Revisiting Carrying Capacity: Area-Based Indicators of Sustainability

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Conventional wisdom suggests that because of technology and trade, human carrying capacity is infinitely expandable and therefore virtually irrelevant to demography and development planning. By contrast, this article argues that ecological carrying capacity remains the fundamental basis for demographic accounting. A fundamental question for ecological economics is whether remaining stocks of natural capital are adequate to sustain the anticipated load of the human economy into the next century. Since mainstream (neoclassical) models are blind to ecological structure and function, they cannot even properly address this question. The present article therefore assesses the capital stocks, physical flows, and corresponding ecosystems areas required to support the economy using "ecological footprint" analysis. This approach shows that most so-called "advanced" countries are running massive unaccounted ecological deficits with the rest of the planet. Since not all countries can be net importers of carrying capacity, the material standards of the wealthy cannot be extended sustainably to even the present world population using prevailing technology. In this light, sustainability may well depend on such measures as greater emphasis on equity in international relationships, significant adjustments to prevailing terms of trade, increasing regional self-reliance, and policies to stimulate a massive increase in the material and energy efficiency of economic activity.

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Also see: Ecological Footprints of Nations at http://www.ecouncil.ac.cr/rio/focus/report/english/footprint/

WHY CARRYING CAPACITY?

According to Garrett Hardin (1991), "carrying capacity is the fundamental basis for demographic accounting." On the other hand, conventional economists and planners generally ignore or dismiss the concept when applied to human beings. Their vision of the human economy is one in which "the factors of production are infinitely substitutable for one another" and in which "using any resource more intensely guarantees an increase in output" (Kirchner *et al.*, 1985). As Daly (1986) observes, this vision assumes a world "in which carrying capacity is infinitely expandable" (and therefore irrelevant). Clearly there is great division over the value of carrying capacity concepts in the sustainability debate.

This article sides solidly with Hardin. I start from the premise that despite our increasing technological sophistication, humankind remains in a state of "obligate dependence" on the productivity and life support services of the ecosphere (Rees, 1990). Thus, from an ecological perspective, adequate land and associated productive natural capital are fundamental to the prospects for continued civilized existence on Earth. However, at present, both the human population and average consumption are increasing while the total area of productive land and stocks of natural capital are fixed or in decline. These opposing trends demand a revival of carrying capacity analysis in sustainable development planning. The complete rationale is as follows:

Definitions: Carrying Capacity and Human Load

> An environment's carrying capacity is
> its maximum persistently supportable load (Catton 1986).

For purposes of game and range management, carrying capacity is usually defined as the maximum population of a given species that can be supported indefinitely in a defined habitat without permanently impairing the productivity of that habitat. However, because of our seeming ability to increase our own carrying capacity by eliminating competing species, by importing locally scarce resources, and through technology, this definition seems irrelevant to humans. Indeed, trade and technology are often cited as reasons for rejecting the concept of human carrying capacity out of hand. [According to orthodox theory, free trade is invariably good, resulting in improved living standards and increased aggregate productivity and efficiency -- increased carrying capacity -- through comparative advantage.]

This is an ironic error -- shrinking carrying capacity may soon become the single most important issue confronting humanity. The reason for this becomes clearer if we define carrying capacity not as a maximum population but rather as the maximum "load" that can safely be imposed on the environment by people. Human load is a function not only of population but also of *per capita* consumption and the latter is increasing even more rapidly than the former due (ironically) to expanding trade and technology. As Catton (1986) observes: "The world is being required to accommodate not just more people, but effectively 'larger' people . . ." For example, in 1790 the estimated average daily energy consumption by Americans was 11,000 kcal. By 1980, this had increased almost twenty-fold to 210,000 kcal/day (Catton 1986). As a result of such trends, *load* pressure relative to carrying capacity is rising much faster than is implied by mere population increases.

The Ecological Argument

Despite our technological, economic, and cultural achievements, achieving sustainability requires that we understand human beings as ecological entities. Indeed, from a functional perspective, the relationship of humankind to the rest of the ecosphere is similar to those of millions of other species with which we share the planet. We depend for both basic needs and the production of artifacts on energy and material resources extracted from nature and all this energy/matter is eventually returned in degraded form to the ecosphere as waste. The major material difference between humans and other species is that in addition to our biological metabolism, the human enterprise is characterized by an industrial metabolism. In ecological terms, all our toys and tools (the "capital" of economists) are "the exosomatic equivalent of organs" (Sterrer, 1993) and, like bodily organs, require continuous flows of energy and material to and from "the environment" for their production and operation. It follows that in a finite world:

* Economic assessments of the human condition should be based on, or at least informed by, ecological and biophysical analyses.

* The appropriate ecological analyses focus on the flows of available energy/matter (essergy) particularly from primary producers--green plants and other photosynthesizers -- to sequential levels of consumer organisms in ecosystems (specifically, humans and their economies) and on the return flows of degraded energy and material (wastes) back to the ecosystem.

This approach shows that humankind, through the industrial economy, has become the dominant consumer in most of the Earth's major ecosystems. We currently "appropriate" 40% of the net product of terrestrial photosynthesis (Vitousek *et al.*, 1986) and 25-35% of coastal shelf primary production (Pauly & Christensen, 1995), and these may be unsustainable proportions. [Global fisheries yields have fallen since 1989.] At the same time some global waste sinks seem full to overflowing.

A fundamental question for *ecological* economics, therefore, is whether the physical output of remaining species populations, ecosystems, and related biophysical processes (i.e., critical self-producing natural capital stocks -- see Box 1), and the waste assimilation capacity of the ecosphere, are adequate to sustain the anticipated load of the human economy into the next century while simultaneously maintaining the general life support functions of the ecosphere. This "fundamental question" is at the heart of ecological carrying capacity but is virtually ignored by mainstream analyses.

Box 1: On Natural Capital

Natural capital refers to "a stock [of natural assets] that yields a flow of valuable goods and services into the future." For example, a forest or a fish stock can provide a flow or harvest that is potentially sustainable year after year. The stock that produces this flow is " natural capital" and the sustainable flow is "natural income." Natural capital also provides such services as waste assimilation, erosion and flood control, and protection from ultra-violet radiation (the ozone layer is a form of natural capital). These life support services are also counted as natural income. Since the flow of services from ecosystems often requires that they function as intact systems, the structure and diversity of the system may be an important component of natural capital.

There are three broad classes of natural capital: *Renewable* natural capital, such as living species and ecosystems, is self-producing and self-maintaining using solar energy and photosynthesis. These forms can yield marketable goods such as wood fibre, but may also provide unaccounted essential services when left in place (e.g., climate regulation). *Replenishable* natural capital, such as groundwater and the ozone layer, is non-living but is also often dependent on the solar "engine" for renewal. Finally, non-renewable natural capital such as fossil fuel and minerals, are analogous to inventories - any use implies liquidating part of the stock.

This article takes the position that since adequate stocks of self-producing and replenishable natural capital are essential for life support (and are generally non-substitutable), these forms are more important to sustainability than are non-renewable forms.

Source: Rees (1995), liberally adapted from Costanza and Daly (1992).

Second Law Arguments

A related rationale for revisiting carrying capacity flows from consideration of the Second Law of Thermodynamics. In particular, modern formulations of the second law suggest that all highly-ordered systems develop and grow (increase their internal order) "at the expense of increasing disorder at higher levels in the systems hierarchy" (Schneider & Kay, 1992). In other words, complex dynamic systems remain in a nonequilibrium state through the continuous dissipation of available energy and material (essergy) extracted from their host environments. They require a constant input of energy/matter to maintain their internal order in the face of spontaneous entropic decay. Such self-organising nonequilibrium systems are therefore called "dissipative structures."

This extension of the second law is critical to human carrying capacity. Consider that:

* The human economy is one such highly-ordered, dynamic, far-from equilibrium dissipative structure. At the same time . . .

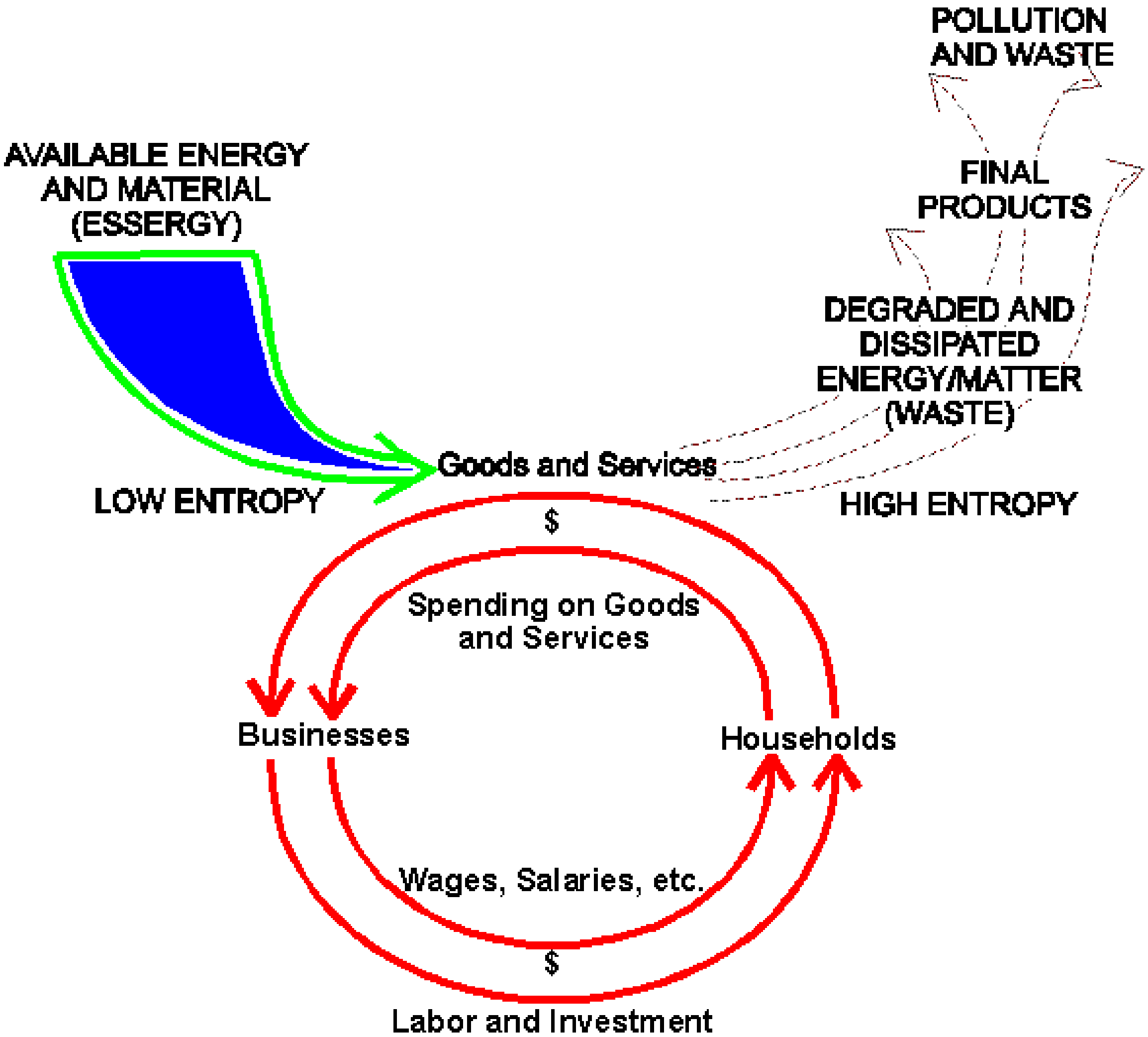
* The economy is an open, growing, subsystem of a materially closed, nongrowing ecosphere (Daly, 1992), and is therefore dependent on the formation of essergy in the ecosphere for its growth and developments. [This input to the economy from nature is the "natural income" referred to in Box 1]

This relationship implies that beyond a certain point, the continuous growth of the economy can be purchased only at the expense of increasing disorder or entropy in the ecosphere. This is the point at which consumption by the economy exceeds natural income and would be manifested through the continuous depletion of natural capital --reduced biodiversity, air/water/land pollution, deforestation, atmospheric change, etc. In other words, the empirical evidence suggests that the aggregate human load already exceeds, and is steadily eroding, the very carrying capacity upon which the continued humane existence depends. Ultimately this poses the threat of unpredictable ecosystems restructuring (e.g., erratic climate change) leading to resource shortages, increased local strife, and the heightened threat of ecologically induced geopolitical instability.

In this light, the behavior of complex systems and the role of the economy in the global thermodynamic hierarchy should be seen as fundamental to sustainability, yet both concepts are alien to the dominant development-oriented institutions in the world today.

Why Economics Cannot Cope

FIGURE1. The linear throughput of energy/matter



The linear throughput of low-entropy energy and matter (upper part of diagram) sustains the economy and drives the circular flows of exchange value (lower part of diagram), yet is invisable to conventional economic analysis.

Box 2: The Blind Spot in Conventional Analysis

Mainstream economics approaches the issue of adequate capital stocks through monetary analysis. However, money and prices are excessively abstracted from the material wealth they are supposed to represent. For example:

Where there are markets for ecologically significant "goods and services," prices do not reflect the size of the corresponding natural capital stocks, whether there are critical minimal levels below which stocks can no longer replenish themselves (the real measure of biophysical scarcity), the functional roles of such stocks in relevant ecosystems, or their ultimate value in sustaining life. Meanwhile...

Many ecological goods and most life-support services remain unpriced and therefore not subject to market signals or related behavioral change of *any* kind. (The ozone layer is a case in point.)

Unfortunately, current efforts to "internalise the externalities," "get the prices right" and otherwise commodify the environment suffer from major data gaps, the functional transparency of natural processes (we don't know they're valuable until they're gone), and other theoretical problems that often render futile attempts to quantify, let alone price, many critical ecological goods and services (Vatn and Bromley 1993). In short...

Standard monetary analyses are blind to ecological structure and function and are therefore incapable of indicating either ecologically meaningful scaricity of incipient systems destabilisation.

Part of the reason for this perceptual gulf is that many of the questions raised by ecological and thermodynamic considerations are invisible to mainstream approaches. Economic analysis is based on the circular flow of exchange value (money flows) through the economy, not on physical flows and transformations. Prevailing economic models of growth and sustainability thus "lack any representation of the materials, energy sources, physical structures, and time-dependent processes basic to an ecological approach" (Christensen, 1991). Thus while, the second law is arguably the ultimate governor of economic activity, standard models do not recognize the unidirectional and thermodynamically irreversible flux of available energy and matter upon which the economy depends (Figure 1). Similarly, conventional approaches to conservation and sustainability focus mainly on the money values of marketable resource commodities (e.g., timber) and are insensitive to the intangible (but ultimately more valuable) nonmarket ecological functions of the natural capital that produces them (e.g., the forest ecosystem). Box 2 summarizes this problem.

In this light, economists' lack of concern about carrying capacity would seem to derive, in large part, from conceptual weaknesses in their analytic models. The necessary conditions for ecological sustainability can better be defined through the analysis of physical stocks and flows interpreted in light of appropriate ecological and complex systems theory.

Technology and Trade: No Boon to Carrying Capacity

As previously noted, conventional analysts often argue that trade and technology expand ecological carrying capacity. This is a misconception. Even in the best of circumstances, technological innovation does not increase carrying capacity per se but only the efficiency of resource use. In theory, shifting to more energy- and material-efficient technologies should enable a defined environment to support a given population at a higher material standard, or a higher population at the same material standard, thereby seeming to increase carrying capacity. However, in either case, the best we could hope for in an increasingly open global economy would be to maintain total human load constant in the vicinity of carrying capacity -- the latter would still ultimately be limiting.

In practice, we have not done even this well -- the steady gains in efficiency throughout the post-war period have been accompanied by steadily increasing *per capita* and aggregate consumption. It seems that efficiency gains may actually work *against* conservation through the price and income effects of technological savings.

As Saunders (1992) notes, this counter intuitive hypothesis has been the focus of considerable controversy. He tested it using neoclassical growth theory and found that energy efficiency gains might well increase aggregate energy consumption by making energy cheaper and by stimulating economic growth, which further "pulls up" energy use. How might this work? If a firm saves money by switching to more energy- and material efficient manufacturing processes, it will be able to raise wages, increase dividends, or lower prices, which can lead to increased net consumption by workers, shareholders, or consumers respectively. These behavioral responses to changes in prices and income are referred to as the "rebound effects" by economists (Jaccard, 1991). Similarly, technology-induced money savings by individuals are usually redirected to alternative forms of consumption, canceling some or all of the initial potential benefit to the environment (Hannon, 1975). To the extent that such mechanisms contribute to increased aggregate material consumption and accelerated stock depletion, they indirectly *reduce* carrying capacity.

[Rebound effects can be avoided if adequate stock depletion taxes or marketable resource quotas are imposed. (Such incentives should be used to stimulate conservation in the first place.) "Ecological taxation" would raise unit resource prices, effectively capturing any efficiency savings and preventing their further circulation in the economy. However, because of reduced material and energy intensity, consumer prices for goods and services would increase less rapidly than resource prices (Rees, 1994a).]

More generally, however, technology can directly reduce carrying capacity while creating the illusion of increasing it! We often use technology to increase the short-term energy and material flux through exploited ecosystems. This seems to enhance systems productivity while actually permanently eroding the resource base. For example, the effectiveness of electronic fish-finding devices and high-tech catching technology has overwhelmed the reproductive capacity of fish stocks; energy-subsidized intensive agriculture may be more productive than low-input practices in the short term, but it also increases the rate of soil and water depletion. The net effect is to create unsustainable dependencies on enhanced material flows (the technologies involved are often based on nonrenewable resources) while reducing longterm carrying capacity.

The carrying capacity gains from trade are also illusory. While commodity trade may release a local population from carrying capacity constraints in its own home territory, this merely displaces some fraction of that population's environmental load to distant export regions. In effect, local populations import others' "surplus" carrying capacity. The resultant increase in population and resource use in import regions increases the aggregate load of humanity on the ecosphere but there is *no net gain* in carrying capacity since trade reduces the load-bearing capacity of the export regions. Indeed, like technology, trade may even result in reduced global carrying capacity if access to cheap imports (e.g., food) lowers the incentive for people to conserve their own local natural capital stocks (e.g., agricultural land) and leads to the accelerated depletion of natural capital in distant export regions.

These comments are not to be taken as arguments against technology or trade per se. Rather the point is to emphasize that conventional assumptions about both should be carefully reexamined in light of carrying capacity considerations and that certain conditions must be satisfied before either can contribute to ecological sustainability.

APPROPRIATED CARRYING CAPACITY AND ECOLOGICAL FOOTPRINTS

We can now redefine human carrying capacity as the maximum rates of resource harvesting and waste generation (the maximum load) that can be sustained indefinitely without progressively impairing the productivity and functional integrity of relevant ecosystems wherever the latter may be located. The size of the corresponding population would be a function of technological sophistication and mean *per capita* material standards (Rees, 1988). This definition reminds us that regardless of the state of technology, humankind depends on a variety of ecological goods and services provided by nature and that for sustainability, these must be available in increasing quantities from somewhere on the planet as population and mean *per capita* resource consumption increase (see also Overby, 1985).

Now, as noted earlier, a fundamental question for ecological economics is whether supplies of natural capital will be adequate to meet anticipated demand into the next century. Inverting the standard carrying capacity ratio suggests a powerful way to address this critical issue. Rather than asking what population a particular region can support sustainably, the carrying capacity question becomes: How large an area of productive land is needed to sustain a defined population indefinitely, *wherever on Earth that land is located?* (Rees, 1992; Rees & Wackernagel, 1994; Wackernagel & Rees, 1995). Since many forms of natural income (resource and service flows) are produced by terrestrial ecosystems and associated water bodies, it should be possible to estimate the area of land/water required to produce sustainably the quantity of any resource or ecological service used by a defined population at a given level of technology. The sum of such calculations for all significant categories of consumption would give us a conservative area-based estimate of the natural capital requirements for that population.

A simple mental exercise serves to illustrate the ecological reality behind this approach. Imagine what would happen to any modern human settlement or urban region, as defined by its political boundaries or the area of built-up land, if it were enclosed in a glass or plastic hemisphere completely closed to material flows. Clearly the city would cease to function and its inhabitants would perish within a few days. The population and economy contained by the capsule would have been cut off from both vital resources and essential waste sinks leaving it to starve and suffocate at the same time. In other words, the ecosystems contained within our imaginary human terrarium would have insufficient carrying capacity to service the ecological load imposed by the contained population.

This mental model illustrates the simple fact is that as a result of high population densities, the enormous increase in *per capita* energy and material consumption made possible by (and required by) technology, and universally increasing dependencies on trade, *the ecological locations of human settlements no longer coincide with their geographic locations.* Twentieth century cities and industrial regions are dependent for survival and growth on a vast and increasingly global hinterland of ecologically productive landscapes. It seems that in purely ecological terms, modern settlements have become the human equivalent of cattle feedlots!

Cities necessarily appropriate the ecological output and life support functions of distant regions all over the world through commercial trade and the natural biogeochemical cycles of energy and material. Indeed, the annual flows of natural income required by any defined population can be called its "appropriated carrying capacity. Since for every material flow there must be a corresponding land/ecosystem source or sink, the total area of land/water required to sustain these flows on a continuous basis is the true "ecological footprint" of the referent population on the Earth. (See Box 3 for definitions of these and related indicators.) Calculating its ecological footprint provides a rough measure of the natural capital requirements of any subject population for comparison with available supply.

"Footprinting" the Human Economy

Box 3: A Family of Area-based Sustainability Indicators

Appropriated Carrying Capacity - The biophysical resource flows and waste assimilation capacity appropriated per unit time from global totals by a defined economy or population.

Ecological Footprint - The corresponding area of productive land and aquatic ecosystems required to produce the resources used, and to assimilate the wastes produced, by a defined population at a specified material standard of living, wherever on Earth that land may be located.

Personal planetoid - The per capita ecological footprint (EF_p/N).

Fair Earthshare - the amount of ecologically productive land "available" per capita on Earth, currently about 1.5 hectares (1995). A fair seashare (ecologically productive ocean - coastal shelves upwellings and esturaries - divided by total population) is just over .5 ha.

Ecological Deficit - The level of resource consumption and waste discharge by a defined economy or population in excess of locally/regionally sustainable natural production and assimilative capacity (also, in spatial terms, the difference between that economy/population's ecological footprint and the georgraphic area it actually occupies)

Sustainability Gap - A measure of the decrease in consumption (or the increase in material and economic efficiency) required to eliminate the ecological deficit. (Can be applied on a regional or global scale.)

The first step in calculating the ecological footprint of a study population is to estimate the *per capita* land area appropriated (aa) for the production of each major consumption item 'i.' We do this by dividing average annual consumption of that item ['c,' in kg/capital] by its average annual productivity or yield ['p,' in kg/ha] per hectare:

$aa_i = c_i/p_i$

In practice, it is often only possible to estimate average *per capita* consumption by dividing aggregate consumption by the referent population size. Of course, many consumption items (e.g., clothing and furniture) embody several inputs and we have found it useful to estimate the a areas appropriated by each significant input separately. Ecological footprint calculations are therefore both more complicated and more interesting than appears from the basic concept. So far we have estimated the land requirements to produce 23 categories of consumer goods and services (Wackernagel & Rees, 1995).

We then compute the total *per capita* ecological footprint ('ef') by summing all the ecosystem areas appropriated by individual items in the annual shopping basket of consumption goods and services:

$$ef = \sum_{i=1}^{i=n} aa_i$$

Thus, the ecological footprint (EF_p) of a study population is the *per capita* footprint multiplied by population size (N): $EF_p = N(ef)$

We account for direct fossil energy consumption and the energy content of consumption items by estimating the area of carbon-sink forest that would be required to sequester the carbon dioxide emissions associated with burning fossil fuels ([carbon emissions/capital/[assimilation rate/hectare]), on the assumption that atmospheric stability is central to sustainability. (An alternative is to estimate the area of land required to produce the biomass energy equivalent [ethanol] of fossil energy consumption. This produces a larger energy footprint than the carbon assimilation method.)

Every effort is made to avoid double-counting in the case of multiple land uses and where there are data problems or significant uncertainty we err on the side of caution. Also, while we define the footprint comprehensively to include the land/water areas required for waste assimilation, our calculations to date do not account for waste emissions other than carbon dioxide. Accounting fully for this ecological function would add considerably to the ecosystem area appropriated by economic activity. Together these factors suggest that our ecological footprint calculations to date are more likely to be under-estimates than over-estimates.

Data from my home city, Vancouver, British Columbia, Canada, serve to illustrate application of the concept. Vancouver proper has a population (1991) of 472,000 and an area of 114 km^2 (11,400 hectares). However, the average Canadian requires over a hectare (ha) of crop and grazing land under current land management practices to produce his/her high meat protein diet and about .6 ha for wood and paper associated with various other consumption items. In addition, each "occupies" about .2 ha of ecologically degraded and built-over (e.g., urban) land. Canadians are also among the world's highest fossil energy consumers with an annual carbon emission rate of 4.2 tonnes carbon (15.4 tonnes CO2) *per capita* (data corrected for carbon content of trade goods). Therefore, at a carbon sequestering rate of 1.8 tonnes/ha/yr an additional 2.3 ha of middle-aged North temperate forest would be required as a continuous carbon sink to assimilate the average Canadian's carbon emissions (assuming the need to stabilize atmospheric carbon dioxide levels).

Considering only these data, the terrestrial "personal planetoid" of a typical Vancouverite approaches 4.2 ha, or almost three times his/her "fair Earthshare." [An additional .74 ha of continental shelf "seascape" is appropriated to produce the average Canadian's annual consumption of 24kg of fish.] On this basis, the 472,000 people living in Vancouver require, conservatively, 2.0 million ha of land for their exclusive use to maintain their current consumption patterns (assuming such land is being managed sustainably). However, the area of the city is only about 11,400 ha.

This means that the city population appropriates the productive output of a land area nearly 174 times larger than its political area to support its present consumer lifestyles. [The Vancouver Regional District (metropolitian area), with 1.6 million inhabitants and a land-base of 2930 km^2, has an ecological footprint of 6,720,000 ha, 23 times its geographic area.] While this result might seem extraordinary, other researchers have obtained similar results. Folke et al. (1994) report that the aggregate consumption of wood, paper, fiber, and food (including seafood) by the inhabitants of 29 cities in the Baltic Sea drainage basin appropriates an ecosystem area 200 times larger that the area of the cities themselves. (The latter study does not include energy land.)

Many whole developed countries have a similar overwhelming dependence on external ecoproductivity. The Netherlands (area: 33,920 sq km) serves to illustrate: We estimate that the people of Holland require a land area more than 14 to 15 times larger than their country to support current domestic consumption of food, forest products, and energy (Figure 2) (Rees & Wackernagel, 1994). The food footprint alone is more than 100,000 square kilometers, based on world average productivities. Indeed, Dutch government data suggest that the Netherlands appropriates 100,000 to 140,000 km^2 of agricultural land, mostly from the third world, for food production (including value-added food products produced in the

Netherlands for export) (RIVM, 1991, cited in Meadows et al. 1992). [Most of the imported "food" is fodder for domestic livestock. This is a sufficient "Second Law" explanation of the fact that animal manure represents one of the most pressing waste disposal problems confronting the Netherlands!] This "imported" land is five to seven times the area of Holland's domestic arable land.

It is worth remembering that the Netherlands, like Japan, is often held up as an economic success story and an example for the developing world to follow. Despite small size, few natural resources, and relatively large populations, both Holland and Japan enjoy high material standards and positive current account and trade balances as measured in monetary terms. However, our analysis of physical flows shows that these and most other so-called "advanced" economies are running massive, unaccounted, ecological deficits with the rest of the planet (Table 1). The last two columns in Table 1 represent low estimates of these *per capita* ecological deficits in a selection of developed countries. Even if their land were twice as productive as world averages, many European countries would still run a deficit more than three times larger than domestic natural income.

These data emphasize that all the countries listed, except for Canada, are over-populated in ecological terms -- they could not sustain themselves at current material standards if forced by changing circumstances to live on their remaining endowments of domestic natural capital. This is hardly a good model for the rest of the world to follow.

FIGURE2. The Ecological Footprint of the Netherlands

With an area of 33,920 square kilometers and a human population density of 440/km^2, the Netherlands depends on the ecological productivity (carrying capacity) of an area almost 15 times larger than the entire country.

Canada (large area, resource rich, small population) is one of the few developed countries that consumes less than its natural income domestically. However, Canada's natural capital stocks are being depleted by exports of energy, forest, fisheries, agricultural products, etc. In short, Canada's apparent ecological surpluses are being incorporated in part by trade into the ecological footprints -- and deficits -- of other countries, particularly those of the United States and Japan.

Sustaining Development with Phantom Planets?

	Ecologically Productive Land (In Hectares)	Population (1995)	Ecologically Productive Land *Per Capita* (In Hectares)	National Ecological Deficit *Per Capita*	
				(In Hectares)	(In % Available)
Country	a	b	c = a/b	d = Footpr.-c	e = d/c
Countries with 2-3 ha Footprints				*Assuming a 2 Hectare Footprint*	
Japan	30,340,000	125,000,000	0.24	1.76	730%
Korea	8,669,000	45,000,000	0.19	1.81	950%
Countries with 3-4 ha Footprints				*Assuming a 3 Hectare Footprint*	
Austria	6,740,000	7,900,000	0.85	2.15	250%
Belgium	1,987,000	10,000,000	0.20	2.80	1,400%
Denmark	3,270,000	5,200,000	0.62	2.38	380%
France	45,385,000	57,800,000	0.78	2.22	280%
Germany	27,734,000	81,300,000	0.34	2.66	780%
Netherlands	2,300,000	15,500,000	0.15	2.85	1,900%
Switzerland	3,073,000	7,000,000	0.44	2.56	580%
Countries with 4-5 ha Footprints				*Assuming 4.3 (Can) and 5.1 (US) Hectare*	
Canada	433,000,000	28,500,000	15.19	(10.89)	(250%)
United States	725,643,000	258,000,000	2.81	2.28	80%

Ecological deficits are a measure of the entropic load and resultant "disordering" being imposed on the ecosphere by so-called advanced countries as the unaccounted cost of maintaining and further expanding their wealthy consumer economies. This massive entropic imbalance invokes what might be called the first axiom of ecological footprint analysis: On a finite planet, not all countries or regions can be net importers of carrying capacity. This, in turn, has serious implications for global development trends.

The current objective of international development is to raise the developing world to present first world material standards. To achieve this objective, the Brundtland Commission argued for "more rapid economic growth in both industrial and developing countries" and suggested that "a five to ten fold increase in world industrial output can be anticipated by the time world population stabilizes some time in the next century" (WCED, 1987).

Let us examine this prospect using ecological footprint analysis. If just the present world population of 5.8 billion people were to live at current North American ecological standards (say 4.5 ha/person), a reasonable first approximation of the total productive land requirement would be 26 billion ha (assuming present technology). However, there are only just over 13 billion ha of land on Earth, of which only 8.8 billion are ecologically productive cropland, pasture, or forest (1.5 ha/person). In short, we would need an additional two planet Earths to accommodate the increased ecological load of people alive today. If the population were to stabilize at between 10 and 11 billion sometime in the next century, five additional Earths would be needed, all else being equal -- and this just to maintain the present rate of ecological decline (Rees & Wackernagel, 1994).

While this may seem to be an astonishing result, empirical evidence suggests that five phantom planets is, in fact, a considerable underestimate (keep in mind that our footprint estimates are conservative). Global and regional-scale ecological change in the form of atmospheric change, ozone depletion, soil loss, ground water depletion, deforestation, fisheries collapse, loss of biodiversity, etc., is accelerating. This is direct evidence that aggregate consumption exceeds natural income in certain critical categories and that the carrying capacity of this one Earth is being steadily eroded. [We should remember Liebigs "Law of the Minimum" in this context. The productivity and ultimately the survival of any complex system dependent on numerous essential inputs or sinks is limited by that single variable in least supply.] In short, the ecological footprint of the present world population/ economy already exceeds the total productive area (or ecological space) available on Earth.

This situation is, of course, largely attributable to consumption by that wealthy quarter of the world's population who use 75% of global resources. The WCED's "five- to ten-fold increase in industrial output" was deemed necessary to address this obvious inequity while accommodating a much larger population. However, since the world is already ecologically full, sustainable growth on this scale using present technology would require at [least] five to ten additional planets.

ADDRESSING THE DOUBLE-BIND OF SUSTAINABILITY

Humankind now seems to be the victim of a global "catch-22" of its own making. More material growth, at least in the poor countries, seems essential for socioeconomic sustainability, yet any global increase in material throughput is ecologically unsustainable. What does ecological footprint analysis have to say about this double bind and how we might get out of it? One can draw several conclusions from the above analysis that address one or both sides of the dilemma:

- The wealthy already consume on average three times their fair share of sustainable global output. Since additional material growth in rich countries would appropriate additional carrying capacity further reducing the ecological space available to poor countries, it is both ecologically dangerous and morally questionable. To the extent we can create room for growth, it should be allocated to the third world.
- Confidence in the ability of unregulated trade and technology to overcome ecological limits on material growth cannot be justified. Indeed, it is arguable that under prevailing assumptions, expanding trade and dominant technologies are allowing humanity dangerously to overshoot long-term global carrying capacity.
- Trade has been a major contributor to increasing gross world product in recent years. However: a) trade is one of the mechanisms by which the rich appropriate carrying capacity and increase their own ecological footprints, and b) to the extent that trade increases total human load on the ecosphere and accelerates the depletion of natural capital, it reduces the ecological safety net for all and brings us closer to global limits. Global terms of trade must therefore be reexamined to ensure that it is equitable, socially constructive, and confined to true ecological surpluses. At the very least/ prices must reflect ecological externalities and the benefits of growth from trade should flow to those who need them most (see Rees, 1 994b).
- On a finite planet, ecological trade is a zero-sum game -- there can be no net importation of carrying capacity for the world as a whole. Ecological footprint analysis provides a useful tool for the development of regional ecological (i.e., physical) accounts. These

would assist countries tries or (bio-) regions to compute their true ecological loads on the ecosphere and to monitor their ecological/thermodynamic trade balances. Such accounts would also enable the world community to ensure that aggregate global flows do not exceed sustainable natural income (global carrying capacity).

- Urbanization, globalization, and trade all reduce the negative feedback on local populations from unsustainable land and resource management practices. (For example, trade enables us to discount the value of local natural capital and blinds us to the negative consequences of our over-consumption which often accrue in distant export regions.) This provides a further argument to shift the emphasis in development from global economic integration and inter-regional dependency toward intra-regional ecological balance and relative self-reliance. (If all regions were in ecological steady-state the aggregate effect would be global stability.) This position is compatible with Daly's and Goodland's (1993) recommended alternative "default position" on international trade, that we should strive "to reduce rather than increase the entanglement between nations."
- Ecological footprint analysis supports the argument that to be sustainable, economic growth must be much less material and energy intensive than at present (see, for example, Pearce, 1994). It therefore supports the case for ecological tax reform in aid of resource conservation (von Weizsacker, 1994). For example, depletion taxes and marketable quotas on natural capital inputs to the economy would: a) stimulate the search for more materially and energy efficient technologies; b) preempt any resultant cost savings, thereby preventing the economic benefits of efficiency gains from being redirected to additional or alternative forms of consumption, and; c) generate an investment fund that could be used to rehabilitate important forms of self-producing natural capital (Rees, 1 994a).
- Ecological footprint analysis provides a measure of both individual countries' ecological deficits and the global sustainability gap (Box 3). The latter in particular is a measure of the extent to which the human economy must be dematerialized in order to fit within global carrying capacity. The present and related analyses confirm that a "factor-10" reduction in the material and energy intensity per unit of economic service, as suggested by researchers at the Wuppertal Institute in Germany (Schmidt-Bleak, 1993a;b), is a reasonable if daunting goal. ["Reasonable" because a reduction in throughput of

this magnitude seems necessary, "daunting" because a reduction of this magnitude through material efficiency alone seems impossible, at least within in the next few decades. Sustainability may require that competitive individualism and the consumer lifestyle give way to cooperative mutualism and an economy of sufficiency.]

CONCLUSION

Appropriated carrying capacity and ecological footprint analysis provide several informative area-based indicators of sustainability. Unfortunately, these same indicators reveal that we are presently falling distressingly short of achieving that elusive goal. Such findings do not, however, support a counsel of despair. Rather, ecological footprint analysis raises a cautionary signal, suggests a variety of concrete sustainability guidelines, and supports a broadly-based program of reforms that could redirect us in the direction we all seem to want to go. In short, to the extent that the assumptions and prescriptions of this approach are a better reflection of material reality that those of mainstream models, the present analysis is a good news story. The bad news is that most of the world seems committed as never before to the well-worn expansionist path.

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