

Natural Capital, Human Capital, and Sustainable Economic Growth¹

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I. Introduction

Economic growth is an explicit economic and political goal in nearly every nation. Yet comprehensive and independent scientific investigations provide compelling evidence that the growth of the global economy is not sustainable because it consumes many of the environmental services that underpin the production of goods and services (e.g., Houghton et al., 1996; Heywood, 1995; Postel et al., 1996; Vitousek et al., 1997). There also is a growing realization that economic growth does not necessarily go hand-in-hand with growth in the well-being of people. Standard measures of economic output such as Gross National Product do not reflect the growing disparity between rich and poor in most nations (UNDP, 1996), or the environmental degradation which diminishes the health of people, communities, ecosystems, and the economy (Daly and Cobb, 1989).

Underlying the universal prescription for economic growth are theoretical models which describe the process of growth itself. Developed and hawked by economists in universities, consulting firms and think-tanks, these models (and their derivatives) reflect the conventional wisdom about the driving forces behind the historic growth in living standards, the role of the environment in the economic process, and the ability of substitution and technical change to overcome resource scarcity and environmental degradation. We believe that such models fundamentally misrepresent these important relations, and therefore contribute to the expectation that the type of economic growth we have experienced in this half-century is sustainable. Below we explore the important assumptions of the standard growth models, and propose an alternative framework and revised model which accounts for the physical and ecological basis of economic activity, and for the important feedbacks between the economy and the environment.

II. The Standard Model of Economic Growth

The neoclassical theory of economic growth has been used to argue that there are no environmental limits to growth. However, there are a number of reasons to question this conclusion. The basic growth model in the Nobel-prize winning work by Solow (1956) does not include resources at all. This model subsequently was extended with nonrenewable resources, renewable resources, and some waste assimilation services (for surveys see Kamien and Schwartz, 1982; Toman et al., 1994). Most limits-to-growth analyses have focused on nonrenewable resources because environmental scientists and economists in the 1970s regarded them as critical limiting factors (Meadows et al., 1972;

Review of Economic Studies, 1974). The implicit assumption is that if infinite growth (meaning a strictly positive growth rate for an infinite amount of time) is possible with nonrenewable resources, then it certainly is possible with renewable resources.

A common interpretation of standard growth theory is that substitution and technical change can effectively de-couple economic growth from resources and environmental services. The critical, tacit assumption of the Solow growth model, all those that follow it, is that the inputs to production are independent. This means that a change in the quantity of one input is independent of changes in the quantity of other inputs, and hence are perfect or near-perfect substitutes for each other. Thus, depleted resources or degraded environmental services can be replaced by more abundant substitutes, or by “equivalent” forms of human capital (people, machines, factories, etc.).

Ecological economists note that the perfect substitution argument violates the law of the conservation of matter and the first law of thermodynamics (Ayres and Nair 1984; Georgescu-Roegen, 1971; Daly, 1991; Cleveland et al., 1984, Gutés, 1996). Perfect substitution implies, for example, that a sawmill could produce two-by-fours without an input of timber if sufficient amounts and types of human labour and machines are supplied.

Neoclassical economists counter that the class of growth models that include resources can account for mass balance and thermodynamic constraints with the “essentiality condition.” This condition holds that given positive non-resource inputs, output is only zero when the resource input is zero, and strictly positive otherwise. Economists argue that this at least accounts for the fact that *some* amount of energy and materials are required to produce goods and services. Models that include the essentiality condition still suggest that a constant level of economic output can be maintained indefinitely if the degree of substitution between resources and capital is sufficiently high (Solow, 1974).

But is this representation really consistent with mass balance and the first law of thermodynamics? Not really, because those models assume that production can be maintained with an infinitesimal amount of resources and environmental services if labour and capital can be sufficiently increased (e.g., Dasgupta and Heal, 1979). A notable result in this context is the Hartwick rule (Hartwick, 1977), stating that an economy can grow forever merely by reinvesting the proceeds from resource extraction in people and machines, which in turn can substitute for resources. But ecological economists dismiss this as a conjuring trick because it assumes that production can remain constant even when only an infinitesimal amount of resource materials enters production. An increase in the use of capital in one sector of the economy clearly drives an increase in the use of energy

and material elsewhere in the economy to produce it (Georgescu-Roegen, 1979; Ayres and Nair, 1984).

Modern growth theory has sought to improve the standard theory by “endogenizing” technical change through more explicit accounting for investments in human capital (education, health care) and new technology (research and development). These may prove to be important advances, but this work still assumes that human knowledge is unbounded and infinitely substitutable for resources and environmental services (e.g., Gradus and Smulders, 1993).

Suffice it to say that despite the increased emphasis by economists to “account” for the role of the environment in economic production, most of the basic assumptions made by Solow (1956, 1974) concerning the role of the environment in production remain intact today. The conventional model is criticized for a number of other questionable assumptions, including those regarding equilibrium, profit and utility maximization, perfect markets and information, among others (Ayres, 1994; Nelson, 1995). As important as these are, here we focus specifically on the role of the environment in growth models. Below we develop a modified growth framework which elevates the role of the environment in the economic process. We believe this is a more realistic approach because it recognizes the limits to the degree to which we can substitute for depleted resources and a degraded environment, and because it accounts for *all* the services provided by the environment.

III. The Ecological-Economic Worldview

The economic process is sustained by a flow of low entropy (high quality) energy, materials, and environmental services from the environment. As materials and energy are transformed in production and consumption processes, higher entropy waste heat and matter ultimately are released to the environment. Thus, the production and exchange of goods and services is an intermediate step between the initial generation of resources and environmental services, and the ultimate assimilation and recycling of wastes.

The production of goods and services is accomplished by human and natural capital. Capital refers to any stock--human or natural--that yields a flow of valuable goods or services into the future. Standard growth models emphasize the role of capital produced by humans, of which there are two types. Human-made or manufactured capital refers to factories, buildings, tools, and other physical artifacts. Human capital refers to the stock of education, skills, culture, and knowledge stored in human beings themselves.

Natural capital refers to the various ways that the environment powers production-- and indeed supports most aspects of human existence (Costanza and Daly, 1992). We differentiate two broad types of natural capital. Nonrenewable natural capital refers to the fossil fuel and mineral deposits that do not renew themselves on a time scale close to the rate that human use them. For all practical purposes, fossil fuels literally are consumed by use. Nonrenewable natural capital generally yields no services until extracted.

Renewable natural capital is active and self-maintaining using energy from the sun and the Earth's core. Ecosystems are renewable natural capital. A forest or marine ecosystem provides a flow or annual yield of timber or seafood, a flow which can be sustained year after year if the ecosystem itself is not deteriorating. But the generation of natural resources is just one function of natural capital. They also yield a flow of ecosystem services when left in place. The assimilation and recycling of wastes, water catchment and erosion control, maintenance of biological diversity, and the regulation of regional and global climates are just a few example of services provided by the environment (Ehrlich and Mooney, 1982; De Groot, 1992; Daily, 1997). Since the flow of services from ecosystems requires that they function as whole systems, the structure and diversity of the system is an important component in natural capital (Barbier et al., 1994)

Standard growth models that make some accounting for the environment have focused on nonrenewable natural capital and ecosystem goods such as timber, food, and water, principally because they are traded in markets. Ecosystems and their services have largely been ignored, a serious omission given unique features which define their irreplaceable role in economic production. Species and their environment are connected in a complex web of interrelations that fundamentally are non-linear and evolutionary, with lags, discontinuities, thresholds and limits (Perrings, et al., 1995). Change in ecosystems, whether "natural" or human-induced, often is not continuous. Rather, it often is episodic and rapid (Holling et al., 1995). Degradation of ecosystems, and hence the services they provide, often is irreversible. These characteristics imply that ecosystems are of limited predictability.

IV. Substitution: A Key to Sustainability

We return to the linchpin of the standard model of economic growth: a constant output can be maintained indefinitely only if there is a high degree of substitutability between manufactured and natural capital, i.e., if the elasticity of substitution is greater or equal to one. Substitution also is critical in the development of empirical indicators of

sustainability. A high degree of substitution is implicit in the concept of weak sustainability. Pearce and Atkinson (1993) argue that a nation is sustainable if it saves more than the combined depreciation of manufactured and natural capital. Like the growth models, their “savings rule” clearly assumes that natural capital inputs can be drawn down to close to zero so long as manufactured capital can be increased by functionally equivalent amounts.

Complementarity Limits Substitution

There is good reason to assume that the degree of substitutability between manufactured and natural capital is smaller, perhaps much smaller, than assumed in the standard growth model and the concept of weak sustainability. One reason is the complementary relation between manufactured and natural capital (Hall et al., 1986; Ayres and Nair, 1984; Costanza and Daly, 1992; Victor, 1994). The case for complementarity is based on the following arguments.

1. Historically, manufactured capital and natural capital have been developed as complements, not substitutes (Daly, 1991). The stock of manufactured capital such as tractors, oil rigs, and fishing vessels has been increased with the express intent of increasing the use of natural capital such as fertile soil, oil deposits and fish populations. It is ridiculous to talk of one without the other. As Costanza and Daly (1992) observe, if manufactured and natural capital were perfect substitutes, there would be no need to develop and accumulate manufactured capital since an equivalent form already exists!
2. Production is a work process that uses energy to transform materials into goods and services (Cleveland et al., 1984). Georgescu-Roegen's (1976) fund-flow model describes production as a transformation process in which a flow of materials, energy, and information is transformed by two agents of transformation, human labor and manufactured capital. The flow of energy, materials and services from natural capital is what is being transformed (the material cause), while manufactured capital effects the transformation (the efficient cause). For example, all machines require energy for their operation and they function by acting on a flow of materials from natural capital (Victor, 1994). Thus, adding to the stock of pulp mills does not produce an increase in pulp unless there also is the wood fiber to feed them. The two clearly are complements.

3. There is a biophysical interdependence between manufactured and natural capital. The construction, operation, and maintenance of tools, machines, and factories require a flow of materials, energy from natural capital. Similarly, the humans which direct manufactured capital energy and materials (i.e., food and water). Thus, producing more of the “substitute,” i.e. manufactured capital, requires more of the thing that it is supposed to substitute for.
4. Natural capital is multi-functional. A forest ecosystem produces a range of energy and materials (wood, chemicals) and services (habitat for biodiversity, climate regulation, flood protection). Some functions may be substitutable by manufactured capital, e.g., wood as a raw material, while others are non-substitutable, e.g., climate regulation. In the latter case no amount or type of human capital can replace natural capital. Ecosystems which provide critical life support services that have no human equivalent cannot be reduced below a minimum threshold levels.

Complementarity limits but does not exclude substitution. There undoubtedly are many opportunities for mitigating resource depletion and environmental degradation through the substitution of manufactured capital. Our point is that such opportunities are more limited than many people assume, and that the appropriate starting point is recognition of complementarity rather than the dubious assumption of near perfect sustainability.

Substitution and Sustainability at Local, National, and Global Scales

The substitution issue has been clouded by inattention to system boundaries. For example, home insulation directly substitutes for heating fuel, a clear substitution of manufactured capital for natural capital *within the household sector*. But complementarity means that insulation requires fuel to manufacture, so for the economy as a whole the net substitution of insulation for fuel is less than that indicated by an analysis of the household sector in isolation from the rest of the economy. Put another way, the aggregate of potential savings at the macroeconomy is less than the sum of the savings one would calculate by adding the savings from sectoral-level analyses that do not account for the indirect costs. Elasticities of substitution between manufactured and natural capital calculated for individual processes, firms, or industries may accurately reflect substitution possibilities *at those scales* (Berndt and Field, 1981). However, they may not accurately reflect possibilities for the economy as a whole because they do not account for the indirect natural capital costs of producing and maintaining manufactured capital.

Similar mistakes are made in international comparisons of substitution and sustainability where the system boundary is the individual nation. Some analysts suggest that the current paths of the US and Japanese economies are sustainable because they invest in human capital faster than they depreciate all forms of *domestic* human and natural capital (Pearce and Atkinson, 1993). But all industrial nations use and depreciate “shadow” natural capital from foreign and global stocks, and thus live beyond the means sustainable by domestic sources. There are numerous regional examples of the shadow natural capital used by populations. The 30 largest cities in the Baltic Sea drainage basin use 200 km² of terrestrial and aquatic ecosystem for every 1 km² of urban area to produce their use of agricultural, forestry, and fishery products (Folke et al., 1996). The Netherlands’ shadow use of natural capital is at least 15 times its own size (Wackernagel, 1996).

The potential to use shadow natural capital disappears at the global scale. This raises a critical question: can we increase the standard of living in developing nations to anything approaching that in the US, Japan, or the Netherlands? This would require a substantial increase in the size of the human economy relative to regional and global stocks of natural capital. Comprehensive and independent scientific investigations provide compelling evidence such growth of the global economy is not sustainable. Humans are dominant actors in many of the planet’s biogeochemical cycles and we extract a significant fraction of the globally available quantities of many renewable natural resources (Vitousek et al., 1997). In doing so, we degrade the systems that underpin our biological and economic existence. Examples include:

- Humans use about 40 percent of global terrestrial net primary production, the total food resource on the planet, (Vitousek, 1994), more than one-half of global available freshwater (Postel et al., 1996), and have fully exploited, overexploited or depleted two-thirds of marine fisheries (Food and Agriculture Organization, 1994).
- The release of carbon stored in fossil fuel deposits and vegetation contributes to the increasing CO₂ concentration in the atmosphere, and the balance of evidence suggests that has resulted in a discernible human influence on global climate (Houghton et al., 1996).
- Through fertilizer production and fossil fuel combustion humans already fix more nitrogen than all other biological processes combined, contributing to local and regional air pollution and climate change (Vitousek, 1994).
- Human mobilization of many toxic trace metals such as cadmium and lead now exceeds their flow in “natural” cycles (Nriagu, 1990), leading to their accumulation in soils and incorporation in food chains (Thomas and Sprio, 1994).

- About one-third of the non-ice land surface of the planet has been converted to human-dominated landscapes, predominantly cropland and pasture (Buringh, 1987). The resulting loss of original habitat is a major driving force behind the loss of biological diversity, and with it ecosystem functions that support human existence in countless ways (Heywood, 1995).

V. Technological Change

Along with substitution, the second important force in the standard growth model is technical change. Even if substitution possibilities were limited, constant production could be maintained indefinitely if technical change were natural capital-augmenting, i.e., if it sufficiently increased the productivity of natural capital.

The arguments for technical change would be more convincing if the role of innovation in economic growth were rigorously and explicitly represented in growth models. In reality, no convenient measures of technical change emerge from the neoclassical economic framework (Victor, 1991). Empirically, it is very difficult to distinguish pure substitution among inputs within a given technology from technical change caused by changes in the relative prices of those inputs. Due the problems of definition and measurement, in most empirical work on growth accounting technological change is defined as a nebulous statistical residual that mops up the all the growth in production not accounted for by labor and manufactured capital.

Another question is whether technology will follow the “right” direction (Gutés, 1996). A critical assumption in the theory of endogenous technical change is that the relative price of inputs accurately reflect their relative scarcities. If this is the case, the depletion or degradation of natural capital will lead to an increase in its price, and market forces will induce technological change towards saving or improving the productivity of natural capital. If prices fail to signal scarcity, there is no guarantee that technology will be biased in the “right” direction. There is ample evidence that in most nations market failures such as government regulation, subsidies, monopolies, and externalities significantly distort the price of energy and material resources. For most ecosystem services, markets, and hence prices, do not even exist.

Another reason to temper our technological optimism is that new technologies often are double-edged sword in terms of their overall effect on natural capital. New technologies that mitigate the scarcity of nonrenewable resources, for example, may release

greater quantities or more harmful types of wastes, and hence have greater impact on renewable natural capital and ecosystem services. A defining characteristic of technical change since the Industrial Revolution is a shift from renewable to nonrenewable resources, especially fossil fuels. The use of fossil fuel-based technologies has greatly improved the productivity of renewable resources such as agriculture, forestry, and fisheries. But fossil fuel-based technologies have not improved or even maintained the productive capacity of the ecosystems that generate the crops, timber, and fish. On the contrary, society faces widespread soil degradation, deforestation, and over-exploitation of fish stocks. Pollution from the use of fossil fuels and metals in extraction, production, and consumption further deteriorates the productive capacity of ecosystems.

Any argument that postulates the feasibility of indefinite growth implicitly assumes the existence so-called “backstop” technologies that are the functional equivalent of conventional fossil fuel-based technologies. Backstop energy technologies are assumed to provide unlimited services with a unit cost which is constant but higher than today’s technology. If it exists, such a technology limits the extent to which the price of fossil fuels can rise and the extent to which their exhaustion impedes growth. Frequently cited possibilities are electricity from fusion or breeder reactors, liquid fuel from biomass or oil shale, and various forms of solar energy. Fusion reactors are not even close to commercialization despite decades of massive financial investment in research and development. Oil shale and many solar technologies suffer from low net energy returns, meaning they require substantial investments of energy to build and operate the infrastructures that deliver the energy (Cleveland et al., 1984). Many potential backstop technologies also have impacts on renewable natural capital and ecosystem services that are as bad or worse than current technologies (Pimentel, 1995). Low net energy returns and high environmental costs make it highly questionable whether such technologies represent the “functional equivalents” of conventional fossil fuel technologies. On the other hand, there have been significant advances in some renewable technologies (wind, photovoltaics). Our point is that the timely development of backstop technologies is by no means a foregone conclusion.

V. What Are We Trying To Sustain?

Global biophysical constraints to the scale of human economy and complementarity between manufactured and natural capital limit the means of production. But towards what ends to do we use these means? The ultimate goal of the economic process is to meet

humans need and desires. The degree to which this is achieved often is equated with measures of economic output such as GNP. Rises in per capita GNP frequently are used to assess whether one nation is “better off” than another, or whether people within a nation are “better off” than last year. However, there is a growing realization that GNP does not accurately reflect real changes in the quality of life. One reason for this is that GNP does not adequately account for the use and depletion of natural capital caused by the production and consumption of goods and services.

There are important distinctions between economic income, economic welfare, and human welfare (Table 1). The most common measure of economic income is GNP which deals exclusively with marketed goods and services. GNP can be revised to account for the depreciation of manufactured capital to arrive at Net National Product (NNP). GNP also can be revised to account for non-marketed environmental (and other) services. The Environmental National Product (ENP) (Mäler, 1991; Hamilton and Lutz, 1996), the United Nations’ System of Environmental Economic Accounts (SEEA) (Bartelmus et al., 1994), and Sustainable National Income (Hueting, 1995) adjust the standard system of national accounts to account for natural capital, among other things.

Economic income is not always correlated with economic welfare because most measures of income include costs that detract from human welfare (e.g., the depletion of natural capital) and exclude some benefits (e.g., unpaid household labor). The Measure of Economic Welfare (MEW) (Nordhaus and Tobin, 1972) adjusts GNP for some of these factors, but make no adjustments for environmental costs or distributional effects. The Index of Sustainable Economic Welfare (ISEW) (Daly and Cobb, 1989) extends the MEW to account for such effects.

Measures of economic income such as GNP and economic welfare such as ISEW tacitly assume that consumption is directly tied to welfare. A completely different approach is to separate the means (consumption) from the ends (well-being) without assuming that the two are correlated. The United Nations’ Human Development Index (HDI) (UNDP, 1996) attempts to directly measure the degree to which some basic human needs are met. The HDI includes factors such as life expectancy, access to education, and per capita GDP adjusted to account for the declining contribution of higher incomes to well-being. The Human Needs Assessment (HNA) (Max-Neef, 1992) approaches well-being from the “ends” perspective. The key idea here is that the economy is only one of many means towards various ends such as shelter, protection, identity, freedom, etc.

The assessment of well-being over time and among nations varies tremendously depending on the measure. For example, GNP/capita in the United States rises from 1950 to 1994 (Figure 1). ISEW/capita parallels GNP/capita in the early part of the period, but

then levels and declines. The same leveling in ISEW/capita is observed in every other industrial nation for which it has been calculated (Max-Neef, 1995). The difference in well-being among nations varies greatly depending on whether it is measured by GNP/capita or the Human Development Index (Figure 2). For example, Israel and Oman have similar per capita GNPs, but greater life expectancies and education levels give Israel a much higher HDI ranking.

Alternative Models of Production, Wealth and Utility

We can summarize the foregoing discussion with reference to two alternative models of production, wealth and utility (Figure 3). Model 1 shows the conventional economic view. The primary factors of land and human capital (labor and manufactured capital) combine to produce goods and services (GNP) which is divided into consumption (which is the sole contributor to individual utility and welfare) and investment (which goes into maintaining and increasing the capital stocks). Preferences are fixed. In this model the primary factors are near-perfect substitutes for each other, so the role of “land”, i.e., natural capital, has been downplayed, and the lines between all the forms of capital are fuzzy. Property rights are usually simplified to either private or public and their distribution is usually taken as fixed and given.

Model 2 shows the ecological economics view of the process. Notice that the key elements of the conventional view are still present, but more has been added and some priorities have changed. There is limited substitutability between natural and human capital and property rights regimes are complex and flexible, spanning the range from individual to common to public property. Natural capital captures solar energy and behaves as an autonomous complex system. Both economic goods and services and ecological services and amenities are produced, and they contribute in different ways to satisfying basic human needs and creating both individual and community well-being. Waste production by the economic process contributes negatively to well being and has a negative impact on capital and ecological services. Preferences are adapting and changing but basic human needs are constant.

We emphasize that the relationships, complexities and feedbacks in the ecological-economic model are not a simple elaboration or fine-tuning of the standard model. They fundamentally alter basic relationships such as the relation between human and natural capital, and basic assumptions about the role of the role of production in meeting human wants and needs. Ignoring them conventional analysis produces serious errors in

assessing what is biophysically possible and morally desirable (Ekins and Max-Neef, 1992).

To evaluate the potential for sustainable growth and the viability of policies for moving economic activity in that direction, growth models must account for the relation between human and natural capital described Figure 3. A revised growth model could answer the following questions: (1) to what degree can resource depletion limit growth; (2) to what degree can the environment's ability to process wastes limit growth; (3) to what degree can an increasingly efficient human capital substitute for natural capital; (4) to what degree can an educated work force substitute for natural capital? We offer some specific suggestions in these directions.

Will resource depletion limit growth?

Much of the debate about the potential for resource depletion to limit economic growth focuses on the potential to substitute for natural resources should they become scarce. The scale issue is critical here. Microeconomic analysis indicates that substitution can allow economic activity to continue, but they ignore the macroeconomic and global effects of substitution. Resource depletion often increases the quantity of human capital required to extract a unit of natural resource. The complementary relation between human and natural capital implies that depletion may cause the resource extraction sector to grow at the expense of other sectors.

To represent the effect of resource depletion on economic activity, we suggest that the quantity of manufactured capital, labor, and natural resources required to extract a unit of natural resource should be modeled separately from production by other sectors. In addition, the feedback loop from resource depletion to the quantity of factor inputs required should be modeled explicitly. Technology has the potential to offset the effects of depletion, but the effects of technology should be represented consistent with the historical record of diminishing returns to the ability of technology to reduce the quantity of human and natural capital required to extract resources (Cleveland and Ruth, 1996).

Will the environment's ability to process wastes limit economic growth?

Current models use damage functions to represent the reduction in economic output relative to levels that are possible in an unpolluted environment. For example, the DICE model specifies a 1.67 percent reduction in GDP when temperature rises 3° F relative to pre-industrial levels (Nordhaus, 1994). This is based a single damage function that

arbitrarily assumes that all types of environmental damage reduce output at a specific rate in the future.

These types of damage functions do little to advance our understanding of how energy and material flows between the economy and the environment and within economic systems feed back to the production of output. We must represent the flows of matter and energy explicitly in three ways. First, energy and material flows in the environment create the natural capital which humans extract and transform to raw materials. Second, the use and depreciation of human capital creates material and energy wastes. Third, those wastes are assimilated by natural capital. Growth models must represent the accumulation of wastes in the environment should economic activity generate wastes faster than natural capital can process them

Growth models should account for the fact that the accumulation of wastes has negative feedbacks on economic output that often are lagged in time and space. The accumulation of waste materials can reduce the productivity of natural capital, as when ozone accumulates in the troposphere and depresses crop yields. This increases the quantity of human capital required to produce a given quantity of food. The accumulation of wastes also slows the rate at which natural capital can process waste material, as when sewage reduces the ability of aquatic ecosystems ability to process organic material. Finally, the accumulation of waste materials reduces the productivity of human capital in intermediate sectors, as when pollution increases workdays lost to illness.

To what degree can human capital substitute for services derived from natural capital?

The notion that the economy can grow *ad infinitum* depends in large part on the assumption that technical advances can reduce the quantity of natural capital required to produce a unit of economic output. There is a considerable body of evidence which indicates substitution and technical change have reduced the quantity of many forms of energy, metals, and minerals required to produce a unit of GDP over the last fifty years (Wernick, et al., 1996). Similarly, some of the research on environmental Kuznets curves postulate that rising incomes eventually reduce the use of resources and the emission of wastes. Nonetheless, there is good reason to believe that these analyses overstate the ability to substitute human capital for natural capital.

Growth models must account for the forces that produced these broad patterns of energy and material use. Much of the reduction in energy use per dollar of GDP in industrial nations is associated with the substitution of high quality for low quality fuels (Cleveland, et al., 1984; Kaufmann, 1992). Further reductions in the energy intensity of

economic activity should be assessed relative to the availability of high quality fuels. Similarly, a significant portion of the reduction in the use of mineral and metals per unit output may be associated with changes in trade patterns. Many developed nations now import large quantities of metal and minerals embodied in finished goods such as automobiles. These embodied metal and mineral flows rarely are accounted for in growth models. Finally, models must represent the factors that cause resource use and waste production to change with income. In fact, income often is not the causal factor, but rather income is *correlated* with causal factors such as the spatial intensity of economic activity and imports (Kaufmann, et al., in press).

To what degree can an educated work force substitute for natural capital?

Investments in education increase labor productivity, which we recognize as economic growth. Thus, it may be possible to sustain economic growth with little or no increase in the flow of services from natural and manufactured capital by producing a more educated work force. To assess this potential, growth models must represent the costs of increasing the level of education. Education consumes considerable amounts of natural and human capital. These costs may be small now, but they could become quite large over time. Some models assume that the skill level of the work force grows steadily over time. Over a long enough time horizon, the costs associated with such an increase could become quite large. For example, what is the educational effort required to increase the skill level a modest 2 percent per year over the next century? Does this increase imply that every person goes to college or get an advanced degree? The costs of such an effort would be large, both in terms of the educational work force and the opportunity cost of extended schooling.

VI. Conclusions

Although national economies are in very different stages of development, in the aggregate we must view them as a global economy that relies on natural capital which transcends political boundaries. To guide the development of sustainable economies, we need economic models that properly reflect the physical and ecological basis of economic activity, and for the important feedbacks between the economy and the environment. Specifically, they must embody realistic limits to the degree to which we can substitute human capital for natural capital, and account for critical role of ecosystem services as well as marketed natural resources. This is not a pessimistic assessment because we assume

considerable potential for substitution between human and manufactured capital and among various forms of natural capital. However, some ecosystem services are irreplaceable, and complementarity among the factors of production effectively limits many potential substitutions by imposing large opportunity costs. Furthermore, the potential for nations to use shadow natural capital to sustain growth diminishes as rising populations and incomes deplete more global natural capital.

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Figure Legends

Figure 1. A comparison of GNP/capita and ISEW/capita in the United States from 1950 to 1994.

Figure 2. The relation between per capita GNP and the Human Development Index (Data from UNDP, 1996).

Figure 3. Alternative models of the economic process (modified from Ekins, 1992).