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THE CONCEPT OF ENVIRONMENTAL SUSTAINABILITY[1]

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ABSTRACT

This paper reviews the current status of the debate about the concept of environmental sustainability and discusses related aspects of growth, limits, scale, and substitutability. While the paths leading to environmental sustainability in each country or sector will differ, the goal remains constant. But this conceptualization is far from an academic exercise. Ensuring, within less than two human generations, that as many as 10 billions people are decently fed and housed without damaging the environment on which we all depend represents a monumental challenge.

INTRODUCTION

As soon as Prime Minister Gro Harlem Brundtland and her United Nations commission (105), in a brilliant feat, garnered almost worldwide political consensus on the urgent need for sustainability, many countries and institutions started to grapple with the same problem: Precisely what is sustainability, and, specifically, what does it mean for this particular sector, nation, or region? This paper outlines the concept of sustainability, then focuses on environmental sustainability (ES).

This paper seeks to define environmental sustainability partly by sharply distinguishing it from social sustainability and, to a lesser extent, from eco-

[1]NOTE: These personal opinions should in no way be construed as representing the official position of the World Bank Group.

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nomic sustainability. These are contrasted in Figure 1. While overlap exists among the three, economic sustainability and ES have especially strong linkages. Defining each component of sustainability distinctly may help organize the action required to approach global sustainability in real life. Although this paper focuses more on the environmental aspects of sustainability, perhaps in the future, a general sustainability will come to be based on all three aspects—environmental, social, and economic.

Historically, economic theory has focused on efficiency of use of goods and, to a much lesser degree, on equity of distribution. Recent recognition of the pervasive economic significance of environmental conditions has forced two changes. First, the relatively new criterion of scale must now be added to the traditional criteria of allocation of resources and efficiency of use (30, 66). The "growth" debate emphasizes the scale of the growing human economic subsystem relative to the finite ecosystem. Ecologists and other biophysical scientists need to take more responsibility for leading the thinking on sustainable development and for seeing that efforts to achieve it are implemented promptly. Second, we must recognize that markets are almost invariably deficient as distributive mechanisms when natural resources are concerned.

Economic sustainability focuses on that portion of the natural resource base that provides physical inputs, both renewable (e.g. forests) and exhaustible (e.g. minerals), into the production process. ES adds consideration of the physical inputs into production, emphasizing environmental life-support systems without which neither production nor humanity could exist. These life-support systems include atmosphere, water, and soil—all of these need to be healthy, meaning that their environmental service capacity must be maintained. A healthy ozone shield, for example, prevents damage by ultraviolet b radiation to biota such as humans and crops. Continuous depletion or damage by human activities to irreplaceable and unsubstitutable environmental services would be incompatible with sustainability.

SOCIAL SUSTAINABILITY

The environment has now become a major constraint on human progress. Fundamentally important though social sustainability is, environmental sustainability or maintenance of life-support systems is a prerequisite for social sustainability. Redclift (74–76) claims that poverty reduction is the primary goal of sustainable development, even before environmental quality can be fully addressed. Poverty is increasing in the world in spite of global and national economic growth (see below). Poverty reduction has to come from qualitative development, from redistribution and sharing, from population stability, and from community sodality, rather than from throughput growth. Politicians will doubtless want the *impossible* goal of increasing throughput—

Social Sustainability	Economic Sustainability	Environmental Sustainability (ES)
Achieved only by systematic community participation and strong civil society. Cohesion of community, cultural identity, diversity, sodality, comity, tolerance, humility, compassion, patience, forbearance, fellowship, fraternity, institutions, love, pluralism, commonly accepted standards of honesty, laws, discipline, etc, constitute the part of social capital least subject to rigorous measurement, but for social sustainability. This "moral capital," as some call it, requires maintenance and replenishment by shared values and equal rights, and by community, religious and cultural interactions. Without this care it will depreciate as surely as will physical capital. Human capital—investments in education, health, and nutrition of individuals—is now accepted as part of economic development (102–104 108), but the creation of social capital as needed for social sustainability is not yet adequately recognized.	Economic capital should be stable. The widely accepted definition of economic sustainability "maintenance of capital", or keeping capital intact, has been used by accountants since the Middle Ages to enable merchant traders to know how much of their sales receipts they and their families could consume without reducing their ability to continue trading. Thus Hicks' (48) definition of income—"*the amount one can consume during a period and still be as well off at the end of the period*"—can define economic sustainability, as it devolves on consuming interest, rather than capital. We now need to extrapolate the definition of Hicksian income from sole focus on human-made capital and its surrogate (money) now to embrace the other three forms of capital (natural, social and human). Economics has rarely been concerned with natural capital (e.g., intact forests, healthy air) because until relatively recently it had not been scarce. This new scarcity, that of natural capital, arose because the scale of the human economic subsystem has now grown large relative to its supporting ecosystem (26–32). To the traditional economic criteria of allocation and efficiency must now be added a third, that of scale (28). The scale criterion would constrain throughput growth—the flow of material and energy (natural capital) from environmental sources to sinks, via the human economic subsystem. Economics values things in money terms, and is having major problems valuing natural capital, intangible, intergenerational, and especially common access resources, such as air. Because people and irreversibles are at stake, economics needs to use anticipation and the precautionary principle routinely, and should err on the side of caution in the face of uncertainty and risk.	Although ES is needed by humans and originated because of social concerns, ES itself seeks to improve human welfare by protecting the sources of raw materials used for human needs and ensuring that the sinks for human wastes are not exceeded, in order to prevent harm to humans. Humanity must learn to live within the limitations of the biophysical environment. ES means natural capital must be maintained, both as a provider of inputs ("sources"), and as a "sink" for wastes (23, 25, 72, 73, 74, 81, 83, 101). This means holding the scale of the human economic subsystem to within the biophysical limits of the overall ecosystem on which it depends. ES needs sustainable production and sustainable consumption. On the sink side, this translates into holding waste emissions within the assimilative capacity of the environment without impairing it. On the source side, harvest rates of renewables must be kept within regeneration rates. Non-renewables cannot be made fully sustainable, but quasi-ES can be approached for non-renewables by holding their depletion rates equal to the rate at which renewable substitutes can be created (38, 39). Ultimately, there can be no social sustainability without ES. ES supplies the conditions for social sustainability to be approached.

Figure 1. Comparison of social, economic and environmental sustainability

the flow of materials and energy from the sources of the environment, used by the human economy, and returned to environmental sinks as waste—by increasing consumption by all.

Countries truly sustaining themselves, rather than liquidating their resources, will be more peaceful than countries with unsustainable economies (41). Countries with unsustainable economies—those liquidating their own natural capital or those importing liquidated capital from other countries (e.g. Middle East oil or tropical timber 'mining') are more likely to wage war than are those with sustainable economies. When social sustainability has been clarified, possibly it will be relinked with ES, the whole contributing to sustainable development. Just as much of the world is not yet environmentally sustainable, neither is it socially sustainable. Disaggregation of social unsustainability will show what needs to be changed.

SUSTAINABILITY AND DEVELOPMENT

Sustainable development (SD) should integrate social, environmental, and economic sustainability and use these three to start to make development sustainable. The moment the term development is introduced, however, the discussion becomes quite different and more ambiguous. This paper is not focused on sustainable development, here assumed to be development that is socially, economically, and environmentally sustainable, or "development without throughput growth beyond environmental carrying capacity and which is socially sustainable" (27, 28, 30). World Wildlife Fund's (107) definition of sustainable development is similar: "Improvement in the quality of human life within the carrying capacity of supporting ecosystems." These definitions need to have the social aspects clarified, but they are less ambiguous than the Brundtland (105) definition: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[2]

Part of the success of the Brundtland Commission's definition stems from its opacity (49), and the definition of sustainability in a growth context. But when the World Commission on Environment and Development (WCED) (106) reconvened five years later, calls for growth were striking for their absence. HRH Prince Charles commended WCED in their publication (106)

[2]This UN definition does not distinguish among the different concepts of growth and development. While development can and should go on indefinitely for all nations, throughput growth cannot. Sustainability will be achieved only when development supplants growth; when the scale of the human economy is kept within the capacity of the overall ecosystem on which it depends. If we acknowledge the finite nature of our planet, "sustainable growth" is an oxymoron (28, 29). Throughput growth has to be kept within carrying capacity or within the capacity of the environmental services of assimilation and regeneration.

for dropping their 1987 call for huge (5- to 10-fold) increases in economic growth.

This paper offers the case that ES does not allow economic growth, much less sustained economic growth. On the contrary, environmentally sustainable development implies sustainable levels of both production (sources), and consumption (sinks), rather than sustained economic growth. The priority for development should be improvement in human well-being—the reduction of poverty, illiteracy, hunger, disease, and inequity. While these development goals are fundamentally important, they are quite different from the goals of environmental sustainability, the unimpaired maintenance of human life-support systems—environmental sink and source capacities.

The need for sustainability arose from the recognition that the profligate, extravagant, and inequitable nature of current patterns of development, when projected into the not-too-distant future, leads to biophysical impossibilities. The transition to environmental sustainability is urgent because the deterioration of global life-support systems—which compose the environment—imposes a time limit. We do not have time to dream of creating more living space or more environment, such as colonizing the moon or building cities beneath the ocean. We must save the remnants of the only environment we have and allow time for and invest in the regeneration of what we have already damaged. We cannot "grow" into sustainability.

The tacit goal of economic development is to narrow the equity gap between the rich and the poor. Almost always this is taken to mean raising the bottom (i.e. enriching the poor), rather than lowering the top by redistribution (44). Only very recently has it been admitted that bringing the low-income countries up to the affluent levels of the countries of the Organization for Economic Cooperation and Development (OECD) in 40 or even 100 years is a totally unrealistic goal. Most politicians and most citizens have not yet realized that this goal is unrealistic. Most people would accept that it is desirable for southern low-income countries to be as rich as those in the northern hemisphere—and then leap to the false conclusion that it must therefore be possible. But if greater equality cannot be attained by growth alone, then sharing and population stability will be necessary.

Serageldin (78) makes the persuasive case that in low income countries achieving per capita income levels of $1,500 to $2,000 (rather than OECD's $21,000 average) is quite possible. Moreover, that level of income may provide 80% of the basic welfare provided by a $20,000 income—as measured by life expectancy, nutrition, education, and other aspects of social welfare. This tremendously encouraging case remains largely unknown, even in development circles. Its acceptance would greatly facilitate the transition to environmental sustainability. Colleagues working on the northern hemisphere's overconsumption should address the corollary not dealt with by Serageldin (78):

Can $21,000/capita countries cut their consumption by a factor of 10 and suffer "only" a 20% loss of basic welfare? If indeed both raising the bottom (low income rises to $2000) and lowering the top (OECD income declines to $16,000) prove feasible, that would be tremendously encouraging and would speed ES. But to accomplish the possible parts of the imperative of development, we must stop idolizing the impossible. The challenge to development specialists is to deepen this important argument.

Intergenerational and Intragenerational Sustainability

Most people in the world today are either impoverished or live barely above subsistence; the number of people living in poverty is increasing. Developing countries can never be as well off as today's OECD average. Future generations seem likely to be larger and poorer than today's generation. Sustainability includes an element of not harming the future (intergenerational equity), and some find the intergenerational equity component of sustainability to be its most important element (e.g. 105). If the world cannot move toward intragenerational sustainability during this generation, it will be that much more difficult to achieve intergenerational sustainability sometime in the future, for the capacity of environmental services will be lower in the future than it is today.

World population soars by 100 million people each year: Some of these people are OECD overconsumers, but most of them are poverty stricken. World population doubles in a single human generation—about 40 years. This makes achieving intergenerational equity difficult, although achieving intergenerational equity will probably reduce total population growth. Rather than focusing on the intergenerational equity concerns of ES, the stewardship approach of safeguarding life-support systems today seems preferable.

WHAT SHOULD BE SUSTAINED?

Environmental sustainability seeks to sustain global life-support systems indefinitely (this refers principally to those systems maintaining human life). Source capacities of the global ecosystem provide raw material inputs—food, water, air, energy; sink capacities assimilate outputs or wastes. These source and sink capacities are large but finite; sustainability requires that they be maintained rather than run down. Overuse of a capacity impairs its provision of life-support services. For example, accumulation of CFCs is damaging the capacity of the atmosphere to protect humans and other biota from harmful UVb radiation.

Protecting human life is the main reason anthropocentric humans seek environmental sustainability. Human life depends on other species for food, shelter, breathable air, plant pollination, waste assimilation, and other environmental life-support services. The huge instrumental value of nonhuman species to humans is grossly undervalued by economics. Nonhuman species of no present value to humans have intrinsic worth, but this consideration is almost entirely excluded in economics (exceptions are existence and option values). A question rarely posed by economists and not yet answered by any is: With how many other species is humanity willing to share the earth, or should all other species be sacrificed to make room for more and more of the single human species? Surely it is arrogant folly to extinguish a species just because we think it is useless today. The anthropocentric and ecocentric views are contrasted by Goodland & Daly (42).

Although biodiversity conservation is becoming a general ideal for nations and development agencies, there is no agreement on how much should be conserved, nor at what cost. Leaving aside the important fact that we have not yet learned to distinguish useful from nonuseful species, agreeing on how many other species to conserve is not central to the definition of environmental sustainability. Reserving habitat for other species to divide among themselves is important; let evolution select the mix of species, not us. But reserving a nonhuman habitat requires limiting the scale of the human habitat. "How much habitat should be conserved?", while an important question to ask, is moot; the answer is probably "no less than today's remnants." This brings us to the precautionary principle: In cases of uncertainty, sustainability mandates that we err on the side of prudence. Because survival of practically all the global life-support systems is uncertain, we should be very conservative in our estimate of various input and output capacities, and particularly of the role of unstudied, apparently "useless," species.

Many writers (15, 16, 19, 32, 40, 46, 52, 54, 60, 84) are convinced that the world is hurtling away from environmental sustainability, but economists have not reached consensus that the world is becoming less sustainable. What is not contestable is that the modes of production prevailing in most parts of the global economy are causing the exhaustion and dispersion of a one-time inheritance of natural capital—topsoil, groundwater, tropical forests, fisheries, and biodiversity. The rapid depletion of these essential resources, coupled with the degradation of land and atmospheric quality, shows that the human economy as currently configured is already inflicting serious damage on global supporting ecosystems, and future potential biophysical carrying capacities are probably being reduced (21, 22).

A HISTORY OF SUSTAINABILITY

A notion of economic sustainability was firmly embodied in the writings of JS Mill (61), and TR Malthus (57, 58). Mill (61) emphasized that environment ("Nature") needs to be protected from unfettered growth if we are to preserve human welfare before diminishing returns set in. Malthus emphasized the pressures of exponential population growth on the finite resource base. The modern neo-Malthusianism version is exemplified by Ehrlich & Ehrlich (33a–35) and by Hardin (45, 46). Daly's "Toward a Steady State Economy" (25, 26) and "Steady State Economics" (23) synthesized and extended these viewpoints on population and resources. Daly's "Steady State Economics" is a seminal work in which population and consumption pressures on environmental sources and sinks are clearly demonstrated—the flow of matter and energy from the environment, used by the human economy, and released back into the environment as wastes. Daly magisterially subsumes the issues of population and consumption factors into the single critical factor of *scale*.

Neither Mill nor Malthus is held in great esteem by most of today's economists, who are more likely to follow the technological optimism of David Ricardo (77). Ricardo believed that human ingenuity and scientific progress would postpone the time when population would overtake resources or "the niggardliness of nature." However, as poverty is increasing worldwide, that postponement seems to have ended.

The definition of environmental sustainability (Figure 2) hinges on distinguishing between throughput growth and development. The "Growth Debate" moved into the mainstream two decades after World War II. Boulding (12–14), Mishan (62, 63), and Daly (23–26), for example, seriously questioned the wisdom of infinite throughput growth on a finite earth. Throughput growth is defended by most economists, including Beckerman (7–9), who still rejects the concept of sustainability (10). "The Limits to Growth" (59) and "Beyond the Limits" (60) shook the convictions of the technological optimists. Meadows et al (59) concluded that "it is possible to alter these growth trends and establish a condition of ecological and economic stability that is sustainable into the future." Barney's (5) US Global 2000 Report (1980) amplified and clarified the limits argument. Large populations, their rapid growth and affluence, are unsustainable. The Ricardian tradition that still dominates conventional economics is exemplified by the Cornucopians Simon & Kahn in their 1984 response to the Global 2000 Report. Panayotou (70), Summers (89), and Fritsch et al (39) found growth compatible with sustainability and even necessary for it. The 1980 World Conservation Strategy (51) by the International Union to Conserve Nature and the World Wildlife Fund, and Clark & Munn's 1987 International Institute for Applied Systems Analysis report "Sustainable Development of the Biosphere" (17), reinforced these conclusions. Daly & Cobb's (32) prizewinning "For the Common Good" estimated that growth, at least in the United States, actually decreased people's well-being, and they outlined pragmatic operational methods to reverse environmental damage and reduce poverty. The growth debate and sustainability issues are usefully synthesized by Korten (54).

Few Nobel prizewinners in economics write on sustainability. Haavelmo &

Hansen (44) and Tinbergen & Hueting (90) repudiate throughput growth and urge the transition to sustainability. Solow's earlier writings (85) questioned the need for sustainability, but he is now modifying that position (87, 88). The World Bank adopted environmental sustainability in principle rather early on, in 1984, and now promotes it actively (2, 56, 65, 80–82). Major contributions to the sustainability debate were published as contributions to the 1992 UN Commission on Environment and Development conference in Rio de Janeiro, such as WCS's 1991 "Caring for the Earth: a strategy for sustainable living." An addendum to the Brundtland Commission (106) rectified and reversed the earlier (105) calls for "5- to 10-fold more growth," by placing the population issue higher on the agenda to achieve sustainability. Goodland, Daly, and El Serafy (43), supported by two Economics Nobelists (Tinbergen and Haavelmo), made the case that there are indeed limits, that the human economy has reached them in many places, that it is impossible to grow into sustainability, that source and sink capacities of the environment complement human-made capital (which cannot substitute for their environmental services), and that there is no way the southern hemisphere can ever catch up with the north's current consumerist life-style.

Since the late 1980s, a substantial corpus of literature on "Ecological Economics" [which now has a journal, society and textbook of the same name (19)], has espoused stronger types of sustainability (e.g. 3, 4, 18, 48, 50, 52, 64, 91, 94).

GROWTH COMPARED WITH DEVELOPMENT

The dictionary distinguishes between growth and development. "To grow" means "to increase in size by the assimilation or accretion of materials;" "to develop" means "to expand or realize the potentialities of; to bring to a fuller, greater or better state."

Growth implies quantitative physical or material increase; development implies qualitative improvement or at least change. Quantitative growth and qualitative improvement follow different laws. Our planet develops over time without growing. Our economy, a subsystem of the finite and nongrowing earth, must eventually adapt to a similar pattern of development without throughput growth. The time for such adaptation is now. Historically, an economy starts with quantitative throughput growth as infrastructure and industries are built, and eventually it matures into a pattern with less throughput growth but more qualitative development. While this pattern of evolution is encouraging, qualitative development needs to be distinguished from quantitative throughput growth if environmental sustainability is to be approached.

Development by the countries of the northern hemisphere must be used to free resources (the source and sink functions of the environment) for the growth and development so urgently needed by the poorer nations. Large-scale transfers to the poorer countries also will be required, especially as the impact of economic stability in northern countries may depress terms of trade and lower economic activity in developing countries. Higher prices for the exports of poorer countries, as well as debt relief, will be required. Most importantly, population stability is essential to reduce the need for growth everywhere. This includes both where population growth has the greatest impact (i.e. in the northern high-consuming nations) and where population growth is highest (i.e. in the southern, poor, low-consuming countries).

THE DEFINITION OF ENVIRONMENTAL SUSTAINABILITY

The definition of ES as the "maintenance of natural capital" constitutes the input/output rules in Figure 2.

The two fundamental environmental services—the source and sink functions—must be maintained unimpaired during the period over which sustainability is required (23, 27, 31). ES is a set of constraints on the four major activities regulating the scale of the human economic subsystem: the use of renewable and nonrenewable resources on the source side, and pollution and waste assimilation on the sink side. This short definition of ES is the most

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1. *Output Rule:*
   Waste emissions from a project or action being considered should be kept within the assimilative capacity of the local environment without unacceptable degradation of its future waste absorptive capacity or other important services.
2. *Input Rule:*
   (a) *Renewables:* harvest rates of renewable resource inputs should be within regenerative capacities of the natural system that generates them.
   (b) *Nonrenewables:* depletion rates of nonrenewable resource inputs should be set below the rate at which renewable substitutes are developed by human invention and investment according to the Serafian quasi-sustainability rule (36–38). An easily calculable portion of the proceeds from liquidating nonrenewables should be allocated to research in pursuit of sustainable substitutes.
3. *Operational Principles:*
   (a) The scale (population × consumption per capita × technology) of the human economic subsystem should be limited to a level which, if not optimal, is at least within the carrying capacity and therefore sustainable.
   (b) Technological progress for sustainable development should be efficiency-increasing rather than throughput-increasing.
   (c) Renewable resources should be exploited on a profit-optimizing, sustained-yield, and fully sustainable basis.

Figure 2. The definition of environmental sustainability

useful so far and is gaining adherents. The fundamental point to note about this definition is that ES is a natural science concept and obeys biophysical laws (Figure 2). This general definition seems to be robust irrespective of country, sector, or future epoch.

The paths needed by each nation to approach sustainability will not be the same. Although all countries need to follow the input/output rules, countries differ in the balance of attention between output and input that will be needed to achieve ES. For example, some countries or regions must concentrate more on controlling pollution (e.g. former centrally planned economies); some countries must pay more attention to bringing harvest rates of their renewable resources down to regeneration rates (e.g. tropical timber–exporting countries); some countries must bring their population to below carrying capacity; others must reduce their per capita consumption (e.g. all OECD countries).

There are compelling reasons why industrial countries should lead in devis-

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Laws:

1. Neither growth in human population nor growth in the rates of resource consumption can be sustained.
2. The larger the population of a society and the larger its rates of consumption of resources, the more difficult it will be to transform the society to the condition of sustainability.
3. The response time of populations to changes in the total fertility rate is the length of time people live from their childbearing years to the end of life, or approximately 50 years.
4. The size of population that can be sustained (the carrying capacity) and the sustainable average standard of living are inversely related to one another.
5. Sustainability requires that the size of the population be less than or equal to the carrying capacity of the ecosystem for the desired standard of living.
6. The benefits of population growth and of growth in the rate of consumption of resources accrue to a few individuals; the costs are borne by all of society (the tragedy of the commons).
7. (Any) growth in the rate of consumption of a nonrenewable resource, such as a fossil fuel, causes a dramatic decrease in the life expectancy of the resource.
8. The time of expiration of nonrenewable resources, such as a fossil fuel, causes a dramatic decrease in the life expectancy of the resource.
9. When large efforts are made to improve the efficiency with which resources are used, the resulting savings are easily wiped out by the added resource needs that arise as a consequence of modest increases in population.
10. When rates of pollution exceed the natural cleansing capacity of the environment, it is easier to pollute that it is to clean up the environment.
11. Humans will always be dependent on agriculture so land and other renewable resources will always be essential.

Figure 3a. Bartlett's Laws relating to sustainability and hypotheses about sustainability

Hypotheses:

1. For the 1994 average global standard of living, the 1994 population of the earth exceeds carrying capacity.
2. Increasing population size is the single greatest and most insidious threat to representative democracy.
3. The costs of programs to stop population growth are small compared to the costs of population growth.
4. The time required for a society to make a planned transition to sustainability increases with increases in the size of its population and the average per capita consumption of resources.
5. Social stability is a necessary, but not a sufficient, condition for sustainability. Social stability tends to be inversely related to population density.
6. The burden of the lowered standard of living that results from population growth and from the decline of resources falls most heavily upon the poor.
7. Environmental problems cannot be solved or ameliorated by increases in the rates of consumption of resources.
8. The environment cannot be enhanced or preserved through compromises.
9. By the time overpopulation and shortage of resources are obvious to most people, the carrying capacity has been exceeded. It is then too late to think about sustainability.

Figure 3b. Bartlett's Sustainability Hypothesis (6)

ing paths toward sustainability. They have to adapt far more than do developing countries. If OECD countries cannot act first and lead the way, it is less likely that developing countries will choose to do so (95). Not only would it be enlightened self-interest for the north to act first, but it could also be viewed as a moral obligation. Second, developing countries are rightly pointing out (1, 11) that OECD countries have already consumed substantial amounts of environmental sink capacity (e.g. nearly all CFCs that are damaging the atmosphere were released by OECD countries) as well as source capacity (e.g. several species of great whales are extinct, and many stocks of fish and tropical timbers have been depleted below economically harvestable levels). Third, OECD countries can afford the transition to sustainability because they are richer. The rich would do themselves good by using the leeway they have for cutting overconsumption and waste (Figure 3a, 3b).

CAUSES OF UNSUSTAINABILITY

When the human economic subsystem was small, the regenerative and assimilative capacities of the environment appeared infinite. We are now painfully learning that environmental sources and sinks are finite. These capacities were very large, but the scale of the human economy has exceeded them. Source and sink capacities have now become limited. As economics deals only with scarcities, in the past source and sink capacities of the environment did not have to be taken into account. Conventional economists still hope or claim that economic growth is infinite or at least that we are not yet reaching limits to growth; hence the fierce recent repudiation of *Beyond the Limits of Growth* (60), and the welcome for Brundtland's call for "5- to 10-fold more growth" (105). The scale of the human economy is a function of throughput—the flow of materials and energy from the sources of the environment, used by the human economy, and then returned to environmental sinks as waste. Throughput growth is a function of population growth and consumption. Throughput growth translates into increased rates of resource extraction and pollution (use of sources and sinks). The scale of throughput has exceeded environmental capacities: That is the definition of unsustainability.

There is little admission yet that consumption above sufficiency is not an unmitigated good. The scale of the human economy has become unsustainable because it is living off inherited and finite capital (e.g. fossil fuels, fossil water); because we do not account for losses of natural capital (e.g. extinctions of species), nor do we admit the costs of environmental harm. The second reason for unsustainability is related to the first: government failure to admit that pollution and fast population growth are doing more harm than good.

THE TIME FOR ENVIRONMENTAL SUSTAINABILITY

Approaching sustainability is urgent. Consider that if release were halted today of all substances that damage the ozone shield, the ozone shield may need as much as one century to return to pre-CFC effectiveness. Every passing year means sustainability has to be achieved for an additional 100 million people. Though environmental sources and sinks have been providing humanity with their services for the last million years, and until recently have seemed vast and resilient, we have at last begun to exceed them and to damage them worldwide. Where environmental services are substitutable, the substitution achieved has been marginal. Most natural capital or environmental services cannot be substituted for, and their self-regenerating properties are slow and cannot be significantly hastened. That is why environmental sustainability has a time urgency.

Much of the resistance to accepting the necessity of a sustainability approach is that politicians have considered the consequences of doing so—controlling consumerism and waste, halting human population growth, and probably reducing population size, and relying on renewable energy—to be politically unacceptable. These are all felt to be politically damaging, so they are not put forward as much-needed societal goals. Instead, society calls for incremental progress in such disparate areas as enforcing the 'polluter pays' principle, support of women's reproductive health, educating girls, or clean technology. Important though these goals are, they are not enough, yet no one calls for the redistribution of resources from rich to poor. It is impossible for us to grow out of poverty and environmental degradation. It is precisely the nonsustainability of throughput growth beyond a certain scale that gives urgency to the concept of sustainability (27, 28). All forms of growth are unsustainable, whether in the number of trees, people, great whales, levels of atmospheric CO_2, or GNP.

The world will in the end become sustainable, one way or another. We can select the timing and nature of that transition and the levels of sustainability to be sought, or we can let depletion and pollution dictate the abruptness of the final inevitable transition. The former will be painful; the latter deadly. The longer we delay agreement on goals for levels of sustainability, the more the source and sink capacities will be damaged, the larger the number of people that will have to be accommodated on earth, and the more difficult the transition will be. For example, species extinctions are happening fast now, and they are accelerating. If that process continues for several decades, we will inevitably reach sustainability at a much poorer and less resilient level.

NATURAL CAPITAL AND SUSTAINABILITY

Of the four kinds of capital (natural, human, human-made, and social), environmental sustainability requires maintaining natural capital; understanding ES thus includes defining "natural capital" and "maintenance of resources" (or at least "non-declining levels of resources"). Natural capital—the natural environment—is defined as the stock of environmentally provided assets (such as soil, atmosphere, forests, water, wetlands), which provide a flow of useful goods or services; these can be renewable or nonrenewable, and marketed or nonmarketed. Sustainability means maintaining environmental assets, or at least not depleting them. "Income" is sustainable by the generally accepted Hicksian definition of income (47). Any consumption that is based on the depletion of natural capital is not income and should not be counted as such. Prevailing models of economic analysis tend to treat consumption of natural capital simply as income and therefore tend to promote patterns of economic activity that are unsustainable. Consumption of natural capital is liquidation, or disinvestment—the opposite of capital accumulation.

Now that the environment is so heavily used, the limiting factor for much economic development has become natural capital. For example, in marine fishing, fish have become limiting, rather than fishing boats. Timber is limited by remaining forests, not by sawmills; petroleum is limited by geological deposits and atmospheric capacity to absorb CO_2, not by refining capacity. As natural forests and fish populations become limiting, we begin to invest in plantation forests and fish ponds. This introduces an important hybrid category that combines natural and human-made capital—a category we may call "cultivated natural capital." This category is vital to human well-being, accounting for most of the food we eat, and a good deal of the wood and fibers we use. The fact that humanity has the capacity to "cultivate" natural capital dramatically expands the capacity of natural capital to deliver services. But cultivated natural capital (agriculture) is separable into human-made capital (e.g. tractors, diesel irrigation pumps, chemical fertilizers, biocides) and natural capital (e.g. topsoil, sunlight, rain). Eventually the natural capital proves limiting.

Natural Capital Is Now Scarce

In an era in which natural capital was considered infinite relative to the scale of human use, it may have been reasonable not to deduct natural capital consumption from gross receipts in calculating income. That era is now past. Environmental sustainability needs the conservative effort to maintain the traditional (Hicksian) meaning and measure of income now that natural capital is no longer a free good but is more and more the limiting factor in development. The difficulties in applying the concept arise mainly from operational problems of measurement and valuation of natural capital, as emphasized by Ahmad et al (2), Lutz (56), and El Serafy (37, 38).

Three Degrees of Environmental Sustainability

Sustainability can be divided into three degrees—weak, strong and absurdly strong—depending on how much substitution one thinks there is among the four types of capital (natural, human, human-made, and social) (32):

Weak environmental sustainability: Weak ES is maintaining total capital intact without regard to the partitioning of that capital among the four kinds. This would imply that the various kinds of capital are more or less substitutes, at least within the boundaries of current levels of economic activity and resource endowment. Given current liquidation and gross inefficiencies in resource use, weak sustainability would be a vast improvement as a welcome first step but would by no means constitute ES. Weak sustainability is a necessary but not sufficient condition for ES. Weak sustainability is rejected by Beckerman (10), but the concept is finding some acceptance in economic circles. It means we could convert all or most of the world's natural capital into human-made capital or artifacts and still be as well off! For example, society would be better off, it is claimed by those espousing weak sustainability, by converting forests to houses, and oceanic fish stocks into nourished humans. Human capital—educated, skilled, experienced, and healthy people—is largely lost at the death of individuals, and so it must be renewed each generation, whereas social capital persists in the form of books, knowledge, art, family and community relations.

Strong environmental sustainability: Strong ES requires maintaining separate kinds of capital. Thus, for natural capital, receipts from depleting oil should be invested in ensuring that energy will be available to future generations at least as plentifully as that enjoyed by the beneficiaries of today's oil consumption. This assumes that natural and human-made capital are not perfect substitutes. On the contrary, they are complements at least to some extent in most production functions. A sawmill (human-made capital) is worthless without the complementary natural capital of a forest. The same logic would argue that if there are to be reductions in one kind of educational investments, they should be offset by increased investments in other kinds of education, not by investments in roads. Of the three degrees of sustainability, strong sustainability seems greatly preferable mainly because of the lack of substitutes for much natural capital, the fact that natural capital and not human-made capital is now limiting, and the need for prudence in the face of many irreversibilities and uncertainties. Pearce et al (71–73), Costanza (19), Costanza & Daly (20), Opschoor, Van der Straaten, van den Bergh, most ecologists, and most ecological economists prefer or are coming round to some version of strong sustainability.

Absurdly strong environmental sustainability: We would never deplete anything. Nonrenewable resources—absurdly—could not be used at all. All minerals would remain in the ground. For renewables, only net annual growth increments could be harvested in the form of the overmature portion of the stock. Some ecologists fear we may be reduced to this type of sustainability—harvesting only overmature growth increments of renewables, in which case this sustainability is better called "superstrong" sustainability (67).

There are tradeoffs between human-made capital and natural capital. Economic logic requires us to invest in the limiting factor, which now is often natural rather than human-made capital, which was previously limiting. Operationally, this translates into three concrete actions as noted in Figure 4.

SUSTAINABILITY AND SUBSTITUTABILITY

Conventional economics and technological optimists depend heavily on substitutability as the rule rather than the exception. Ecology has paid inadequate

1) FOSTER REGENERATION OF NATURAL CAPITAL:
   Encourage the growth of natural capital by reducing our current level of exploitation of it. For example, lengthen rotations (of forest cutting or arable crops) to permit full regeneration; limit catches (e.g. of fish) to prudently well within long-term sustained yield estimates.
2) RELIEVE PRESSURE ON NATURAL CAPITAL:
   Invest in projects to relieve pressure on natural capital stocks by expanding cultivated natural capital, such as tree plantations to relieve pressure on natural forests. Reducing pollution and waste provides more time for assimilative capacities to regenerate themselves.
3) IMPROVE EFFICIENCY IN USE OF NATURAL CAPITAL:
   Increase the end-use efficiency of products (such as improved cookstoves, solar heaters and cookers, wind pumps, solar pumps, manure rather than chemical fertilizer). Extend the life-cycle, durability, and recyclability of products to improve overall efficiency, as would taxing planned obsolescence and ephemerata.

Figure 4. Rebuilding natural capital stocks

attention to the extent of substitutability between natural and human-made capital, yet it is central to the issue of sustainability. Substitutability is the ability to offset a diminished capacity of environmental source and sink services to provide healthy air, water, etc, and to absorb wastes. The importance of substitutability is that if it prevails, then there can be no limits, because if an environmental good is destroyed, it is argued, a substitute can replace it. When White Pine or sperm whales became scarce, there were acceptable substitutes. When easily gathered surficial oil flows were exhausted, drilling technology enabled very deep deposits to be tapped. In Europe, when the native forest was consumed, timber for houses was replaced with brick. If bricks did not substitute for timber, then timber was imported.

The realization that substitutability is the exception, rather than the rule, is not yet widespread, despite Ehrlich's warning (33, 34). However, once limits of imports cease to mask substitutability (e.g. US Pacific Northwest and British Columbia timber controversies show the limits of imports), then it becomes plain that most (but not all) forms of capital are more complementary or neutral and are less substitutable. Economists who hope that natural capital and human-made capital are substitutes claim that total capital (i. e. the sum of natural and human-made capital) can be maintained constant in some aggregate value sense. This reasoning, built on the questionable premise that human-made capital is substitutable for natural capital, means it is acceptable to divest natural capital (i.e. deplete environmental source or sink capacities) as long as an equivalent value has been invested in human-made capital. Even this weak sustainability is not required by national accounting rules. Indeed, our national accounts simply count natural capital liquidation as income (37, 38).

Unfortunately, that is also the way the world is being run at the micro or firm level; user costs are rarely calculated (53). We consume environmental source capacity by releasing many wastes (e.g. CO_2, CFCs, oxides of sulfur and nitrogen that make acid rain) into the air because we claim the investment in energy production and refrigeration (human-made capital) substitutes for healthy air or atmosphere. We extinguish species (depletion of biodiversity source capacity) by converting jungle to cattle ranches because the human-made capital (or strictly quasi-human made agriculture) is a substitute for the natural capital of biodiversity. Such "weak sustainability" has not yet been achieved, and it would be a great improvement were it attained. But, because human-made and natural capital are far from perfect substitutes, weak sustainability is a dangerous goal. It would be risky as an interim stage on the way to any reliable concept of sustainability.

Ecologists attach great importance to Baron Justus von Liebig's Law of the Minimum—the whole chain is only as strong as its weakest link. The factor in shortest supply is the limiting factor because factors are complements, not substitutes. If scarcity of phosphate is limiting the rate of photosynthesis, then photosynthesis would not be enhanced by increasing another factor such as nitrogen, light, water, or CO_2. If one wants faster photosynthesis, one must ascertain which factor is limiting and then invest in that one first, until it is no longer limiting. More nitrogen fertilizer cannot substitute for lack of phosphate, precisely because they are complements. Environmental sustainability is based on the conclusion that most natural capital is a complement for human-made capital, and not a substitute. Complementarity is profoundly unsettling for conventional economics because it means there are limits to growth, or limits to environmental source and sink capacities. Human-made capital is a very poor substitute for most environmental services. Substitution for some life-support systems is impossible.

A compelling argument that human-made capital is only a marginal substitute for natural capital is the reductio ad absurdum case in which all natural capital is liquidated into human-made capital. We might survive the loss of fossil fuels, but what would substitute for topsoil and breathable air? Only in science fiction could humanity survive by breathing bottled air from backpacks, and eating only hydroponic greenhouse food. If there is insufficient substitutability between natural capital and human-made capital, then throughput growth must be severely constrained and eventually cease. While new technology may postpone the transition from quantitative growth to qualitative development and environmental sustainability, current degradation shows that technology is inadequate. *"For natural life-support systems no practical substitutes are possible, and degradation may be irreversible. In such cases (and perhaps in others as well), compensation cannot be meaningfully specified."* (92, 93).

COMMON MISCONCEPTIONS ABOUT ENVIRONMENTAL SUSTAINABILITY

Is ES the Same as Sustained Yield?

There is a lively debate, especially in forestry and fishery circles, about whether environmental sustainability is "sustained yield" (S-Y). Clearly ES includes, but is far from limited to, sustained yield. ES is applied at the aggregate level to all the values of an ecosystem, not to just a few species of timber trees or fish. ES is akin to the simultaneous S-Y of many interrelated populations in an ecosystem. S-Y is ES restricted to a small fraction of the members of the ecosystem under consideration. S-Y is often used in forestry and fisheries to determine the optimal—most profitable—extraction rate of timber or fish. ES counts all the natural services of the sustained resource. S-Y counts only the service of the product extracted and ignores all other natural services. S-Y forestry counts only the timber value extracted; ES forestry counts all services, including protecting vulnerable ethnic-minority forest dwellers, biodiversity, genetic values, intrinsic as well as instrumental values, climate, wildlife, carbon balance, water source and water moderation values, ecosystem integrity in general (96), and of course, timber extracted. The relation between the two is that if S-Y is actually achieved, then the stock resource (e.g. the forest) will be nearer sustainability than if S-Y is not achieved. S-Y in tropical forestry is doubtful now (55) and will be more doubtful in the future as human population pressures intensify. But even were S-Y to be achieved, that resource is unlikely to have also attained ES. The optimal solution for a single variable, such as S-Y, usually (possibly inevitably) results in declining utility or declining natural capital sometime in the future, and therefore it is not sustainable.

Is ES Certain or Uncertain?

Environmental sustainability is a rather clear concept. However, there is much uncertainty about the details of its application. After scientists have spent centuries trying to estimate sustained yield for a few species of timber trees or fish, they are now questioning whether they can ever be successful (55), leaving aside whether humans would accept sustainable yield extraction rates once they were determined. Considering that ES is more complex than S-Y suggests a high degree of uncertainty. Today we are largely empirical in our assessment of assimilative capacity also. We allow a limit to be exceeded, often for years, before we muster the political will to start addressing the problem. Damage to the ozone shield was argued for years before CFC manufacturers agreed to phase CFCs out, and then they did so only when economic substitutes had been found. Even so, scientific understanding of biophysical linkages is weak, so there is much uncertainty, and hence a compelling need for the precautionary principle to prevail widely. Colleagues addressing ES should seek rough rather than precise indicators of sustainability so that we can move on. Better to be roughly right than precisely wrong.

Is ES More of a Concern for Developing Countries?

The countries of the northern hemisphere are responsible for the overwhelming share of global environmental damage today, and it is unlikely that poor countries will want to move toward sustainability if the north doesn't do so first. The northern hemisphere more than the southern can decrease global warming risks by reducing greenhouse gas emissions, for example. The north has to adapt to ES more than the south, and arguably before the south. The main exception is biodiversity, most of which is contained in tropical ecosystems. The north can afford to exert leadership on itself. But because developing economies depend to a much greater extent than do OECD economies on natural resources, especially renewables, the south has much to gain from reaching ES. In addition, because much tropical environmental damage is irreversible, it is either impossible or more expensive to rehabilitate tropical than temperate environments, so the south will gain more from a preventive approach than from emulating the short-sighted and expensive curative approach and similar mistakes of the north.

Does ES Imply Reversion to Autarky or the Stone Age?

As soon as society perceives that environmental sustainability means conservation of life-support systems, people will demand it on the grounds of welfare, equity, or economics. The poor suffer most from pollution and from the higher prices caused by depletion. The poor are least able to protect themselves against scarcities (e.g. of clean water, clean air) and pollution. Among the rich, only a few are acting on the message that affluence and overconsumption do not increase welfare. Much more education is needed for overconsumers to realize that rides in limousines are often slower as well as more polluting than those on the metro, and that eating three steaks a day reduces fitness. As the costs of overconsumption increase (sickness and decreased productivity, health costs, heart attack, stroke), this message will spread. Reducing waste means needing fewer land fills and trash incinerators, which would improve human welfare. The concept of sufficiency (doing more or enough with less) needs dissemination.

ES Involves Public Choice

ES as biophysical security is connected to welfare, and both are somewhat connected to economics, especially to efficiency of use. Public choice governs the rate at which society elects to approach ES voluntarily and purposefully, or, as at present, to recede from it. Society has the choice of an orderly transition to environmental sustainability on our terms, or of letting biophysical damage dictate the timing and speed of the transition. If society allows biophysical deterioration to make the transition to ES for us, the transition is likely to be unacceptably harsh for humans. That is why clarity and education are so important in the race to approach ES. Partly because recognition of the need for ES is so recent, political will and institutional capacity now have to catch up. There will be powerful losers when society decides to move toward ES and toward making polluters pay. Institutional strengthening therefore is a necessary condition for ES.

CONCLUSION

This paper reviews the current status of the debate about the concept of environmental sustainability and discusses related aspects of growth, limits, scale, and substitutability. While the paths leading to ES in each country or sector will differ, the goal remains constant. But this conceptualization is far from an academic exercise. The monumental challenge of ensuring, within less than two human generations, that as many as ten billion people are decently fed and housed without damaging the environment on which we all depend, means that the goal of environmental sustainability must be reached as soon as humanly possible.

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