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Many people believe that human ingenuity and technological change will mitigate scarcity problems, but biophysical analysts generally argue that basic physical and ecological laws must constrain (not determine) economic choices. A biophysical model of natural resource scarcity has been developed and is applied here to an empirical analysis of scarcity trends in the US mining, forestry, fishing and agriculture sectors. The theoretical model and empirical results are compared to their counterparts in neoclassical economics.

THE NEOCLASSICAL MODEL OF NATURAL RESOURCE SCARCITY

The 19th century classical economists Ricardo and Malthus argued that nature was the primary constraint to economic expansion. According to Malthus, the fixed supply of arable land would be limiting, while Ricardo thought the constraint would be declining land quality as production expanded.

Following Hotelling's (1931) theory of optimal depletion and the empirical analysis of resource depletion by Barnett and Morse (1963), the neoclassical school rejected the classical view that nature was a constraint to economic expansion. The Barnett and Morse study found that there was no increasing scarcity between 1870 and 1957 in the US in the agriculture, mining and fishing sectors, despite massive physical depletions of the highest grade resources during this period. Increasing scarcity was only found for forest resources. The neoclassical model argues that the solution to increasing scarcity lies in the market mechanism. That is, as a resource becomes scarce its price will increase, and this will lead to a number of endogenous changes, including increased explorations for new deposits, recycling, substitution of alternative resources, increased efficiency and, most importantly, technological innovations.

A BIOPHYSICAL CRITIQUE OF THE NEOCLASSICAL MODEL

The neoclassical model of scarcity assumes that labor, capital and land (and sometimes energy) are primary, independent factors of production. A biophysical perspective, on the other hand, distinguishes between "primary factors" of production and "intermediate inputs." A primary factor of production cannot be produced inside the economic system. Low-entropy energy-matter is therefore the only primary factor of production. Intermediate inputs are produced or recycled by some combination of primary factors and other intermediate inputs. Capital, labor and technology are considered intermediate inputs, as they are produced from low-entropy energy-matter.

According to Daly and Cobb[1] (1990), the neoclassical model frequently ignores land as an input in the production process. Land is seen as property, rather than for its unique role as a provider of natural resources and environmental services. When perceived as property, land is no different from capital and labor, making the importance of nature disappear from the neoclassical model.

The neoclassical model also ignores the massive amounts of energy used to harvest resources. From a biophysical perspective, an important relationship exists between energy costs and the quality of resources, since energy is required to upgrade the organization of resources. Moreover, the declining labor costs of resource extraction documented in the Barnett and Morse study were not due to "self-generating" technological change as the study suggests, but rather resulted from the substitution of higher quality surplus fossil fuel energy for labor in the resource transformation process. The extraction of a fossil fuel results in a net energy surplus, i.e., the quantity of energy available in the fuel, less the energy costs of extracting it. The quantity of goods and services that can be produced in an economy is then limited by the absolute amount of surplus energy available and the efficiency with which it is used. The period that Barnett and Morse studied included two complete transformations in which high-quality fuels displaced the use of lower-quality fuels: first coal replaced wood, and then oil and natural gas replaced coal. It was these substitutions of higher-quality fuels that reduced the labor-capital costs of extracting fuels.

RESOURCE SCARCITY FROM A BIOPHYSICAL PERSPECTIVE

The two fundamental points underlying the biophysical model of the production process are:

1) High-quality resource deposits require less work to locate, upgrade, and refine than low quality resources. In addition, in the process of the transformation of resources, some high-quality economically useful energy is degraded into lower-quality economically useless energy. The laws of thermodynamics dictate that, for any given material and given amount of increase in order, there is a minimum amount of energy required; in the real world, even more energy must be used than the minimum energy requirements. Technological change cannot change the minimum energy requirements in the transformation process, but it can help move towards the minimum requirements.

2) The technological change in industrial countries has a physical basis. Historically, mechanical energy from humans, draft animals, and inanimate energy converters powered by fossil fuels and electricity were the main sources of energy in the extractive sectors. During the last century, however, fossil fuels have become dominant, replacing humans and draft animals. Most importantly, increasing amounts of energy subsidize the efforts of labor, boosting labor productivity.

Humans usually use natural resources in order of decreasing quality. The relationship between energy costs and resource quality can be obtained by constructing the biophysical resource conversion function, which describes the amount of direct (E_d) and indirect (E_i) energy used to upgrade a unit of resources with heterogeneous, lower quality physical and locational attributes (R_u) into a unit of a "standard resource" with homogeneous physical and locational attributes (R).

THE ENERGY COST OF EXTRACTIVE OUTPUT

This section tests the hypothesis that the energy costs of natural resources have increased over time in the US due to changes in the relative strength of depletion and technical innovations. The hypothesis is tested by calculating the direct and indirect fuel used to produce a unit of resource in the mining, agriculture, forest products and fisheries industries, where Q is the total output of the industry, and $Q/(E_d + E_i)$ is the output per unit of energy input in the industry.

1) **Mining**

Empirical Results: In the metal mining industry, $Q/(E_d + E_i)$ increased from 1919 through the mid-1950s, and then decreased by a factor of two by the 1980s. The non-metal mining sector shows varying trends for different types of output, but the general trend in the sector was substantially decreasing energy costs per unit of output. In the fossil fuel sector, output per unit of energy input is measured by the energy return on investment (EROI). The EROI for the fossil fuel sector rises in the first half of the century, and then declines in the 1960s and 1970s. The EROI for petroleum peaked in the early 1970s, and then declined by a factor of two in the 1980s. Coal production showed a similar decline, beginning a decade earlier than petroleum.

Discussion: In the metal mining industry, resource depletion is the main cause of the increasing energy costs. The declining quality of ores and the increased mine depth, which results in increases in the amount of waste rock mined per ton of ore, contributed to the increasing costs. While the nonmetal mining sector also saw increases in the amount of waste rock mined per ton of ore, energy costs still decreased because of improvements in recovery techniques. Increases in the energy costs in the coal industry were a result of depletion, with anthracite showing greater levels of depletion than bituminous coal. Energy costs in the oil and gas industry have increased because depletion has outstripped the gains from technical innovation.

2) **Agriculture**

Empirical Results: Measuring the output of the agricultural sector in physical terms is not straightforward. Three different measures can be used: gross domestic product originating on farms, the USDA farm output index, and the total calories produced in principal crops. For all three measures, the energy cost of producing a unit of output increased between 1910 and 1973, and decreased between 1974 and 1988.

Discussion: While energy costs in agriculture increased between 1910 and 1970, prices to consumers generally declined over that period. This apparent paradox arises because savings from innovation and improvements in labor productivity offset the increases in direct and indirect energy use. The fall in energy costs per unit of output between 1974 and 1988 was a consequence of the energy price shocks of the early 1970s, which caused major reductions in farm energy use.

3) **Forest Products**

Empirical Results: In the forest product sector, output per unit of energy used declined between 1950 and 1973, and then increased by 40% between 1974 and 1986.

Discussion: The forest product sector has been similar to the agriculture sector. Between 1950 and 1973, increased mechanization and energy use increased total output and labor productivity, but decreased $Q/(E_d + E_i)$. The energy price increases of the 1970s then increased the energy efficiency of the sector. These interpretations of the forest sector must be qualified by noting that wood waste fuel use - the main energy source in this sector - can only be estimated, and the uncertainty associated with these estimates may be substantial.

4) **Fisheries**

Empirical Results: National data on energy use in fisheries is not collected, so the trends presented here are based on the energy use and output of the New Bedford, Massachusetts fleet, which has the largest catch by value and the sixth largest by poundage in the country. Between 1968 and 1988, there have been sharp increases in the energy costs per unit of output. At present, 35 BTU of fuel are used to harvest 1 BTU of edible fish protein.

Discussion: The rising energy costs are a result of increases in the total number of vessels in the fleet, in the average horsepower per vessel, and in the time required to travel to and from the point of harvesting due to the depletion of fish stocks. On the output side, there have been sharp declines in output due to decreased fishing effort and competition from foreign fleets.

CONCLUSION

Economic models showing declining dollar costs of resource extraction mask significant increases in energy costs per unit of output in several sectors. Of these, the increase in the energy costs of obtaining fossil fuels have the most serious long-run implications, since these fuels are essential for the extraction of all other resources. In addition, declines in the quality of non-fuel resources will cause positive feedback effects, accelerating the depletion of fossil fuels and the accompanying increase in their own energy costs.[2]

Notes

1. Herman E. Daly and John B. Cobb, *For the Common Good: Redirecting the Economy Toward Community, the Environment, and a Sustainable Future* (Boston: Beacon Press, 1989 and 1994).
2. Author's note: The empirical analyses in this paper have been enriched and updated. An additional decade of information substantiates the basic conclusions of the paper. The interested reader is referred to: Cutler J. Cleveland, "Energy Quality and Energy Surplus in the Extraction of Fossil Fuels in the US," in Ecological Economics 6 (1992): 139-162; Cutler J. Cleveland, "An Exploration of Alternative Measures of Natural Resource Scarcity: The Case of Petroleum Resources in the US," in Ecological Economics 7 (1993): 123-157; and Cutler J.

Cleveland and David I. Stern, "The Scarcity of Forest Products Revisited: An Empirical Comparison of Alternative Indicators," Canadian Journal of Forest Research 23 (1993): 1537-1549.