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This article sets forth a minimum necessary condition for sustainability: the maintenance of the total natural capital stock at or above the current level. This condition embodies a precautionary principle: given the extent to which natural capital has already been damaged or depleted, it would be too risky to allow significant further loss of natural capital. Methodological issues raised by this basic condition include the measurement and valuation of natural capital, the use of discounting, differentiating between growth and development, and the shortcomings of current macroeconomic measures such as the Gross National Product. Technological issues include the degree to which technical progress can overcome resource constraints on growth. While there are wide disagreements on these issues, this article suggests that a prudent policy for sustainable development must avoid natural capital depletion.

Different Types of Capital

A fundamental definition of capital is "a stock that yields a flow of valuable goods and services over time." Both manufactured capital and natural capital satisfy this definition. While manufactured capital is produced by humans, natural capital is made up of all the natural resources and environmental functions which are essential for human life and economic activity. Natural capital and its products can be viewed simply as physical entities, or they can be given a more economic dimension through valuation. Natural capital can be further differentiated into renewable (or active) and non-renewable (or inactive) components. Ecosystems are renewable natural capital which actively produce a flow of services; non-renewable resources generally yield no services until extracted. A third form of capital is human capital: the stock of education, skills, culture, and knowledge stored in human beings themselves.[1]

A sustainable system must prevent depletion of its capital stock. Manufactured, natural, and human capital all require continual maintenance. Excessive harvest of ecosystem products can reduce the capacity of renewable natural capital to produce services and to maintain itself. Non-renewable natural capital requires little or no maintenance, but is depleted with use over time. The concept of sustainability is implicit in a Hicksian definition of income[2]; consumption that requires the depletion of natural capital cannot be counted as income.

Economic theory has focused on manufactured and human capital, because natural capital has been implicitly or explicitly viewed as abundant. But we are now entering an era in which natural rather than manufactured or human capital will be the limiting factor on economic

activity. The concern of classical economists (including Smith, Malthus, and Ricardo) with the constraints of natural resource on economic growth gains new relevance in a period when the scale of human activities has an impact which can significantly reduce the flow of ecosystem goods and services. The economy must be viewed as a subsystem of the larger ecological system.

The failure of standard neoclassical economics to account for natural capital distorts analysis at all levels from project evaluation to the health of the entire ecological/economic system. Analyses which have attempted to account for natural capital, and to measure sustainable economic welfare, show that "[i]f we continue to ignore natural capital, we may well push welfare down while we think we are building it up." (40)

Substitutability Between Natural and Human-made Capital

Neoclassical economic theory holds that "reproducible capital is a near-perfect substitute for land and other exhaustible resources."[3] Natural capital is often omitted entirely from growth models, which are based on the two factors of labor and human-made capital. Even if natural capital is included in the production function, mathematical forms such as the Cobb-Douglas function imply high substitutability between natural and human-made capital. But in most cases natural and human-made capital are complements, not substitutes. "It should be obvious that the human-made capital of fishing nets, refineries, saw mills, and the human capital skill to run them does not substitute for, and would in fact be worthless without, the natural capital of fish populations, petroleum deposits, and forests." (41)

While technological possibilities do exist for substitution among various forms of capital, there are strict limits to these possibilities for many goods. In the production process, natural resources are transformed into products, while the other forms of capital are used to effect this transformation. The object of increasing the stock of human-made capital is to process a larger flow of natural capital, not to make possible a reduced flow. Recycling and efficiency-increasing technical progress may contribute to reducing rather than increasing the flow of "throughput" (inputs processed into outputs), but in general economic growth serves to increase throughput and resource use.

Valuation of Natural Capital

A rational micro-allocation of resources can be achieved through balancing the marginal costs and benefits of different resource uses. But the macro-allocation of resources between the ecosystem and the economic system is a social decision which is not well handled through the market pricing system. Since the benefits of appropriating resources and ecosystem functions are mostly private, while the costs are largely social, there is an inherent tendency to over expand the size of the economy relative to the ecosystem.

Because the value of natural capital is not well captured in existing markets, it is necessary to estimate its value. A variety of methods can be used, ranging from willingness-to-pay surveys which attempt to mimic market behavior to energy flow analysis, which is not dependent on human preferences. The latter evaluates natural capital in terms of its embodied or captured

energy. For example, the value of the endangered coastal wetlands of Louisiana has been estimated in terms of their capacity to capture solar energy for productive use.4

A major issue in valuation is the use of discounting to calculate the present value of a stream of benefits or costs over time. While standard economic theory views discounting as rational optimizing behavior, the discount rate is governed by the preferences of current individuals, and gives little weight to future benefits and costs on an inter-generational time-scale. The discount rate for public policy decisions should therefore be significantly lower than the market rate used for private investment decisions. "The government should have greater interest in the future than individuals currently in the market because continued social existence, stability and harmony are public goods for which current individuals may not be willing to fully pay."5

Growth, Development, and Sustainability

Development, or qualitative improvement, can occur without growth in the throughput of resources. But it is excessively optimistic to assume, as the Brundtland Commission did, that a five- to ten-fold economic expansion can come from development rather than growth. Thus if the needs of the world's poor (which undoubtedly require some growth) are to be met, population control, consumption limits, and redistribution must be considered along with economic expansion. Other principles for sustainable development include:

· Limit economic scale to the carrying capacity of natural capital;
· Promote efficiency-increasing technological progress;
· Harvesting rates for renewable resources should not exceed regeneration rates;
· Waste emissions should not exceed the renewable assimilative capacity of the environment.
· Non-renewable resources should be exploited at a rate equal to the creation of renewable substitutes.

To achieve these ends, the burden of taxes should be shifted from income taxes to taxes on energy use and natural capital consumption.[6] This would create powerful incentives for efficiency-improving technological progress. Implementation of this proposal would pose political difficulties, and it would require international agreement and perhaps the use of ecological tariffs to prevent "dumping" of untaxed resource-intensive products. But it may be the most feasible way of providing the economic incentives to achieve sustainability.

Notes

1. Some theorists prefer to divide these stocks between human capital (embodied in individuals) and social capital (embodied in culture and institutions), thus giving a four-capital system. See e.g. Ekins et al eds. (1992).
2. Sir John Hicks defined income as the maximum amount that a person can consume during a period and still be as well-off at the end of the period as he was at the beginning. See Hicks (1946).
3. William Nordhaus and James Tobin (1972).
4. Costanza et al. (1989)..
5. See Kenneth Arrow, (1976).
6. See Jeff Hamond, *Tax Waste, Not Work* (Part IX, this volume).