THE ECOLOGICAL FOOTPRINT: AN INDICATOR OF PROGRESS TOWARD REGIONAL SUSTAINABILITY

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Abstract. We define regional sustainability as the continuous support of human quality of life within a region's ecological carrying capacity. To achieve regional sustainability, one must first assess the current situation. That is, indicators of status and progress are required. The ecological footprint is an area-based indicator which quantifies the intensity of human resource use and waste discharge activity in relation to a region's ecological carrying capacity. If the ecological footprint of a human population is greater than the area which it occupies, the population must be doing at least one of the following: receiving resources from elsewhere, disposing of some of its waste outside of the area, or depleting the area's natural capital stocks. To achieve global sustainability, the sum of all regional footprints must not exceed the total area of the biosphere. This paper explains the mechanics of a footprint calculation method for nations and regions. As the method is standardized, the relative ecological load imposed by nations and regions can be compared. Further, a nation's or region's consumption can be contrasted with its local ecological production, providing an indicator of potential vulnerability and contribution to ecological decline.

1. Introduction: Why are Ecological Footprints needed in Environmental Monitoring and Assessment?

Environmental Monitoring and Assessment programs such as those presented at this EMAP conference attempt to monitor temporal changes in the environment, and to assess their possible causes. Almost without exception, however, the monitoring tools which are used focus on specific and isolated conditions of the physical, chemical, or biotic "environment," ignoring the activities of the dominant (or "keystone") species, *Homo sapiens*. Yet human population size and consumptive behavior are often the ultimate source of the stressors which result in a degradation of ecological integrity in a location.

Since the early 1970s, one report after another has warned that unlimited growth of human population and consumption is not sustainable. Among the most prominent of these reports are *The Limits to Growth* (Meadows *et al.*, 1972), the Brundtland Commission's *Our Common Future* (WCED, 1987), and the Worldwatch Institute's annual *State of the World* publications. In spite of these warnings the human economy continues to expand, with more people, more consumption, more waste and more poverty, along with less biodiversity, less forest area, less available fresh water, less soil, less fossil oil in the ground and less protective ozone in the stratosphere (World Resources Institute, 1994, 1996; United Nations Development Program, annual). We seem to be getting further and

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further away from sustainability. But how far? Indicators of progress are needed. This paper presents one of them – the ecological footprint (Wackernagel and Rees, 1996), and shows how it can be applied as a planning and monitoring tool for sustainability.

Ecological footprint analysis is an area-based indicator (Rees, 1996) which quantifies the intensity of human resource use and waste discharge activity in a specified area in relation to the area's capacity to provide for that activity. Ecological footprint analysis is based on two assumptions. First, that it is possible to keep track of most of the resources that a human population consumes and most of the wastes that the population generates. Second, that these resource and waste flows can be converted to a biotically productive area necessary to provide the resources and to assimilate the wastes. The biotically productive area which performs these functions is termed the "ecological footprint" of the human population. Thus, ecological footprints quantify the biotically productive area that a population uses. Locations (nations, regions, states, watersheds, etc.) in which the ecological footprint of the resident human population is greater than the area which they occupy must be doing at least one of the following: receiving resources from elsewhere, disposing of some of its waste outside of the area, or depleting the area's natural capital stocks. To deplete natural capital stocks means to withdraw more ecological services than the biotic capacity of the defined area can regenerate; for example by harvesting timber faster than it can regrow or by discharging sewage at a rate faster than can be assimilated.

Attempts to estimate the biosphere's capacity to support human needs go back several centuries, and the debate continues (Cohen, 1995). These estimates are based on a variety of approaches. Many have assumed that human population size is limited by food, and have attempted to sum agricultural productivity in various regions of the earth to obtain total agriculturally productive area and capability. Others have considered limiting factors in addition to, or other than, food. Most estimates, however, attempt to determine human carrying capacity as the number of people that can be supported by a given area of the earth's surface. Ecological footprint analysis, on the other hand, inverts the process. Rather than asking how many people can live in an area, it estimates the area of the earth's surface required to support a given human population. For other terrestrial animal species the two approaches are equivalent and relatively invariant across subpopulations. For humans, however, the area required to support subpopulations is highly variable, because subpopulations differ greatly in their intensity of resource use and waste discharge. This variability has given rise to the erroneous assertion that human carrying capacity is meaningless.

The purpose of this paper is to explain a method for measuring how much ecological capacity humans use to sustain themselves, and to indicate how this method could be useful in an environmental monitoring and assessment context. To move toward sustainability – that is, to develop sustainability – a necessary step is to clarify what it means. Many confusing definitions and statements, including the one in the Brundtland report (WCED, 1987), have impeded progress. To sustain something means "to provide for its support or maintenance" (Webster's Third New International Dictionary, Unabridged, 1976). It also means "to continue without interruption or diminution." We therefore find it useful to define regional sustainability as *"the continuous support of human quality of life within a region's ecological carrying capacity."* By "support of human quality of life" we mean that people's subjectively perceived well-being (that is their physical and psychological comfort, including their health, security, and friendly connections to other people) must be at least maintained (or possibly improved, in the case of the poor). Otherwise, people could feel worse off as society moves toward sustainability. In addition, not living decently and equitably may cause conflict and degrade the social fabric. This would make the necessary cooperation unworkable. By "a region's ecological carrying capacity" we mean the ecological or biotic capacity within a region to regenerate used resources and to assimilate waste.

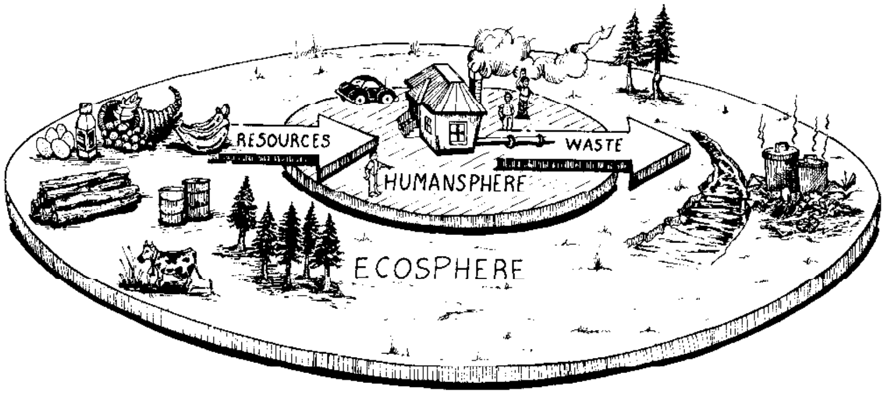

Fig. 1. People are part of nature. The humansphere is a dependent subsystem of nature. There are no activities of the human economy that fall outside of nature's economy. Nature supports humanity by dispensing resources, absorbing waste, and securing life-support services. (Illustration after Phil Testemale).

2. The conceptual basis of ecological footprints

People depend on the biosphere for a steady supply of the basic requirements for life: energy for warmth and mobility; wood for housing, furniture and paper products; fibers for clothing; quality food and water for healthy living; ecological sinks for waste absorption; and many non-consumptive life-support services. This human use of nature is termed the ecological footprint. Obviously, this footprint is not a continuous piece of land. Due to international trade, the land and water areas used by most global citizens are scattered all over the planet. It would take a great deal of research to determine where their exact locations are, assuming that an exact location could even be specified. To simplify comparisons among various regions of the earth, the occupied space is calculated by adding up the areas (using world average productivity) that are necessary to provide a human population with all the ecological services it consumes.

Every person, and every assemblage of people (e.g. a city or country), has an impact on the Earth. The ecological impact corresponds to the ecological footprint of the individual or assemblage. This use of nature includes the areas used for waste discharge assimilation, *and* the productive areas used for resource regeneration. The ecological footprint quantifies for any given population the mutually exclusive biotically productive area that must be in continuous use to provide its resource supplies and to assimilate its wastes. Area that is in continuous use to support one human population cannot simultaneously support another population without depleting natural capital stocks.

As mentioned above, ecological footprint studies build on a wide range of methods to assess nature's capacity to support human life. Apart from the early attempts (Cohen, 1995), much intellectual ground-work was laid in the 1960s and 1970s. Examples are Howard Odum's "emergy" analysis examining systems through embodied energy flows (Odum, 1994; Campbell, this volume), Jay Forrester's advancements on modeling world resource dynamics (Meadows *et al.*, 1972, 1992), John Holdren's and Paul Ehrlich's I=PAT formula (Holdren and Ehrlich, 1974), or, in the context of the International Biological Programme, Robert Whittaker's calculation of net primary productivity of the world's ecosystems (Whittaker, 1975, Lieth and Whittaker, 1975). The last ten years have witnessed exciting new developments: life cycle assessments (e.g., Abel *et al.*, 1990), lifestyle energy assessments (e.g., Hofstetter, 1991), environmental space calculations building on ideas of Johann Opshoor (Buitenkamp *et al.*, 1992), human appropriation of net primary productivity (Vitousek *et al.*, 1986), documentation of regional and industrial metabolisms (Ayres *et al.*, 1994), mass intensity measures such as Mass Intensity per Unit of Service MIPS (Schmidt-Bleek, 1994), measures of human processes such as the Sustainable Process Index SPI (Krotscheck and Narodoslawsky, 1996), national resource inventories (as performed by the Norwegians and the French), resource accounting input-output models (Duchin and Lange, 1994), computer based gradient models for analyzing land-use developments and ecological potentials (Hall, 1996), the "Polstar" scenario model (Gallopin *et al.*, 1997), and ecological footprint assessments (Wackernagel and Rees, 1996; Folke, 1996), to name just a few. Their applications and representations may vary, but their output is mostly the same: quantification of the human use of nature. As most of these approaches are compatible, results from one strengthens the others.

What differentiates the ecological footprint from other assessment methods is the way it interprets throughput analyses of human activities: it aggregates human impacts in an ecologically meaningful way, expressing them in mutually exclusive ecological spaces which are appropriated to provide the functions and services of nature. Therefore, we have also called the ecological footprint "appropriated carrying capacity." Of course, ecological functions that can be provided on the same space at the same time must only be counted once – otherwise the footprint overestimates the use of nature. This is why we refer to "mutually exclusive" biotically productive spaces. For example, in the case of doublecropping, photovoltaic use of roofs for energy supply, or water collection in a sufficiently humid timber plantation, only one utilization is added to the footprint. However, some forest uses are mutually exclusive. Biodiversity protection may depend on undisturbed ancient forests which cannot serve for timber-production without endangering biodiversity. On the other hand, recent research indicates that forests producing timber and agroforestry crops also may be credited with significant carbon dioxide (CO_2) sequestration in soils and long-lived forest commodities such as furniture or housing components (Moffat, 1997; Janzen, 1997).

This biogeophysical interpretation used by the ecological footprint concept has two advantages. First it makes the results more accessible. Everyone has experienced space, while many other quantities (like embodied energy content or erosion rates) may require more technical skills to interpret or to appreciate. Second, and more importantly, the human "demand" for ecological space can be compared easily to the earth's finite "supply" of space. The surface of the Earth is finite; therefore the available ecologically productive space must be finite. By providing the means of comparing human demand and nature's supply in the same units, the assessment results show clearly, at each geographical scale of analysis, the magnitude of the human load on the biosphere.

Fig. 2. The ecological footprint measures our use of nature. Every person, region or nation depends on ecological capacity to sustain itself. A population's ecological footprint corresponds to the aggregate land and water area in various ecosystem categories that is claimed by that population to produce all the resources it consumes, and to absorb all the waste it generates on a continuous basis, using prevailing technology. (Illustration: Phil Testemale).

3. Biotic productivity available on the Earth

Many human uses of nature compete for space. Land used for wheat production cannot be used for roads, forests or grazing, and vice versa. These mutually exclusive uses of nature are summed to assess the total ecological footprint. In this analysis, six main categories of ecologically productive area are distinguished: crop land, pasture, forest, ocean, built-up land and energy land:

Crop land is the land used to grow fruits, vegetables and grain for human consumption either directly, or indirectly by feeding it to livestock. Typically it is, from an ecological perspective, among the most productive land; it can grow the largest amount of human-consumable plant biomass per unit area. Today, there exists less than 0.25 hectares per capita worldwide of such highly productive land.

Pasture is grazing land for livestock, to produce dairy products and meat. Most of the 3.35 billion hectares of pasture, or 0.6 hectares per person, are significantly less productive than crop land. That is, its potential for accumulating biomass is much lower than that of crop land. In addition, conversion efficiencies from plant to animal reduce the available biochemical energy to humans by typically a factor of ten.

Forest refers to tree plantations or natural forests that can yield timber products. Of course, they may provide many other functions too, such as erosion prevention, climate stability, maintenance of hydrological cycles, and if they are managed properly, biodiversity protection. With 3.44 billion hectares covering the planet, there are 0.6 hectares per capita worldwide. Today, most of the remaining forests occupy ecologically less productive land.

Ocean covers 36.3 billion hectares of the planet, or a little over 6 hectares per person. Roughly 8 percent of this area, concentrated along the continental coasts, provides over 95% of the sea's ecological production. In per capita terms, there are 0.5 hectares of ecologically productive sea space out of these 6 hectares ocean. Measuring the ecological activity of the sea by its area (and not its volume as one might intuitively think) makes sense ecologically. It is surface which limits its productivity, as both the capturing of solar energy and gas exchanges with the atmosphere are proportional to surface area.

Built-up land refers to land used for human settlements and roads and consists of approximately 0.03 hectares per capita worldwide. As most human settlements are located in the most fertile areas of the world, *built-up land* often leads to the irrevocable loss of significant amounts of ecological capacity.

Energy land is the land that would be required for sequestration of CO_2 released by fossil fuel combustion. Alternately, it is the land area that would be required to accumulate an equivalent amount of usable energy via wood biomass. This latter approach would require a larger land area than for CO_2 absorption, because not all accumulated biomass would be usable for energy. Currently, no land is used exclusively to sequester CO_2 or to replenish the biochemical energy stock lost through fossil fuel burning (but see Moffat, 1997; Janzen, 1997).

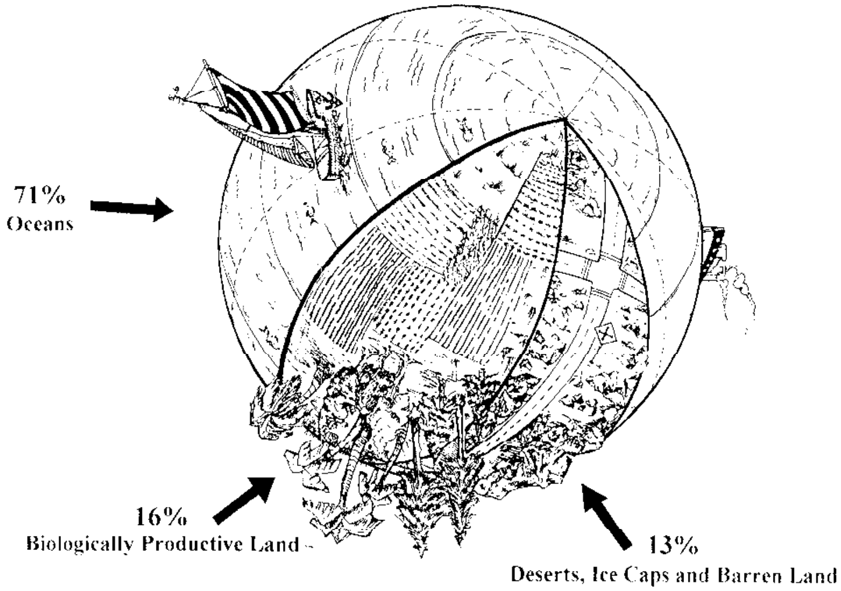

Fig. 3. The biotically productive areas on our planet. The Earth has a surface area of 51 billion hectares, of which 36.3 billion are sea and 14.7 billion are land. Only 8.3 billion hectares of the land area are biotically productive for human use. The remaining 6.4 billion hectares are marginally productive or unproductive for human use, as they are covered by ice, have unsuitable soil conditions or lack water. (Illustration after Phil Testemale).

4. A reference point for sustainability: ecological space per global citizen

Adding up the biotically productive land per capita worldwide; 0.25 hectares of arable crop land, 0.6 hectares of pasture, 0.6 hectares of forest and 0.03 hectares of built-up land; shows that there exist approximately 1.5 hectares per capita, or 2 hectares per capita including ecologically productive sea space. However not all that space is available for human use, as this area must also provide for the millions of species with whom humanity shares the planet. The World Commission on Environment and Development proposed to set aside for biodiversity protection at least 12 percent of the earth's ecological capacity, representing all ecosystem types. Although 12 percent may not be enough for securing biodiversity in the long term (Noss and Cooperrider, 1994), conserving more at this time may not be politically feasible.

If we accept 12 percent as a minimum number for biodiversity preservation, one can calculate that from the approximately 2 hectares per capita of biotically productive area that exist on our planet, **only 1.7 hectares per capita, at most, are available for human use.** These 1.7 hectares become the ecological benchmark for comparing ecological footprints.

It is the current ecological reality. Therefore, to achieve sustainability with current population numbers, the average footprint needs to be reduced to at least this size. If some people need or demand much more ecological capacity, then in a sustainable world economy others must use much less than the average amount available. Assuming no further ecological degradation, the amount of available biotically productive space will drop to approximately 1 hectare per capita if the world population reaches its predicted 10 billion. If current growth trends persist, this will happen in little more than 30 years.

5. Using the U.S. as an example: the calculation procedure for assessing national footprints

As indicated, footprints can be calculated at every scale: from global, national, regional, and municipal down to household size. In fact, footprint studies exist for each of the mentioned scales. To demonstrate the mechanics of these calculations, a national case is presented here.

Earlier national footprint calculations were much cruder and more simplified estimates, using an eclectic variety of data sources (Wackernagel *et al.*, 1993; Neumann, 1995; Wackernagel and Rees, 1996; Graszl, 1996). As they were still first attempts, they did not follow a consistent methodology. Subsequently, Wackernagel *et al.* (1997) have developed more consistent and complete national calculations in the form of spreadsheet-based yearly accounts of the resource flows of a nation. The presented example shows the U.S. footprint for 1993, the latest year with a complete United Nations data set available when the study was completed early in 1997 (see Table 1). Mainly United Nations data were used for this assessment to make countries comparable among themselves. These current estimates show larger footprints than previously, as consumption is documented more completely and as productivity data for forest and pasture are lower than assumed in earlier estimates. In fact, the presented calculations lead in the case of the U.S. to footprints that are about one quarter larger than the ones presented in Wackernagel and Rees (1996).

The full spreadsheet for the United States contains 120 lines and 14 columns. Table 1 presents a condensed version for illustrative purposes.

The spreadsheet is composed of three main areas. The upper part consists of a consumption analysis of over 20 main resources. The rows represent resources or product types. The columns specify the productivity, production, import, export and consumption of these resource or product types. Consumption is calculated by adding imports to production and subtracting exports. Using estimates from the Food and Agriculture Organization of the United Nations (FAO) of world average yield, consumption and waste absorption are translated into appropriated ecologically productive area. In other words, the consumption quantities are divided by their corresponding (world average) biotic productivity which gives us the land and sea areas necessary to sustain this consumption. These areas form a part of the total footprint.

Table I

Calculation of the American's average Ecological Footprint (1993 data)

population of the United States of America: 258,262,000

LAND AND SEA AREA ACCOUNTING			(biotic resources)					
CATEGORIES	*Yield*	*Production*	*Import*	*Export*	*Consumption*	***Footprint component***		
units if not specified	[kg/ ha] (global average)	[t]	[t]	[t]	[t]	[ha/cap]		
FOODS								
.meat (average animal units)	74	31,277,000	1,211,559	2,129,258	30,359,300			
meat (fresh)			977,112	1,946,500				
..bovine, goat, mutton, buffalo	33	10,737,000	714,840	412,305	11,039,535	1.302	pasture	
..non-bovine,-goat, mutton, buffalo		20,540,000	496,719	1,716,953	19,319,765	(already in cereals)		
.dairy (milk equiv.)		68,303,000	1,521,211	7,127,226	62,696,985	0.483	pasture	
..milk	502	68,303,000	37,891	5,734,796				
..cheese	50		146,091	18,522				
..butter	50		2,241	120,721				
.marine fish	29		consumption in [kg/cap]		33	1.137	sea	
.cereals	2,744	258,952,000		100,659,208	158,292,792	0.223	arable land	
..wheat				35,666,000	(35,666,000)			
..maize				40,365,000	(40,365,000)			
.animal feed	2,744			18,758,000	(18,758,000)	-0.026	arable land	
.veg & fruit	18,000	63,040,000	11,259,373	8,073,933	66,225,440	0.014	arable land	
.veg etc			2,480,020	2,676,121				
..fresh fruit			5,367,738	3,430,552	1,937,186			
.roots and tubers	12,607	19,949,000	323,229	244,680	20,027,549	0.006	arable land	
.pulses	852	1,265,000	80,601	469,545	876,056	0.004	arable land	
.coffee & tea	566	500	2.187.899		2,188,399	0.015	arable land	
.cocoa	454				625,917	0.005	arable land	
.sugar	4,893	6,964,000	1,784,840	321,280	8,427,560	0.007	arable land	
.div.food	2,744			490,878	(490,878)	-0.001	arable land	
.oil seed (incl. soya)	1,856	63,340,000	505,696	2,388,813	61,456,883	0.128	arable land	
TIMBER(roundwood equivalent,m3)	1.48	449,150,000	103,565.960	72,943,407	479,772,553	1.255	forest	
.roundwood [m3/ha,m3]	*waste factors*	495,800,000	2,406,000	26,680,000	471,526,000		*final use*	
.fire wood	0.5	93,300,000	597,000	261,000	93,636,000	10	% of cons.	fire wood
.direct roundwood consumption [m3]	1				9,900,000	2	% of cons.	mines
.sawnwood [m3]	1.65	106,167,000	36,489,000	9,411,000	133,245,000	46	% of cons.	sawn wood
.wood based panels [m3]	2.48	31,568,000	5,446,000	3,359,000	33,655,000	17	% of cons.	panels
.wood pulp [t]	1.98	58,310,000	4,915,000	5,961,000	57,264,000		(not a final use)	
.paper and paper board [t]	1.47	77,250,000	11,885,000	7,146,000	81,989,000	25	% of cons.	paper
OTHER CROPS								
.tobacco	1,548	3,512,000		1,240,556	2,271,444	0.009	arable land	
.cotton	1,000				2,176,245	0.008	arable land	
.jute	1,500				76,686	0.000	arable land	
.rubber	1,000				842,954	0.003	arable land	
.wool	15				104,693	0.027	pasture	
.hide	33				459,663	0.054	pasture	

ENERGY BALANCE:				
	100 [Gj/ha/yr]	**fossil and nuclear energy consumption**	**313**	**[Gj/yr/cap]**
	1,000 [Gj/ha/yr]	**hydro-electricity consumption**	**4**	**[Gj/yr/cap]**
	100 [Gj/ha/yr]	**energy embodied in net import**	**6**	**[Gj/yr/cap]**

SUMMARY

DEMAND		***SUPPLY***			
FOOTPRINT (per capita)		**EXISTING CAPACITY WITHIN THE U.S.A. (per capita)**			
Category	**[ha/cap]**	**Category**	**yield factor**	**local area [ha/cap]**	**yield adjusted area [ha/cap]**
fossil energy	**3.23**	**CO2 absorption land**		0.00	**0.00**
arable land	**0.43**	**arable land**	1.56	0.73	**1.14**
pasture	**1.84**	**pasture**	1.92	0.93	**1.78**
forest	**1.26**	**forest**	2.72	1.11	**3.02**
built-up area	**0.61**	**built-up area**	1.56	0.39	**0.61**
sea	**1.14**	**sea**	1.00	1.24	**1.24**
TOTAL used	**8.49**	**TOTAL existing**		4.38	**7.77**

OTHER INDICATORS (all in [ha/capita] with world average productivity)

footprint on the land:	**7.35**	**available capacity within the U.S.A. (incl. sea space):**	**6.84**
existing land within the U.S.A.:	**6.54**	**national ecological deficit:**	**1.65**

The middle part of the table provides an energy balance of the traded goods. Such an analysis is necessary to adjust the energy directly consumed within the country by the amount of energy that was previously consumed in producing the exported and imported goods. This traded energy is calculated by multiplying, for each trade category, the amount of net import by the typical embodied energy of these commodities. Particularly for small countries, embodied energy in net imports can be a significant portion of the consumed energy. To keep the table simple, only the net result of this energy trade analysis is listed in Table I.

In the bottom part, the results are summarized in two boxes. Here all of the footprint components are added to obtain the total footprint. The left box itemizes the ecological footprint in six ecological categories and gives the total. The results are presented as *per* *capita* figures. Multiplying the per capita data by the country's population gives the total footprint of the nation. The right box shows how much biotically productive capacity exists within the country. Worldwide, there exist 2 hectares of ecologically productive space per person, as mentioned above, and with a 12% set-aside for biodiversity protection, only 1.7 hectares are available for human use. However, some countries are better endowed with ecological productivity by having either more space available and/or ecosystems and agroecosystems of higher productivity per unit area. Therefore, to document the ecological production available within a country, the number of physical hectares of biotically productive area that exist in each ecological category within the country (second column in the right box) is multiplied by the factor by which the country's ecosystems differ in productivity from the world average (first column in the right box). We call this factor the "yield factor." A yield factor of 1.5 would mean that the local productivity is 50 percent higher than world average – absorbing 50 percent more CO_2 or producing 50 percent more potatoes per hectare. A yield factor smaller than one indicates that the area is less productive than world average. Multiplying the yield factors by the number of physically existing hectares gives an equivalent area with world average productivity. This area we identify as the "yield adjusted area" (third column in the right box).

For example, the U.S. yield factor for arable land is assessed to be 1.56 based on the U.S. yield of cereals as compared to world average. The U.S. yield factor for forest is assumed to be 2.72. It is extrapolated from European yields as we have been unable so far to find a reliable estimate of sustainable timber yield in the U.S..

From the 7.77 hectares per person of existing yield-adjusted area, 12 percent is subtracted to get 6.84 ha/capita of locally available capacity. This area is a measure of the biotic capacity in the US. The number is listed at the bottom under "other indicators." With this adjustment, both footprints and ecologically productive spaces (or capacities) are expressed in the same units: in areas with world average productivity. Footprints and available capacity can now be compared among all nations of the world.

In this presented case study of the average U.S. citizen, the calculations show a footprint of 8.49 hectares. This means that over eight hectares of biotically productive space (based on world average productivity) must be in constant production to support the average United States citizen. This footprint occupies five times more space than the available 1.7 hectares per world citizen. Only countries with footprints lower than 1.7 hectares per person have a global impact that could sustainably be replicated by everybody; that is, without depleting the natural capital stock of the earth.

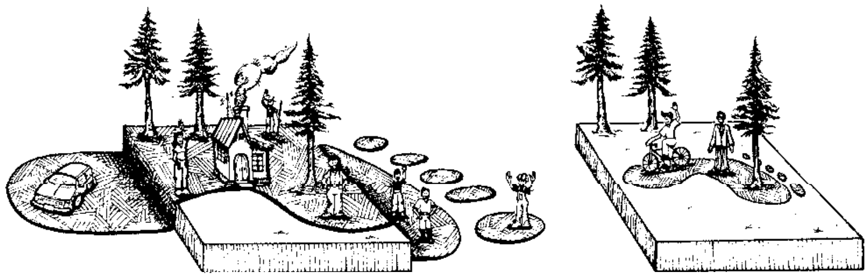

Fig. 4. National ecological deficits. The ecological footprint measures how much ecological capacity people occupy. Through the magnitude of their economic activity, some regions claim more ecological capacity than there is within their boundaries. This means that the region runs an ecological deficit. Consequently, the local population needs to import the missing ecological capacity -- or deplete their local natural capital stocks (on the left). Regions with footprints smaller than their capacity live within their nation's ecological means (on the right). Often, however, the remainder is used for producing export goods which partially cover the deficits incurred by other regions.

While the ecological footprint shows the global impact of local consumption, it may also be of interest to determine to what extent local ecological productivity could provide for local consumption. Therefore Wackernagel *et al.* (1997) compared the ecological footprints of 52 large countries in the world with the biotically productive space available within the country. If the footprint exceeds the available biotically productive area of the country, as in the U.S. example presented here, it runs a national ecological deficit. In that case, the country's area alone cannot sustainably provide sufficient ecological services to satisfy its population's current patterns of consumption. Consequently, as mentioned above, they need to either import services or deplete their natural capital stock. The United States is fortunate to have available 6.8 hectares of ecologically productive space per citizen. For the U.S., consequently, the national ecological deficit is 1.7 hectares per person (8.5 ha US footprint less 6.8 ha available in the U.S.). The U.S. global ecological deficit is even larger: 6.8 hectares per person (8.5 ha U.S. footprint less 1.7 ha available in the world). In comparison, the world as a whole with an average footprint of 2.3 hectares per capita and an available space of 1.7 runs a deficit of 0.6 hectares per capita (Wackernagel *et al.*, 1997). As the world cannot import ecological capacity from somewhere else, this global deficit corresponds to an unsustainable ecological overuse: more timber cut than can reproduce, more CO_2 released than can be absorbed, etc.

The above study by Wackernagel *et al.* (1997) showed that there are only ten countries whose citizens use less than the amount available on a worldwide per capita basis. In other words, if all people of the world adapted the lifestyle of the first 43 countries, the world's ecological assets would be rapidly depleted. Footprints beyond per capita available world capacity show local contribution to global ecological decline. The national ecological deficit shows that 41 of the countries examined consume beyond national ecological capacity. This national ecological deficit becomes an indicator of potential vulnerability to external instabilities.

6. Some Environmental Monitoring and Assessment applications

National calculations are just starting points for more comprehensive sustainability studies. Monitoring footprint assessments over time could reveal progress toward sustainability by tracking a country's or a region's ecological deficit. The paper by Ko *et al.* in this volume shows such a possible study (1997). Such monitoring analyses and assessments can indicate to what extent economic and demographic change have expanded or contracted a nation's or region's footprint. They thereby become indicators of countries' (in most cases increasing) potential vulnerability to economic dislocations and their contribution to global ecological decline. For most countries, these time series could be calculated with comparatively little effort as most of the necessary data can be found in already existing statistical collections of each nation. The appropriate data would only have to be fitted into the ecological footprint accounting framework explained above.

At the sub-national level, particularly for regions or watersheds that live directly from local resources, accounting for local natural capital becomes vital. For managing these resource-exporting or subsistence economies, decision-makers need to know how much natural capital is available for use within their region and how much, if any, is available for export. With the gradual extension of the global economy, a community's security may no longer be provided by government institutions. Further, for most countries the value of monetary savings is diminishing rapidly as their currencies lose purchasing power. For the majority of the people living in these countries, monetary savings are therefore also an unreliable option for securing their long-term well-being. In lack of institutional or market support, local natural capital therefore becomes the ultimate source of security and wealth. Thus nature preservation, such as erosion control, reforestation, or decontamination, becomes not merely an altruistic deed but a necessary investment strategy for the local community to ensure a better and more secure future.

Watershed or ecoregional (Omernick, 1987) assessments would start from an inventory of the ecologically productive spaces in the watershed or ecoregion. Ecoregional assessments, where ecoregion designations are available, have the advantage of relatively uniform ecological productivity throughout the region. In fact, this is one of the distinguishing characteristics of ecoregions. Geographic Information Systems (GIS) may be useful to capture the dimensions of all the ecologically productive space categories and to register their respective productivities and uses. Such a survey would provide an estimate of the local ecological capacity – the supply side. The demand side, that is the footprint of the local population, can be documented with various degrees of precision. Given an estimated per-capita demand for ecosystem services, and the productivity of the ecoregional categories in a watershed or other region, an estimate of the human carrying capacity deficit or excess of the region could, in principle, be obtained. If comparable watershed or ecoregional assessments were conducted over a gradient of ecological capacity and of human population footprint, it may even be possible to correlate carrying capacity deficits with more traditional indicators of ecological integrity.

A first estimate of per-capita demand may be extrapolated from the national footprint assessments. For more precision, the national per capita footprint can be adjusted according to the differential between national and local purchasing power. For even finer scaled analyses, consumption patterns of households representing the basic income categories need to be surveyed.

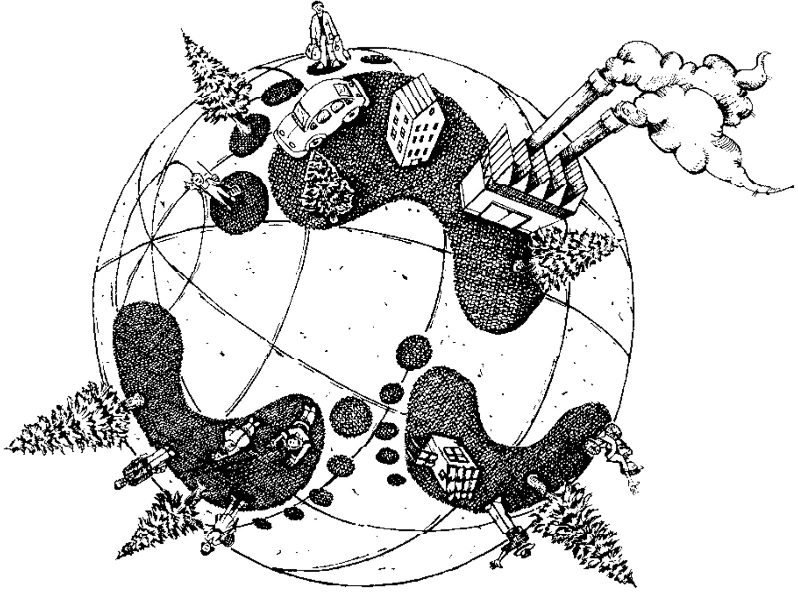

Fig. 5. Humanity's ecological impact. Every individual human has an impact. Is nature able to cope with humanity's cumulative impact? Our calculations show that the ecological footprint of humanity is already larger than the biotically productive space on the planet (Wackernagel et al., 1997). This overshoot results in costly degradation and erosion of natural capital. The ecological footprint offers a tool to measure this overuse and helps us plan for a sustainable future where people's quality of life can be supported within the carrying capacity of nature.

A "production footprint" can be determined, in addition. While the conventional ecological footprint answers the question of how much ecological capacity is necessary to support a population's consumption (with all its associated resource use and waste generation), the "production footprint" analyzes the ecological capacity necessary to keep the population's economic production running. This corresponds to the ecological functions and services required to generate the population's income so they can purchase their consumption. To illustrate, consider the example of an industrialized farm that sells all its products to the market. All the fields, plus the resources to work and harvest them, correspond to the farm family's production footprint – the natural capacity necessary to sustain their income. Their consumption footprint, however, would correspond to their private garden with their home grown vegetables plus the area required to generate all the food, furniture, medical bills and other consumption goods and services that they buy. Similarly, resource-exporting regions may give up significant amounts of ecological capacity while receiving little capacity in return via imported products. This becomes manifest in the discrepancy between a population's or region's consumption footprint and their production footprint. Such differences point to ecological leakages. These leakages represent potentials for improving the local standard of living by using the local natural capital more effectively.

Current ecological footprint assessments still omit some uses of ecosystems for resource production and waste absorption. Therefore, new developments in the footprint research will focus on making the calculation method more complete. Particularly in arid countries, fresh water supply becomes a critical resource that should be covered by footprint studies. There, human settlements, agriculture and other ecosystems compete for this resource (Pimentel *et al.* 1997). Water is appropriated for human use at high energy costs and often with significant ecological impacts. Some areas are used exclusively to catch water for domestic use (as is done in many areas to ensure the delivery of healthy water). Areas that are dedicated to absorb human waste water are additional ecological spaces that should be added to new footprint assessments. If water is withdrawn from surface freshwater ecosystems for human consumption, thereby reducing ecological productivity, an ecological area necessary to compensate for this loss needs to be included. If groundwater is used beyond its recharge rate, negative ecological effects may not be felt immediately. One possible way of calculating the footprint of groundwater use may be to assess the resource costs that would be associated with restoring the original groundwater level (e.g., by getting water from an area with surpluses). Further, the ecological capacity to provide the infrastructure and operational energy for water withdrawal, transport, distribution and cleaning represents additional ecological capacity to be added to the footprint of a human population.

Examples of ecologically productive area appropriated for human freshwater use include: the 0.27 to 0.37 hectares of land per capita set aside in typical Australian cities to collect domestic fresh water (Foran in Wackernagel and Rees 1996); the "Three Gorges Dam" hydroelectric power project on the Yangtze River in China which is trading off ecologically productive area in return for electricity (World Resources Institute 1994); the extraction of water from rivers supplying the Aral Sea, with loss of marine productive area and salinization of land irrigated by the extracted water (World Resources Institute 1996); reservoirs in the western United States accompanied by salinization problems (WRI 1996); and ground water depletion in Mexico City where pumping rate exceeds natural recharge rate by 50 to 80 percent (Postel 1996). In other cases, ecologically nonproductive desert areas may become productive by irrigation which avoids waterlogging and salinization (as in the Ladakh valley, or in some areas of Israel and California).

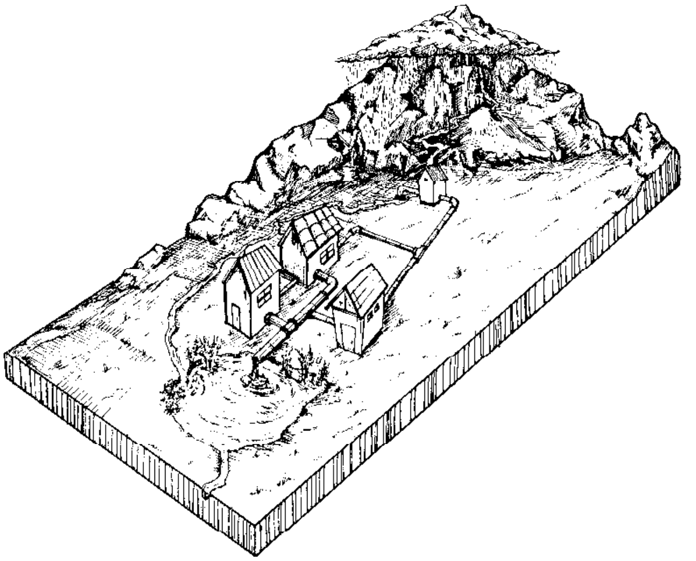

Fig. 6. The water footprint. Domestic water use occupies various ecological spaces: (a) exclusive areas to capture the water, or to compensate lost ecological productivity caused by excessive water withdrawal from an ecosystem, (b) embodied resources in the construction and operation of infrastructure to transport, distribute and dispose the water, and (c) ecological spaces (or human infrastructure) to assimilate and clean the waste water.

In addition to the area appropriated for fresh water or hydropower supply, the ecological impacts of contamination and waste streams are only partially included in current assessments. In current footprint calculations, the major waste stream included in current assessments is the land required to sequester CO_2 from fossil fuel burning. While marine ecosystems are also potential sinks for CO_2, here we focus on terrestrial ecosystems. However, considering the limited ways in which marine ecosystems can be successfully manipulated, the sea's potential as an additional CO_2 sink is questionable (see also Sarmiento and Le Quéré, 1996). Reforestation is therefore the most effective strategy for CO_2 absorption (Moffat, 1997).

Once the use of fresh water is added to the footprints, the appropriation of area by assimilation of waste water would show up as part of the occupied ecological space. Still, the ecological footprint of areas lost due to soil contamination, as manifested, for example, in industrial areas of the former Soviet Union, in radioactively contaminated areas such as Chernobyl, in soil salinization, or in the many cases of acid rain all over the world are still left out due to lack of data. Such contamination can reduce ecological productivity significantly or make products of nature unfit for human use. In the case of regional assessments, data may be available on locally contaminated areas as well as on the amounts of locally discharged contaminants (like SO_x or trophospheric ozone) leaving the region and impacting ecological productivity elsewhere. For example, ozone levels of 200 micrograms per cubic meter may reduce agricultural yields up to 15 percent, according to a Swiss government publication (Baudepartement Basel-Stadt, 1997). Also, the impacts of local solid waste on water, its potential for soil contamination, and the resources necessary for their management, for example in "Superfund" contaminated sites such as Love Canal in the USA (Rosenbaum, 1995) can be incorporated in local assessments if local information is available. These contaminated areas could be added to the "built-up" category as it is no longer useful to people for ecological services.

We could improve accuracy by analyzing fossil energy in finer categories. For example, compared to liquid fossil fuel the CO_2 release per energy unit for natural gas is approximately 25% lower and for coal 25% higher. Also, activities which release greenhouse gases should be included more systematically. Hydroelectricity could be analyzed more specifically to get a more accurate conversion figure (even though in most examples, hydroelectricity occupies only a small percentage of the total footprint). Furthermore, traded goods should be accounted for not only in terms of embodied energy but also according to their embodied material resources and waste discharges.

The merit of our current footprint calculation method is its easy replicability. It is sufficiently detailed to give a general indication of the magnitude of human impact globally. Also, by using the same assumptions for all assessments, the results of all countries are comparable in relative terms.

Current numbers probably underestimate ecological footprints. First, they use forest and agricultural productivities that are doubtlessly too high, at least for the long run. Industrial forestry and agriculture with its high yields may not be sustainable over long periods of time due to erosion and soil depletion. In poorer countries, UN statistics may underestimate production and hence footprint area as they may not capture adequately direct consumption and secondary crops in agricultural production. Second, present footprint calculations leave out various additional ecological functions such as water use and water-borne waste assimilation. These uses may add significant area to the footprint as it is now calculated. Furthermore, there are also clear limits to the accuracy of the presented footprint assessments. Within the current methodological approach, additional uncertainties arise from the lack of differentiation between the carbon intensity of the various fossil energy sources, and from the embodied energy figures and UN statistics which are not equally accurate for each nation. Even within the UN publications, Wackernagel *et al.* (1997) found discrepancies between the same data reported in different publications while preparing their "footprints of nations" study. However current estimates provide a first reference point. In this way, these national calculations offer an analytical framework that may be useful at the regional level and provide benchmark results with which to compare regional analyses.

7. Conclusions

The ecological footprint is designed to provide an area-based indicator of the extent of the human appropriation of nature's goods and services relative to what is available for appropriation. Quantification of the available ecological productivity which is appropriated by categories of human use provides information on where excess appropriation can be reduced. The figures should not lead merely to a more informed discussion of our challenges ahead, but more importantly, such assessments can help governments, businesses and NGOs shape sustainable development. The measure shows where we are, in which direction we need to go, and which projects and programs most effectively move us there. In more specific terms, these biophysical assessments can assist sustainability efforts on various levels. They:

- **Offer a measure of carrying capacity available for human use.** Many countries and other subdivisions of the earth live on footprints larger than what their own ecosystems can provide. This frames the sustainability challenge: if we wish to secure well-being to people for some generations to come and avoid human suffering caused by an ecological down-turn, we need to live again within our ecological means. Footprint assessments would give us an indication to what extent humanity's economic activities would have to become less resource consumptive and less contaminating. Also, it helps us to comprehend the ecological impact of humanity's growth trends.
- **Become an indicator of sustainability.** Not knowing what is sustainable, not knowing where we are or where we are going makes the future more risky. In contrast, understanding our ecological constraints and identifying future risks supports informed decision making. This reduces threatening uncertainties and points to new opportunities.
- **Integrate concerns about the relative importance of human population and consumption.** The numbers show the impact of both population level and per-capita consumption rates. Clearly, the high level of consumption in industrialized countries takes the biggest share of the planet's bounty. But with ever larger populations it becomes less likely that everyone's quality of life can be secured.
- **Provide a target for assessing progress.** Essentially, the sustainability debate reduces to the fact that there are on average only 1.7 biotically productive hectares available per person on this planet. Population growth and ecological deterioration are steadily reducing this area. The key question is therefore: can a high and attractive quality of life for everyone be obtained out of 1.7 hectares? Experiments and case studies to highlight this question and show how it might be possible to live within these limits would be helpful.

Ecological footprint assessments demonstrate that sustainability can be measured. The ecological footprint indicator shows clearly where we are and where we need to be. Ecological examinations as presented here can give direction for local, national and global efforts to close the sustainability gap. They become an effective planning tool and a guidepost for a more secure, equitable and sustainable future.

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