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Ecological Modelling 178 (2004) 39–40

ECOLOGICAL MODELLING

www.elsevier.com/locate/ecolmodel

Short communication

Biogeoeconomics—energy hierarchy, biogeochemical cycles and money

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H.T. Odum began his expansive career, a half-century ago, studying the biogeochemical cycle of the element strontium (Odum, 1957; see Limberg in this section for a review of this early work). In his early years, Dr. Odum conducted many detailed scientific studies to increase his understanding, firsthand, about how systems work. Fifty years later he came full circle and revisited his earlier concepts relating energy to the biogeochemistry of materials (i.e. the processes by which materials circulate), which he had continued to develop during that time. His two articles that appeared in the Proceedings of the First Biennial Energy Analysis Research Conference (Brown, 2000) summarized his general theories and modeling techniques relating energy and material cycles.

In his article "An Energy Hierarchy Law for Biogeochemical Cycles" (Odum, 2000a), Dr. Odum proposed a sixth energy law—*The Principle of Material Hierarchy*, which states that, "as the concentration of materials in biogeoechemical cycles increases, the flow of the materials decreases." To develop this new principle, Odum first reviewed some of the other energy principles, including the second law for the natural depreciation of energy concentration. He then discussed the process of concentrating materials and the resulting increase in the energy per mass.

A trace material that is transported by a carrier material (e.g. water) may become concentrated enough to contribute as an input to a production process. Based on the maximum power principle, the trace material can drive an autocatalytic process if its energy is sufficient enough to reach a critical concentration (for example, a nutrient contributing to plant production). This process of autocatalytic momentum transformation occurs above the critical concentration, and energy per unit mass increases as material concentration increases above this threshold since the trace material once again has the ability to work. Materials are dispersed along each step in the transformation or convergence process, and the skewed or hierarchical distribution of materials in relation to their concentration (Ahrens, 1954) is further evidence of the energy hierarchy basis of material cycles. Ahrens noted that the heavier elements that are formed through higher energy processes are less abundant (Odum, 1983).

Odum also reviewed his principles related to the spatial distribution and hierarchy of materials and energy flows. Materials spatially converge and concentrate into central locations because they are coupled to energy flows, which converge spatially. As a material converges, its energy per mass increases as the total quantity decreases. Odum concluded with the following summary of his sixth energy principle: "Materials of biogeoechemical cycles are hierarchically [and spatially] organized because of the necessary coupling of matter to the universal energy transformation hierarchy." Odum (2001) further linked the universal energy hierarchy to the circulation of money. He suggested an additional energy law, or the seventh law, to

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doi:10.1016/j.ecolmodel.2003.12.006

describe this relationship. At each step in the energy transformation process, value is added and money circulation increases along with the energy/money (price) ratio. The spatial pattern shows that money circulation is more concentrated in centers, but the real buying power of money is less. The sixth and seventh energy principles should be used to formulate environmental policies to spatially redistribute material and energy flows, and associated monetary payments, to improve landscape-scale benefits (see Boggess, 1994 for more on the application of biogeoeconomic principles).

Odum (2000b) developed a BASIC programming language computer simulation program referred to as HIERSTEP.bas to test the hierarchical relationship between energy and material cycles. The program produces bar graph plots for each hierarchical characteristic in the model. Calculations are made with energy flows and materials circulating through the system at a steady state. Material flows are coupled to energy flows through the processes of concentration, recycle, and dispersal. The model has a spatial dimension that relates different hierarchical levels. The simulation model offers a potential framework to test Dr. Odum's energy principles of the self-organization of large-scale systems, and their related energy, material, and monetary cycles. Dr. Odum's pragmatic beginnings in material cycling provided him with the scientific foundation to expand into general systems theory. His early works are "embodied" in his concepts and theories, and his principles are emerging in different forms as they become embedded in the mainstream culture. The study of energy and material resource use and recycling is once again flourishing as public attention has recently turned in this direction Green procurement, which is being practiced by governments worldwide, is driving product choices that incorporate basic principles of resource conservation and reuse (e.g. product take-back and recycle) programs. This has created a need for private businesses to search for innovative ways to reduce waste and tighten the loop on the product life cycle. Dr. Odum's prophetic vision for the future that he shared with many is unfolding in our midst.

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