Urban Ecosystems, 1997, **1,** 63–75

Urban ecosystems: the human dimension

WILLIAM E. REES*
University of British Columbia, School of Community and Regional Planning, Vancouver, British Columbia, Canada V6T 1Z2

This paper develops a human ecological perspective on cities and urban regions. It describes the role of cities in the expanding human ecological niche and its implications for sustainable urban development. I have used a new technique, ecological footprint analysis, to convert the material and energy flows required to sustain the human population and industrial metabolism of ''the city'' into a land/ecosystem area equivalent. This approach emphasizes that, although urbanization has become the dominant human settlement pattern, cities themselves constitute only a small part of the total ecological space appropriated by their human inhabitants. In short, the ecological locations of human settlements no longer coincide with their geographic locations. Every city and urban region depends for its existence and growth on a globally diffuse productive hinterland up to 200 times the size of the city itself. Cities are therefore increasingly vulnerable to global ecological change and geopolitical instability. Given the deteriorating state of the ecosphere, policies to decrease the ecological footprint of cities while increasing regional self-reliance may enhance urban sustainability.

Keywords: urban ecosystems; human carrying capacity; ecological footprints; sustainable development

Urban ecology as human ecology

Cities have long been recognized as the primary human habitat in the presently ''industrialized'' countries; the rest of the human population is now also rapidly urbanizing. Next to the sheer growth in human numbers, this mass migration of people to the cities is arguably the most significant human ecological event of the past 100 years. Nevertheless, the human ecological dimension of the phenomenon has gone virtually unnoticed. We have come to understand both cities and urbanization mainly through the narrow lens of economics and sociology.

If asked, people generally define cities as centers of commerce, as hubs of transportation and communication systems, as wellsprings of culture and the arts, as hosts of our greatest educational institutions, and as seats of government. Indeed, from all these perspectives, cities are among humanity's proudest achievements. A few people may also refer to the inevitable pollution, congestion, and urban decay that plagues city life. However, almost no one will describe the city as an *ecosystem,* and certainly not as a component of the *human* ecosystem. In short, western culture rarely recognizes urbanization and cities as manifestations of human ecology.

We can explain this perceptual gap as reflecting a deep cognitive bias of western industrial culture. People tend not to reflect on themselves as biological beings, certainly not as animals in the same category as all the 'others'. Our Cartesian scientific heritage has been stunningly successful for 300 years in reinforcing the self-serving perceptual barriers we have erected between ourselves and the rest of the natural world. A check of the index of any recent volume of *Ecology* provides a good sense of how strong this scientific 'apartheid' remains even within our own field. Where are the studies of humankind as ecological entity? Despite the oft-cited etymological relationship between their respective disciplines, ecologists have all but abandoned human ecology to the economists. Indeed, their training and bias toward pristine environments leaves many ecologists uncomfortable with the notion that humans are

*To whom correspondence should be addressed.

actually part of nature. So it is that even in this era of purported environmental crisis academic ecology has relatively little to say about the ecology of *Homo sapiens* or about cities as ecological phenomena.*

Even the technical literature treats urban ecology mainly as the ecology of nonhuman species in cities. There is doubtless much of scientific interest to be gleaned from studying the accommodations of various life-forms to this most human-dominated of earthly habitats. One of the more fascinating dimensions of ecology is the adaptive coevolution of species, particularly those that have hitched their wagons to the human train. However, it is time for ecologists to subject their own species to the same analytic scrutiny that has heretofore been reserved for the other organisms with which we share the planet. Humans are the creators of cities and therefore the keystone species in the urban system. Certainly they are dominant in terms of energy flow and biomass. Any urban ecology must therefore eventually converge with human ecology.

Framing the analysis

It should already be clear that a basic premise of this paper is that urban ecology is very much an element of human ecology. My major purpose, therefore, is to describe the role of cities in the expanding human ecological niche and to discuss the implications of the findings for policies for sustainable urban development. [See Rees (1995a) for a discussion of current issues in the sustainability debate.]

Knowledge of the ecological properties of cities as the dominant human habitat is vital even to global sustainability. Unfortunately, these properties are invisible to conventional urban analyses. Most studies of urban health and stability focus on investment flows, income generation, job creation rates, crime statistics, and other socioeconomic indicators. However, economic analyses are so abstracted from physical reality that they reveal nothing of the structural, spatial, and time-dependent factors governing ecosystem behavior. In fact, the prevailing focus on money wealth and the economic surpluses generated by 'successful' cities is positively misleading respecting ecological health and long-term stability. Understanding the urban ecosystem requires a direct focus on the material, energy, and information flows that sustain the human population. In effect, the starting point for urban ecology should begin with modified trophic analysis.

The global context

The urgency of this approach is underscored by the realization that the late 20th century marks a critical 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 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 ecosystem perspective,

*'Environmental studies' and 'environmental science' might seem to fill the gap, but most of the material under these labels tends to focus not on humans *per se* but rather on the impact of human activity on other species or the physical environment. This maintains the psychological separation of humankind and nature.

is the evidence that human beings, one species among millions, now consume, divert, or otherwise appropriate for their own purposes 40% of net 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.

All such empirical evidence suggests that the human economy is converging with the ecosphere from within. Humankind no longer merely affects local environments but rather has co-opted the entire ecosphere for its own purposes. Understanding the sustainability implications of this turn of events requires a focus on human beings as the major consumer organism in all the world's ecosystems.

Human carrying capacity

This perspective also reopens the issue of human carrying capacity. 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 humankind's seeming ability to increase its own carrying capacity by eliminating competing species, by importing locally scarce resources, and, through technology, economists and planners generally dismiss the concept of carrying capacity as irrelevant to people.

By contrast, I argue that shrinking carrying capacity may soon become the single most important issue confronting humanity. The rationale is simple – technological and cultural trappings aside, human beings remain ecological entities. In tropic-dynamic terms, humans are macroconsumers whose relationship to the rest of the ecosphere is similar to those of thousands of other consumers 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 ecosystems 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 a urban-industrial metabolism. In ecological terms, all our toys and tools (the '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). In short, 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).

It follows that assessments of the human condition should at least be informed by biophysical analyses. In particular, sustainability requires that we monitor stocks of critical self-producing 'natural capital' and the flows of ecological goods and services ('natural income') they provide to the human economy.* Indeed, the fundamental question for ecological sustainability is whether remaining natural capital stocks, including ecosystems and biophysical processes, are adequate to support the anticipated demand of the human economy into the next century while simultaneously maintaining the general life-support functions of the ecosphere (Rees, 1995a, 1996). This 'fundamental question' is at the heart of human carrying capacity but is ignored by mainstream development analyses.‡

*Natural capital refers to any 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 ultraviolet radiation (the ozone layer is a form of natural capital). These life-support services are also counted as natural income. Because 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 (Rees, 1995, adapted from Costanza and Daly, 1992).

‡The initial prognosis is not particularly encouraging: 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.

Carrying capacity as maximum human 'load'

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

The unique dimensions of human carrying capacity becomes clearer if we define it not as a maximum sustainable 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 then the former because of (ironically) 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 20-fold to 210 000 kcal/day (Catton, 1986). As a result, load pressure relative to carrying capacity is rising much faster than is implied by mere population increases. This trend is likely to accelerate in coming decades as the world urbanizes and incomes increase.

We can now redefine human carrying capacity as the maximum rates of resource harvesting and waste generation (i.e. the maximum 'load') that can be sustained indefinitely without progressively impairing the productivity and functional integrity of relevant ecosystems wherever the latter are located. the size of the corresponding population would be a function of technological sophistication and mean *per capita* material standards. This definition reminds us that regardless of the state of technology, humankind depends on numerous goods and services from 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.

Ecological footprints: estimating human load

My students and I have developed an approach to human carrying capacity that addresses the objections of conventional development economists. Our method inverts the standard carrying capacity ratio and extends the concept of load. Rather than attempting to determine what population a particular region can support sustainably, we ask instead: How large an area of productive land is needed to support the ecological load imposed by a defined population indefinitely, *wherever that land is located*? This approach recognizes that although populations or economies sustained by trade may be released from local resource or environmental constraints, they consequently impose an even greater ecological load elsewhere on the planet. Human carrying capacity is not irrelevant, merely obscured for a time by trade.

We reason that, because 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 consumption items provides a conservative area-based estimate of the natural capital requirements of that population. We call this aggregate area the population's true 'ecological footprint' (EF). The ecological footprint of a specified population is therefore formally defined as the total area of productive land and water required to produce on a continuous basis all the resources consumed and to assimilate all the wastes produced by that population, wherever on Earth the land may be located (Rees, 1992; Rees and Wackernagel, 1994; Wackernagel and Rees, 1995; Rees, 1996).

Ecological footprinting provides a simple area-based index of a population's ecological load. The method can be used to monitor progress toward sustainability; to compare the ecological impacts of cities, life-styles, or technologies; or to weigh aggregate human demand against available supply.

Basic footprint calculations

As noted, the EF concept is based on the idea that, for every item of material or energy consumption, a certain amount of land in one or more ecosystem categories is required to provide the consumptionrelated resource flows and waste sinks. Although there are tens of thousands of consumer items, a relatively small number of ecologically significant goods and services represents most of the environmental load imposed by consumption. We can thus use such a basic 'shopping basket' of significant items for any referent population to estimate its ecological footprint. Although the following brief description of the method refers mainly to resource consumption, the same logic would apply to many categories of waste production and assimilation. (For full details and examples, see Wackernagel and Rees, 1995.)

First we estimate the annual *per capita* consumption of particular 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 energy, food, and forest products production and consumption, for example. For many categories, national statistics provide both production and trade figures from which trade-corrected consumption can be assessed:

$$\text{Trade-corrected consumption} = \text{production} + \text{imports} - \text{exports}$$

The next step is to estimate the land area appropriated *per capita* (*aa*) for the production of each major consumption item *i*. We do this by dividing average annual consumption of that item as calculated above (c, in kg/capita) by its average annual productivity or yield (p, in kg/ha):

$$aa_i = c_i/p_i$$

We then compute the total average *per capita* ecological footprint (ef) by summing all the ecosystem areas appropriated by individual items:

$$\text{ef} = \sum_{i=1}^{i=n} aa_\text{i}$$

Finally we obtain the ecological footprint (EF_P) of the study population by multiplying the average *per capita* footprint by population size (N):

$$\text{EF}_\text{P} = N \times \text{ef}$$

So far our EF calculations are based on items in five major categories of consumption (food, housing, transportation, consumer goods, and services) and on six major land-use or ecosystem categories (built-up [urban], energy, garden, crop, pasture, forest) (see Table 1).

The energy land category requires additional explanation. We account for direct fossil energy consumption and the energy content of other 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/capita)/(assimilation rate/hectare)], on the assumption that atmospheric stability is a prerequisite of sustainability. (See Box 1 for a sample calculation.) Our approach is relatively conservative. 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 and where there are data problems or significant uncertainty we err on the side of caution. Also, although 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 underestimates than overestimates.

Initial footprint estimates are based on average national consumption and world average land yields. This is a standardization procedure that facilitates 'general case' comparisons among regions or countries. (It is also fairly realistic for many countries given the increasing reliance on multilateral trade flows

Box 1. Fossil energy consumption and carbon sinks

Question: How much ecologically productive land (e.g. carbon sink forest) would be required to sequester all the CO_2 released by the average Canadian's consumption of fossil energy? (See 'total' in Column A of Table 1)

World Resources Institute (1992) data show that Canada's total commercial energy consumption was 8 779 Petajoules (Pj or million Gigajoules) in 1991. Of this amount, 926 Pj were generated by nuclear power and 1,111 Pj by hydrodams. Hence, the fossil fuel consumption was (8 779 − 926 − 1 111 =) 6 742 Pj. Therefore, each of 28 million Canadians would consume:

$$\frac{6\,742\,000\,000\ [\text{Gj/yr}]}{27\,000\,000\ [\text{Canadians}]} = 241\ [\text{Gj/year}]\ \text{of fossil fuel}$$

However, Statistics Canada reports a figure of 234 Gj *per capita* per year. Wishing to err on the side of caution we use the Statscan figure. With a land-for-energy conversion ratio for fossil fuel of 100 Gj/ha/yr, the land requirement for the average Canadian therefore comes to:

$$\frac{234\ [\text{Gj/cap/yr}]}{100\ [\text{Gj/ha/yr}]} = 2.34\ [\text{ha/cap}]\ \text{for sequestering the}\ CO_2\ \text{released by this fossil fuel.}$$

(N.B. The same result is obtained by dividing Canadian's annual *per capita* trade-corrected carbon emissions of 4.2 tonnes by the average carbon assimilation rate of the world's forests, 1.8 tonnes/ha/yr = 2.33 ha/cap.)

Source: Revised from Wackernagel and Rees (1995).

and appropriations from the global commons.) However, for more sophisticated or specific analyses, it may be desirable to base the footprint estimate on regional or local consumption and productivity statistics. For example, local data are necessary when computing regional carrying capacities for comparison with actual populations. With sufficient data, locally accurate EFs of consumer units as small as specific municipalities, households, and even individuals can be estimated.

Ecological footprints of cities and urban regions*

Let's now apply the ecological footprint model to the City of Vancouver and to the Lower Fraser Valley region of British Columbia, Canada, within which Vancouver is located. Because there are few regional data for most consumption items, we used national average *per capita* consumption for these local footprint estimates. Because British Columbia's lower mainland is one of Canada's most prosperous areas, this substitution results in an underestimate of 'appropriated' land areas to the extent that consumption is positively correlated with income.

The relevant consumption and land use data are assembled in Table 1. Data entries in this matrix show the land areas required to provide the current lifestyle of an average Canadian. For example, if we read across row '43 books/magazines' to the 'F Forest' column, we find that 0.1 ha of forest land are required to produce his/her reading materials. In addition, the embodied energy land associated with books and magazines is 0.06 ha. This means that on average 0.16 ha of land are required continuously to produce the fiber for each Canadian's newsprint consumption.

The bottom right corner of Table 2 shows that the total land required to support present consumption levels by the average Canadian is 4.27 ha (2.3 ha for carbon dioxide assimilation alone). Thus, the *per*

*Section revised and abstracted from Rees and Wackernagel (1996) and Wackernagel and Rees (1995).

Table 1. The consumption-land use matrix for the average Canadian (1991 data)[a]

	A Energy[b]	B Urban	C Garden	D Crop	E Pasture	F Forest	Total
1 Food	**0.33**		**0.02**	**0.60**	**0.33**	**0.02**	**1.30**
11 fruit, vegetables, grain	0.14		0.02	0.18		0.01?	0.35
12 animal products	0.19			0.42	0.33	0.01?	0.95
2 Housing	**0.41**	**0.08**	**0.002?**			**0.40**	**0.89**
21 constrn/maint.	0.06					0.35	
22 operation	0.35					0.05	
3 Transportation	**0.79**	**0.10**					**0.89**
31 motorized private	0.60						
32 motorized public	0.07						
33 transp'n of goods	0.12						
4 Consumer goods	**0.52**	**0.01**		**0.06**	**0.13**	**0.17**	**0.89**
40 packaging	0.10					0.04	
41 clothing	0.11			0.02	0.13		
42 furniture & appli.	0.06					-0.03?	
43 books/magazines	0.06					0.10	
44 tobacco & alcohol	0.06			0.04			
45 personal care	0.03						
46 recreation equip.	0.10						
47 other goods	0.00						
5 Services	**0.29**	**0.01**					**0.30**
51 gov't (+ military)	0.06						
52 education	0.08						
53 health care	0.08						
54 social services	0.00						
55 tourism	0.01						
56 entertainment	0.01						
57 bank/insurance	0.00						
58 other services	0.05						
Total	**2.34**	**0.20**	**0.02**	**0.66**	**0.46**	**0.59**	**4.27**

Source: Revised from Wackernagel and Rees (1995).
[a]Cell entries = ecologically productive land in hectareo *per capita.* (0.00 = less than 0.005 [ha] or 50 [m^2]; blank = probably insignificant; ? = lacking data)
[b]The abbreviations used are: (A) Energy, fossil energy consumed expressed in the land area necessary to sequester the corresponding CO_2 emissions; (B) Urban, built-up environment and degraded land; (C) Garden, gardens for vegetable and fruit production; (D) Crop, crop land; (E) Pasture, pastures for dairy, meat, and wool production; (F) Forest, prime forest area. (An average roundwood harvest of 163 [m^3/ha] every 70 years is assumed.)

capita ecological footprint of Canadians is about 4.3 ha, almost three times their 'fair Earthshare' of 1.5 ha.‡

Footprinting Vancouver

Vancouver had a 1991 population of 472 000 and an area of 11 400 hectares. Assuming a *per capita* land consumption rate of 4.3 hectares, the 472 000 people living in Vancouver require, conservatively, 2.03

‡There are only about 8.9 billion hectares of ecologically productive land, usable cropland, pasture land, forests and woodlands, on Earth. If this were allocated equitably among the 1996 human population of 5.8 billion, each person would receive 1.5 ha.

million hectares of land for their exclusive use to maintain their current consumption patterns (assuming such land is being managed sustainably). However, since the area of the city is only about 11 400 hectares, the residents of Vancouver continuously appropriate the productive output of a land area nearly 180 times larger than the physical area of their municipality to support their consumer lifestyles. If we add the estimated *per capita* marine footprint of 0.7 ha to this terrestrial footprint, § the total area of Earth needed to support Vancouver's population is 2.36 million hectares or over 200 times the geographic area of the city.

Other researchers have obtained similar results. 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). In a more extensive analysis, 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 included a marine component for seafood production, but no energy land component.)

These studies all show that whatever their socioeconomic importance, the densely populated built-up areas we call 'cities' constitute a minor spatial component of the functional human ecosystem. Each city is dependent for its growth and survival on an area of productive ecosystems two to three orders of magnitude larger than the geographic area of the city itself. The resources and assimilative capacities (i.e. natural income) of these distant ecosystems is acquired through a combination of commercial trade and natural biogeochemical cycles.

Table 2. Estimated ecological footprints of Vancouver and the Lower Fraser Basin

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

A regional assessment: the Lower Fraser Basin

Vancouver is located at the mouth of the broad deltaic valley of the Lower Fraser River. This valley contains some of the richest agricultural soils, the most rapidly growing forests, and the most temperate climate in Canada. It should therefore be capable of supporting a large human population relative to less favored areas of similar size.

If we extend our EF analysis to cover the entire Lower Fraser Basin region (population = 1.78 million; area = 555 000 ha) we find that even though only 18% of the area 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 at least 13.8 times larger than the basin itself. In other words, of the people of the Lower Fraser region

§To estimate the marine footprint, we first divide the global fish catch by total productive ocean area. The maximum sustainable yield of the oceans is about 100 million tonnes of fish per year. Although the seas occupy about 71% of the Earth's total surface (about 362 million square kilometers), only 8.2% of this (about 29.7 million square kilometers) is responsible for about 96% of the world's fish catch. In other words, average annual production is about 32.3 kg of fish per productive hectare or 0.03 ha/kg of fish. An equal 'seashare' of ocean (productive area divided by total human population) would be about 0.5 ha per capita, which correspond to about 16.2 kg of fish per year. Because Canadians consume about 23.4 kg of marine fish per capita annually, their marine footprint is about 0.7 ha.

in enjoying their consumer lifestyles, has 'overshot' the carrying capacity of their geographic home territory by a factor of about 14. These results are summarized in Table 2.

Ecological deficits and global interdependence

Ecological footprinting shows that even the relatively rural Lower Fraser Valley is dependent for its 'sustainability' on imports of ecologically significant goods and services from a scattering of areas elsewhere on Earth whose aggregate area is much larger than the region itself. In effect, however healthy the region's economy may be in monetary terms, the Lower Fraser Valley is running a massive 'ecological deficit' (Rees 1996) with the rest of Canada and the world.

This situation is actually typical of urban-industrial (i.e. high-income) regions and even for some entire countries. Table 3 shows that many economically advanced countries run an ecological deficit about an order of magnitude larger than the sustainable natural income that could be generated by the ecologically productive land within their political territories. The last two columns of Table 3 represent low estimates of typical *per capita* deficits. Even if their land were twice as productive as the world average, European countries would still run a deficit more than three times larger than domestic natural income. These data throw a skeptical new light on current world development models. For example, Japan and the Netherlands both boast positive monetary trade balances and their populations are among the most prosperous on earth. Densely populated yet relatively resource-poor, these highly urbanized 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 ha/capita and the Netherlands a 3.3 ha/capita ecological footprint

Table 3. The ecological deficits of industrialized countries[a]

Country	Ecologically Productive Land (in hectares) *a*	Population (1995) *b*	Ecologically Productive Land *per Capita* (in hectares) *c = a/b*	National Ecological Deficit *per Capita* (in hectares) *d = ftprint − c*	(in % available) *e = d/c*
Countries with 2–3-ha footprints				assuming a 2-ha footprint	
Japan	30 417 000	125 000 000	0.24	1.76	730
South Korea	8 716 000	45 000 000	0.19	1.81	950
Countries with 3–4-ha footprints				assuming a 3-ha 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
Britain	20 360 000	58 000 000	0.35	2.65	760
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				Aust 4.7; Can 4.3; US 5.1 ha	
Australia	575 993 000	17 900 000	32.18	(27.48)	(590)
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: Revised from Wackernagel and Rees (1995).
[a]Footprints estimated from studies by Ingo Neumann from Trier University, Germany; Dieter Zürcher from Infras Consulting, Switzerland; Rod Simpson, Katherine Gaschk, and Shannon Rutherford of Griffiths University, Australia; and our own analysis using World Resources Institute (1992) data.

which gives these countries national footprints about 8 and 15 times larger than their total domestic territories, respectively. (Note that Table 3 is based on areas of ecologically productive land only.)

The marked contrast between the physical and monetary accounts of such economic successes 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. The question is: How should this reality be reflected in national and global strategies for ecologically sustainable socioeconomic development?

It is worth noting in this context that Canada and Australia are among the few developed countries that consume less than their domestic natural income (Table 3). Low in population and rich in resources, these countries have yet to exceed their own carrying capacities. However, both these 'underpopulated' nations' natural capital stocks are being depleted by exports of energy, forest, fish, agricultural products, etc., to the rest of the world. In short, Canada's and Australia's apparent surpluses are being incorporated by trade into the ecological footprints of countries running deficit accounts.

Summary and conclusions: wither urban (eco)systems?

We have examined cities and urban regions with an emphasis on some of the ecological demands of their human inhabitants. The analysis shows that these most concentrated forms of human settlement constitute only a small part of the ecological space actually appropriated by their human residents. This contrasts with other species adapted to the urban environment for which the city comprises a complete ecosystem. Indeed, entire assemblages of certain organisms – autotrophs, heterotrophs, and decomposers – are able to survive on energy and material flows generated within the city itself. However, for human beings, the dominant species in the urban system, the city is only one structural component of a geographically much more extensive human-dominated superecosystem.

Within this increasingly global human ecosystem, cities serve key functions as centers of sociocultural interaction, of information exchange and processing, of economic growth. However, seen through an ecological lens, cities appear as dense nodes of energy/material consumption and residuals production. Large concentrations of people and industrial activity necessarily consume more available energy and material than can be produced, and produce more waste (entropy) than can be assimilated, within the relatively small areas they physically occupy. Indeed, ecological footprint analysis reveals that cities, urban regions, and many whole countries depend for their maintenance and growth on resource stocks and waste sinks scattered all over the world. The aggregate ecosystem area required to support a typical high-income, consumer-oriented city may be 200 times the size of the city itself.

Several important conclusions and policy implications flow from these findings. First, it is clear that without massive increases in material and energy efficiency, the present material standards of high-income urbanized countries cannot be extended sustainably to even the present world population. There is simply not sufficient natural capital to go around. With prevailing technology, 3 to 5 ha of ecologically productive land *per capita* is required to sustain average levels of material consumption in wealthy countries today. Unfortunately, there are only about 1.5 ha of such land for each person on Earth. [Wackernagel and Rees (1995) suggest that the wealthy quarter of the world's population have already effectively claimed the entire long-term human carrying capacity of the Earth.]

With specific reference to cities:

- Humans perceive themselves as an increasingly urban species, 'abandoning' the countryside for the economic and cultural benefits of urban life. However, because of growing populations and rising *per capita* consumption, we have actually simultaneously become the dominant species in all the seas, forests, and grasslands of the world. Much of the ecological output of the planet is required to sustain our increasingly 'urban' culture. As more and more of the products of photosynthesis are appropriated by the growing human enterprise, the economy is effectively converging with the ecosphere. The ecosphere is becoming the 'homosphere'.

• Urbanization has joined with trade and technology to foster the illusion that humans have achieved virtual independence from 'the environment'. The reality is that with rising *per capita* consumption, humans are more dependent than ever on flows of goods and services provided by nature.

• Indeed, cities are totally dependent components of the homosphere. No city could survive cut off from the rest of nature. Enclosed in an impermeable glass or plastic bubble, any city would simultaneously starve and suffocate in short order.

• Cities are far removed from the ecosystems that sustain them. In this respect, *the ecological locations of human settlements no longer coincide with their geographic locations.* (Ecologically speaking, cities have become the human equivalent of cattle feedlots.)

• The emphasis in urban planning today is on growth management and on maintaining economic health. Ecological health and geopolitical security are taken for granted. However, in a finite world with a growing population, rising material expectations, and increasing evidence of global ecological change, urban sustainability may depend on more holistic approaches. Should urban planning not take into account the increasing ecological vulnerability of major cities? This requires consideration of the entire land/ecosystem base upon which cities are dependent. For example:

  • Cities should work with higher levels of government to develop policies that will reduce both the physical footprints of the settlements themselves and the *per capita* ecological footprints of their human inhabitants.* The greatest leverage is likely to be found in taxation and transportation policies designed to reduce energy and material consumption (Rees, 1995b; von Weizsäcker, 1994). This in turn will work to enhance the efficiency of urban land and infrastructure use by increasing gross urban densities.

  • It may be prudent to implement policies to increase regional self-reliance (i.e. to decrease dependence on distant elsewheres). Urban and regional development policy should encourage the conservation of, and investment in, local stocks of natural capital; much stronger zoning and densification measures may be necessary to prevent the conversion of local agricultural and forest land to urban land uses.

  • It may make sense for many irreversibly dependent urban regions and even entire countries to negotiate more formal long-term trade and resource management arrangements with the surplus (export) regions upon which they are dependent to ensure sustainable use of vital natural capital stocks and to enhance long-term ecological security.‡

The foregoing is not to suggest that the global network of cities is an inappropriate settlement pattern or that cities are ecological disasters. We have yet to determine whether the peculiar properties of cities make them inherently more or less sustainable than other settlement patterns. In fact, it may be that the sheer concentration of population and consumption gives cities significant advantages over more dispersed settlement patterns in dealing with many of the ecological problems associated with them (see Mitlan and Satterthwaite, 1994).

Rather, the intent here has been to explore the role of cities in the human ecosystem and to raise to consciousness the absolute ecological dependency of cities on other components of the ecosphere/homosphere. In a finite and increasingly crowded world should cities and urban regions continue to take

*Ecological impacts that can be traced to cities are not necessarily the impacts of cities *per se.* Much of a city's ecological footprint is attributable to items of personal consumption that are independent of settlement patterns.

‡This is not as far-fetched as it may seem. For example, Japan, conscious of the increasing market influence and rising consumer demand of China, is anxious to secure its future supplies of vital oil seeds such as the canola it purchases from Canada and takes an increasingly active role in determining the canola varieties and cultivation methods used in the latter country.

for granted the ready availability of biophysical goods and life-support services produced elsewhere on the planet? If not, the question becomes: What policy and planning measures are available to enhance the ecological and economic security of cities and their human populations?

Such questions are foreign to the techno-optimists and economists who dominate the current global development debate. Nevertheless, accelerating global change suggests that the time has come for people everywhere to come to know themselves again as ecological beings. This is necessary to generate the political support for the public policy measures needed to protect the global common-pool assets and ecological life-support functions upon which we all depend.

Making this shift may require abandonment of the prevailing emphasis in international development on export-led economic growth and increasing inter-regional dependence. Our growth-bound economics has contributed to a human ecological footprint which is already larger than the planet (Wackernagel and Rees, 1995), much of it attributable to frivolous energy/material consumption. If we are to avoid consuming the ecosphere, we must turn to policies that emphasize qualitative development rather than quantitative growth (see Daly, 1991). This new approach to sustainability might restrict trade to the exchange of true ecological surpluses within an overall framework of increasing regional self-reliance. No country nor international agency can manage the ecosphere. However, if all urban regions and nations manage to achieve local sustainability, the aggregate effect would be global sustainability.

Acknowledgments

I am grateful for a Canadian Tri-Council EcoResearch Grant to the University of British Columbia which has supported my work and that of my students on ecological footprinting. Thanks too to my colleagues on UBC's Healthy and Sustainable Communities Task Force for their continuing support and encouragement.

References

Catton, W. (1986) Carrying capacity and the limits to freedom. Paper prepared for Social Ecology Session 1, XI World Congress of Sociology. New Delhi, India, 18 August 1986.

Costanza, R., and Daly, H. (1992) Natural capital and sustainable development. *Conserv. Biol.* **1,** 37–45.

Daly, H. (1991) Sustainable development: From concept and theory toward operational principles. In *Steady-State Economics* (H. Daly, ed), 2nd edition, pp. 241–60. Island Press, Washington, DC.

Folke, C., Larsson, J., and Sweitzer, J. (1994) Renewable resource appropriation by cities. Paper presented at ''Down to Earth: Practical Applications of Ecological Economics,'' the Third International Meeting of the International Society for Ecological Economics, San José, Costa Rica, 24–28 October 1994.

IIED (1995) *Citizen Action to Lighten Britain's Ecological Footprint.* A report prepared for the UK Department of the Environment, International Institute for Environment and Development, London.

Mitlin, D., and Satterthwaite, D. (1994) Cities and sustainable development. Background Paper prepared for ''Global forum '94,'' Manchester, 24–28 June 1994. International Institute for Environment and Development, London.

Pauly, D., and Christensen, V. (1995) Primary production required to sustain global fisheries. *Nature* **374,** 255–7.

Rees, W. E. (1990) *Sustainable Development and the Biosphere.* Teilhard Studies Number 23. American Teilhard Association for the Study of Man; or The ecology of sustainable development. *The Ecologist* **20,** 18–23.

Rees, W. E. (1992) Ecological footprints and appropriated carrying capacity: What urban economics leaves out. *Environ. Urban.* **4,** 121–30.

Rees, W. E. (1995a) Achieving sustainability: Reform or transformation? *J. Plann. Lit.* **9,** 343–61.

Rees, W. E. (1995b) More jobs, less damage: A framework for sustainability, growth, and employment. *Alternatives* **21,** 24–30.

Rees, W. E. (1996) Revisiting carrying capacity: Area-based indicators of sustainability. *Popul. Environ.* **17,** 195–215.

Rees, W. E. and Wackernagel, M. (1994) Ecological footprints and appropriated carrying capacity: measuring the natural capital requirements of the human economy. In *Investing in Natural Capital: The Ecological Economics Approach to Sustainability* (A-M. Jansson, M. Hammer, C. Folke, and R. Costanza, eds.) pp. 362–90. Island Press, Washington.

Rees, W. E. and Wackernagel, M. (1996) Urban ecological footprints: Why cities cannot be sustainable (and why they are a key to sustainability). *EIA Rev.* (forthcoming).

Sterrer, W. (1993) Human economics: a non-human perspective. *Ecol. Econ.* **7,** 183–202.

Vitousek, P. (1994) Beyond global warming: Ecology and global change. *Ecology* **75,** 1861–76.

Vitousek, P., Ehrlich, P., Ehrlich, A., and Matson, P. (1986) Human appropriation of the products of photosynthesis. *BioScience* **36,** 368–74.

Wackernagel, M., and Rees, W. E. (1995) *Our Ecological Footprint: Reducing Human Impact on the Earth.* New Society Publishers, Gabriola Island, British Columbia and Philadelphia, PA.

Wilson, E. O. (1988) The current state of biological diversity. In *Biodiversity* (E. O. Wilson, ed.), National Academy Press, Washington, DC.

von Weizsäcker, E. U. (1994) Ecological tax reform. In *Earth Politics,* (E. U. von Weizsäcker, ed.), pp. 129–140. Zed Books, London.

World Resources Institute (1992) *World Resources 1992–93: A Guide to the Global Environment.* Oxford University Press, New York and Oxford.