"Summary of article by Paul P. Christenson: Historical Roots for Ecological Economics – Biophysical Versus Allocative Approaches" in Frontier Issues in Economic Thought, Volume 1: A Survey of Ecological Economics. Island Press: Washington DC, 1995. pp.6-10

Social Science Library: Frontier Thinking in Sustainable Development and Human Well-being

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Economic theory has become a highly axiomatic and deductive science. While institutionalists have attempted to use results from other social sciences in their analysis, the biophysical foundations of economic activity are still missing. Both the other social sciences and also physics, chemistry, biology and ecology must inform economic analysis. The foundations for a theory that can do this are found in the works of the pre-classical Physiocrats and the classical economists. This essay considers these foundations and traces the genealogy of modern economic theory. It establishes the links between a biophysical theory of the economy and the classical economists.

The Classical Production Approach

The early classical economists saw production as a set of sequential activities. The extraction of materials and food preceded the processing and fabrication of materials. The capital stock was divided into fixed capital - machines and structures - and circulating capital, i.e., food, fodder, raw materials and working finance. A distinction was made in the production process between land and industrial machinery. Earlier the Physiocrats had regarded land as productive and manufacturing activities as unproductive, because it was thought that land created a surplus, whereas machinery only transformed materials. Similar views on the differences between land and machinery were also held by classicists such as Malthus, who argued that only "the machinery of the land" could produce food and raw materials, and Ricardo, who spoke of the "original and indestructible powers of the soil." They recognized the inability of industrial machines to produce without materials and sources of power, and believed that all surplus was due to the productive power of land. However, only the Italian writer Pietro Verri made it clear that productivity is not an inherent property of land, but rather is dependent on material and energy flows through the land.

The importance of power (energy) in the new technologies of the industrial revolution was also recognized by the post-Ricardian classical economists, under the influence of technical writers such as Smeaton, Babbage and Ure. The industrial prosperity of Britain was seen as a result of the use of coal as a source of fuel. In analyzing the use of coal, some writers emphasized its physical aspects, while others emphasized its commercial aspects.

Influenced by engineering mechanics (via Babbage), Senior[1] (1836) emphasized a physical taxonomy of production inputs: labor and skills, natural agents, and capital. Capital was divided into fixed and circulating, the former being tools and machines, the latter the *materials* embodied in the product (production obeyed the law of conservation of matter: a doubling of material output required a doubling of raw material input). Machines were further divided into engines producing power and machines transmitting and applying power. Senior put food and coal (energy resources) with fixed capital since these were not embodied in output. He needed another category for motive powers.

Mill maintains Senior's tripartite classification but includes motive powers (food, coals, and other natural powers) with materials, judging the distinction between materials and fuels to be of no scientific importance. This lack of differentiation between inputs contributed to the absence of an appropriate terminology for understanding physical processes of production. Marshall's[2] (1920) choice of a "commercial" rather than scientific terminology for capital appears to follow Mill.

Neoclassical Production Theory

Neoclassical theory shifted from a production approach to the economy and prices to an exchange approach. Eventually this resulted in a model which combined a marginal utility theory of demand and a marginal productivity theory of supply (the latter was only developed in the 1890s). Early theorists first had to grapple with the classical legacy of a materials-energy-machine conception of production. A common feature of all early models was the elimination of the distinction between fixed and circulating capital (and thus the most obvious problem of complementarity between inputs). Jevons[3] (1871) took the approach of reducing fixed capital to a version of circulating capital. The latter in turn was reduced to the subsistence of workers. Materials, fuels, and fixed capital as direct inputs in production were thereby eliminated.

Menger[4] (1871) and Walras[5] (1874) were influential in the further elimination of raw materials from the production theory. Menger supports his theory of prices with a universal assumption of variable proportions. Thus the possibility of substitution of techniques (with their distinct material and machine requirements) was confused with factor substitution along an isoquant. Walras (1874) formalized the elimination of raw materials from the production process by vertically aggregating manufacturing and agricultural production. Walras argued that final products are obtained by combining raw materials, land, labor and capital, but raw materials themselves are obtained by combining land, labor and capital. Consequently raw materials and time do not need to be included explicitly along with the other factors, and they are therefore eliminated from the representation of production. Marshall (1920) further excludes raw materials, referring to them as incidental expenses. Marshall's neglect may be attributable to a recognition of the incompatibility of their inclusion within the marginal framework of analysis. This incompatibility arises because the marginal framework requires substitutability among inputs, while raw materials are clearly complements to other inputs in the production process, and are therefore not substitutable.

Thus the neglect of raw materials, energy, and complementarity in production facilitated development of marginal productivity theory. However, this theory is not based on a physical analysis of production activity. Resource valuation depends only on individual preferences and initial endowments alone as determinants of prices, ignoring the importance of environmental and social systems in shaping these processes.

A Biophysical Approach to Production

A biophysical approach, like the classical one, sees production as the starting point of economic theory. From a biophysical perspective the basic factors of production are materials, energy, information flows, and the physical and biological processes which convert, transmit or apply them. Solar energy is identified as the primary net input. Neoclassical factors of production are seen as hopelessly aggregative and incomplete.

Complementarity of inputs is also a central component of the biophysical approach. All inputs in a production process are seen as complements rather than as substitutable, and machines and other capital equipment must be designed with this in mind. This notion of complementarity is extended across sectors; technologies, organizational structures and resource and energy needs are seen to co-evolve across sectors and activities. The neoclassical notion of marginally changing one factor while holding all else constant is therefore not viewed as an appropriate form of analysis, nor is partial equilibrium analysis.

There are several other differences between the biophysical and neoclassical approaches. One is the recognition in the former of the fundamental differences between resource extraction and resource processing, as opposed to the neoclassical view of production as a one step process, from primary factors to final products. Another is the claim of the biophysical approach that movement from a largely renewable resource base to the use of large stocks of coal and petroleum implies inherent limits to economic growth, limits that are not recognized by neoclassicists. Biophysicists see a cycle set up whereby resources are used to produce machines, which are used to extract materials, which are used to produce more machines, and so on. Several problems can be expected to arise from this. First of all, resource inputs may become scarce. Secondly, natural systems may not be able to absorb increasing levels of material and toxic wastes. These inconsistencies between maximizing the use of high grade nonrenewable sources of energy and environmental limits indicate the need for control mechanisms to keep economic systems in balance with environmental systems.

Classical/Post-Keynesian Production Prices

The biophysical approach to production calls for a reformulation of the theory of interactions within the economy. For example, the effects of primary commodity price shocks on output, productivity and inflation, are not fully explained by conventional economic theory. This deficiency calls for a macro model that incorporates sectoral pricing and a focus on the short run price and quantity dynamics of commodity price shocks.

The early classical economists developed a sectoral model of asymmetric price behavior where manufacturing prices were determined by cost of production, and agricultural and raw material prices were determined by the forces of supply and demand. More recently, such a dual pricing model - mark-up pricing for manufactures and market prices for natural resources - has been taken up by some post-Keynesian economists. The differences in the nature of price formation in the two categories and the underlying physical conditions that cause them are important determinants of the behavior of broader macroeconomic variables. A materials and energy-based, cost-plus pricing model can account for these effects, and is consistent with a Keynesian process of quantity adjustment at the macro level.

From the biophysical point of view, neoclassical price theory has significant shortcomings. Neoclassical price theory values resources at marginal costs of extraction (not reproduction), and values environmental effects in terms of disposal costs. While the existence of user costs and external costs is recognized, these tend to be undervalued based on current market prices. Sraffa[6] (1960) attempted to address these shortcomings by extending the classical model to incorporate reproduction prices. He did not, however, incorporate the reproduction of materials and sources of energy from natural systems. Such an incorporation into the Sraffian framework would provide a different policy emphasis, focusing on the long-term maintenance of environmental and resource systems rather than on short-term market price adjustment.

Notes

1. N. Senior, *An Outline of the Science of Political Economy*. (New York: Kelley, 1965; original publication 1836).
2. A. Marshall, *Principles of Economics* (London: Macmillan; 8th ed. 1920).
3. W.S. Jevons, *The Theory of Political Economy* (London: Macmillan, 1871; reprinted by Penguin, 1970).
4. C. Menger, *Principles of Economics* (Glencoe, Illinois: Free Press, 1950; translation of Grundsatze der Volkswirtschafts-lehre).
5. L. Walras, *Elements of Pure Economics* (London: Allen and Unwin, 1954; tr. W. Jaffe).
6. P. Saffra, *The Production of Commodities by Means of Commodities: Prelude to a Critique of Economic Theory* (Cambridge University Press, 1960).