Ecological Footprint

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Introduction

Ecosystems provide many critical services to human society, including both the direct provision of goods, such as food and fiber products, as well as less-visible services, such as water filtration and climate stabilization. The availability of these ecosystem services depends closely on the functioning of biological capital. Broadly defined, biological capital consists of all of the ecosystems and various components of the biosphere that directly or indirectly provide goods and services. Careful management of this capital is central to maintaining not only the health of the natural environment but also human well-being into the future.

Managing biological capital, however, requires tools that are able to track its availability and its use. The Ecological Footprint is an accounting tool that calculates human demand on the biosphere, and compare this to the planet's ability to meet these demands. By answering the specific research question, "how much of the Earth's regenerative capacity is occupied by human activities?," footprint analysis helps governments, businesses, and individuals track the use and availability of biological capital over time. Similar to financial balance sheets, the resulting ecological accounts can be used as a quantitative input into decision making at all levels.

Metabolism: An Ecological Model of Society

The Ecological Footprint applies principles of ecology to human society to create a framework for mapping society's metabolism. In a generalized ecosystem model, primary producers fix energy from sunlight through photosynthesis. This energy is then available for consumers, who use this primary production for growth and maintenance activities. All material ingested by consumers, however, eventually returns to the biosphere as waste products, where it is broken down and recycled back into the raw materials for primary production.

This model, where every input eventually turns into waste, holds for any organism that exists in a natural environment, including human society. The human economy takes high-quality matter and energy as inputs from the environment and returns these in degraded form as material waste and heat. Societies consume resources in order to maintain themselves. Between resource intake and waste discharge, matter accumulates in these systems, leading to increased body mass in the case of animals, or an accumulation of material stocks in societies.

From a human perspective, the ability of the biosphere to absorb wastes and regenerate resources is known as the regenerative capacity of the planet. Although the Earth's regenerative capacity is robust, it can be eroded in three significant ways, according to *The Natural Step*:

1. Natural cycles can be overwhelmed by harvesting renewably generated resources, such as trees or fish, faster than they can be replenished. Direct physical interference, such as the paving over of green surfaces or farming practices that cause soil erosion, can also damage the underlying capital that creates these resources, further reducing the Earth's total regenerative capacity.
2. Substances produced by society that are persistent and do not readily break down, and which ecosystems have not developed abilities to assimilate, can compromise regenerative capacity as they accumulate in the biosphere. Examples include synthetic chemicals such as DDT and PCBs. Many of these man-made substances have no natural analogs, and the biosphere as a whole has not evolved efficient means to break down and re-assimilate these products on human timescales.
3. Substances normally buried deep with the Earth's crust can be extracted, refined, and introduced into the biosphere at quantities that ecosystems are not able to assimilate. Examples include heavy metals, radioactive elements, minerals, and mined carbon. Because there are few natural cycles that can return these substances to the crust within human time spans, these substances systematically accumulate in the biosphere.

The fundamental insight of the metabolism model is that, in the long term, the biosphere must be able to turn wastes back into resources faster than the human society turns the resources into waste. If the extraction of resources becomes too large, or if nature's regenerative capacity is compromised, biological capital will be systematically degraded and wastes will accumulate.

While in the past, most 'environmental' problems arose from poor management of some local aspects of society's metabolism, such as careless waste disposal, smokestacks, or overuse of a river basin, now the very size of society's global metabolism that has become the overarching concern. While local overuse of the biosphere has a long history (e.g., overfishing, deforestation, soil erosion), the global human economy has now become so large, relative to the regenerative capacity of planet Earth, that it is now for the first time in human history confronting global limits.

Fundamental Assumptions

In order to provide a quantitative answer to the research question of how much regenerative capacity is required to maintain a given resource flow through human society, Ecological Footprint analysis uses a methodology grounded on six basic assumptions:

1. *The annual amounts of resources consumed and wastes generated by countries are tracked by national and international organizations.* Most countries have extensive annual statistics documenting their resource use, particularly in the areas of energy, forest products and agricultural products. United Nations agencies, like the Food and Agriculture Organization (FAO), compile many of these national statistics in a consistent format.
2. *The quantity of biological resources appropriated for human use is directly related to the amount of bioproductive land area necessary for regeneration and the assimilation of waste.* Bioproductive processes are associated with surfaces that capture sunlight for photosynthesis. Even three-dimensional processes that represent layers of such surfaces, as in aquatic ecosystems or rainforests, can be mapped on the two-dimensional area.
3. *By weighting each area in proportion to its usable biomass productivity (i.e., its potential annual production of usable biomass), the different areas can be expressed in terms of a standardized average productive hectare.* This unit is referred to as a global hectare, a hectare of surface area with world-average useful biological productivity.
4. *The overall demand in global hectares can be aggregated by adding all mutually exclusive resource-providing and waste-assimilating areas required to support the demand.*
5. *Aggregate human demand (Ecological Footprint)and nature's supply (biocapacity) can be directly compared to each other.* By using the standardized unit of a global hectare, demand and supply can be compared, as can different components of demand and supply.
6. *Area demanded can exceed area supplied.* A footprint greater than available biocapacity at any given scale indicates that demand exceeds the regenerative capacity of existing biological capital. This condition, known as 'overshoot', is possible in the short term, as resources can be harvested faster than they regenerate (e.g., deforestation) and wastes can accumulate (e.g., carbon dioxide in the atmosphere). In the long term, however, such overshoot leads to increasing risks of ecological degradation or collapse.

Ecological Footprint and Biocapacity Accounting

Ecological Footprint analysis examines the size of society's metabolism with a specific research question: how much of the regenerative capacity of the biosphere is being occupied by human activities? To answer this question, footprint analysis measures how much biologically productive land and water area an individual, a city, a country, a region, or humanity uses to produce the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management schemes.

This demand can be compared with supply, or biocapacity, the total available biologically productive surface of the planet. The common unit used for this analysis, as the term 'footprint' suggests, is a global hectare, one hectare of land or sea with world-average biological productivity.

Calculating Demand: Footprint

At present, human demands on ecosystems, a population's footprint, are translated into demands for six major land types – cropland, grazing land, fishing grounds, forest, built-up land, and 'carbon land' (**Table 1**). The first four

Table 1 Major land types in Ecological Footprint and biocapacity accounting. The biocapacity associated with emissions of carbon dioxide is represented by forest land

Ecological Footprint	*Biocapacity*
Cropland	Cropland
Grazing land	Grazing area
Fishing grounds	Fishing grounds
Forest	Forest
Built-up land	Built-up land
'Carbon land'	NA

From Global Footprint Network (2005) National Footprint Accounts, 2005 edition. Available at http://www.footprintnetwork.org.

of these land types produce food, fiber, and timber products for human consumption. These products may be consumed directly or processed further before final consumption. Regardless of the forms they eventually take within society, however, all products produced from these four land types can be translated, through the use of yields (annual tonnes per hectare) and conversion factors (tonnes of processed product per tonnes of raw material), back into the amount of area required to produce the products. This land and water area can be located anywhere on the planet.

The fifth land type, built-up land, represents the area required for the physical infrastructure associated with human society, such as cities and roads. The sixth land type, carbon land, represents the amount of biologically productive space required to absorb one of the human economy's most significant waste products: carbon dioxide. This footprint is currently calculated as the amount of forested area required to sequester a given amount of carbon dioxide, effectively removing it from the atmosphere, after accounting for absorption by the oceans.

This approach of translating fossil fuel use into bioproductive area does not suggest that afforestation or other types of biological sequestration are the solution to reducing atmospheric carbon dioxide concentrations. These measures do show, however, how much larger the biosphere would need to be to stabilize carbon dioxide concentrations in the atmosphere without further human intervention. The 2005 Edition of the National Footprint Accounts, for example, calculates that in 2002 the release of one tonne of carbon dioxide per year has a footprint of approximately 0.27 global hectares. Other human-supported methods exist for sequestering carbon dioxide, and the use of these technologies will be reflected in a decrease in the energy footprint as they are brought on line. Similarly, the introduction of renewable energy technologies with lower carbon intensities will also lead to a reduced carbon footprint.

Calculating Supply: Biocapacity

Human demand, or footprint, can be compared to the total availability of biologically productive land and sea, or biocapacity. Biocapacity is currently measured in five major land types (**Table 1**), analogous to the six land types of footprint with the exception of 'carbon land' (the regenerative capacity available for sequestering carbon dioxide emissions is included in the other major land types).

Globally, footprint analysis identifies, for 2002, approximately 11.2 billion hectares of biologically productive land and sea that can provide economically useful concentrations of renewable resources. These 11.2 billion hectares cover just under one quarter of the planet's surface and include 1.5 billion hectares of cropland, 3.5 billion hectares of grazing land, 3.6 billion hectares of forest, 2.3 billion hectares of marine and inland fisheries, and 0.2 billion hectares of built-up land.

These areas concentrate the bulk of the biosphere's regenerative capacity. There are not yet concrete estimates of precisely how much of the total usable annual biomass generation or net primary production is concentrated on these 11.2 billion hectares, but the number is likely not lower than 80% or possibly 90%. While the remaining areas of the planet are also biologically active, such as the deep oceans or deserts, their renewable resources are not concentrated enough to be a significant addition to the overall biocapacity.

Many materials and pollutants place demands on the biosphere primarily by reducing the ability of ecosystems to provide goods and services, which leads to a loss in biocapacity. Toxics, heavy metals, and other persistent pollutants fall into this category. The amount of bioproductive area required to mine mercury, for example, is vanishingly small compared to the extent of the ecosystems that this metal affects. Similarly, the area required to absorb this product is an undefined quantity, as ecosystems do not have a well-defined or understood ability to assimilate this metal naturally. As a result, the impacts of mercury, as well as other toxics, do not appear primarily in the material's footprint but rather in the widespread loss of biocapacity that it can cause when released widely into the environment.

The Common Unit: Global Hectares

Given the widely varying scope of human demands, and the wide variety of ecosystems available on the planet, any aggregate analysis or indicator requires a common metric for comparison. Ecological Footprint accounts compare different types of footprints to each other and to available biocapacity using a global hectare, defined as a hectare with world-average ecological productivity of the 11.2 billion bioproductive hectares on Earth.

In the context of global hectares, biological productivity does not refer to a rate of biomass production, such as net primary production (NPP). Rather, productivity is the potential to achieve maximum yields of products considered useful for human purposes. As a result, one hectare of highly productive land (e.g., cropland) is equal to more global hectares than one hectare of less productive land (e.g., pasture). Global hectares are normalized so that the number of actual hectares of biologically productive land and sea on the planet is equal to the total worldwide budget of global hectares in any given year.

What products are useful is defined in any year by the types of products that are actually extracted from global ecosystems. Useful yields, and hence total biocapacity, will increase if largely unharvested ecosystem products (e.g., tree bark) are extracted on a large scale in the future.

Methodology

Data Sources

The most robust Ecological Footprint accounts exist at the national and international scales. Although subnational footprint calculations are both possible and common, because of limitations on the availability and accuracy of data sources, the quality of subnational footprint calculations can be more variable. The international community of footprint practitioners is currently in the process of developing standards and certification procedures for subnational footprint applications.

The National Footprint Accounts are currently maintained by Global Footprint Network, a nonprofit organization headquartered in Oakland, California, and its over 65 partner organizations throughout the world. This high-level analysis relies heavily on data published by the FAO, the United Nations Statistics Division, the Intergovernmental Panel on Climate Change (IPCC), and the International Energy Agency (IEA). Other data sources, including meta-analyses, scientific publications, and thematic collections, are used to fill in the gaps between these international sources.

Yield Factors and Equivalence Factors

Two conversion factors, yield factors and equivalence factors, are used in calculations of footprint and biocapacity.

Yield factors are calculated as the ratio of national, country-specific yields for a given land type to the average world yield for that same land type. This ratio describes the extent to which a biologically productive area in a given country is more (or less) productive than the global average of the same land type. Differences in national and global yields can be due to a wide variety of factors, including variation in climate, soil conditions, available technology, and management regimes. Yield factors are specific to individual land types, countries, and years.

Equivalence factors relate the average productivity of a given land type to the world-average productivity of all biologically productive land types. Cropland, for example, has a higher productivity than world average land. Grazing land is, on average, less productive than the average of all land types. Equivalence factors are currently calculated using Global Agro-Ecological Zones (GAEZ) data, which provide a spatial model of potential agricultural yields. The equivalence factor for a land type depends on its level of potential agricultural productivity relative to other land types.

Calculating Footprint and Biocapacity

The general formula for calculating the Ecological Footprint associated with the consumption of a quantity of product is given as

$$\mathrm{EF} = (M/\mathrm{NY}) \times \mathrm{YF} \times \mathrm{EQF} \qquad [1]$$

where EF is the Ecological Footprint of a given product flow (in global hectares), M is the mass of the product flow (in tonnes per year), NY is the national yield of the country in which that product was produced (in annual tonnes per hectare per year), YF is a yield factor calculated as the ratio of national yields to world yields for a given product, and EQF is an equivalence factor reflecting the relative productivity of a given land type compared to world-average productivity.

This formula can be applied directly to all products harvested directly from the first four major productive land types: cropland, grazing land, fishing ground, and forest land. The footprints of secondary products (e.g., flour) that are created from primary products (e.g., wheat) are calculated by converting them back into primary-product equivalents.

The footprint of built-up land is calculated by using the physical extent of the area occupied in built area (in hectares) instead of the product of mass (M) and national yield (NY). Yield and equivalence factors for cropland are applied, reflecting the assumption that most built land occupies former cropland, unless more accurate data are available. The footprint of 'carbon land' is calculated using the total mass of carbon dioxide emissions released from a given activity and the world-average sequestration rate of forested land in place of the ratio of national yield (NY) and yield factor (YF).

To calculate the footprint of a nation, the footprint of all products consumed within that country is calculated using the formula above and then summed. The global Ecological Footprint is calculated as the sum of all national footprints.

The biocapacity associated with a given productive land or sea area is calculated in a similar fashion:

$$\mathrm{BC} = A \times \mathrm{YF} \times \mathrm{EQF} \qquad [2]$$

where BC is the useful biocapacity of a given area (in global hectares), A is physical extent of the area under analysis (in country-specific hectares), YF is a yield factor for that country and land type, and EQF is an equivalence factor for that land type. Note that this formula is identical to that for Ecological Footprint, except here area substitutes for the ratio of mass and national yield. This formula can be applied equally to all five major productive land types on the planet: crop land, grazing land, fishing grounds, forest land, and built-up land.

Key Global and Regional Results

At the largest scales, global Ecological Footprint analysis shows that the total human footprint, or demand on ecosystems, exceeds the planet's available biocapacity, or its ability to supply resources and waste sinks. Figure 1 shows that this condition of overshoot has existed since the mid-1980s. The most significant growth in Ecological Footprint over this time period has been a result of an increase in the productive land area required to meet human demands for fossil fuel energy. This energy land footprint made up nearly 50% of the total Ecological Footprint at a global level in 2002. The growth in available biocapacity over time largely reflects increases in the productivity of cropland. These increases also led, however, to increases in application of fertilizers and pesticides, the creation of which contributed to the rapidly growing Ecological Footprint over this same time period.

These consistently growing global trends, however, mask significant regional variation (Figure 2). In 2002, the per person Ecological Footprint of North America and Western Europe was more than double the biological capacity available within those regions. If everyone in the world lived with a level of ecological demand equal to the typical North American or western European, humanity would require the equivalent production of three to five planets. Other regions, such as Asia Pacific, have an average level of ecological demand that could be extended globally without causing overshoot.

Levels of demand also vary significantly between high-, middle-, and low-income countries (Figure 3). In 2002, high-income countries had an average Ecological Footprint of 6.4 global hectares, compared to 1.8 global hectares for middle-income nations and 0.8 global hectares for low-income nations. Over the past 40 years, consumption of ecological resources, per capita, has increased by nearly 90% in high-income countries but fallen by 15% in low-income countries.

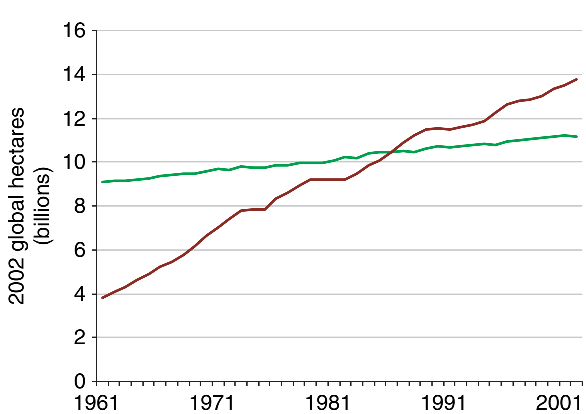

Figure 1 Global Ecological Footprint and biocapacity, 1961–2002. Data in units of 2002 global hectares, hectares with equivalent biological productivity to a world-average bioproductive hectares in the year 2002. From Global Footprint Network (2005). National Footprint Accounts, 2005 edition. Available at http://www.footprintnetwork.org.

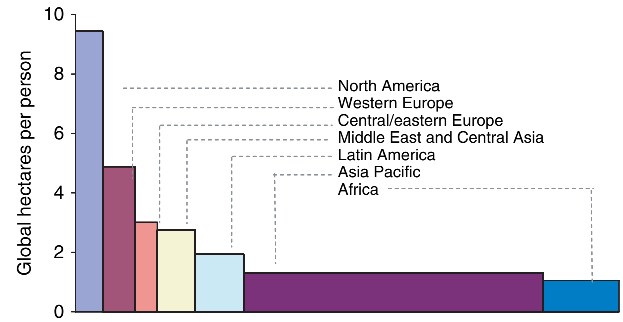

Figure 2 Regional Ecological Footprint and biocapacity, 2002. From Global Footprint Network (2005). National Footprint Accounts, 2005 edition. Available at http://www.footprintnetwork.org.

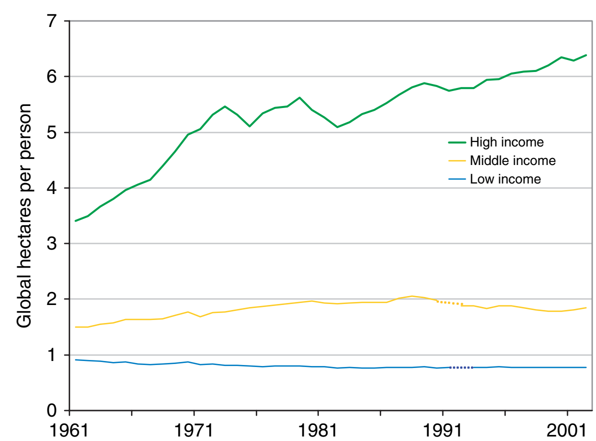

Figure 3 Ecological Footprint and biocapacity by national income grouping, 1961–2002. Dotted lines indicate discontinuities due to lack of data. From Global Footprint Network (2005). National Footprint Accounts, 2005 edition. Available at http://www.footprintnetwork.org.

More detailed national-level footprint results are published in annual editions by Global Footprint Network. A wide range of subnational footprint assessments have also been completed by organizations located throughout the world. Links to these data sets and reports are available on Global Footprint Network's website (http://www.footprintnetwork.org).

The Footprint of Consumption Activities

While the methods and national analysis presented above provide information on the Ecological Footprint and biocapacity of different land types, they do not indicate which types of consumption are responsible for placing these demands. The provision of food products, for example, requires significant quantities of cropland, grazing land, fishing grounds, and carbon land. Dividing the Ecological Footprint into its specific consumption components can be valuable for policy applications and communication programs. These results are commonly used in scenario analysis and by individuals who wish to find ways to reduce their own personal footprints.

Various techniques, including input–output analysis and process-based allocation, can be applied to apportion the Ecological Footprint into consumption categories. All of these types of analyses can generate a consumption land-use matrix, a table that allocates the total footprint in each of the major land types across a series of consumption categories. The different methods employed by practitioners around the world to create these matrices are currently being aligned by a global Ecological Footprint standards process.

Table 2 shows that energy land and crop land are the land types that make the largest contribution to the average Australian's Ecological Footprint. By consumption

Table 2 Process-based consumption land-use matrix for Australia

	'Carbon land'	*Cropland*	*Grazing land*	*Forest*	*Built-up land*	*Fishing grounds*	*Total (gha/cap)*
Food	0.5	1.1	0.7	0.0		0.3	2.7
Plant based	0.3	0.3		0.0			0.6
Animal based	0.3	0.7	0.7	0.0		0.3	2.1
Housing	1.1	0.0		0.3	0.1		1.4
New construction	0.1	0.0		0.3	0.0		0.4
Maintenance	0.0	0.0		0.0	0.1		0.1
Residential energy use	0.9						0.9
Electricity	0.8						0.8
Natural gas	0.1						0.1
Fuelwood	0.1						0.1
Fuel oil, kerosene, LPG, coal	0.0						0.0
Mobility	0.7	0.0			0.1		0.8
Passenger cars and trucks	0.5	0.0			0.1		0.6
Motorcycles	0.0	0.0			0.0		0.0
Buses	0.0	0.0			0.0		0.0
Passenger raif transport	0.0	0.0			0.0		0.0
Passenger air transport	0.1	0.0			0.0		0.1
Passenger boats							
Goods	1.4	0.0	0.0	0.4	0.0		1.9
Appliances (not including operation energy)	0.0			0.0	0.0		0.0
Furnishing	0.0	0.0	0.0	0.0	0.0		0.1
Computers and electrical equipment (not inclu.	0.0			0.0	0.0		0.0
Clothing and shoes	0.0	0.0	0.0	0.0	0.0		0.1
Cleaning products	0.0			0.0	0.0		0.1
Paper products	0.1			0.2	0.0		0.3
Tobacco	0.0	0.0		0.0	0.0		0.0
Other misc. goods	1.2	0.0		0.1	0.0		1.3
Services	0.7	0.0		0.1	0.0		0.9
Water and sewage	0.0			0.0	0.0		0.0
Telephone and cable service	0.0			0.0	0.0		0.0
Solid waste	0.0			0.0	0.0		0.0
Financial and legal	0.0			0.0	0.0		0.1
Medical	0.2	0.0		0.0	0.0		0.2
Real estate and rental lodging	0.1	0.0		0.0	0.0		0.1
Entertainment	0.0			0.0	0.0		0.1
Government	0.1	0.0		0.0	0.0		0.2
Nonmilitary, nonroad	0.1	0.0		0.0	0.0		0.1
Military	0.1	0.0		0.0	0.0		0.1
Other misc. services	0.1	0.0		0.0	0.0		0.2
		0.0			0.0		0.0
Total (gha/cap)	4.4	1.1	0.8	0.8	0.3	0.3	7.7

gha/cap, global hectares per capita.
From Global footprint Network and the University of Sydney, 2001 data.

category, food and goods are the most significant. The finer level of detail in tables such as these can be used to suggest scenarios for policymaking as well as possibilities for individual action. Eliminating animal-based food and doubling plant-based food consumption, for example, could reduce the Ecological Footprint of the average Australian by 20% each year.

Continued Indicator Development

Continued development of the Ecological Footprint methodology and calculations is stewarded by Global Footprint Network and its over 65 international partners. Ongoing initiatives include maintenance and updates to the National Footprint Accounts, extensions of Ecological Footprint accounting techniques, and the creation of standards for subnational footprint applications and projects. More information can be found on Global Footprint Network's website at http://www.footprintnetwork.org.

See also: Climate Change 3: History and Current State; Coevolution of the Biosphere and Climate; Deforestation; Ecosystem Services; Ecosystems; Global Change Impacts on the Biosphere; Urbanization as a Global Ecological Process.

Further Reading

Chambers N, Simmons C, and Wackernagel M (2000) *Sharing Nature's Interest: Ecological Footprints as an Indicator for Sustainability*. London: EarthScan.

Costanza R, Ayres R, Deutsch L, *et al.* (2000) Forum: The dynamics of the ecological footprint concept. *Ecological Economics* 32(3): 341–394.

Global Footprint Network (2005). National Footprint Accounts, 2005 edition. Available at http://www.footprintnetwork.org.

Global Footprint Network and the University of Sydney (2005) The Ecological Footprint of Victoria: Assessing Victoria's Demand on Nature. Report prepared for EPA Victoria. http://www.epa.vic.gov.au/ecologicalfootprint/default.asp (accessed Apr. 2007).

Kitzes J, Wackernagel M, Loh J, *et al.* (forthcoming) Shrink and share: Humanity's present and future Ecological Footprint. *Philosophical Transactions of the Royal Society B.*

Monfreda C, Wackernagel M, and Deumling D (2004) Establishing national natural capital accounts based on detailed ecological footprint and biological capacity accounts. *Land Use Policy* 21: 231–246.

Rees WE (1992) Ecological footprints and appropriated carrying capacity: What urban economics leaves out. *Environment and Urbanization* 4: 121–130.

Wackernagel M, Kitzes J, Moran D, Goldfinger S, and Thomas M (2005) The ecological footprint of cities and regions: Comparing resource availability with resource demand. *Environment and Urbanization* 18(1): 103–112.

Wackernagel M and Rees WE (1996) *Our Ecological Footprint: Reducing Human Impact on the Earth*. Gabriola Island: New Society Publishers.

Wackernagel M, Schulz NB, Deumling D, *et al.* (2002) Tracking the ecological overshoot of the human economy. *Proceedings of the National Academy of Sciences of United States of America* 99(14): 9266–9271.

Wiedmann T, Minx J, Barrett J, and Wackernagel M (2006) Allocating ecological footprints to final consumption categories with input–output analysis. *Ecological Economics* 56(1): 28–48.

WWF International, Global Footprint Network, and Zoological Society of London (2006) Living planet Report 2006. Gland, Switzerland. http://www.panda.org/living planet.

Relevant Website

http://www.footprintnetwork.org – Global Footprint Network.

Ecological Health Indicators

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Indicators

Environmental change has always been a reality, and it is continuous. Change on planet Earth is driven by wind and water; geological activity; astronomical events; and the work of microorganisms, plants, and animals. Usually, forces with the greatest potential for cataclysmic change are rare (such as volcanic eruptions), local (such as tornadoes or lightning fires), or slow to play out (such as the advance and retreat of glaciers).

Although these cataclysmic changes are important for life on Earth, most living organisms are preoccupied more with being keen observers, relying on multiple senses to identify threats, such as the presence of predators or