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Concepts and Measures of Natural Resource Scarcity with a Summary of Recent Trends[1]

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A general model of resource scarcity is presented from which previous models can be derived as special cases. Previous models of scarcity are compared and contrasted, refining the concept of scarcity and leading to a resolution of current disputes over the appropriate measure of scarcity. An update of the original work done by Barnett and Morse is summarized, leading to reconsideration of their original conclusions. It is found that energy and forest products experienced increasing scarcity during the 1970s.

I. INTRODUCTION

The last decade was characterized by measurable increasing scarcity of important natural resources. This trend represents a significant departure from the results of most earlier and recent work [1, 2, 12, 16, 17, 22, 24, 25]. It results in part from factors that make potential scarcity more apparent than in earlier decades and in part from a different way of assessing natural resource scarcity.

Barnett and Morse [2] concluded that unit costs in the extractive sector fell from 1870 to 1957. This is attributed to technological change, discovery of new deposits, imports, substitution offsetting physical scarcity and economies of scale [14]. Barnett [1] updated this work through the early 1970s, drawing the same general conclusions for nonrenewable resources. He attributes a few years of escalating real energy prices to the consequences of environmental and safety regulation, and business cycles. More recently, Barnett *et al.* [3] examined data through 1979 and attributed all the observed scarcity in the 1970s to changing market structure, most notably the OPEC cartel. Other authors [9, 16, 17, 23–25] also assessed scarcity into the early 1970s, but not beyond. Fisher's [9] warning note of a turning point at the end of the 1960s stands as a lone harbinger of things to come.

Data are now available to consider scarcity into the early 1980s. The addition of these years to the data up to the early seventies can be used to further examine the

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extent to which rising prices represent government (domestic and foreign) tampering with the market or the beginning of real economic scarcity in a physical sense. The result of examining this more recent data set is particularly illuminating when combined with a new conceptualization of scarcity and a new interpretation of scarcity indexes which account for common property resources (in particular, environmental waste disposal services).

This paper introduces different concepts of scarcity, presents a generalized model from which each concept of scarcity can be derived as a special case, clarifies and resolves current theoretical disagreement about alternative measures of scarcity, and provides an empirical analysis that disentangles the relative contributions of institutional and physical causes of measurable increasing scarcity in the 1970s.

II. THE NATURE AND MEASUREMENT OF SCARCITY

To an economist, scarcity is reflected in relative prices; however, physical scarcity is not alone in influencing prices, and prices might not fully reflect scarcity. Changing relative prices are a possible consequence of scarcity, not identical to scarcity. Increasing physical scarcity is one causal factor and prices are manifestations. Beyond this it is difficult to reach agreement on what natural resource scarcity is. This is true for myriad reasons: there is an international market yet we look at national prices which ignore international links, foreign and domestic governments directly distort prices, the market mechanism is not perfect, common property resources (air and water) have not moved into the "market" purview until recently, recycling plays an ill-defined role in total supply, and there are different kinds of physical scarcity.

These factors, which make it difficult to define scarcity, also limit our ability to easily compare the results of earlier studies with later ones, as with this one. Because much of the muddle comes from a traditional but artificial division between environmental and resource economics, the first step must be to recognize that this division almost by definition leaves out some important elements of resource scarcity.

The environment itself is a resource, providing a stream of inputs [7]. The environmental sinks which receive waste are, however, limited in their assimilative capacity. Resource and environmental economics conjoin then when increasing scarcity of these sinks reduces the maximum sustainable yield and renewal rate of other renewable resources [6]. This relationship between maximum sustainable yield and renewable resources has been accounted for in estimation procedures [10]. Pollution also limits the rate at which nonrenewable resources can be extracted and used without severe or irreversible impacts on agriculture, human health, and ecosystems. These effects have costs which are properly viewed as a "price" for those nonrenewable resources [22]. These costs were not reflected in the price of nonrenewable resources until the passage and implementation of such legislation as the Clean Air Act (1970, 1973, 1977) and the Surface Mining and Reclamation Act (1976). The incorporation of the cost of using these inputs into the price of nonrenewable resources is a probable cause of increasing real prices in the extractive sector during the 1970s. Since these environmental inputs have limits beyond which they are too degraded to be used, this represents a real constraint to extraction.

Resulting higher prices are therefore a manifestation of real scarcity heretofore unrecognized and unmeasured. This interpretation contrasts sharply with Barnett [1], who explains recent price increases as the result of regulation and government intervention. Some of this intervention is merely the mechanism by which environmental services become priced.

Recognizing that our stock of environmental services limits the flow of our natural resources (renewable and nonrenewable) sets the stage for reconsideration of the two types of scarcity termed here as Malthusian Scarcity and Ricardian Scarcity. Malthus postulated an absolute limit to resources; Ricardo only decreasing quality of available resources. These two concepts of scarcity will be further developed here and applied separately to renewable and nonrenewable resources.

For renewable resources, Malthusian Scarcity is based upon a fixed input (land) which eventually leads to scarcity because of the law of diminishing returns.

For renewable resources, Ricardian Scarcity is based upon continuously diminishing quality. Additional inputs are necessary to transform a physical unit of land on the extensive margin to a standardized unit of land. The long-run marginal cost curve rises forever, without any asymptotic limit on output.

Malthus and Ricardo wrote before the substitution of fossil fuels and other petroleum products for land, and at a time when the extractive sector, primarily agriculture, was 95% of the entire economy and based upon a renewable resource—land. The application of Malthusian or Ricardian scarcity concepts to nonrenewable resources in this paper is a conceptual extrapolation.

Two types of Malthusian scarcity can be delineated for nonrenewable resources: Malthusian Stock Scarcity and Malthusian Flow Scarcity. Malthusian Stock Scarcity applies to resources of uniform quality with an ultimate limit. Hotelling's [13] classic paper dealt with Malthusian Stock Scarcity. Given this type of scarcity, the value of the resource in situ, previously termed rent, is now called the user cost—the opportunity cost of present consumption which equals foregone future consumption. Strip mined coal is an example of a nonrenewable resource of relatively uniform quality. Given Malthusian Stock Scarcity, extraction cost equals a constant and, formally, a constraint delineates the total available resource stock. Malthusian Flow Scarcity applies to resources for which, in addition to a binding constraint on the total available resource stock, the average extraction costs depend upon the rate of extraction. For example, consider a number of identical pools of oil. To increase the rate of output, an additional pool is put into production, up to the extensive margin (the last pool). To increase output further, additional inputs are applied at the intensive margin, pumping oil at a greater rate and a greater cost from each pool. Malthusian Flow Scarcity also has a binding constraint on the total available stock. Malthusian Stock Scarcity is formally a special case of Malthusian Flow Scarcity.

Similarly, two types of Ricardian Scarcity can be identified for nonrenewable resources: Ricardian Flow Scarcity and Ricardian Stock Scarcity. In the former, average costs depend upon the rate of extraction and in the latter, average costs depend upon the total extracted to date in addition to the rate of extraction. Neither type of Ricardian scarcity includes a limit on the total available resource stock. Formally Ricardian Flow Scarcity is a special case of Ricardian Stock Scarcity, which, in turn, is formally a special case of Malthusian Flow Scarcity. An example of Ricardian Stock Scarcity is an underground coal mine wherein the average cost for an additional ton is a function both of how rapidly coal is extracted and of how many tons have already been mined, with average cost rising with mine depth. The case of a backstop technology discussed by Nordhaus [19] and the model presented by Solow and Wan [26] are examples of Ricardian Stock Scarcity.

Three measures of scarcity are debated in the literature: unit cost, favored by Barnett and Morse [2] and Johnson, Bell, and Bennett [16]; in situ resource prices, favored by Brown and Field [4, 5]; and relative prices of output, favored by Smith [23–25]. None of the models presented in the debate, however, is dynamic. Fisher [8] remedies this defect, but his contribution is overlooked by Johnson, Bell, and Bennett because he does not relate prices and rent to average[2] cost. Moreover, Fisher only entertains Malthusian Stock Scarcity.

In the Appendix, four dynamic models are presented which relate prices to average cost for the four concepts of scarcity introduced above: Ricardian Flow Scarcity (RFS), Ricardian Stock Scarcity (RSS), Malthusian Stock Scarcity (MSS), and Malthusian Flow Scarcity (MFS).

Model 4 in the Appendix represents a generalization of other simpler models found in the literature. All four concepts of scarcity can be derived as special cases from this model. For each type of scarcity, output price is related to average cost and rent as follows:

RFS—price equals average (unit) cost.

RSS—price equals average (unit) cost plus the present value of the increase in future average cost which, as a result of current extraction, will be borne in perpetuity.

MSS—price equals average (unit) cost plus user cost.

MFS—price equals average (unit) cost plus the present value of the increase in future average cost to be borne in perpetuity plus the user cost.

In Fisher's [8] incisive paper, he states that the ideal measure of scarcity has "just one essential property: it should summarize the sacrifices, direct and indirect, made to obtain a unit of the resource." Applying this standard, *the appropriate measure of resource scarcity depends upon the nature of scarcity: alternative definitions of scarcity lead to different indexes.* Ricardian Flow Scarcity is aptly measured with unit costs. Malthusian Stock Scarcity is best measured by user cost, captured by in situ resource prices. Given the lack of data on in situ prices, three types of scarcity (RSS, MSS, MFS) are best measured by prices of extractive output. For example, in the face of impending exhaustion, the opportunity cost of present consumption is the foregone value in use at some future date—the user cost, which must be included in an ideal measure of scarcity.

Ideal measures of Ricardian Stock Scarcity, Malthusian Stock Scarcity, and Malthusian Flow Scarcity are forward looking by definition, capturing increases in future average cost and/or user cost. Relative prices are the only available measure of scarcity which is forward looking. Ricardian Stock Scarcity, for example, requires expected future increases in extraction costs to be included in an ideal measure of scarcity. Hence the unit cost index is insufficient for nonrenewable resources characterized by Ricardian Stock Scarcity, Malthusian Flow Scarcity, or Malthusian Stock Scarcity.

[2] Strictly speaking, average cost includes all inputs while unit costs only include capital and labor, or even just labor, in empirical work. For theoretical purposes, the two are treated identically here.

Unit cost trends, however, do capture Ricardian Stock Scarcity and one component of Malthusian Flow Scarcity in a historical, or backward-looking sense; unit cost trends show how costs have historically increased as a function of depletion.

Disagreements over the appropriate measure of scarcity can be resolved by interpreting the type of scarcity each author(s) had in mind and noting whether a comparative static or dynamic model is employed. None of the models yet developed can adequately cope with all forms of scarcity. Barnett and Morse [2] rely on a comparative static model of Ricardian Flow Scarcity, leading naturally to changes in unit cost over time as a measure of scarcity. Hanson [12], however, develops a dynamic model of Ricardian Stock Scarcity which leads him to support relative prices over unit costs as the better measure of scarcity. He assumes a backstop technology with constant returns to scale (no Malthusian Scarcity is entertained). Brown and Field [4, 5] have "impending exhaustion" (p. 237) in mind when criticizing the unit cost index as backward looking rather than forward looking: Malthusian Stock Scarcity results in prices rising over time due to rising user costs, which equal rent or in situ price. Brown and Field [4, 5] criticize Barnett and Morse [1, 2] without distinguishing Ricardian and Malthusian Scarcity, and Johnson, Bell, and Bennett [16] protest Brown and Field in turn, making the same error of omission. Smith [23] focuses exclusively on Malthusian Scarcity for renewable resources, assuming production functions with constant returns to scale (no Ricardian Scarcity) and assuming a fixed flow of natural resource input.

A number of practical criteria have been discussed for selecting an index of scarcity. Foremost is the availability of data. Second, factors which can mitigate scarcity have differing effects on each index. Third, relative prices of extractive output always face the problem of determining the appropriate deflator. Fourth, relative prices and rent as indexes have the defect that they are influenced by interest rates, tax policy, subsidies, and the formation of cartels. Fifth, all of the indexes discussed are affected by unions and other institutional vagaries. Sixth, as noted in Norgaard's [20] pathbreaking work, all unit cost indexes previously proposed suffer the defect caused by omitting a large number of other inputs (e.g., materials such as water, pesticides, and lumber; and public sector inputs such as education, transportation networks, and research). A particular measure of scarcity is useful only when appropriately matched to the resource in question.

The interesting question is really whether scarcity has been and will continue to be mitigated. The choice of an index to investigate this question depends upon the purpose of the analysis and type of scarcity to be analyzed. Hence, if the question is whether technical advances in the extraction process or input substitution have offset Ricardian Flow Scarcity, the trend of unit cost in the extractive sector is a sufficient index because it includes the impact of these factors. Given Ricardian Flow Scarcity, if the question is whether technological change and input substitution occur at a greater rate in the extractive sector relative to the nonextractive sector, relative unit costs of the two sectors is an appropriate index. If it is desirable to determine the relative importance of a particular resource *input* over time, in situ prices would be an appropriate index. If the question is whether some combination of types of scarcity has been mitigated over time by all of these factors, the relative (deflated) price of output in the extractive sector is the relevant index.

Within any short period of time, temporary scarcity can occur with an impact on the world economy, human welfare, and the social fabric, including the probability of war. Technological change does not occur in a smooth, continuous fashion. In the face of uncertainty regarding technological change, prices of oil will reflect the possibility of Malthusian Scarcity in the short run. With this in mind, an empirical evaluation of resource scarcity spanning as short a time as two decades can be of interest.

III. EMPIRICAL ANALYSIS

No single index can adequately measure scarcity. Each index has its drawbacks. In order to mitigate the weaknesses in each individual index, the hypothesis of increasing scarcity will be empirically tested by both relative prices and unit cost.

The fundamental hypothesis tested here is that diminishing scarcity in the extractive sector during the 1960s was replaced by increasing physical scarcity in the 1970s. Particular focus is on the importance of energy as an *input* in the extractive sector. The magnitude of the effect of energy prices and availability on the U.S. economy [15] recommends this as an important question.

Simple visual inspection of the data[3] from 1960 through 1980 suggests four conclusions. Unit costs for petroleum and gas, coal and electricity declined in the 1960s, reaching a minimum between 1968 and 1973 and then rising. Unit costs for coal and electric power rose from their minima before the OPEC embargo. This suggests that present and/or historical Ricardian Flow Scarcity, Ricardian Stock Scarcity, and/or one component of historical Malthusian Flow Scarcity appeared before the embargo. This perhaps strengthened the hand of the cartel. Relative prices of most energy commodities (depending on the deflator) fell during the early 1960s and bottomed out during the late 1960s and early 1970s. Finally, relative prices of most energy commodities rose between their minima and 1973. A notable example is given by the deflated prices of coal which rose 64–74% between 1966 and 1973.

In order to formally test this basic hypothesis the following models, earlier used by Smith [24] and Johnson, Bell, and Bennett [16], but modified here to account for market intervention, were employed on data from 1960 to 1980.

$$Y_t = \alpha_1 + \alpha_2 D_1 + \alpha_3 D_2 + \beta_1 t + \beta_2 D_1 t, \tag{1}$$

$$\ln(Y_t) = \alpha_1 + \alpha_2 D_1 + \alpha_3 D_2 + \beta_1 t + \beta_2 D_1 t, \tag{2}$$

where

Y_t = index of scarcity (either unit costs or relative prices),

t = time, 1960–1980,

D_1 = 0 for $t < 1969$
1 for $t \geq 1969$,

D_2 = 0 for $t < 1974$
1 for $t \geq 1974$.

These two models were applied to both unit costs (Table I) and relative prices (Table II).

[3]Available from the authors upon request.

TABLE I

Summary of Unit Cost Trends[a,b]

Commodity	R^2	Scarcity trend during 1960s: β_1		Change in scarcity trend: β_2		Scarcity trend during 1970s: $\beta_1 + \beta_2$		Impact of OPEC formation: α_3	
		Sign	Statistical significance	Sign	Statistical significance	Sign	Statistical significance	Sign	Statistical significance
Renewable resources									
Agriculture	Very high	−	Significant	+	Significant	−	Significant	+	Insignificant
Nonrenewable resources									
Coal	Very high	−	Significant	+	Significant	+	Significant	+	Insignificant
Petroleum and gas	Very high	−	Significant	+	Significant	+	Significant	−	Insignificant
Electric power	Very high	−	Significant	+	Significant	+	Indeterminant	−	Insignificant
Ferro alloys	Moderate	−	Insignificant	−	Insignificant	−	Indeterminant	+	Insignificant
Nonferrous metals	Moderate	+	Significant	−	Significant	−	Significant	+	Significant

[a] Very high: $R^2 \geq 0.80$; high: $0.70 \leq R^2 < 0.80$; moderate: $0.35 \leq R^2 < 0.70$; low: $R^2 < 0.35$
Significant: Statistically significant for all deflators and in both models.
Insignificant: Statistically insignificant for all deflators and in both models.
Indeterminant: Statistically significant for some deflators and/or models, or significant for all deflators and models at a significance level equal to 0.1.
Sign: +, positive coefficient for all deflators and in both models given by Eq. (1), (2).
Sign: −, negative coefficient for all deflators and in both models.
Sign: + −, sign of coefficient varys between deflators and/or model.
[b] Y = unit cost in Eqs. (1) and (2).

TABLE II

Summary of Relative Price Trends[a]

Commodity	SIC	R^2	Scarcity trend during 1960's: β_1 Sign	Scarcity trend during 1960's: β_1 Statistical significance	Change in scarcity trend: β_2 Sign	Change in scarcity trend: β_2 Statistical significance	Scarcity trend during 1970's: $\beta_1 + \beta_2$ Sign	Scarcity trend during 1970's: $\beta_1 + \beta_2$ Statistical significance	Impact of OPEC formation: α_3 Sign	Impact of OPEC formation: α_3 Statistical significance
Renewable resources										
Farm products	01	Moderate to low	+ −	Insignificant	+ −	Insignificant	+ −	Insignificant	+	Insignificant
Meat, fish, poultry	022	Moderate	+ −	Insignificant	+ −	Insignificant	+ −	Insignificant	+ −	Insignificant
Fish	0223	high	+	Insignificant	+	Insignificant	+	Insignificant	+	Insignificant
Lumber and wood	08	High to moderate	+ −	Insignificant	+	Indeterminant	+	Significant	−	Insignificant
Nonrenewable Resources										
Fuels and related products and power	05	Very High	−	Indeterminant	+	Significant	+	Significant	+	Indeterminant
Coal	051	Very High	−	Insignificant	+ −	Insignificant	+ −	Insignificant	+	Significant
Anthracite	0511	Very High	−	Indeterminant	+	Insignificant	+ −	Insignificant	+	Significant
Bituminous	0512	Very High	+ −	Insignificant	+ −	Insignificant	+ −	Insignificant	+	Significant
Coke	052	Very High	+ −	Insignificant	+	Indeterminant	+	Indeterminant	+	Significant
Natural gas	0531	Very High	+ −	Insignificant	+	Significant	+	Significant	−	Indeterminant
Electric power	054	Very High	−	Significant	+	Significant	+	Significant	+	Significant
Crude petroleum	0561	Very High	−	Insignificant	+	Significant	+	Significant	+	Significant
Refined petroleum products	057	Very High	−	Insignificant	+	Significant	+	Significant	+	Indeterminant
Metals and products	010 }	Very	+ −	Indeterminant	+ −	Indeterminant	+ −	Insignificant	+	Significant
Iron and steel	101 }	High	−	Indeterminant	+	Indeterminant	+	Indeterminant	+	Significant
Nonferrous metals	102	Moderate	+	Insignificant	−	Insignificant	−	Insignificant	+	Indeterminant

[a] Y = relative price in Eqs. (1) and (2).

Some comments on the models and indexes employed are in order. The second dummy variable, D_2, can be expected to partially capture the impact of OPEC and changes in market structure which influence trends of scarcity indexes apart from increasing scarcity. For example, when Y_t equals the unit cost of oil and gas, the coefficient on the dummy variable D_2 estimates the extent to which the OPEC oil embargo raised the cost of domestic oil production as additional production shifted to more expensive arctic lease holds, the outer continental shelf, secondary recovery and tertiary recovery. Rising energy prices were reflected in the indexes of scarcity for other commodities in the extractive sector, but not completely when Y_t equals a unit cost index since capital and labor are included in this index but energy is not included.[4]

Deflated prices can be constructed using alternative deflators, revealing the extent to which the arbitrary choice of a deflator affects the analysis. Each commodity is deflated by three deflators resulting in three sets of time series for each commodity. The deflators are the Consumer Price Index, the Implicit Price Deflator for gross national product, and the Producer Price Index.

The coefficient β_1 can be interpreted as an indicator of the scarcity trend for the 1960s. If β_1 is negative and statistically significant, for example, then the scarcity index supports the hypothesis of diminishing scarcity in the 1960s. β_1 plus β_2 can be interpreted as indicating the scarcity trend in the 1970s, while β_2 is the change in the scarcity trend between the two decades.

Results of the econometric analysis are summarized when Y_t equals unit costs in Table I and when Y_t equals relative prices in Table II, with details of the estimated parameters available from the authors.

The trends for present and/or historical manifestation of Ricardian Scarcities (stock and/or flow) and one component of Malthusian Flow Scarcity are given in Table I. These estimates are based on unit costs and show the impact of the OPEC embargo on costs, in addition to the impact of scarcity. Based on relative prices, the results in Table II, in a theoretical world of perfect competition with no government intervention, give the historical trend for Ricardian Flow Scarcity and the forward-looking trend for Ricardian Stock Scarcity and/or both types of Malthusian Scarcity. Table II also shows the impact of the OPEC embargo on prices.

Interpretation of Table II is critically dependent upon recognizing the impact of changes in government policies—including price controls—and changes in market structure apart from OPEC. Given this caveat, several conclusions can be drawn from Tables I and II. The most basic is that *all* primary fuels became more scarce in the 1970s. Coal and oil show increasing scarcity as measured by unit costs. All energy products, except coal, experienced Ricardian Scarcity, and/or some form of Malthusian Scarcity as measured by relative prices.

From the 1960s to the 1970s, there was a significant shift in the direction of scarcity. The change in the trend of Ricardian Flow Scarcity was significantly positive for agriculture and energy products. The change in the trend of Ricardian Scarcity and/or Malthusian Scarcity, as measured by relative prices, was significantly positive for energy products, excepting coal.

The effect of the OPEC oil embargo on costs was generally insignificant. The effect on prices was insignificant for renewable resources but, in general, significantly positive for nonrenewable resources.

[4] See Hall, Kolk, and Hall [11].

The 1970s jump in real oil prices reverberated in cascading price increases in other energy commodities. Coal is a particularly interesting commodity given the trends in unit cost and deflated prices during the 1970s. It can be concluded that present and/or historical Ricardian Flow Scarcity, Ricardian Stock Scarcity, and/or the historical impact of one component of Malthusian Flow Scarcity appeared during the 1970s. This is shown by the 50% increase in the unit cost index, much larger than the pollution abatement costs estimated by Barnett [1, p. 186]. The price of coal almost doubled during the 1970s, rising at a rate significantly faster than unit costs. This differential between increasing prices and increasing costs cannot be explained by Ricardian Stock Scarcity nor by user costs, resulting from Malthusian Scarcity, appearing in the price: $\beta_1 + \beta_2$ was statistically insignificant. Moreover, this seems an unlikely explanation given the large coal reserves in the United States. An alternative explanation[5] is that as coal production shifts to the western states, the unit cost incorrectly omits increasing transportation costs.

Although rising unit costs for coal indicate some increasing scarcity in the 1970s, the results in Table II suggest that rising coal prices in the last decade are better explained by market structure: α_3 is postive and statistically significant while $\beta_1 + \beta_2$ is statistically insignificant, irrespective of the deflator or functional form. Johnson, Gaskins, *et al.* [18] found that virtually all coal contracts after 1974 contained escalation clauses, by no means a universal feature prior to the oil embargo, suggesting a noncompetitive industry. Also, substitution of coal for OPEC oil cannot explain the results in Table II since such substitution requires capital investments by industries switching from oil to coal. The time lag for such investments would be expected to have an impact on coal prices over time. Rising coal prices over time would be reflected in a significant β_2, whereas a sudden price increase is reflected by α_3, yet the results indicate the opposite.

Oil production demonstrates apparent cartel-like behavior. The OPEC oil embargo had an insignificant effect on extraction costs (Table I), but based upon the results of both models, the embargo increased the price of oil and the increase was statistically significant. One reason for the cohesive behavior of U.S. and OPEC prices might have been the close links created by the U.S. refinery entitlements program which increased the indifference of buyers to foreign crude oil prices.

As noted above, a statistically significant postembargo increase in coal prices is demonstrated by both models. Since metals (especially iron and steel) and electricity rely heavily upon coal and oil, it is not surprising that the impacts of the embargo appear as statistically significant increases in the prices of those commodities.

One anomaly is the results for nonferrous metals which exhibit increasing scarcity in the 1960s, and a reversal of that trend for the 1970s. These results are statistically insignificant using the relative price index, but significant using the unit cost index. One explanation is that the unit cost index only includes the inputs capital and labor, omiting significant costs for energy.

One result which was not surprising is that unit costs decreased during the 1960s, with a notable exception already mentioned. This result is statistically significant for agriculture and energy.

For renewable resources, results differ between agriculture, forest products and fisheries. The unit cost index reveals statistically discernable decreasing scarcity for

[5] This was suggested by John Myers, who also pointed out errors in the statistical analysis in an earlier draft of this paper.

agriculture during the 1960s and during the 1970s, even though a statistically significant slowing in that trend occurred between decades. The tremendous investment in agricultural research and development in the United States was able to continue reducing costs over the last decade, but not at the same rate experienced in the previous decade. As might be expected, fluctuations in agricultural prices obscure any statistically discernable trend during either decade, and similar results hold for fish. On the other hand, based upon relative prices, forest products faced statistically discernible increasing scarcity during the 1970s.

No single index of scarcity is without practical or theoretical flaws. None of the indexes adequately account for common property resources, public goods and the fundamental importance of uncertainty in the long run. Yet, taken together, the two indexes of scarcity analyzed here confirm the hypothesis that scarcity increased in the 1970s for nonrenewable energy resources and for some renewable resources.

IV. IMPLICATIONS

The view that scarcity is static or diminishing deserves reconsideration. It is no longer supported by the data and has not been supported by the data for a decade. This view is not consistent with the possibility of Malthusian Scarcity occurring in the long run and the probability of transitional Malthusian Scarcity in the short run due to time lags between R & D and widespread diffusion of new technology. Scarcity in and of itself is not in any event a sufficient argument for market intervention. It is also necessary to argue that the *form* of market intervention likely to emerge from the existing political forces and institutions results in an improvement in economic conditions greater than a free market by an amount sufficient to pay for all administrative, judicial and legislative costs concomitant with the intervention.

Scarcity has implications not only for the production of material commodities, but also for the production of environmental amenities. Research and development more easily mitigate the effect of scarcity on the former than on the latter, which justifies the eventual shifting of property rights from those who pollute to those harmed by pollution [21].

Whether scarcity results from resources diminishing faster than technological change can evolve or whether scarcity results from institutional changes (e.g., formation of OPEC) is irrelevant for considering economic and social loss, but essential for formation of the appropriate policy response. For example, a significant portion of the U.S. electorate believes that energy is not scarce but rather that the "energy crisis" is just an elaborate hoax to benefit certain groups. The results presented here support the conclusion that the formation of OPEC and increasing scarcity coincided to produce the "energy crisis," providing the basis for recommending that policies be entertained which focus upon improving market efficiency. OPEC was a catalyst or an accelerator but could not have had the same impact without concurrent increasing scarcity.

Policies can be designed to avoid scarcity by two alternate routes. One approach is to implement policies which echo conservationists' adumbrations to develop provident habits of consumption. Another is to include impending scarcity as a criterion for allocating funds for R & D. One persuasive argument against conservation is that if *output* is thereby reduced, fewer resources will be available for research, development and education, retarding the rate of technological change, the major force ameliorating scarcity. By this logic, conservation exacerbates scarcity by reducing the urgency for backstop development. This argument, combined with the assertion that there are increasing returns to technological change, can be used to justify abandonment of any conservation ethic. Perhaps those who subscribe to this view could be persuaded in the face of the last decade of increasing scarcity to accept the application of conservationists' principles to focus the level and direction of research. In principle, research should then: (a) help ensure that the regenerative capacity of renewable resources is not damaged or destroyed, (b) shift away from nonrenewable resources toward renewable resources, (c) help avoid damage to the ecosystem and reduce the risk to public health from pollution, and (d) develop substitute goods and services with less concomitant pollution and nonrenewable resource use.

Technological change does not inevitably result from increasing costs or prices. Tremendous efforts can be expended on searching at great length for something not there. Yet hope is a renewable resource which compels a continuing effort. Cognizance of increasing scarcity and application of principles that mitigate its effects can only lead to greater economic strength.

APPENDIX

Notation

$$\begin{aligned}
\bar{Q} &= \text{total amount of resource,}\\
\dot{Q}_t &= \text{rate of extraction of resource at } t,\\
Q_t &= \text{cumulative amount mined by } t,\\
p(\dot{Q}_t) &= \text{the inverse market demand equation,}\\
\text{ac}(Q_t, \dot{Q}_t) &= \text{average cost,}\\
R(\dot{Q}_t) &= \dot{Q}_t p(\dot{Q}_t), \text{ total revenue.}
\end{aligned}$$

Model 1: Malthusian Stock Scarcity

Define current profit as follows:

$$\pi(\dot{Q}_t) = R(\dot{Q}_t) - \dot{Q}_t c. \tag{1}$$

Note that $\text{ac}(Q_t, \dot{Q}_t) = c$, a constant. We wish to maximize discounted profit over time subject to the Malthusian stock scarcity constraint. This problem in a different form was first solved by Hotelling [13] using the classical calculus of variations:

$$\left\{ \max_{Q(t), T} \right\} \int_0^T \pi(\dot{Q}_t) e^{-rt}\, dt \tag{2}$$

$$\text{s.t.} \int_0^T \dot{Q}_t\, dt \leq \bar{Q}. \tag{3}$$

Equations (2) and (3) are an isoperimetric problem, which is solved by maximizing the Lagrangian

$$\left\{ \max_{Q(t),T} \right\} L = \int_0^T \left[\pi(\dot{Q}_t) - \lambda_t \dot{Q}_t \right] e^{-rt}\, dt,$$

where λ_t is the current value of the costate variable.

Given the form of the constraint (3), the total amount extracted will be determined optimally. The transversality conditions and first-order necessary condition for optimal extraction are given by

Transversality.

$$\frac{\partial}{\partial \dot{Q}_t} \left\{ \left[\pi(\dot{Q}_t) - \lambda_t \dot{Q}_t \right] e^{-rt} \right\} = 0 \qquad \text{at } T, \tag{4}$$

$$\left[\pi(\dot{Q}_t) - \lambda_t \dot{Q}_t \right] e^{-rt} = 0 \qquad \text{at } T. \tag{5}$$

Euler Equation.

$$\frac{d}{dt} \left\{ \frac{\partial}{\partial \dot{Q}_t} \left[\pi(\dot{Q}_t) e^{-rt} - \lambda_t e^{-rt} \dot{Q}_t \right] \right\} = \frac{\partial}{\partial Q_t} \left\{ \left[\pi(\dot{Q}_t) - \lambda_t \dot{Q}_t \right] e^{-rt} \right\}. \tag{6}$$

Assuming

$$\frac{\partial^2}{\partial \dot{Q}_t^2} \left\{ \left[\pi(\dot{Q}_t) - \lambda_t \dot{Q}_t \right] e^{-rt} \right\} < 0, \tag{7}$$

(4)–(6) are sufficient for optimization and result in an interior solution. Given perfect competition, (6) can be simplified to

$$P_t - c = \lambda_t. \tag{8}$$

Equation (8) relates the current price to *average* (unit) cost, c, and user cost, λ_t, which is the current in situ price of the resource. In this case, the price of the resource in situ reflects increasing scarcity, and grows at the rate of interest. Similarly, the net price minus a constant also grows at the rate of interest. Unit costs do not reveal scarcity since they are constant. This model is somewhat strained in its assumptions, but it reveals the error in Johnson, Bell, and Bennett's [16] conclusion in favor of unit costs over Brown and Field's [4, 5] choice for the in situ price of resources.

Model 2: Ricardian Flow Scarcity

In this model, average (unit) cost is a function of the rate of extraction:

$$\text{average cost} = \mathrm{ac}(\dot{Q}_t),\ \mathrm{ac}_{\dot{Q}} > 0 \tag{9}$$

Since there is no stock scarcity, the model is not dynamic. The average cost curve is rising forever. In this model, unit cost equals price, both reflecting scarcity. This is the model used by Barnett and Morse [2], who dismiss Malthusian scarcity, bolstering the case for the unit cost measures of scarcity they employ.

Model 3: Ricardian Stock Scarcity

Define current profit as follows:

$$\pi(Q_t, \dot{Q}_t) = P(\dot{Q})\dot{Q} - \mathrm{ac}(Q_t, \dot{Q}_t) \cdot \dot{Q}_t. \tag{10}$$

The objective functional for a free horizon, free end value problem is given by

$$\left\{ \max_{Q(t), Q(T), T} \right\} \int_0^T \pi(\dot{Q}_t, Q_t) e^{-rt}\, dt \tag{11}$$

subject to the constraint

$$Q_t = \int_0^t \dot{Q}_\tau \, d\tau. \tag{12}$$

After integrating (12) over $(0, T)$, an isoperimetric problem is specified. The Lagrangian for the isoperimetric problem is given by

$$\left\{ \max_{Q(t), Q(T), T} \right\} \int_0^T \left[\pi(Q_t, \dot{Q}_t) - \lambda_t \left(Q_t - \int_0^t \dot{Q}_\tau \, d\tau \right) \right] e^{-rt}\, dt, \tag{13}$$

where λ_t is the current value of an increase in the stock.

Considering a variational around the optimal path, it can be shown that the first-order conditions are given by (14)–(17):

Transversality.

$$\pi_{\dot{Q}} e^{-rT} = 0 \tag{14}$$

$$\left[\pi(Q_t, \dot{Q}_t) - \lambda_t \left(Q_t - \int_0^t \dot{Q}_\tau \, d\tau \right) \right] e^{-rt} = 0 \text{ at } T. \tag{15}$$

Euler Equation.

$$-r\pi_{\dot{Q}} e^{-rt} = \pi_Q e^{-rt}. \tag{16}$$

Constraint.

$$Q_t = \int_0^t \dot{Q}\, d\tau. \tag{17}$$

Now, the constraint (17) must hold for all t, and, in particular, at T. Substituting (17) into (15) simplifies the expression to

$$\pi(Q_T, \dot{Q}_T) e^{-rT} = 0. \tag{15'}$$

Given perfect competition, $P_t = p(\dot{Q}_t)$ in (10) and (16) becomes

$$\left(P_t - \mathrm{ac}_t - \mathrm{ac}_{\dot{Q}}\dot{Q}\right)e^{-rt} = \mathrm{ac}_Q\dot{Q}e^{-rt}/r. \tag{18}$$

Equation (18) can now be interpreted. The unit cost of extraction at t is given by two terms, $\mathrm{ac} + \mathrm{ac}_{\dot{Q}}\dot{Q}_t$. The first term is the unit cost for the first unit produced at t. The second term is the change in unit cost due to total extraction at time t, times the number of units extracted at t. Hence, the l.h.s. of (18) is just the per unit present value of net profit at t. For an interior maximum to occur, this must equal the term on the r.h.s. of (18). Now, $\mathrm{ac}_Q\dot{Q}_t$ is the change in average cost due to a change in the stock times the change in the stock that occurs at t, a cost increase which will be borne throughout the remaining economic life of the resource, and $\mathrm{ac}_Q\dot{Q}/r$ is the present value—at time t—of that cost in perpetuity. Hence, the r.h.s. is the present value of the increase in cost which will be borne in perpetuity.

From (15′), either $T \to \infty$ or at terminal time, T, profit is zero. In the latter case unit costs increase until economic exhaustion occurs. In the former case the transversality conditions given by (14) and (15′) become

$$\lim_{T \to \infty} \pi_{\dot{Q}}e^{-rT} = 0, \tag{19}$$

$$\lim_{T \to \infty} \pi(Q_T, \dot{Q}_T)e^{-rT} = 0. \tag{20}$$

From (10) and (19) and assuming perfect competition,

$$\lim_{T \to \infty} \left(P_T - \mathrm{ac}_T - \mathrm{ac}_{\dot{Q}}Q_T\right)e^{-rT} = 0. \tag{21}$$

Equation (21) requires that the difference between the rate of growth of demand and unit costs be no greater than the discount rate. If extraction occurs forever, then

$$P_t = \mathrm{ac} + \mathrm{ac}_{\dot{Q}}\dot{Q}_t + \mathrm{ac}_Q\dot{Q}_t/r. \tag{22}$$

Price equals the average cost ($\mathrm{ac} + \mathrm{ac}_{\dot{Q}}\dot{Q}_t$) during t plus the present value of the increase in average cost borne in perpetuity. The present value of the increase in average cost borne in perpetuity is the in situ price. In this model, average (unit) cost is not an adequate measure of scarcity since it omits the lost interest, but neither is the in situ price since it omits the current increase in average cost.

Model 4: Malthusian Flow Scarcity

This model is identical with Model 3 except that an additional constraint is added to denote the total amount of the resource available. The Lagrangian is given by

$$\left\{\max_{Q(t), Q(T), T}\right\}\int_0^T\left[\pi(Q_t, \dot{Q}_t) - \lambda_t\left(Q_t - \int_0^t \dot{Q}_\tau\, d\tau\right) - \eta_t\dot{Q}_t\right]e^{-r}\,dt. \tag{23}$$

Euler Equation.

$$\frac{d}{dt}\left\{\left[\pi_{\dot{Q}} - \eta_t\right]e^{-rt}\right\} = \pi_Q e^{-rt}. \tag{24}$$

After appropriate substitutions and manipulations, the equivalent to (18) in Model 3 can be given as

$$\left(P_t - \mathrm{ac} - \mathrm{ac}_{\dot{Q}}\dot{Q}_t - \eta_t\right)e^{-rt} = \mathrm{ac}_Q\dot{Q}e^{-rt}/r. \tag{25}$$

With an infinite time horizon this becomes

$$P_t = \mathrm{ac} + \mathrm{ac}_{\dot{Q}}\dot{Q}_t + \mathrm{ac}_Q\dot{Q}/r + \eta_t. \tag{26}$$

That is, price equals average cost ($\mathrm{ac} + \mathrm{ac}_{\dot{Q}}\dot{Q}_t$) plus the present value of the increase in average cost borne in perpetuity plus the user cost, η_t. Here, user cost is defined as the opportunity cost of present consumption, equal to the value in use of future consumption. Again, for this model neither unit cost nor in situ price is an adequate measure of scarcity.

Note that Models 1, 2, and 3 are all special cases of Model 4. Dropping the constraint on the total resource stock, Model 4 simplifies to Model 3. Dropping Q_t as an argument in the cost function, Model 4 simplifies to Model 1. Dropping both the constraint on the total resource stock and Q_t as an argument in the cost function, Model 4 simplifies to Model 2.

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