem by calculating energy cost as:

$$\dot{I} = - \dot{Q} + (C / V) (U \dot{+} E) \qquad (13)$$

where C and V are cost and revenue as above. Hence use of biophysical measures of scarcity implies acceptance of the energy theory of value despite the assurances of some researchers to the contrary (eg. Hall *et al*., 1986). The empirical evidence of such studies as Mitchell and Cleveland (1993) and Cleveland (1995) falsifies the energy theory of value. But a true biophysical theory of value is not falsified by any such data (and if knowledge is unmeasurable is not falsifiable). This true theory views the productive powers of the intermediate products as being a function of both the energy and knowledge embodied in them. In the absence of our ability to measure knowledge directly our second best approach is to use data on the capital stock, labor hours etc as proxies for the embodied knowledge. This leads naturally to inverse MFP as a proxy biophysical use scarcity indicator.

On the other hand I do not wish to leave the reader with the impression that energy and thermodynamic analysis does not have a useful role to play in scarcity analysis. Quite to the contrary, thermodynamics can tell us important things about the maximum efficiencies of various processes in energy terms and hence the limits to technical change in mitigating resource scarcity. This information needs to be combined with information on production functions in order to construct realistic scenarios about future scarcity trends.

VI. CONCLUSIONS

There is no "correct" way to measure resource scarcity. To a large extent arguments over the meaning of and indicators of scarcity reflect fundamental disagreements among economists regarding the nature and purposes of economics (Cole *et al*., 1983). However, I believe that these different views are complementary and I have tried to show just how this is so.

There are at least two meanings attached to the term scarcity in the economic literature which I name exchange scarcity and use scarcity. They relate to the Hotelling or Ricardian scarcity models, Commons' discussions of scarcity and efficiency, and a non-marginal vs. a marginal approach to value and scarcity. Rents and prices measure the private exchange scarcity of stocks and commodities respectively for those wishing to purchase them. They are not necessarily good measures of scarcity for society as a whole or for resource owners. Unit cost or its generalization as inverse MFP is a possible indicator of use scarcity but it is not perfect either as a social scarcity indicator - it does not reflect downstream technical improvements in resource use, nonlinear utility functions, or, as in the case of price, the impact of environmental damage associated with resource extraction and use on welfare. Inverse MFP does not have the shortcoming of being affected by

information and resource market imperfections which affect the exchange scarcity indicators. The biophysical indicators, however, fail in that they imply the acceptance of an energy theory of value despite knowledge and information's role as a primary factor of production in a biophysical sense. Energy and thermodynamic analysis can, however, provide us with useful information regarding future possibilities for technical change.

Perhaps more useful than the simple calculation of scarcity indicators would be a research program aimed at modeling resource supply that takes into account both physical and economic factors. Rather than just observing the trend in MFP or prices and assuming that this will continue into the future this approach would seek to differentiate between the various causes of change in scarcity. This would give us a better picture of the limits to improvements in the future. One study of this sort was conducted by Cleveland and Kaufmann (1991) to model oil supply. Perrings and Stern (1995) model rangeland degradation in Botswana as the outcome of physical processes and a changing economic environment. Stern *et al*. (1995) decompose MFP in Sri Lankan agriculture as in equation (6) by using an econometric model of the agricultural sector.

Together with information on the possibilities for future technical change and natural processes such models could be used to produce scenarios about the possible future scenarios of resource scarcity trends that could used to inform debate and policy making. I believe that this would be a more productive endeavor than the search for the perfect resource scarcity indicator.

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Notes

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[1] As discussed in section IV, I use MFP to refer to factor productivity calculated with respect to aggregate inputs with the exception of the resource base itself, and TFP to refer to factor productivity calculated with respect to all inputs including the resource base.

[2] But they praise the use of prices compared to unit cost as price "is comprehensive as regards cost coverage in its inclusion of all purchased inputs" (Barnett and Morse, 1963, 211).

[3] Barnett and Morse do not discuss the concept of value, whether use value or exchange value.

[4] Unless the utility function is quasilinear there is no unique measure of the utility derived from an individual good (Varian, 1992).

[5] For example if electricity generation now requires less coal per kWh than before holding all other inputs constant then the use value derived from a unit of coal has increased. Substitution of other inputs for coal in the generation process is a response to scarcity not a reduction in scarcity itself.

[6] $RTS^{-1} \Sigma \sigma_i = C/V$ where C is cost and R is revenue. The remaining profit is distributed as rent to the resource owners. Total factor productivity is defined with respect to all the inputs - not just the purchased inputs. Barnett and Morse's (1963) unit cost indicator is the inverse of MFP defined with respect to just labor and capital or just capital.

[7] In neoclassical growth theory capital is an endogenous variable while in distribution theory

capital is a primary factor of production. In both cases labor is a primary exogenously produced factor of production.

[8] I use the term information in a wide sense as in everyday English rather than in the more narrow sense of information science. Berg (1988) and Chen (1994) discuss, in more depth, many of the issues that I touch on here.

[9] Low energy particles were the first to be discovered, today more resources are required to discover a particle because of the higher energy levels involved. There could be no better parallel to the Ricardian frontier economy model.

[10] Information supports, the physical objects into which information is incorporated, are of course subject to the laws of thermodynamics and will decay if not maintained. Information can be destroyed through use if a separate record of the information is not kept. For example information contained in the shape of tools will be destroyed if a plan of the tool is not kept elsewhere. Even the plans gradually decay so that knowledge may be subject to depreciation and require resources for its maintenance as do conventional manufactured capital stocks.

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