ELSEVIER

URBAN ECOLOGICAL FOOTPRINTS: WHY CITIES CANNOT BE SUSTAINABLE—AND WHY THEY ARE A KEY TO SUSTAINABILITY

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Introduction: Transforming Human Ecology

It is sometimes said that the industrial revolution stimulated the greatest human migration in history. This migration swept first through Australia, Europe, and North America and is still in the process of transforming Asia and the rest of the world. We refer, of course, to the mass movement of people from farms and rural villages to cities everywhere. The seeming abandonment of the countryside is creating an urban world—75% or more of the people in so-called industrialized countries now live in towns and cities, and half of humanity will be city dwellers by the end of the century.

Although usually seen as an economic or demographic phenomenon, urbanization also represents a human ecological transformation. Understanding the dramatic shift in human spatial and material relationships with the rest of nature is a key to sustainability. Our primary purpose, therefore, is to describe a novel approach to assessing the ecological role of cities and to estimate the scale of the impact they are having on the ecosphere. The analysis shows, that as nodes of energy and material consumption, cities are causally linked to accelerating global ecological decline and are not by themselves sustainable. At the same time, cities and their inhabitants can play a major role in helping to achieve global sustainability.

Starting Premise

Our analysis starts from the premise that the late 20th century marks a nontrivial turning point in the ecological history of human civilization. For the first time, since the dawn of agriculture and the possibility of geographically fixed settlements 12,000 years ago, the aggregate scale of

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human economic activity is capable of altering global biophysical systems and processes in ways that jeopardize both global ecological stability and geopolitical security.

Examples abound—more artificial nitrate is now applied to the world's croplands than is fixed from the atmosphere by microbial activity and other natural processes combined (Vitousek 1994); the rate of human-induced species extinctions is approaching the extinction rates driven by "the great natural catastrophes at the end of the Paleozoic and Mesozoic era—in other words, [they are] the most extreme in the past 65 million years" (Wilson 1988); "residuals" discharged by industrial economies are depleting stratospheric ozone and altering the preindustrial composition of the atmosphere, and both these trends contribute to (among other things) the threat of climate change, itself the most potent popular symbol of widespread ecological dysfunction. Perhaps most significant from an ecosystems perspective is the evidence that human beings, one species among millions, now consume, divert, or otherwise appropriate for their own purposes 40% of the product of net terrestrial photosynthesis (Vitousek et al. 1986) and up to 35% of primary production from coastal shelves and upwellings, the most productive marine habitats (Pauly and Christensen 1995). Were it not for the fact that fish catches are in decline from stock depletion, both these proportions would be steadily increasing.

The empirical evidence suggests that the human economy is overwhelming the ecosphere from within. This unprecedented situation has prompted some development analysts to argue that the world has reached an historic turning point, a point at which the world must shift from the assumptions of "empty-world" to those of "full-world" economics (Daly 1991).

Carrying Capacity as Maximum Human "Load"

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

The notion that humanity may be up against a new kind of limit has rekindled the Malthusian debate about human carrying capacity (see, for example, *Ecological Economics*. November 1995. 15(2)). 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 we humans seem to be capable of continuously increasing the human carrying capacity of Earth by eliminating competing species, by importing locally scarce resources, and through technology, conventional economists and planners generally reject the concept as applied to people. As Herman Daly critically observes, the prevailing vision assumes a world in which the economy floats free of any environmental constraints. This is a world "in which carrying capacity is infinitely expandable"—and therefore irrelevant (Daly 1986).

By contrast, we argue that the economy is an inextricably embedded subsystem of the ecosphere. Despite our technological and economic achievements, humankind remains in a state of "obligate dependence" on the productivity and life support services of the ecosphere (Rees 1990). The trappings of technology and culture aside, human beings remain biophysical entities. From a trophic-dynamic perspective, the relationship of humankind to the rest of the ecosphere is similar to those of thousands of other consumer species with which we share the planet. We depend for both basic needs and the production of cultural 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 thermodynamic terms, all our toys and tools (the human-made "capital" of economists) are "the exosomatic equivalent of organs" and, like bodily organs, require continuous flows of energy and material to and from "the environment" for their production and operation (Sterrer 1993). Carrying capacity therefore remains central to sustainabilty.

Because of this continuing functional dependence on ecological processes, some analysts have stopped thinking of natural resources as mere "free goods of nature." Ecological economists now regard the species, ecosystems, and other biophysical entities that produce required resource flows as forms of "natural capital" and the flows themselves as types of essential "natural income" (Pearce et al. 1989; Victor 1991; Costanza and Daly 1992). This capital theory approach provides a valuable insight into the meaning of sustainability—no development path is sustainable if it depends on the continuous depletion of productive capital. From this perspective, society can be said to be economically sustainable only if it passes on an undiminished per capita stock of essential capital from one generation to the next (Pearce 1994; Solow 1986; Victor 1991).[1]

In the present context, the most relevant interpretation of this "constant capital stocks" criterion is as follows:

> Each generation should inherit an adequate per capita stock of natural capital assets no less than the stock of such assets inherited by the previous generation.[2]

[1] We acknowledge that the heterogeneity and interdependence of various forms of natural capital make this criterion difficult to operationalize. For example, ecosystems are constantly developing and evolving, and there are many combinations of natural capital stocks that could be sustainable. However, this does not detract from the general principle that for each potentially viable combination, sustainability requires some minimal individual and aggregate quantity of these component stocks.

[2] "Natural assets" encompasses not only material resources (e.g., petroleum, the ozone layer, forests, soils) but also process resources (e.g., waste assimilation, photosynthesis, soils formation). It includes renewable as well as exhaustible forms of natural capital (Costanza and Daly 1992). Our primary interest here is in essential renewable and replenishable forms. Note that the depletion of nonrenewables could be compensated for through investment in renewable natural capital.

Because of its emphasis on maintaining natural (biophysical) capital intact, the foregoing is a "strong sustainability" criterion (Daly 1990). The prevailing alternative interpretation would maintain a constant *aggregate* stock of humanmade and natural assets. This latter version reflects the neoclassical premise that manufactured capital can substitute for natural capital and is referred to as "weak sustainability" (Daly 1990; Pearce and Atkinson 1993; Victor et al. 1995).

We prefer strong sustainability because it best reflects known ecological principles and the *multifunctionality* of biological resources "including their role as life support systems" (Pearce et al. 1989). Most importantly, strong sustainability recognizes that manufactured and natural capital "are really not substitutes but complements in most production functions"(Daly 1990). In other words, many forms of biophysical capital perform critical functions that cannot be replaced by technology. For sustainability, a critical minimal amount of such capital must be conserved intact and in place. This will ensure that the ecosystems upon which humans depend remain capable of continuous self-organization and production.[3]

In this light, the fundamental question for ecological sustainability is whether remaining *natural* capital stocks (including other species populations and ecosystems) are adequate to provide the resources consumed and assimilate the wastes produced by the anticipated human population into the next century, while simultaneously maintaining the general life support functions of the ecosphere (Rees 1996). In short, is there adequate human carrying capacity? At present, of course, both the human population and average consumption are increasing, whereas the total area of productive land and stocks of natural capital are fixed or in decline. In this light, we argue that shrinking carrying capacity may soon become the single most important issue confronting humanity.

The issue becomes clearer if we define human carrying capacity not as a maximum population but rather as the maximum (entropic) "load" that can safely be imposed on the environment by people (Catton 1986). Human load is clearly a function not only of population but also of average per capita consumption. Significantly, the latter is increasing even more rapidly than the former due (ironically) to expanding trade, advancing technology, and rising incomes. 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 per capita. By 1980, this had increased almost 20-fold to 210,000 kcal/day (Catton 1986). As a result of such trends, *load*

[3]The only ecologically meaningful interpretation of constant stocks is in terms of constant *physical* stocks as is implied here. However, some economists interpret "constant capital stock" to mean constant monetary value of stocks or constant resource income over time (for a variation on this theme, see Pearce and Atkinson 1993). These interpretations allow declining physical stocks as value and market prices rise over time.

pressure relative to carrying capacity is rising much faster than is implied by mere population increases.

Ecological Footprints: Measuring Human Load

By inverting the standard carrying capacity ratio and extending the concept of load, we have developed a powerful tool for assessing human carrying capacity. Rather than asking what population a particular region can support sustainably, the critical 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 and Wackernagel 1994). Most importantly, this approach overcomes any objection to the concept of human carrying capacity based on trade and technological factors. In the language of the previous section, we ask how much of the Earth's surface is appropriated to support the "load" imposed by a referent population, whatever its dependence on trade or its level of technological sophistication.

Since most forms of natural income (resource and service flows) are produced by terrestrial ecosystems and associated aquatic ones,[4] 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 or economy at a given level of technology. The sum of such calculations for all significant categories of consumption would provide a conservative area-based estimate of the natural capital requirements for that population or economy. We call this area the population's true "ecological footprint."

A simple two-step mental experiment serves to illustrate the ecological principles behind this approach. First, imagine what would happen to any modern city as defined by its political boundaries if it were enclosed in a glass or plastic hemisphere completely closed to material flows. This means that the human system so contained would be able to depend only on whatever remnant ecosystems were initially trapped within the hemisphere.

It is obvious to most people that 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—and any real world city—would have insufficient carrying capacity to service the ecological load imposed by the contained population.

The second step pushes us to contemplate urban ecological reality in more concrete terms. Let's assume that our experimental city is surrounded by a diverse landscape in which cropland and pasture, forests and watersheds—all the different ecologically productive land-types—are repre-

[4] Exceptions include the ozone layer and the hydrologic cycle both of which are purely physical forms of natural capital.

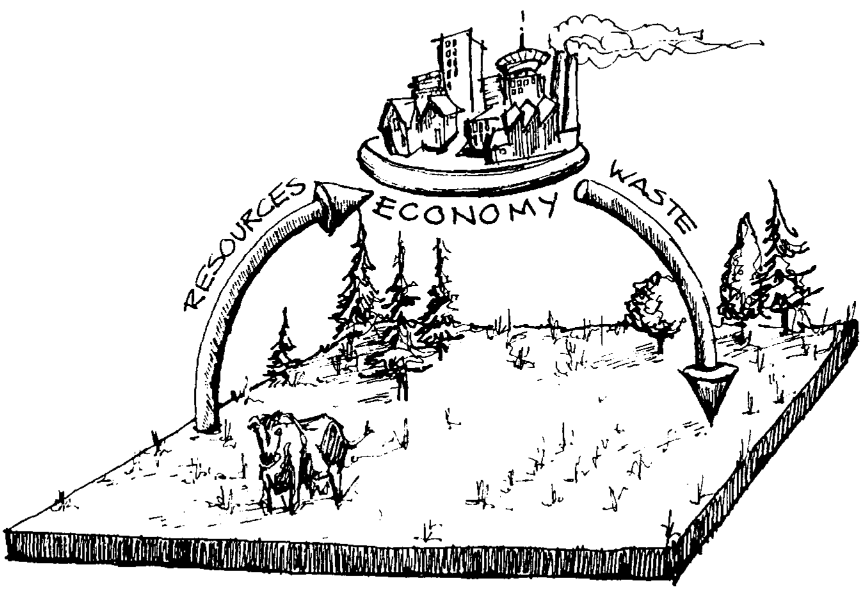

FIGURE 1. What is an ecological footprint? Think of a city as having an "industrial metabolism." In this respect, it can be compared to a large animal grazing in its pasture. Just like the beast, the city consumes resources and all this energy and matter eventually passes through to the environment again. Thus, the footprint question becomes: "How large a pasture is necessary to support that city indefinitely—to produce all its 'feed' and to assimilate all its wastes sustainably" (*Source:* Wackernagel and Rees 1995).

sented in proportion to their actual abundance on the Earth and that adequate fossil energy is available to support current levels of consumption using prevailing technology. Let's also assume our imaginary glass enclosure is elastically expandable. The question now becomes: How large would the hemisphere have to grow before the city at its center could sustain itself indefinitely and exclusively on the land and water ecosystems and the energy resources contained within the capsule?[5] In other words, what is the total area of different ecosystem types needed continuously to supply the material demands of the people of our city as they go about their daily activities (Figure 1)?

Answering this question would provide an estimate of the de facto ecological footprint of the city. Formally defined, the ecological footprint (EF) is the total area of productive land and water required continuously to produce all the resources consumed and to assimilate all the wastes pro-

[5]For simplicity's sake, the question as posed does not include the ecologically productive land area needed to support other species independent of any service they may provide to humans.

duced, by a defined population, wherever on Earth that land is located. As noted, the ecological footprint is a land-based surrogate measure of the population's demands on natural capital.

Method in Brief

The basic calculations for ecological footprint estimates are conceptually simple. First we estimate the annual *per capita* consumption of major consumption items from aggregate regional or national data by dividing total consumption by population size. Much of the data needed for preliminary assessments is readily available from national statistical tables on, for example, energy, food, or forest products production and consumption. For many categories, national statistics provide both production and trade figures from which trade-corrected consumption can be assessed:

trade-corrected consumption = production + imports − exports

The next step is to estimate the land area appropriated per capita for the production of each consumption item by dividing average annual consumption of that item by its average annual productivity or yield.[6] Box 1

BOX 1. Productive Forest Area Required for Paper Production

Question: How much productive forest is dedicated to providing pulp-wood for the paper used by the average Canadian? ("Paper" includes food wrappings, other packaging, reading material and construction paper.)

Answer: Each Canadian consumes about 244 kilograms of paper products each year. In addition to the recycled paper that enters the process, the production of each metric ton of paper in Canada currently requires 1.8 m^3 of wood. For Ecological Footprint analyses an average wood productivity of 2.3 [m^3/ha/yr] is assumed. Therefore, the average Canadian requires...

$$\frac{244\ [\text{kg/cap/yr}] \times 1.8\ [\text{m}^3/\text{t}]}{1{,}000\ [\text{kg/t}] \times 2.3\ [\text{m}^3/\text{ha/yr}]} = 0.19\ [\text{ha/capita}]\ \text{of forest in continuous production of paper.}$$

provides a sample calculation showing the land requirement for paper consumption by the average Canadian. A similar calculation can be made for the land required to assimilate certain individual waste products such as carbon dioxide.

[6] We generally use world average productivities for this step in ecological footprint calculations. This is a reasonable first approximation, particularly for trade-dependent urban regions importing ecological goods and services from all over the world. Local productivities are necessary, however, to calculate actual local/regional carrying capacity.

We then compile the total average per capita ecological footprint (ef) by summing all the ecosystem areas appropriated by an individual to fill his/her annual shopping basket of consumption goods and services.

Finally we obtain the ecological footprint (EF_P) of the study population by multiplying the average per capita footprint by population size (N): Thus, $EF_P = N \times ef$.

Our EF equation is structually similar to the more familiar representation of human environmental impact (I) as a product of population (P), affluence (A), and technology (T), I = PAT (Ehrlich and Holdren 1971; Holdren and Ehrlich 1974). The ecological footprint is, in fact, a measure of population impact expressed in terms of appropriated land area. The size of the per capita footprint will of course, reflect the affluence (material consumption) and technological sophistication of the subject population.

So far our EF calculations are based on five major categories of consumption—food, housing, transportation, consumer goods and services—and on eight major land-use categories. However, we have examined only one class of waste flow in detail. We account for carbon dioxide emissions from fossil energy consumption by estimating the area of average carbon-sink forest that would be required to sequester them [carbon emissions/capita]/[carbon assimilation/hectare]), on the assumption that atmospheric stability is a prerequisite of sustainability. (Ours is a relatively conservative approach. An alternative is to estimate the area of land required to produce the biomass energy equivalent [ethanol] of fossil energy consumption. Because of thermodynamic losses, this produces a much larger energy footprint than the carbon assimilation method.) Full details of EF calculation procedures and more examples can be found in Rees and Wackernagel 1994; Wackernagel and Rees 1995; and Rees 1996.

Strengths and Limitations of Footprint Analysis

The major strength of ecological footprint analysis is its conceptual simplicity. Our method provides an intuitive and visually graphic tool for communicating one of the most important dimensions of the sustainability dilemma. It aggregates the ecological flows associated with consumption and translates them into appropriated land area, an indicator that anyone can understand. The ecological footprint of any defined population can then be compared with the available supply of productive land. Individuals can contrast their personal footprints with their ecological "fair Earthshares," national footprints can be compared to domestic territories, and the aggregate human footprint can be compared to the productive capacity of the entire planet.

In cases where the ecological footprint is significantly larger than a secure supply of productive land, the difference represents a "sustainability gap" and "ecological deficit" (Rees 1996). This is the amount by which consumption (or the measurable impact of consumption) must be reduced for long-term ecological sustainability. Thus, unlike ordinary measures of total resource use, ecological footprint analysis provides secondary indices that can be used as policy targets. The question then becomes: How large is our ecological deficit and what must be done to reduce it? (We should point out that humanity's ecological deficit may be far more important the fiscal deficit, yet the former is totally ignored in the current frenzy to reduce the latter in many countries.)

Although acknowledging its power to communicate a fundamental message, some commentators have suggested that the footprint concept is too simplistic. For example, the model is static, whereas both nature and the economy are dynamic systems. Ecological footprinting therefore cannot directly take into account such things as technological change or the adaptability of social systems.

It is true, of course, that footprint analysis is not dynamic modeling and has no predictive capability. However, prediction was never our intent. Ecological footprinting acts, in effect, as an ecological camera—each analysis provides a snapshot of our current demands on nature, a portrait of how things stand *right now* under prevailing technology and social values. We believe that this in itself is an important contribution. We show that humanity has exceeded carrying capacity and that some people contribute significantly more to this ecological "overshoot" than do others. Ecological footprinting also estimates how much we have to reduce our consumption, improve our technology, or change our behavior to achieve sustainability.

Moreover, if used in a time-series study (repeated analytic "snap-shots" over years or decades) ecological footprinting can help monitor progress toward closing the sustainability gap as new technlogies are introduced and consumer behavior changes. (After all, even a motion picture is a series of snap-shots.) Footprint analysis can also be used in static simulation studies to test, for example, the effect of alternative technologies or settlement patterns on the size of a population's ecological footprint (see Walker 1995, for an example). To reiterate, ecological footprint analysis is not a window on the future, but rather a way to help assess both current reality and alternative "what if" scenarios on the road to sustainability.

A more substantive criticism of ecological footprinting is that it ignores many other factors at the heart of sustainability. It is certainly true that the ecological footprint does not tell the entire sustainability story—indeed, any single index can be misleading (consider the problems with GDP!). In fact, our calculations to date do not even tell the whole *consumption* story. Only major categories of consumption have been included, and we are only beginning to examine the land area implications of waste discharges other than carbon dioxide. This means that our current footprint calculations are almost certainly significant *underestimates* of actual ecosystem appropriations and that improvements in the basic calculations will produce considerably larger footprint estimates. In short, improvements that increase the scope of our analyses will add to our sense of urgency but not necessarily shift the direction of needed policy change.

More important, *ecological* footprinting is precisely that—it provides an index of biophysical impacts. It therefore tells us little about the sociopolitical dimensions of the global change crisis. Of equal relevance to achieving sustainability are considerations of political and economic power, the responsiveness of the political process to the ecological imperative, and chronic distributional inequity which is actually worsening (both within rich countries and between North and South) as the market economy becomes an increasingly global affair. In fact, our current approach does not even account for myriad indirect effects of production/consumption such as the disruption of traditional livelihoods and damage to public health, which are often the most interesting local impacts of expanding economic activity on the environment. As use of the concept spreads, however, the term "footprint" is increasingly being used to encompass the *overall* impacts of high-income economies on the developing world (or of cities on the countryside) (see IIED 1995).

None of these limitations detracts from the fundamental message of ecological footprint analysis—that whatever the distribution of power or wealth, society will ultimately have to deal with the growing global ecological debt.[7] Our original objective in advancing the ecological footprint concept was to bolster our critique of the prevailing development paradigm and to force the international development debate beyond its focus on GDP growth to include ecological reality. This much seems to have been achieved. It is therefore gratifying that adherents to the ecological footprint concept are now extending it to claim even more of the conceptual jousting grounds in the quest for more holistic approaches to sustainability. The following section shows the footprint model at work.

Ecological Footprints of Modern Cities and "Developed" Regions

Canada is one of the world's wealthiest countries. Its citizens enjoy very high material standards by any measure. Indeed, ecological footprint analysis shows that the total land required to support present consumption levels by the average Canadian is at least 4.3 hectares, including 2.3 hectares for carbon dioxide assimilation alone (Figure 2) (Wackernagel and Rees 1995). Thus, the per capita ecological footprint of Canadians (their average "personal planetoid") is almost three times their "fair Earthshare" of 1.5 hectares.[8]

[7]Naturally, the objective would be to achieve this fairly and equitably with a minimum of civil and geopolitical strife.

[8]There are fewer than 8.9 billion hectares of ecologically productive land on Earth (including those areas that should be left untouched to preserve biodiversity). If this were allocated evenly among the 1995 human population of 5.8 billion, each person would receive 1.5 hectares.

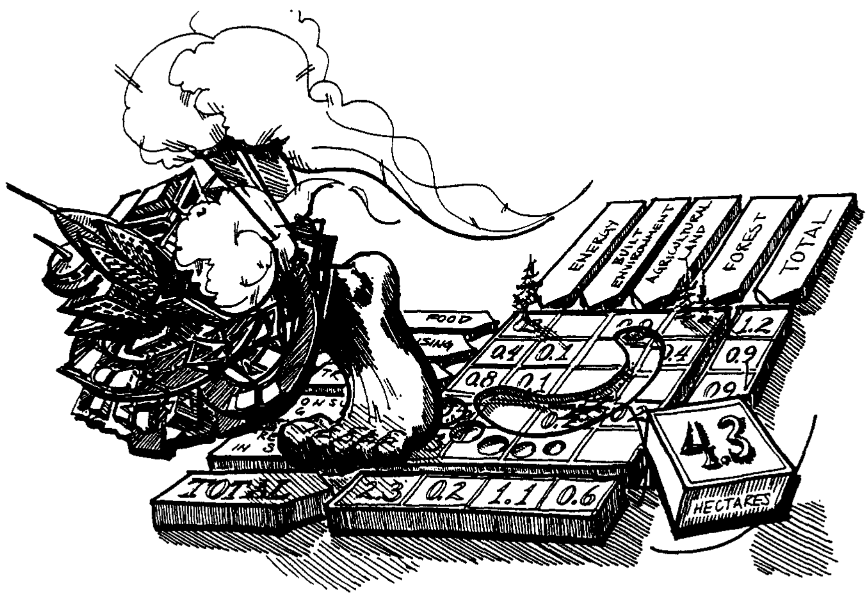

FIGURE 2. The high-income footprint. The ecological footprint of the average Canadian spans several land/ecosystem types and measures over 4 hectares (*Source:* Wackernagel and Rees 1995).

Let's apply this result to a densely populated high-income region, the Lower Fraser Basin in the Province of British Columbia. Within this area, the city of Vancouver had a 1991 population of 472,000 and an area of 114 km^2 (11,400 hectares). Assuming a per capita land consumption rate of 4.3 hectares, the 472,000 people living in Vancouver require, conservatively, 2 million ha of land for their exclusive use to maintain their current consumption patterns (assuming such land is being managed sustainably). This means that the city population appropriates the productive output of a land area *nearly 180 times larger than its political area* to support its present consumer lifestyle.

We can also estimate the "marine footprint" of the city's population based on fish consumption. Available data suggest a maximum sustainable yield from the oceans of about 100 million tons of fish per year. First we divide the global fish-catch by total productive ocean area. About 96% of the world's fish catch is produced in shallow coastal and continental shelf areas that constitute only 8.2 % of the world's oceans (about 29.7 million square kilometers). Average annual production is therefore about 32.3 kg of fish per productive hectare (0.03 hectares per kilogram of fish). Since Canadians consume an average of 23.4 kg of marine fish annually (including discards?), their marine footprint is about 0.7 ha each. If we add this per

TABLE 1. Estimated Ecological Footprints of Vancouver and The Lower Fraser Basin (terrestrial component only)

Geographic Unit	Population	Land Area (ha)	Ecol. Ftprnt (ha)	Overshoot Factor
Vancouver City	472,000	11,400	2,029,600	178.0
L. Fraser Basin	1,780,000	555,000	7,654,000	13.8

capita marine footprint to the terrestrial footprint, the total area of Earth needed to support Vancouver's population is 2.36 million hectares (5.83 million acres) or more than 200 times the geographic area of the city.

Although these findings might seem extraordinary to the uninitiated, other researchers have obtained similar results for other modern cities. Using our methods, British researchers have estimated London's ecological footprint for food, forest products, and carbon assimilation to be 120 times the surface area of the city proper (IIED 1995). 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. (Although this study includes a marine component for seafood production, it has no energy land component.)

Extending our Canadian example to the entire Lower Fraser Basin (population = 1.78 million) reveals that even though only 18% of the region is dominated by urban land use (i.e., most of the area is rural agricultural or forested land), consumption by its human population "appropriates" through trade and biogeochemical flows the ecological output and services of a land area about 14 times larger than the home region of 5,550 square kilometres. In other words, the people of the Lower Fraser Basin, in enjoying their consumer lifestyles, have "overshot" the terrestrial carrying capacity of their geographic home territory by a factor of 14. Put another way, analysis of the ecological load imposed by the regional population shows that at prevailing material standards, *at least* 90% of the ecosystem area needed to support the Lower Fraser Basin actually lies outside the region itself. These results are summarized in Table 1.

It seems that the "sustainability" of the Lower Fraser Basin of British Columbia depends on imports of ecologically significant goods and services whose production requires an area elsewhere on Earth vastly larger than the internal area of the region itself. In effect, however healthy the region's economy appears to be in monetary terms, the Lower Fraser Basin is running a massive "ecological deficit" with the rest of Canada and the world.

Global Context

This situation is typical of high-income regions and even for some entire countries. Most highly urbanized industrial countries run an ecological

TABLE 2. Ecological Deficits of Urban-Industrial Countries[a]

Country	Ecologically Productive land (in hectares) *a*	Population (1995) *b*	Ecol. Productive Land *per capita* (in hectares) *c = a/b*	National Ecological Deficit per capita (in hectares) *d = Ftprint − c*	(in % available) *e = d/c*
				assuming a 2.5 hectare Footprint	
Japan	30,417,000	125,000,000	0.24	2.26	940%
countries with 3–4 ha Footprints				*assuming a 3 hectare Footprint*	
Belgium	1,987,000	10,000,000	0.20	2.80	1,400%
Britain	20,360,000	58,000,000	0.35	2.65	760%
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 Can 4.3 and US 5.1 hectare Footprints*	
Canada	434,477,000	28,500,000	15.24	(10.94)	(250%)
United States	725,643,000	258,000,000	2.81	2.29	80%

Source: Abstracted and revised from Wackernagel and Rees (1995). Ecologically productive land means cropland, permanent pasture, forests and woodlands as compiled by the World Resources Institute (1992). Semi-arid grasslands, deserts, ice-fields, etc., are not included.

[a] Footprints estimated from studies by Ingo Neumann of Trier University, Germany; Dieter Zürcher from Infras Consulting, Switzerland; and our own analysis using World Resources Institute (1992) data.

deficit about an order of magnitude larger than the sustainable natural income generated by the ecologically productive land within their political territories (Table 2). The last two columns of Table 2 represent low estimates of these per capita deficits.

These data throw new light on current world development models. For example, Japan and the Netherlands both boast positive trade and current account balances measured in monetary terms, and their populations are among the most prosperous on earth. Densely populated yet relatively resource- (natural capital) poor, these countries are regarded as stellar economic successes and held up as models for emulation by the developing world. At the same time, we estimate that Japan has a 2.5 hectare/capita, and the Netherlands a 3.3 hectare/capita ecological footprint which gives these countries national ecological footprints about eight and 15 times larger than their total domestic territories respectively. (Note that Table 2 is based on areas of ecologically productive land only.) The marked contrast between the physical and monetary accounts of such economic success stories raises difficult developmental questions in a world whose principal strategy for sustainability is economic growth. Global sustainability cannot be (ecological) deficit-financed; simple physics dictates that *not all countries or regions can be net importers of biophysical capacity.*

It is worth noting in this context that Canada is one of the few high (money) income countries that consumes less than its natural income domestically (Table 2). Low in population and rich in natural resources, this country has yet to exceed domestic carrying capacity. However, Canada's natural capital stocks are being depleted by exports of energy, forest, fish, agricultural products, etc., to the rest of the world. In short, the apparent surpluses in Canada are being incorporated by trade into the ecological footprints of other countries, particularly that of the United States (although the entire Canadian surplus would be insufficient to satisfy the US deficit!). How should such biophysical realities be reflected in local and global strategies for ecologically sustainable socioeconomic development?

Discussion and Conclusions: Cities and Sustainability

Ecological footprint analysis illustrates the fact that as a result of 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 high-density human settlements no longer coincide with their geographic locations.* Twentieth-century cities and industrial regions for survival and growth depend on a vast and increasingly global hinterland of ecologically productive landscapes. Cities necessarily "appropriate" the ecological output and life support functions of distant regions all over the world through commercial trade and natural biogeochemical cycles. Perhaps the most important insight from this result is that *no city or urban region can achieve sustainability on its own.* Regardless of local land use and environmental policies, a prerequisite for sustainable cities is sustainable use of the global hinterland.

The other side of this dependency coin is the impact urban populations and cities have on rural environments and the ecosphere generally. Combined with rising material standards and the spread of consumerism, the mass migration of humans to the cities in this century has turned urban industrial regions into nodes of intense consumption. The wealthier the city and the more connected to the rest of the world, the greater the load it is able to impose on the ecosphere through trade and other forms of economic leverage. Seen in this light and contrary to popular wisdom, the seeming depopulation of many rural areas does not mean they are being abandoned in any ecofunctional sense. Whereas most of the people may have moved elsewhere, rural lands and ecosystem functions are being exploited more intensely than ever in the service of newly urbanized human populations.

Cities and the Entropy Law

As noted, the populations of "advanced" high-income countries are 75% or more urban and estimates suggest that over 50% of the entire human population will be living in urban areas by the end of the century. If we accept the Brundtland Commission's estimate that the wealthy quarter of the world's population consume over three-quarters of the world's resources (and therefore produce at least 75% of the wastes), then the populations of wealthy cities are responsible for about 60% of current levels of resource depletion and pollution. The global total contribution from cities is probably 70% or more.

In effect, cities have become entropic black holes drawing in energy and matter from all over the ecosphere (and returning all of it in degraded form back to the ecosphere). This relationship is an inevitable expression of the Second Law of Thermodynamics. The second law normally states that the entropy of any isolated system increases. That is, available energy spontaneously dissipates, gradients disappear, and the system becomes increasingly unstructured and disordered in a inexorable slide toward thermodynamic equilibrium. This is a state in which "nothing happens or can happen" (Ayres 1994).

What is often forgotten is that all systems, whether isolated or not, are subject to the same forces of entropic decay. In other words, any complex differentiated system has a natural tendency to erode, dissipate, and unravel. The reason open, self-organizing systems such as modern cities do not run down in this way is that they are able to import available energy and material (essergy) from their host environments which they use to maintain their internal integrity. Such systems also export the resultant entropy (waste and disorder) into their hosts. The second law therefore also suggests that all highly-ordered systems can grow and develop (increase their internal order) only "at the expense of increasing disorder at higher levels in the systems hierarchy" (Schneider and Kay 1992). Because such systems continuously degrade and dissipate available energy and matter, they are called "dissipative structures."

Clearly, cities are prime examples of highly-ordered dissipative structures. At the same time, these nodes of intense economic activity are open sub-systems of the materially closed, nongrowing ecosphere. Thus, to grow, or simply to maintain their internal order and structure, cities necessarily appropriate large quantities of useful energy and material from the ecosphere and "dissipate" an equivalent stream of degraded waste back into it.

This means that in the aggregate, cities (or the human economy) can operate sustainably only within the thermodynamic load-bearing capacity of the ecosphere. Beyond a certain point, the cost of material economic growth will be measured by increasing entropy or disorder in the "environment." We would expect this point (at which consumption by humans exceeds available natural income) to be revealed through the continuous depletion of natural capital—reduced biodiversity, fisheries collapse, air/water/land pollution, deforestation, desertification, etc. Such trends are the stuff of headlines today. World Bank ecologist Robert Goodland uses them to argue that "current throughput growth in the global economy cannot be sustained" (Goodland 1991). It seems we have already reached the entropic limits to growth.

This brings us back to our starting premise, that with the onset of global ecological change, the world has reached an historic turning point that requires a conceptual shift from empty-world to full-world economics (and ecology). Ecological footprint analysis underscores the urgency of making this shift. As noted, the productive land "available" to each person on Earth has decreased increasing rapidly with the explosion of human population in this century. Today, there are only about 1.5 hectares of such land for each person, including wilderness areas that probably shouldn't be used for any other purpose.

At the same time, the land area appropriated by residents of richer countries has steadily increased. The present per capita ecological footprints of North Americans (4–5 ha) represents three times their fair share of the Earth's bounty. By extrapolation, if everyone on Earth lived like the average North American, the total land requirement would exceed 26 billion hectares. However there are fewer than 9 billion hectares of such land on Earth. This means that we would need three such planets to support just the *present* human family. In fact, we estimate that resource consumption and waste disposal by the wealthy quarter of world's population alone exceeds global carrying capacity and that total global overshoot is as much as 30% (Wackernagel and Rees 1995). (Again, these are underestimates based on the assumption that our present land endowment is being used sustainably, which it is not.)

Cities and Global Trade

> The structure of trade, as we know it at present, is a curse from the perspective of sustainable development (Haavelmo and Hansen 1991, p. 46).

Acknowledging the energy and material dependence of cities also forces recognition of the city's role as an engine of economic growth and global trade. According to the conventional view, trade increases both incomes and carrying capacity. Individual trading regions can export local surpluses and thereby earn the foreign exchange needed to pay for imports of locally scarce resources. Hence both the economy and the population are freed to grow beyond limits that would otherwise be imposed by regional carrying capacity. The fact that 40% of global economic growth today is sustained by trade supports this argument.

There are, however, serious flaws in the conventional interpretation. First, trade reduces the most effective incentive for resource conservation in any import region, the regional population's otherwise dependence on local natural capital. For example, the Vancouver region's seasonal access to cheap agricultural imports from California and Mexico reduces the potential money income from local agricultural land.[9] Fraser Valley farmers themselves therefore join the developers in pressing for conversion of agricultural land to urban uses which produce a higher short-term return. Because of trade, the consequent loss of foodlands in the Fraser basin proceeds without immediate penalty to the local population. Indeed, the latter are actually rewarded in the short-term by the boost to the local economy! Ironically, then, while appearing to do the opposite, trade actually *reduces* both regional and global carrying capacity by facilitating the depletion of the total stock of natural capital. By the time market prices reflect incipient ecological scarcity, it will be too late to take corrective action.

By throwing new light on commercial trade and natural flows, ecological footprint analysis also suggests a disturbing interpretation of contemporary North-South relationships. Much of the wealth of urban industrial countries comes from the exploitation (and sometimes liquidation) of natural capital, not only within their own territories, but also within their former colonies. The energy and material flows in trade thus represent a form of thermodynamic imperialism. The low cost essergy represented by commodity imports is required to sustain growth and maintain the internal order of the so-called "advanced economies" of the urban North. However, expansion of the human enterprise proceeds at the expense of "a net increase in [global] entropy as natural resource [systems] and traditional social structures are dismembered" (Hornborg 1992a, 1992b). Colonialism involved the forceful appropriation of extraterritorial carrying capacity, but today economic purchasing power secures the same resource flows. What used to require territorial occupation is now achieved through commerce (Figure 3) (Rees and Wackernagel 1994).

In summary, to the extent that competitive open global markets and liberated trade accelerate the depletion of essential natural capital, it is counterproductive to sustainability. Trade only appears to increase carrying capacity. In fact, by encouraging all regions to exceed local limits, by reducing the perceived risk attached to local natural capital depletion, and by simultaneously exposing local surpluses to global demand, uncontrolled trade accelerates natural capital depletion, reducing global carrying capacity and increasing the risk to everyone (Rees and Wackernagel 1994).

Toward Urban Sustainability

Ecological footprint analysis not only measures the sustainability gap (Rees 1996), it also provides insight into strategies for sustainable urban develop-

[9] The competitive advantage to imports comes from superior climate and longer growing season, abundant cheap labor, underpriced energy, and various direct and indirect subsidies (e.g., California producers pay a fraction of the real cost of providing their irrigation water).

FIGURE 3. Ecological inequity. In today's ecologically overloaded world, we all compete for the finite natural income flows produced by the ecosphere. The high money incomes and excessive consumption of affluent countries extends their ecological footprints into ecological space that could otherwise be occupied by the poorer nations. Even within countries, footprint sizes vary significantly as income disparity increases (*Source:* Wackernagel and Rees 1995).

ment. To begin, it is important to recognize that cities are themselves vulnerable to the negative consequences of overconsumption and global ecological mismanagement. How economically stable and socially secure can a city of 10 million be if distant sources of food, water, energy or other vital resource flows are threatened by accelerating ecospheric change, increasing competition, and dwindling supplies? Does the present pattern of global development, one that increases interregional dependence on vital natural income flows that may be in jeopardy, make ecological or geopolitical sense? If the answer is "no," or even a cautious "possibly not," circumstances may already warrant a restoration of balance away from the present emphasis on global economic integration and interregional dependency toward enhanced ecological independence and greater intraregional self-reliance. (If all regions were in ecological steady-state, the aggregate effect would be global stability.)

To reduce their dependence on external flows, urban regions and whole countries may choose to develop explicit policies to invest in rehabilitating their own natural capital stocks and to promote the use of local fisheries, forests, agricultural land, etc. This would increase regional independence thus creating a hedge against rising international demand, global ecological change, and potentially reduced productivity elsewhere.

Although greater regional self-reliance is a desirable goal on several grounds, we are not arguing for regional closure. In any event, self-sufficiency is not in the cards for most modern urban regions. The more important issue before us is to assure urban security and define an appropriate role of cities in achieving global sustainability. How can we be certain "that the aggregate performance of cities and urban systems within nations and worldwide is compatible with sustainable development goals" (Mitlan and Satterthwaite 1994) and—we would add—compatible with shrinking global carrying capacity?

Ecological Pros and Cons of Cities

A major conclusion of ecological footprint analysis and similar studies is that urban policy should strive to minimize the disruption of ecosystems processes and massively reduce the energy and material consumption, associated with cities. Various authorities share the view of the Business Council on Sustainable Development that "industrial world reductions in material throughput, energy use, and environmental degradation of over 90% will be required by 2040 to meet the needs of a growing world population fairly within the planet's ecological means" (BCSD 1993).

Addressing these issues shows that cities present both unique problems and opportunities. First, the fact that cities concentrate both human populations and resource consumption results in a variety of ecological impacts that would not occur, or would be less severe, with a more dispersed settlement pattern. For example, cities produce locally dangerous levels of various pollutants that might otherwise safely be dissipated, diluted, and assimilated over a much larger area.

More importantly from the perspective of ecosystems integrity, cities also significantly alter natural biogeochemical cycles of vital nutrients and other chemical resources. Removing people and livestock far from the land that supports them prevents the economic recycling of phosphorus, nitrogen, other nutrients, and organic matter back onto farms and forests. As a consequence of urbanization, local, cyclically integrated ecological production systems have become global, horizontally disintegrated, throughput systems. For example, instead of being returned to the land, Vancouver's daily appropriation of Saskatchewan mineral nutrients goes straight out to sea. As a result, agricultural soils are degraded (half the natural nutrients and organic matter from much of Canada's once-rich prairie soils have been lost in a century of mechanized export agriculture), and we are forced to substitute nonrenewable artificial fertilizer for the once renewable real thing. All of this calls for much improved accounting for the hidden costs of cities, of transportation, and of mechanized agriculture, and a redefinition of economic efficiency to include biophysical factors.

While urban regions certainly disrupt the ecosystems of which they are a part, the sheer concentration of population and consumption also gives cities enormous leverage in the quest for global sustainability. Some of the advantages of urban settlements are as follows (based on Mitlin and Satterthwaite 1994):

- lower costs per capita of providing piped treated water, sewer systems, waste collection, and most other forms of infrastructure and public amenities;
- greater possibilities for, and a greater range of options for, material recycling, re-use, remanufacturing, and the specialized skills and enterprises needed to make these things happen;
- high population density, which reduces the per capita demand for occupied land;
- great potential through economies of scale, co-generation, and the use of waste process heat from industry or power plants, to reduce the per capita use of fossil fuel for space-heating;
- great potential for reducing (mostly fossil) energy consumption by motor vehicles through walking, cycling, and public transit.

For a fuller appreciation of urban leverage, let us examine this last point in more detail. It is commonplace to argue that the private automobile must give way to public transportation in our cities and just as commonplace to reject the idea (at least in North America) as politically unfeasible. However, political feasibility depends greatly on public support. The popularity of the private car for urban transportation is in large part due to underpriced fossil fuel and numerous other hidden subsidies (up to $2500 per year per vehicle). Suppose we gradually move toward full cost pricing of urban auto use and reallocate a significant proportion of the considerable auto subsidy to public transit. This could make public transportation faster, more convenient, and more comfortable than at present, and vastly cheaper than private cars. Whither political feasibility? People would demand improved public transit with the same passion they presently reserve for increased road capacity for cars.

Most importantly, the shift in incentives and modal split would not only be ecologically more sustainable but also both economically more efficient and socially more equitable. (It *should* therefore appeal to both the political right and left.) Over time, it would contribute to better air quality, improved public health, greater access to the city, more affordable housing, more efficient land use, the hardening of the urban fringe, the conservation of food lands, and levels of urban density at which at least direct subsidies to transit become unnecessary. In short, because of complex systems linkages, seriously addressing even a single issue in the city can stimulate change in many related factors contributing to sustainability. Rees (1995) has previously called this the "urban sustainability multiplier."

Note, in this context, that ecological footprint analysis provides a tool to compare the relative effectiveness of alternative urban development patterns, transportation technologies, etc., in reducing urban ecological impacts. For example, Walker (1995) has shown that the increased density associated with high-rise apartments, compared to single-family houses, reduces those components of the per capita ecological footprint associated with housing type and urban transportation by 40%. There is little question that urban structure and form can have a significant impact on individual resource consumption patterns (Figure 4) (see also Kenworthy and Laube, this issue, pp. 279–308).

At the same time, we should recognize that many consumption-related human impacts that can be traced *to* cities have little to do with the structure, form, or other properties *of* cities per se. Rather, they are a reflection of societal values and behavior and of individual activities and habits. For example, the composition of one's diet may not be much related to place of residence. Similarly, that component of a dedicated audiophile's ecological footprint related to his/her use of stereo equipment will be virtually the same whether s/he resides in a farming village or industrial metropolis. In short, if the fixed elements of an individual's footprint require the continuous output of two hectares of land scattered about the globe, it doesn't much matter where that individual resides. This impact would occur regardless of settlement pattern.

There are, of course, other complications. People often move to cities because of greater economic opportunities. To the extent that the higher incomes associated with urban employment result in increased average

FIGURE 4. The urban sustainability multiplier. High density urban living significantly shrinks our per capita ecological footprints by reducing our energy and material needs. We may also find that through improved urban design, our cities can become more accessible and community-oriented places that are safer and healthier for their residents (*Source:* Wackernagel and Rees 1995).

personal consumption (*net* of any savings resulting from urban agglomeration economies), the urban ecological footprint may well expand beyond the base case. Many categories of elevated urban consumption may not even contribute to improved material well-being. Higher clothing bills, cleaning costs, and increased expenditures on security measures are all necessitated by urban life. However, they contribute nothing to relative welfare while adding to the city's total ecofootprint.

To reiterate, the real issue is whether the material concentrations and high population densities of cities make them inherently more or less sustainable than other settlement patterns. What is the materially optimal size and distribution of human settlements? We cannot say on the basis of the mixed evidence to date. Until we know the answer to this question, we cannot know on ecological grounds whether policy should encourage or discourage further urbanization. In the meantime, we in the wealthiest cities must do what we can to create cities that are more ecologically benign (including, perhaps, learning to live more simply, that others may live at all). Fortunately, ecological footprinting can be use to monitor general progress toward sustainability.

Epilogue

Cities are among the brightest stars in the in the constellation of human achievement. At the same time, ecological footprint analysis shows that they act as entropic black holes, sweeping up the output of whole regions of the ecosphere vastly larger than themselves. Given the causal linkage between global ecological change and concentrated local consumption, national and provincial/state governments should assess what powers might be devolved to, or shared with, the municipal level to enable cities better to cope with the inherently urban dimensions of sustainability.

At the same time, international agencies and national powers must recognize that policies for local, provincial, or national sustainability have little meaning without firm international commitment to the protection and enhancement of remaining common-pool natural capital and global life support services. There can be no ecological sustainability without international agreement on the nature of the sustainability crisis and the difficult solutions that may be necessary at all spatial scales. The prognosis here is not encouraging. As Lynton Caldwell observes:

> The prospect of worldwide cooperation to forestall a disaster... seems far less likely where deeply entrenched economic and political interests are involved. Many contemporary values, attitudes, and institutions militate against international altruism. As widely interpreted today, human rights, economic interests, and national sovereignty would be factors in opposition. The cooperative task would require behavior that humans find most difficult: collective self-discipline in a common effort (Caldwell 1990).

This statement suggests that as a result of political inertia, the world may well simply stay its present development course in the blind hope that things will all work out. If so, and the analysis presented in this article is correct, humans may well become the first species to document in exquisite detail the factors leading to its own demise (without acting to prevent it).

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