CHAPTER

Overview of environmental footprints

5

Lidija Čuček[*], Jiří Jaromír Klemeš[*] and Zdravko Kravanja[†]

[*]*Centre for Process Integration and Intensification - CPI[2], Research Institute of Chemical and Process Engineering - MŰKKI, University of Pannonia, Veszprém, Hungary*

[†]*University of Maribor, Maribor, Slovenia*

"The greatest shortcoming of the human race is our inability to understand the exponential function"
— **Dr. Albert A. Bartlett, Arithmetic, Population and Energy (1969)**

"We never know the worth of water, till the well is dry."
— **Thomas Fuller, Gnomologia (1732)**

"The road we have long been traveling is deceptively easy, a smooth superhighway on which we progress with great speed, but at its end lays disaster."
— **Rachel Carson, Silent Spring (1962)**

GLOSSARY

Carbon footprint (CF) is the more popular environmental protection indicator that commonly signifies a certain amount of gaseous emissions that are relevant to climate change. It is associated with human production or consumption activities (Wiedmann and Minx, 2008). It usually represents the total amount of CO_2 and other greenhouse gases (GHGs) emitted over the full life cycle of a system, and it is expressed in mass units of CO_2 equivalents per functional unit (UK Parliamentary Office of Science and Technology (POST), 2011).

Ecological footprint (EF) is a measure of human demand on the environment and represents the amount of biologically productive land and sea areas necessary for supplying the resources a human population consumes and to assimilate the associated waste (Wackernagel et al., 2002).

Environmental footprint is a quantitative measurement describing the appropriations of natural resources by humans (Hoekstra, 2008). It describes how human activities can impose different burdens and impacts on the global

Assessing and Measuring Environmental Impact and Sustainability.

environment (UNEP/SETAC, 2009). The larger the footprint, the more resources that are needed to support human lifestyles.

Environmental indicator is a numerical value that helps to provide information and insight into the state of the environment. Indicators are developed based on the quantitative measurements or statistics of environmental conditions that are tracked over time (Attorre, 2014).

Footprint tools are tools for footprint calculations and suggested reduction paths. The more common tools are calculators, especially for CF (Padgett et al., 2008) but also for EF, water footprint (WF), nitrogen footprint (NF), and other footprints (Čuček et al., 2012c). Other tools are optimization frameworks, mathematical programming tools such as GAMS (GAMS Development Corporation, 2013), MIPSYN (Kravanja, 2010), and others, and structural optimization tools based on process graphs such as PNS solution (Bertok et al., 2012). Furthermore, there are specific tools available and include Environmental Performance Strategy Map (EPSM) (De Benedetto and Klemeš, 2009), which combines footprints and cost; SPIonExcel (Sandholzer and Narodoslawsky, 2007), which calculates Sustainable Process Index (SPI) (Krotscheck and Narodoslawsky, 1996); regional optimizer (RegiOpt) (Niemetz et al., 2012), which is a tool for sustainability evaluation of regional renewable energy networks; software package Bottomline[3] (Integrated Sustainability Analysis (ISA), 2014) for creating sustainability reports for companies and organizations; and many others.

Footprint family is a set of indicators able to track human pressures on the planet and from different angles (Galli et al., 2012). It represents the major categories of footprints developed to date, which are CF, EF, WF, and energy footprint (ENF), and is related to climate, food, water, and energy security (Fang et al., 2014).

Life cycle analysis (LCA) is a structured, comprehensive, internationally standardized tool (ISO 14040 (International Organisation for Standardisation (ISO), 2006a) and ISO 14044 (International Organisation for Standardisation (ISO), 2006b)) for quantifying those emissions, resource consumptions, and environmental and health impacts associated with processes, products, or activities. It is commonly referred as a "cradle-to-grave" analysis or as an open loop. It takes into account the system's whole life cycle from the extraction and processing of resources through manufacturing, usage, and maintenance to recycling or disposal, including all transportation and distribution steps (Guinée et al., 2002). The LCA principle and framework are divided into four phases: goal and scope definition; life cycle inventory (LCI); life cycle impact assessment (LCIA); and interpretation.

Sustainable development is "a process for improving the range of opportunities that would enable individual humans and communities to achieve their aspirations and full potential over a sustained period of time while maintaining the resilience of economic, social, and environmental systems" (Munasinghe, 2004). It represents the "development that meets the needs of the present without compromising the abilities of future generations to meet their own needs" (World Commission on Environment and Sustainable Development (WCED), 1987).

Water Footprint (WF) is closely linked to the virtual water concept (Hoekstra and Chapagain, 2007). It accounts for the appropriation of natural capital in terms of the water volumes required for human consumption (Hoekstra, 2009). It consists of blue, green, and gray WFs. The blue WF refers to the consumption of surface and groundwater, the green WF refers to the consumption of rainwater stored within the soil as soil moisture, and the gray WF refers to pollution and is defined as the volume of freshwater required for assimilating the load of pollutants based on existing ambient water quality standards (Mekonnen and Hoekstra, 2010).

INTRODUCTION

Environmental and social issues, such as global warming, water pollution, food supply, exponential population growth, security of energy supply, and others are attracting greater awareness when addressing sustainability issues preferably leading toward more sustainable development. Many different methods and tools have been developed over recent decades for measuring and monitoring sustainability and sustainable development to assess and evaluate progress toward more sustainable systems (De Benedetto and Klemeš, 2008). Environmental sustainability has especially emerged as a key issue among the three sustainability pillars, social ("People"), economic ("Prosperity" or "Profit"), and environmental ("Planet").

Environmental impacts are usually defined through a life cycle assessment (LCA). LCA is a set of tools and ideas for evaluating the sustainability of a system (products, processes, or services) throughout the full life cycle of the system (whole supply chain). LCA is usually associated with environmental components (von Blottnitz and Curran, 2007).

Since 1962, when Silent Spring written by Carson (Carson, 1962) was published, and especially from 1987 when the Brundtland report (World Commission on Environment and Sustainable Development (WCED), 1987) was published, the concepts and directions toward quantifying sustainability and sustainable development started to develop. The concept of environmental sustainability was developed in 1995 by Goodland (1995). It "seeks to improve human welfare by protecting the sources of raw materials used for human needs and ensuring that the sinks for human wastes are not exceeded, in order to prevent harm for humans". During last decades environmental sustainability has become widely recognized and accepted, and has led to several policies and treaties, such as The Clean Air Act (Martineau and Novello, 2004), Kyoto protocol (United Nations Framework Convention on Climate Change, 1998), European Union policies (European Commission, 2014), policies in China (China.org.cn, 2014), and many other policies around the world.

Sustainable development and environmental sustainability have been interpreted in many different ways because they are inexactly defined and thus allow certain leeway (Zaccai, 2012). In the 1980s, a variety of definitions had appeared regarding sustainability concepts (Pezzey, 1989). The most quoted definition is that it represents "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This definition was published in the Brundtland Commission report "Our Common Future" in 1987 (World Commission on Environment and Sustainable Development (WCED), 1987).

In addition, several different concepts and methods have been developed for the sustainability evaluations of particular processes, products, or activities (Jeswani et al., 2010). Still, the actual measurements of environmental sustainability and sustainable development remain an open question, and novel concepts and measures are being developed. To achieve sustainable development, the following are needed (Krajnc and Glavič, 2003):

- Changes in industrial processes
- Types and quantities of resources used
- Proper treatment of waste
- Controlling the emissions
- Controlling the produced products

The main goals of environmental protection are (Juhász and Szőllősi, 2008):

- To reduce world consumption of fossil fuels
- To reduce and clean up all sorts of pollution with the future goal of zero pollution
- Emphasis on clean, alternative energy sources with low carbon emissions
- Sustainable use of water, land, and other scarce resources
- Preservation of existing endangered species
- Protection on biodiversity

In this chapter the first part briefly reviews the following: the approach mostly used in environmental assessment, such as life cycle thinking and the LCA framework; the concepts of direct, indirect, and total effects on the environment; and measurements of environmental sustainability. In the second part, special attention is given to key and other environmental footprints, their importance, and overview.

LIFE CYCLE THINKING AND LCA FRAMEWORK

When moving toward (more) sustainable processes, products, or activities, it is essential that the entire life cycle is considered (Allen, 2008); therefore, environmental indicators should be and are usually defined on the basis of LCA (Pozo et al., 2012). LCA is a structured, comprehensive, internationally standardized tool (environmental management standards ISO 14040 (International Organisation for Standardisation (ISO), 2006a) and 14044 (International Organisation for Standardisation (ISO), 2006b)) for quantifying those emissions, resource consumptions, and environmental and health impacts associated with processes, products, or activities. LCA is a

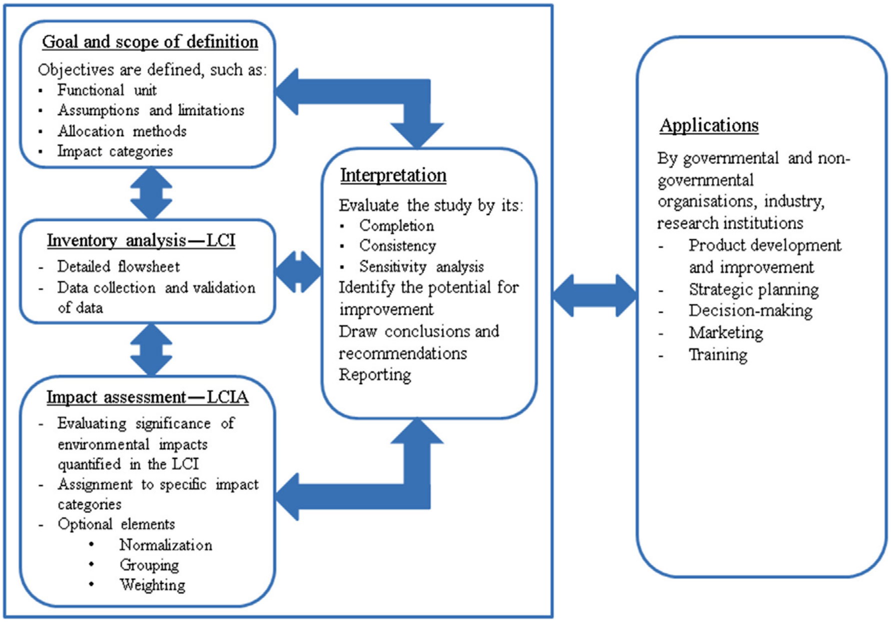

FIGURE 5.1

Four phases and direct applications of life cycle assessment.

Modified from Rebitzer et al. (2004).

relatively young approach that started in the late 1960s and early 1970s; however, before 1990 there was little public concern about LCA (Hunt et al., 1996).

LCA is commonly referred to as a “cradle-to-grave” analysis (Glavič and Lukman, 2007) or as an open loop. It takes into account a system’s full life cycle from the extraction and processing of resources through manufacturing, usage, and maintenance to recycling or disposal, including all transportation and distribution steps (Bojarski et al., 2009). Over the years, a “cradle-to-cradle,” or closed-loop, perspective has been introduced, which attempts to reach 100% utilization of all types of waste (Haggar, 2007).

The comprehensive scope of LCA is useful to avoid problem-shifting, for example, from one phase of the life cycle to another, from one region to another, or from one environmental problem to another (Finnveden et al., 2009). LCA can help reduce environmental pollution and resource usage, and it often improves profitability (McManus, 2010). LCA is an adequate instrument for environmental decision support and has gained wider acceptance over recent years within both academia and industry (von Blottnitz and Curran, 2007).

An LCA principle and framework is divided into four phases: goal and scope definition; Life Cycle Inventory (LCI) LCI; Life Cycle Impact Assessment (LCIA) LCIA; and interpretation. Those phases and direct applications of the LCA framework are shown in Figure 5.1.

1. First phase—Goal and scope definition: During the first phase, the objectives of the analysis and the system's boundaries should be defined, such as functional unit, assumptions and limitations, life cycle stages, allocation methods (when there are several products or functions of the system), and the chosen impact categories. The goals and scope can be adjusted during the iterative process of the analysis.
2. Second phase—Inventory analysis (LCI): The second phase involves data collection relating to inputs of materials and energy and outputs, including releases into air, soil, and water. All data should be related to the functional unit defined during the first phase.
3. Third phase—Impact assessment (LCIA): The third phase of LCA is aimed at evaluating the significances of those environmental impacts quantified in the LCI. The relative contribution of each environmental impact should be assigned to specifically selected impact categories (global warming potential (GWP), acidification potential, CF, NF, land usage, etc.). Other optional LCIA elements such as normalization (e.g., comparing the results to a population or area of Europe), grouping (sorting and ranking of impact categories), and weighting may also be conducted. Weighting, however, brings a high degree of subjectivity into LCA analyses.
4. Fourth phase—Interpretation: This is the last phase of the LCA analysis. It should evaluate the study in a systematic way by considering its completion, consistency, and sensitivity analysis. Interpretation should also identify areas that have the potential for improvement within a system and draw conclusions and recommendations.

LCA enables a holistic view and, therefore, a view from the life cycle perspective. To avoid problem-shifting or limited sustainability evaluation, it is important to select boundaries as wide as possible. The preferred options among the ones listed here are "cradle-to-cradle" and "cradle-to-grave":

- **"Cradle-to-cradle"**: From resource extraction (cradle) to recycling or producing new product (cradle) (100% utilization of waste)
- **"Cradle-to-grave"**: From resource extraction (cradle) to disposal (grave)
- **"Cradle-to-gate"**: From resource extraction (cradle) to factory gate before being sent to consumers (gate); it excludes the use and the disposal phases
- **"Gate-to-gate"**: Includes only one process within the entire production chain (e.g., the processing within a factory)
- **"Well-to-wheel"**: Related to transport fuels and vehicles, from the energy sources to the powered wheels (Daimler, 2011). It comprises two parts: "well-to-tank" (energy supply) and "tank-to-wheel" (energy efficiency) (Fuel-Cell e-Mobility, 2014)

These selected boundaries, except "well-to-wheel," are shown in Figure 5.2 (modified from Procter & Gamble Science-in-the-Box, 2014).

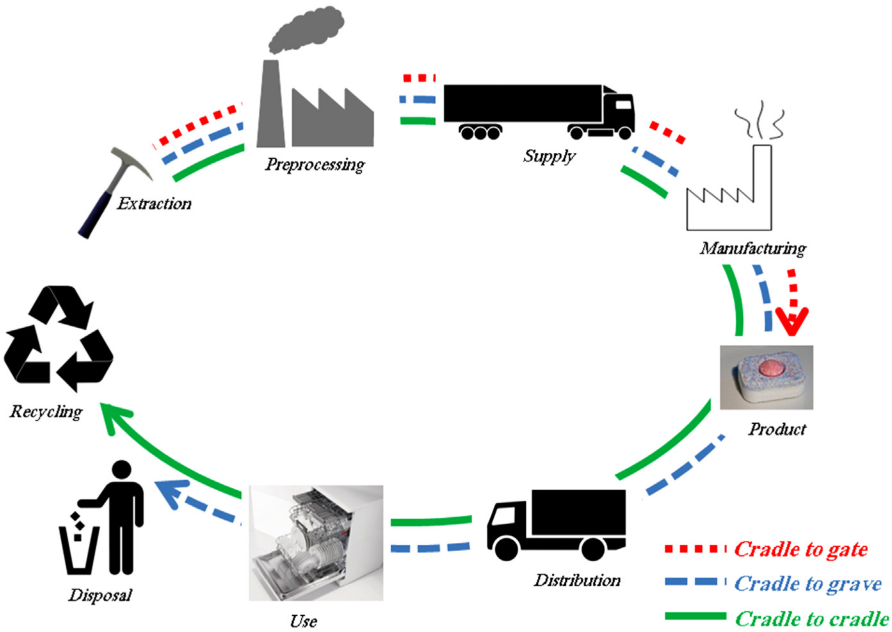

FIGURE 5.2

Mostly used boundaries of LCA.

Modified from Procter & Gamble Science-in-the-Box (2014).

LCA methodology and sustainability assessment, in general, still have some limitations that need to be overcome (Čuček, 2013). The main limitation is the high degree of uncertainty arising from the LCI, which gives rise to results with high variability. Data quality and quantity are often insufficient for comprehensive LCA. A possible consequence of discrepancies in data is that two independent studies analyzing the same products may generate very different results, and different LCIA methodologies can yield different results (McManus, 2010). The results also have low spatial and temporal resolution (de Haes et al., 2004), and LCA only assesses potential impacts and not real impacts (Quantis Sustainability counts, 2009). Another limitation is the lack of a systematic method for generating and identifying sustainable solutions (Grossmann and Guillén-Gosálbez, 2010). There is no single method that is universally acceptable (Hendrickson et al., 1997). It is very challenging to define indicators that are not too broad or too specific (De Benedetto and Klemeš, 2010). Performing the LCA analyses can be costly regarding data and resources, and they can be time-intensive. Table 5.1 illustrates the advantages and drawbacks of LCA approaches.

Table 5.1 Advantages and Drawbacks of LCA Approaches in General

Advantage	Drawback
Comprehensive scope of analysis	Quality and availability of data (uncertainty)
Cradle-to-grave or even cradle-to cradle	Base assumptions and system boundaries
Avoids problem-shifting	Model of the process is needed
Widely accepted	Quantification and normalization
Supports decision-making	Health and safety issues are difficult to assess
Identification of "hot spots"	Limited inclusion of economic and social aspects
Identification of sustainable options	Different studies analyzing the same products may generate very different results
Market advantage (purchasing decisions)	Different LCIA methodologies can yield different results
Enables progress toward more sustainable lifestyles	Costly (money, time, and resources)
	Lack of systematic method for sustainable solutions (economic, environmental, and social)
	May be subjective
	High dimensionality of criteria could be obtained
	Conventional LCAs are generally based on average technology
	For emerging technologies, LCAs are based on an average technology at lab scale or pilot scale extrapolated to large scale
	Improving some criteria may cause worsening of another ones
	In many cases there are several simplifications, because no detailed data are available
	Low spatial and temporal resolution
	LCA only assesses potential impacts and not real impacts

DIRECT, INDIRECT, AND TOTAL EFFECTS

Environmental impacts of raw materials and energy usage, processes, products, and services are usually measured only by their burdening effects on the environment (Hundal, 2000). However, a broader view should also incorporate any possible unburdening effects of an activity (Čuček et al., 2012e). An activity can then be considered environmentally sustainable if its unburdening exceeds its burdening. This may happen, for example, when waste is transformed into a precious green product (Kravanja and Čuček, 2013). In such a case, unburdening occurs twice, first because of the waste not being deposited and second because of fossil-based products being supplemented by the green product. A concept of direct (burdening) and unburdening (indirect) effects, which together form total effects (Kravanja and Čuček, 2013), is described in the following paragraphs.

Direct environmental footprints and any sustainability metric conventionally only measure the directly harmful effects (burdens) on the environment. Direct

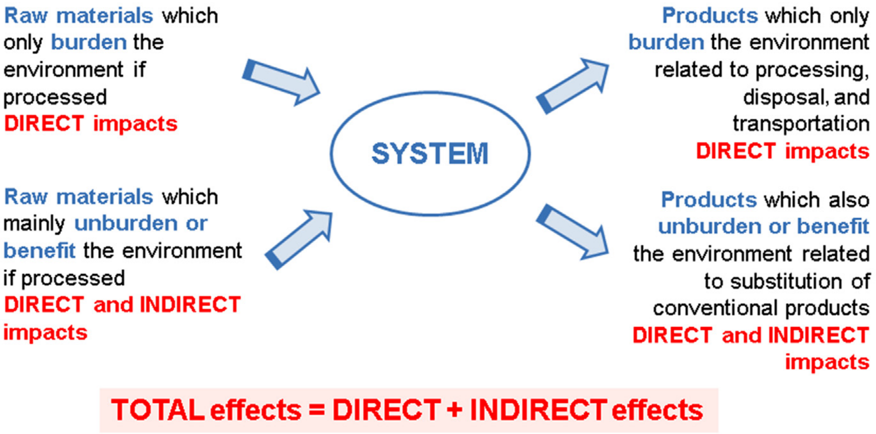

FIGURE 5.3

Representation of direct, indirect, and total effects.

environmental metrics, e.g. footprints, are related to the extraction of resources, production of materials, usage, maintenance, and recycling and/or disposal, including all transportation and distribution steps. However, when a system, in addition to its direct burdening effects on the environment, exhibits a significant unburdening effect on the environment by considering only direct effects, misleading solutions may result (Čuček et al., 2013c).

Indirect footprints represent an unburdening of the environment by substituting harmful products with benign products and the utilization of harmful products rather than discarding them. Several examples include when waste is utilized instead of being discarded, when environmentally benign raw materials, products, and services are used instead of harmful ones, or when conventional energy is replaced by renewable energy. The indirect effect is a reduction in the footprint. Indirect footprints indirectly unburden or benefit the environment (Čuček, 2013).

Total footprints are defined as a sum of the direct and indirect footprints (Kravanja and Čuček, 2013). Considering total effects enables the ability to obtain more realistic solutions than in those cases when only direct effects are considered. An appropriate sustainable synthesis should identify those solutions that unburden the environment the most, rather than only proposing the least-burdening solutions (Čuček, 2013). The concept of total effects is shown in Figure 5.3.

When the sustainability aspect is improved, and therefore minimized, in terms of the direct effects only, there the system does not operate, e.g. there is no production (Kravanja and Čuček, 2013). However, when the total aspects are considered, there are several metrics that are improved and several that are worse. It should be noted that trade-off or compromise solutions are obtained when only direct effects are considered; trade-off and non-trade-off solutions are obtained when total effects are considered. Such a situation could also occur when comparing two systems. Figure 5.4 presents an example using

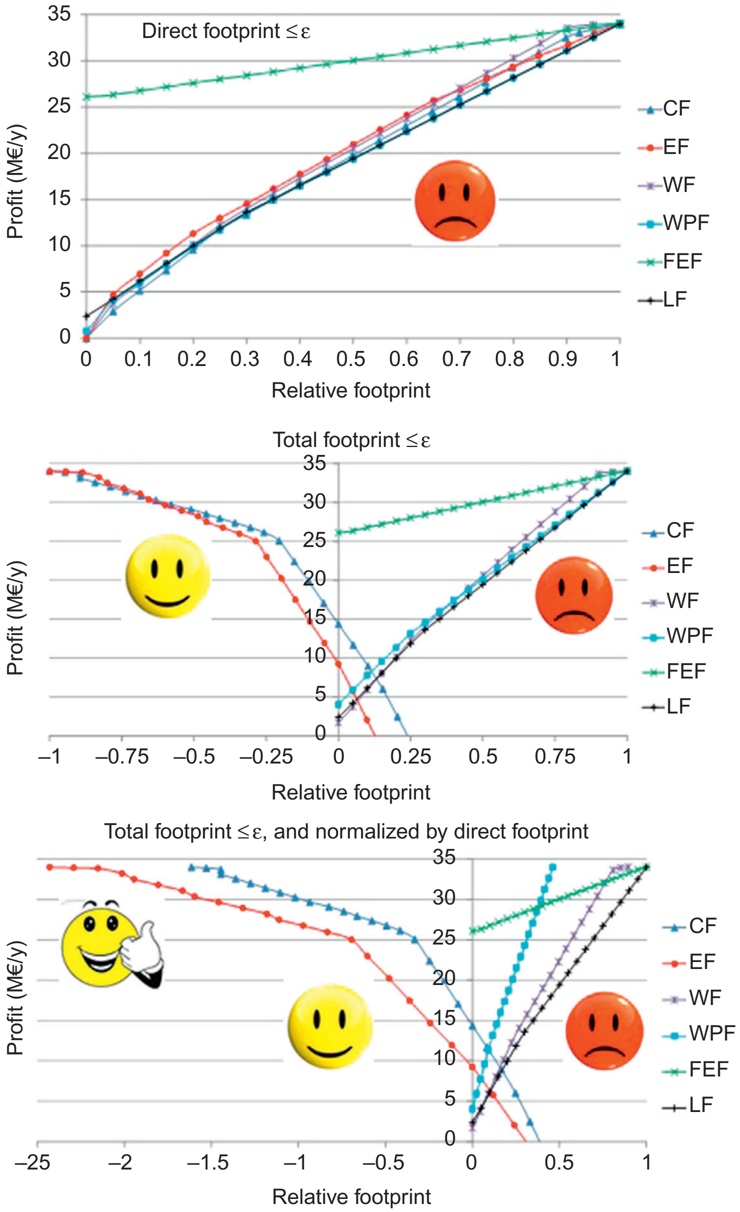

FIGURE 5.4

Difference between solutions obtained by considering only direct, indirect, and total/indirect effects.

Modified from Čuček et al. (2012c).

multi-objective optimization (MOO) of economic vs. environmental criteria - annual profit vs. environmental footprints.

MEASURING ENVIRONMENTAL SUSTAINABILITY

Measuring environmental sustainability requires methods and tools that are to be used for defining the environmental impacts of human activities. Indicators and metrics that can be used to measure and quantify environmental sustainability need to be developed to provide a basis for decision-making. Among the developed metrics measuring environmental sustainability are:

- Indicators of potential environmental impacts
- Eco-efficiency
- Environmental footprints (Čuček et al., 2012c)
- Sustainability indexes (Kravanja and Čuček, 2013)
- Eco and total profit (Čuček et al., 2012a), eco and total net present value (NPV) (Čuček et al., 2013a), and other combined criteria (Kravanja and Čuček, 2013)

INDICATORS OF POTENTIAL ENVIRONMENTAL IMPACTS

Indicators of potential environmental impacts deal with the potential effects and impacts on humans, environmental health, and resources from the LCI (Saur, 1997). They are divided into midpoint-oriented and end-point-oriented or damage impact categories (Figure 5.5).

The following midpoint categories are usually considered:

- *Ozone depletion potential* is the potential for the reduction in the protective stratospheric ozone layer. The ozone-depleting substances are freons, chlorofluorocarbons, carbon tetrachloride, and methyl chloroform. It is expressed as CFC-11 equivalents.
- *Global warming potential* represents the potential change in climate attributable to increased concentrations of CO_2, CH_4, and other GHG emissions that trap heat. It leads to increased droughts, floods, losses of polar ice caps, sea-level rising, soil moisture losses, forest losses, changes in wind and ocean patterns, and changes in agricultural production. It is expressed in CO_2 equivalents usually for time horizon 100 y.
- *Acidification potential* is based on the potential of acidifying pollutants (SO_2, NO_x, HCl, NH_3, HF) to form H^+ ions. It leads to damage to plants, animals, and structures. It is expressed in SO_2 equivalents.
- *Eutrophication potential* leads to an increase in aquatic plant growth attributable of nutrients left by over-fertilization of water and soil, such as nitrogen and phosphorus. Nutrient enrichment may cause fish death, declining

water quality, decreased biodiversity, and foul odors and tastes. It is expressed in PO_4^{3-} equivalents.

- *Photochemical ozone creation potential* is also known as ground-level smog, photochemical smog, or summer smog. It is formed within the troposphere from a variety of chemicals including NO_x, CO, CH_4, and other volatile organic compounds (VOCs) in the presence of high temperatures and sunlight. It has negative impacts on human health and the environment and is expressed as C_2H_4 equivalents.
- *Ecotoxicity (freshwater, marine, terrestrial) potential* focuses on the emissions of toxic substances into the air, water, and soil. It includes the fates, exposures, and effects of toxic substances and is expressed as 2,4-dichlorophenoxyacetic acid equivalents.
- *Human toxicity potential* deals with the effects of toxic substances on human health. It enables relative comparisons between a larger number of chemicals that may contribute to cancer or other negative human effects for the infinite time horizon. It is expressed as 1,4-dichlorobenzene equivalents.
- *Abiotic depletion potential* is concerned with the protection of human welfare, human health, and ecosystems, and represents the depletion of non-renewable resources (abiotic, non-living (fossil fuels, metals, minerals)). It is based on concentration reserves and the rate of de-accumulation and is expressed in kg antimony equivalents.
- Land use
- Water use

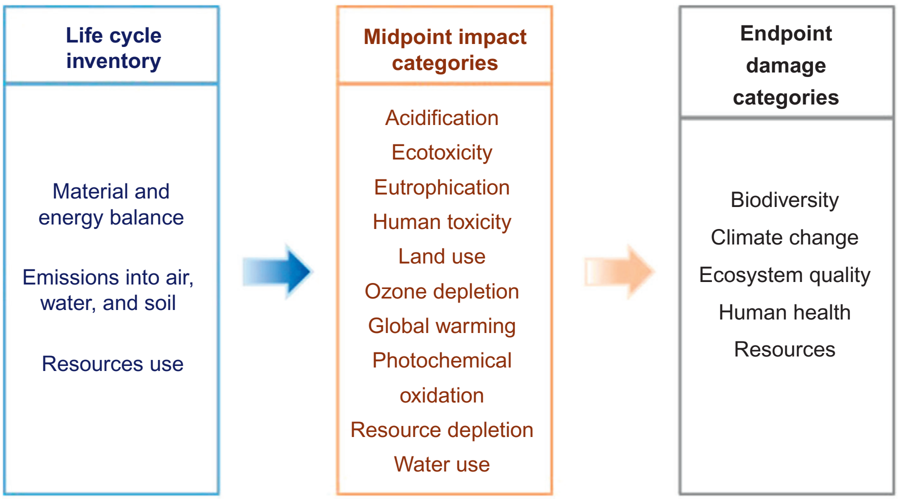

FIGURE 5.5

From LCI to endpoint damage categories.

ECO-EFFICIENCY

Eco-efficiency is a management strategy of doing more with less (Glavič et al., 2012). It is based on the concept of creating more goods and services while using fewer resources and creating less waste and pollution (Glavič et al., 2012). Eco-efficiency is a sustainability measure combining environmental and economic performances. However, a commonly agreed definition does not exist yet (Huppes and Ishikawa, 2005). Eco-efficiency can be seen either as an indicator of environmental performance or as a business strategy for sustainable development (Koskela and Vehmas, 2012). The most common eco-efficiency is defined as (Koskela and Vehmas, 2012):

- A ratio between environmental impact and economic performance
- A ratio between economic performance and environmental impact

Eco-efficiency is achieved through three objectives:

- Increasing product or service values
- Optimizing the usages of resources
- Reducing environmental impacts (Government of Canada, 2013)

A wide variety of terminology referring to eco-efficiency has been developed, with some divergence (Huppes and Ishikawa, 2005). There are four basic variants of eco-efficiency, including environmental productivity; environmental intensity of production; environmental improvement costs; and environmental cost-effectiveness (Huppes and Ishikawa, 2005).

Eco-efficiency offers a number of practical benefits, such as (Government of Canada, 2013):

- Reduced costs through more efficient usages of energy and materials
- Reduced risk and liability by "designing out" the need for toxic substances
- Increased revenue by developing innovative products and increasing market share
- Enhanced brand image through marketing and communicating improvement efforts
- Increased productivity and employee morale through closer alignment of company values with the personal values of the employees
- Improved environmental performance by reducing toxic emissions and increasing the recovery and reuse of "waste" material

ENVIRONMENTAL FOOTPRINTS

Environmental footprints are quantitative measures showing the appropriation of natural resources by humans (Hoekstra, 2008). Footprints are divided into environmental, economic, and social footprints, and combined environmental, social, and/or economic footprints (Čuček et al., 2012c). The concept of "footprint" originates from the idea of ecological footprint - EF (Fang et al., 2014) introduced by Rees (1992). After its introduction, several other environmental footprints have been introduced. Each footprint indicates particular classes of pressures associated with process, product, or activity from the life cycle perspective (Galli et al., 2013).

Several footprints are identified as key footprints because they are essential for sustainability and sustainable development. These recognized footprints are CF, WF, ENF, NF, phosphorus (PF), biodiversity (BF), and land (LF), and they are presented comprehensively. Besides these, various footprints have recently been introduced and are presently being reviewed. For these footprints there is a lack of applications; therefore, more comprehensive reviews cannot be made at this early stage of their development. Environmental footprints are presented in detail in the following sections.

ECO AND TOTAL PROFIT, ECO AND TOTAL NPV, AND OTHER COMBINED CRITERIA FOR MEASURING DIRECT, INDIRECT, AND TOTAL EFFECTS

The eco cost, eco benefit, and eco profit coefficients have the advantage that they can be directly incorporated within the objective function, together with a given economic objective (Kravanja and Čuček, 2013). Therefore, subjective weighting between sustainability objectives is avoided. The advantages of eco cost and eco benefit coefficients are as follows: they are expressed as monetary values; there is no need to compare two products, processes, or services (as is often the aim of LCA); calculations are based on current European price levels; and updated eco cost coefficients can be used (Delft University of Technology, 2012). Economic and eco profits can be merged together, and the preferred solutions are those with maximal total profit (Kravanja and Čuček, 2013). These approaches enable obtaining the better unique solutions and represent fair prices by properly accounting for environmental problems. However, the burden-prevention step is still subjective to some extent. When considering environmental or economic and environmental dimensions within one value, these criteria are:

- Eco cost (Vogtländer et al., 2010)
- Eco benefit or eco revenue (Čuček et al., 2012a)
- Eco profit (Čuček et al., 2012a)
- Net profit (Kravanja and Čuček, 2013)
- Total profit (Čuček et al., 2012a)
- Net NPV (Čuček et al., 2013a)
- Eco NPV (Čuček et al., 2013a)
- Total NPV (Čuček et al., 2013a).

All these criteria use eco cost coefficients (Delft University of Technology, 2012) based on LCA.

To define these criteria, different sets are used, such as R_{B}, R_{UNB}, P_{B}, and P_{UNB} (Čuček et al., 2012a), as defined and used throughout the model for raw materials and products (Figure 5.3):

- R_{B}—set of those raw materials that only burden the environment if processed
- R_{UNB}—set of those raw materials that also unburden or benefit the environment when used
- P_{B}—set of those products that only burden the environment in relation to processing, disposal, and transportation
- P_{UNB}—set of those products that also unburden or benefit the environment (Čuček et al., 2012a)

Eco cost (burdening the environment)

Eco cost (c^{Eco}) is an indicator based on LCA and describes environmental burden on the basis of preventing that burden. It is the sum of the marginal prevention costs during the life cycle, sum of eco costs of material depletion, eco costs of energy and transport, and eco costs of emissions. Eco costs are those costs that should be made to reduce the environmental pollution and material depletion to a level that is in line with the carrying capacity of the Earth (Vogtländer et al., 2010). They are virtual costs and are not yet integrated within current prices ("what if" basis) (Vogtländer et al., 2002). Eco costs include those burdens that originate from the extraction of raw materials, pre-processing, processing, and disposal of harmful products or from purification of the polluted products, from the transportation of raw materials to the plants, from distribution of products to consumers, and from the transportation of products to the locations of disposal.

Eco cost is defined as the sum of all the negative impacts from burdens on the environment, where eco cost coefficients (c_p^{s} and $c_p^{s,\mathrm{tr}}$) are used (Čuček, 2013):

$$c^{\mathrm{Eco}} = \sum_{p \in R_{\mathrm{B}} \cup R_{\mathrm{UNB}} \cup P_{\mathrm{B}} \cup P_{\mathrm{UNB}}} q_p^m \cdot c_p^{\mathrm{s}} + \sum_{p \in R_{\mathrm{B}} \cup R_{\mathrm{UNB}} \cup P_{\mathrm{B}} \cup P_{\mathrm{UNB}}} q_p^m \cdot l_p \cdot D_p \cdot c_p^{s,\mathrm{tr}} \tag{5.1}$$

This summation is performed over all raw materials and products, because all of them contribute to the burdening. The second term represents burdening due to transportation, where the pth flow rate is multiplied by an inverse of the load factor l_p, the distance (D_p/km), and a specific eco cost coefficient for transportation $c_p^{s,\mathrm{tr}}/(\mathrm{kg}(t \cdot \mathrm{km}), \mathrm{kg}/(\mathrm{m}^3 \cdot \mathrm{km}), \ldots)$. Note that the inverse of the load factor is set at 2 when the transport is fully loaded in one direction and empty in the other (Čuček, 2013).

Eco benefit (unburdening the environment)

Eco benefit or eco revenue (R^{Eco}) is defined as the sum of all the positive impacts of unburdens on the environment. Positive impacts are related to raw materials that mainly benefit the environment when used (e.g., the utilization of waste such as industrial wastewater, manure, sludge, etc.); their direct harmful impact on the environment is thus avoided. Positive impacts are also related to products that benefit the environment (e.g., if they are substitutes for harmful products). They are defined using a substitution factor as the ratio between the quantity of conventional product ("currently" used product) and the quantity of the produced product (Čuček et al., 2012a).

Eco benefit or eco revenue (R^{Eco}) represents the unburdening of the environment and is defined as the sum of all the positive impacts of unburdening the environment. Here, the eco benefit coefficients (c_p^{s} and $c_p^{s,\mathrm{tr}}$) are used (Čuček et al., 2012a):

$$R^{\mathrm{Eco}} = \sum_{p \in R_{\mathrm{UNB}}} q_p^m \cdot c_p^{\mathrm{s}} + \sum_{p \in P_{\mathrm{UNB}}} q_p^m \cdot f_p^{S/P_{\mathrm{UNB}}} \cdot c_p^{\mathrm{s}} \tag{5.2}$$

Eco profit (= eco benefit − eco cost)

Eco profit (P^{Eco}) is defined as an analogy with economic profit as the difference between unburdening and burdening the environment expressed as eco benefits and eco costs (Čuček et al., 2012a):

$$P^{\mathrm{Eco}} = R^{\mathrm{Eco}} - c^{\mathrm{Eco}} \tag{5.3}$$

Net profit

Net profit (P^{N}) is defined as the economic profit (P^{Econ}) reduced by the eco cost (c^{Eco}). The synthesis problem, where economic profit and eco cost are optimized simultaneously, takes the following form (Kravanja and Čuček, 2013):

$$\begin{aligned} & P^{\mathrm{N}}(x,y) = \max(P^{\mathrm{Econ}}(\mathbf{x},\mathbf{y}) - c^{\mathrm{Eco}}(\mathbf{x},\mathbf{y})) \\ & \text{s.t.} \quad \mathbf{h}(\mathbf{x},\mathbf{y}) = 0 \\ & \quad \mathbf{g}(\mathbf{x},\mathbf{y}) \le 0 \\ & \quad (\mathbf{x}^{\mathrm{LO}}\mathbf{x} \le \mathbf{x}^{\mathrm{UP}}) \in \mathbf{X} \subset \mathbf{R}^n, \mathbf{y} \in \mathbf{Y} = \{0,1\}^m \end{aligned} \tag{5.4}$$

Total profit

Total profit (P^{T}) is the summation of the economic profit (P^{Econ}) and eco profit (P^{Eco}). For the synthesis problem, where economic profit and eco profit are optimized simultaneously, the solutions obtained are those with maximal total profit (TP) (Kravanja and Čuček, 2013):

$$\begin{aligned} & P^{\mathrm{T}}(x,y) = \max(P^{\mathrm{Econ}}(\mathbf{x},\mathbf{y}) + P^{\mathrm{Eco}}(\mathbf{x},\mathbf{y})) \\ & \text{s.t.} \quad \mathbf{h}(\mathbf{x},\mathbf{y}) = 0 \\ & \quad \mathbf{g}(\mathbf{x},\mathbf{y}) \le 0 \\ & \quad (\mathbf{x}^{\mathrm{LO}}\mathbf{x} \le \mathbf{x}^{\mathrm{UP}}) \in \mathbf{X} \subset \mathbf{R}^n, \mathbf{y} \in \mathbf{Y} = \{0,1\}^m \end{aligned} \tag{5.5}$$

Eco NPV

The eco NPV is an analogy of the economic NPV, which takes into account the complete economics of the project throughout the project's life cycle. Income within the NPV's yearly cash flow is represented by unburdening (eco benefit) and outcome by burdening (eco cost) of the environment (Čuček et al., 2013a). The following simplified formula can be used when fixed yearly cash flows are assumed:

$$W_{\mathrm{NP}}^{\mathrm{Eco}} = \left[(1-r_t)(R^{\mathrm{Eco}} - c^{\mathrm{Eco}})\right]\left[\frac{(1+r_d)^{t_D}-1}{r_d(1+r_d)^{t_D}}\right] \tag{5.6}$$

Total NPV

Similar to economic and eco profit being merged into total profit, economic NPV and eco NPV form total NPV, and the preferred solutions are those with maximal total NPV (Čuček et al., 2013a).

$$\begin{aligned} & W_{\mathrm{NP}}^{\mathrm{T}}(x,y) = \max(W_{\mathrm{NP}}^{\mathrm{Econ}}(\mathbf{x},\mathbf{y}) + W_{\mathrm{NP}}^{\mathrm{Eco}}(\mathbf{x},\mathbf{y})) \\ & \text{s.t.} \quad \mathbf{h}(\mathbf{x},\mathbf{y}) = 0 \\ & \quad \mathbf{g}(\mathbf{x},\mathbf{y}) \le 0 \\ & \quad (\mathbf{x}^{\mathrm{LO}} \le \mathbf{x} \le \mathbf{x}^{\mathrm{UP}}) \in \mathbf{X} \subset \mathbf{R}^n, \mathbf{y} \in \mathbf{Y} = \{0,1\}^m \end{aligned} \tag{5.7}$$

SUSTAINABILITY INDEXES

Sustainability usually has environmental, economic, and social dimensions (Jørgensen et al., 2008). Therefore, the relative sustainability index (RSI) is composed of economic, environmental, and social indicators (Tallis et al., 2002). Here only environmental indicators are briefly summarized.

Environmental indicators

Environmental metrics should provide a balanced view of the environmental impact of inputs (resource usage) and outputs (products, services, activities produced, emissions, effluents, and waste). Environmental indicators are typically grouped into resource usage indicators (material, energy, water, and land) and pollution indicators (global warming, atmospheric acidification, photochemical smog formation, human health effect) (Tallis et al., 2002). The environmental indicators by the optimal solution at the first level (base case solution) often yield the reference point for the second level, which then yields a sustainable solution. For example, the relative environmental index (REI) can be calculated as follows (Kravanja et al., 2005):

$$\begin{aligned} & \mathrm{REI} = \frac{1}{N}\sum_{j=1}^{N}\frac{\mathrm{EI}_j}{\mathrm{EI}_j^0} \quad j \in J \\ & \mathrm{REI} = \frac{1}{N}\left[\underbrace{\sum_{k\in K}\frac{q_{m,k}}{q_{m,k}^0}}_{\text{material usage}} + \underbrace{\sum_{e\in E}\frac{\phi_e}{\phi_e^0}}_{\text{energy usage}} + \underbrace{\sum_{w\in W}\frac{q_{m,w}}{q_{m,w}^0}}_{\text{water usage}} + \sum_{c\in C, j\in J, (c,j)\in CJ}\sum_{o\in O}\frac{q_{m,c,o}}{q_{m,c,o}^0}\mathrm{PF}_{j,c}\right] \end{aligned} \tag{5.8}$$

where

j—the index of environmental indicators from the set of environmental indicators J
k—the index of raw material input streams from the set of input streams K
e—the index of energy sources consumed or generated from the set of energy sources E
w—the index of water streams consumed from the set of water streams W
c—index of substances contributing to the jth pollution indicator from the set of substances C
CJ—set of pairs of substances contributing to the jth pollution indicator, and jth pollution indicator
o—the index of output streams from the set of output streams O
N—the number of environmental indicators
EI_j—the environmental indicator
EI_j^0—the environmental indicator for the base case
$q_{m,k}$—mass flow rate of input stream k (mass unit/time unit)
ϕ_e—heat or energy flow rate of heat or energy source consumed e (energy unit)
$q_{m,w}$—mass flow rate of water stream consumed or generated w (mass unit/time unit)
$q_{m,c,o}$—mass flow rate of substance c in output stream o (mass unit/time unit)
$\mathrm{PF}_{j,c}$—the potency factor of substance c that contributes to environmental indicators j, $j \in J$

Note that in these definitions all the indicators are normalized by their reference values as obtained at the first level.

Relative sustainability index

Different indicators are expressed in different units. Environmental indicators are usually expressed as a burden per a certain functional unit. Because their units are different, they cannot be composed unless they are normalized. When the indicators ($I_{i,f}$) of a studied alternative represent "cradle-to-grave" impacts and are compared with those of the selected base case (I_f^0), relative indicators are obtained, which can then be composed into an RSI_i by suitable weighting factors (w_f, $\sum_f w_f = 1$, $\forall f \in F$):

$$\mathrm{RSI}_i = \sum_f w_f \cdot \frac{I_{i,f}}{I_f^0}, \quad f \in F, \quad i \in I = \{1, \ldots, N+1\} \tag{5.9}$$

where $f \in F$ is a sustainability (economic and/or environmental and/or social) indicator. If only direct effects on the environment and society are considered, then the relative direct sustainability index (RDSI_i) is obtained (Eq. (5.10)). If indirect effects are also considered, then the relative total sustainability index (RTSI_i) is obtained (Eq. (5.11)), which shows how much better RTSI_i is than RDSI_i:

$$\mathrm{RDSI}_i = \sum_{f=1}^{N} w_i \cdot \frac{I_{i,f}^{d}}{I_f^{d,0}}, \quad f \in F, \quad i \in I = \{1, \ldots, N+1\} \tag{5.10}$$

$$\mathrm{RTSI}_i = \sum_{f=1}^{N} w_i \cdot \frac{I_{i,f}^{\mathrm{d}} + I_{i,f}^{\mathrm{ind}}}{I_f^{\mathrm{d},0}} = \sum_{f=1}^{N} w_i \cdot \frac{I_{i,f}^{\mathrm{t}}}{I_f^{\mathrm{d},0}}, \quad f \in F, \quad i \in I = \{1, \ldots, N+1\} \tag{5.11}$$

$I_{i,f}^{\mathrm{d}}$ represents the direct indicator, $I_{i,f}^{\mathrm{ind}}$ represents the indirect indicator, and $I_{i,f}^{\mathrm{t}}$ represents the total indicator. The resulting RDSI_i usually ranges from 1 (worst possible value) to 0 (best possible value), and i is the index of the selected points between 1 and 0. However, the RTSI_i can range from -1, or from more negative values (positive for the environment), to 1. The higher the quotient between the total and direct effects (in the case of alternatives that significantly unburden the environment), the more this indicator changes the RTSI_i and the lower the value of RTSI_i (Kravanja and Čuček, 2013).

MULTI-OBJECTIVE OPTIMIZATION

MOO, also known as multi-criteria, vector, multi-attribute, Pareto optimization, and multi-objective programming (Chakrabortty and Hasin, 2013), simultaneously integrates two or more objectives or goals that are subject to certain constraints. Usually, compromise solutions (trade-offs) that reveal the possibilities for achieving improvements within the system are obtained (Azapagic and Clift, 1999). In general, no single solution exists when all the objectives are optimized simultaneously, but a number of Pareto optimal solutions (a feasible region of optimal solutions, Pareto front) can be obtained (Rao, 2009).

MOO is the use of specific methods for determining the best solutions to the problem subject to given constrains. It is the key methodology used for sustainable system design and synthesis (Klemeš et al., 2010). However, from simultaneous MOO, a number of Pareto optimal solutions (a feasible region of optimal solutions) can be obtained (Rao, 2009) (Figure 5.4).

Several methods have been developed for solving MOO problems. The simplest method is to transform the MOO problem into a single-objective optimization (SOO) problem by applying weights to different criteria (the weighted objective method). Other widely used optimization methods are: the ε-constraint method (Haimes et al., 1971), in which a sequence of constrained single-objective problems are solved; the goal-programming method, in which the solution is obtained by minimizing a weighted average deviation of the objective functions from the goal set by the decision-maker and evolutionary algorithms that involve random search techniques (Bhaskar et al., 2000). The solution for such problems is a set of "non-inferior" or Pareto points (Čuček et al., 2012c).

The ε-constraint method is usually applied (Pieragostini et al., 2012), and a set of non-inferior Pareto optimal solutions are thus generated. A two-level system synthesis is performed when e.g. an economically effective synthesis is performed at the first level to obtain a solution that is then considered as a base case or reference solution for the multi-objective synthesis performed at the second level. The synthesis problem in which a sequence of N problems $(\text{MP-E})_e$ is performed as a maximization or minimization of one objective (e.g., maximization of profit) (O_1) subjected to environmental metric $\mathbf{e} \in E$ takes the following form:

$$
\begin{aligned}
& O_1(x,y) = \max f(\mathbf{x},\mathbf{y}) \ \text{ or } \ \min f(\mathbf{x},\mathbf{y}) \\
& \text{s.t.} \quad \mathbf{h}(\mathbf{x},\mathbf{y}) = 0 \\
& \quad \mathbf{g}(\mathbf{x},\mathbf{y}) \le 0 \qquad (\text{MP-}E)_e \\
& \quad O_e(\mathbf{x},\mathbf{y}) \le \varepsilon_i, \mathbf{e} \in E \\
& \quad (\mathbf{x}^{\text{LO}}\mathbf{x} \le \mathbf{x}^{\text{UP}}) \in \mathbf{X} \subset \mathbf{R}^n, \mathbf{y} \in \mathbf{Y} = \{0,1\}^m \\
& \quad \varepsilon_i = \varepsilon_{i-1} - \Delta\varepsilon \\
& \quad \Delta\varepsilon = \frac{1}{N}, \ \varepsilon_i = \frac{1}{N} \cdot (i-1), \ i \in I = \{1,\ldots,N+1\}, \ i_0 = N+1
\end{aligned}
$$

where x denotes the vector of continuous variables (mass flow rates, temperatures, design variables, etc.), y denotes vector of binary variables (discrete decisions), and $f(x)$, $h(x,y)$, and $g(x,y)$ are (non)linear constraint functions. Objectives O_e decrease sequentially by a suitable step-size until there is no feasible solution. Pareto inferior solutions are usually obtained in this way. However, non-trade-off solutions can also be obtained when objectives have synergistic effects. Inequality $(O_e(\mathbf{x},\mathbf{y}) \le \varepsilon_i)$ should be modified into an equality constraint in such a case.

A more detailed discussion about the advantages and weaknesses of different sustainability measurements, such as footprints, LCA indexes, eco cost, eco profit, and total profit, in relation to MOO synthesis of sustainable systems can be found elsewhere (Kravanja, 2012).

AGGREGATE MEASURE OF ENVIRONMENTAL SUSTAINABILITY

In many cases, GWP or CF are evaluated as criteria for environmental sustainability (castrated type of LCA) (Finkbeiner, 2009). Most of the effort and resources are spent to reduce the CF. In general, there may be either synergies (non-trade-offs) or compromises (trade-offs) within environmental metrics. For example, photovoltaic shows synergies in CF, WF, NF, and ENF. Biogas production, however, reduces CF, NF, and ENF but increases the WF (Vujanović et al., 2014). Usually, there are compromises in environmental footprints and the possibilities for achieving the improvements within the system are revealed (Azapagic and Clift, 1999). Proper decisions are strongly dependent on regional characteristics and climatic conditions. Therefore, more comprehensive analyses that consider all aspects of the natural environment, human health, and resources should be performed (Finkbeiner, 2009).

There are aggregate measures of sustainability consisting of "one number," such as eco-efficiency, eco profit, and total profit, eco NPV and total NPV, and other combined criteria. Their advantage is that a unique (optimal) sustainable solution could be obtained directly, which is especially important when solving large-scale problems when the models are huge and computational times are significant. However, this is not the case with indicators of potential environmental impacts and environmental footprints.

When applying these metrics, a comprehensive list of objectives (indicators of potential impacts or footprints) should be taken into account and evaluated. To "create a pathway" toward more sustainable development, preferred optimal solutions need to be obtained. For this purpose, MOO should be performed.

If several objectives are considered (e.g., all key environmental footprints), then there are limitations. Increased time is spent obtaining all the solutions (the entire solution space) in some cases. Visualization and interpretation of solutions are difficult and, in many cases, unclear. Also, it is possible to present, at most, four-dimensional Pareto projections (Čuček et al., 2014). It is necessary to apply a criteria dimensionality reduction technique to facilitate the comprehension of the solution space when many objectives are involved within MOO problems. Various dimension reduction approaches have been developed for this purpose and are generally categorized into linear and non-linear methods (Lygoe, 2010). Among the methods developed are a method for minimizing the error of omitting objectives (Guillén-Gosálbez, 2011), principal component analysis (Sabio et al., 2012), factor analysis (Huang and Lu, 2014), representative objectives method (Čuček et al., 2012d) applied to direct (Čuček et al., 2013b) and total objectives (Čuček et al., 2014), and others.

KEY ENVIRONMENTAL FOOTPRINTS

A literature review indicates that the major categories of footprints developed to date are CF, EF, WF, and ENF, forming the so-called footprint family (Galli et al., 2011). No single indicator has been able to comprehensively monitor human impact on the environment, but indicators need to be used and interpreted jointly (Galli et al., 2012). EF, ENF, CF, and WF rank as the more important footprint indicators in the existing literature. They are in close relationship with the four worldwide concerns regarding threats to human society: food security; energy security; climate security; and water security (Fang et al., 2013).

Besides these footprints, NF, PF, BF, and LF are recognized as key environmental footprints because they are among those essential for health security, food and water security, and land and species security. The importance of these footprints can also be seen in Figure 5.6, which presents the planet boundaries. These boundaries are associated with the planet's biophysical subsystems or processes (Rockström

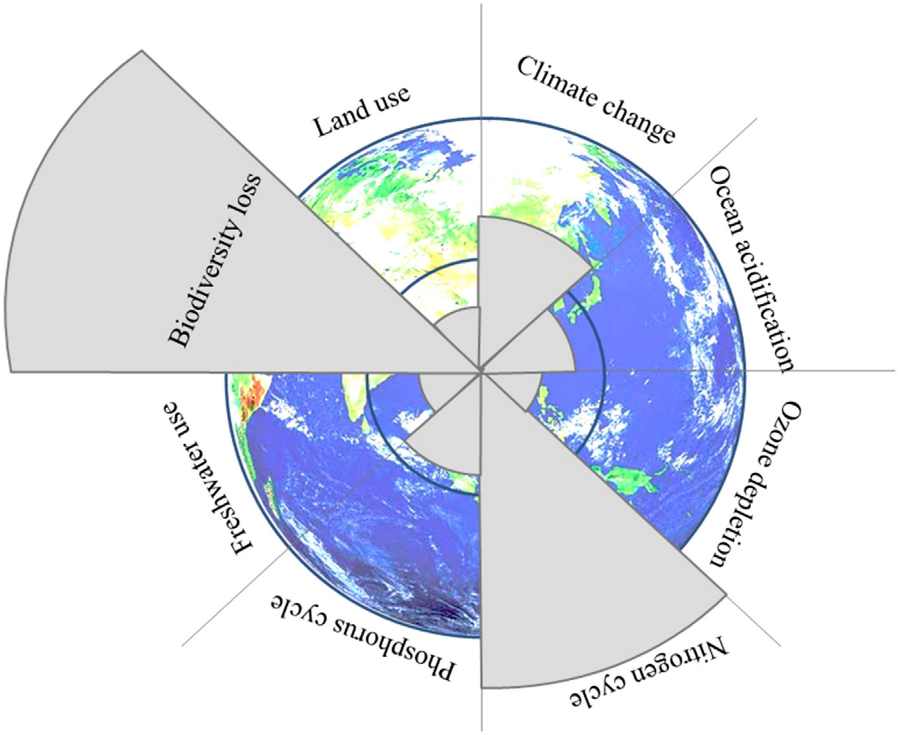

FIGURE 5.6

Planetary boundaries.

Modified from Rockström et al.(2009).

et al., 2009) and define human-determined acceptable levels of a key global variable (Carpenter and Bennett, 2011). It can be seen that climate change (CF), rate of biodiversity loss (BF), and interference with the nitrogen cycle (NF) have already transgressed the boundaries. In addition, other boundaries such as freshwater use (WF), land use (LF), ocean acidification, ozone depletion, and interference with global phosphorus cycle (PF) are fast approaching. The more quoted definitions, policies, and ways of reducing key environmental footprints are presented in Table 5.2.

The footprint family of indicators are frequently used indicators in scientific literature (Figure 5.7). Also, the remaining indicators recognized as key are becoming more and more popular. For those indicators it is foreseen that they will also become “hot footprints” over the next few years. Figure 5.7 shows the number of publications addressing the “footprint family” of indicators in scientific search engines Science Direct and Scopus. Figure 5.7 shows an increased interest in key environmental footprint evaluation in Science Direct and Scopus can be seen over the years to 2014 (June 2014).

Table 5.2 Key Environmental Footprints: Definitions, Policies, and Ways for Footprint Reduction or Prevention

Footprint	Definition	Policy	How to Reduce It
Carbon footprint (CF)	The more quoted definition: CF stands for the amount of CO_2 and other GHGs, emitted over the full life cycle of a process or product. It is expressed in mass of $CO_2{}^{-}$eq (UK Parliamentary Office of Science and Technology (POST), 2011)	Policies include targets for emissions reduction, increased use of renewable energy, and increased energy efficiency. The main current international agreement on reducing emissions of GHGs is the Kyoto protocol (United Nations Framework Convention on Climate Change, 1998)	(Čuček et al., 2012b): – Technological development – Carbon capture and storage (CCS) – Carbon offsetting (compensation for emissions made elsewhere) – Reduced energy consumption – Improved energy efficiency (Perry et al., 2008): – Integration of waste and renewable energy during energy production (Carbonfund.org, 2014): – Reducing, reusing, and recycling of products – Consuming less meat – Reducing food waste – Buying local products if possible

(Continued)

Table 5.2 Key Environmental Footprints: Definitions, Policies, and Ways for Footprint Reduction or Prevention *Continued*

Footprint	Definition	Policy	How to Reduce It
Water footprint (WF)	Indicator of direct and indirect water use by a consumer or producer (Hoekstra et al., 2011). It is divided into blue (consumption of freshwater), green (consumption of rainwater), and gray WFs (indicator of pollution)	Due to increasing pressures on water resources, policies should help to secure water resources for future generations. The Water Framework Directive of the EU aims to protect all water bodies by preventing pollution at the source and set a target date of 2015 to achieve "good status" for all waters (European Commission, 2000). Clean Water Act is the primary law in the United States that addresses surface water quality protection and water pollution control (Clean Water Act, 2002). Also, in other countries there are water protection legislations, such as Water Law of the People's Republic of China (The Central People's Government of The People's Republic of China, 2002), Water Act of Australia (Australian Government, 2013), etc.	– Responsible and efficient water use at all levels – Better water conservation and management – Avoid wasting of blue water (for irrigation, etc.) – Recycling water as much as possible (in industries) – Make better use of green water (planting, use in toiletries, etc.) – Minimize gray WF – Substitute the products with smaller WF (Gruener, 2010)
Ecological footprint (EF), biocapacity, and ecological overshoot	EF is a resource accounting indicator that measures how many bioproductive land and water areas are available on Earth, and how much of this area is appropriated for human use (Kitzes et al., 2007). EF is related to Earth global biocapacity and overshooting Biocapacity is the capacity of an area to provide the resources and absorb waste Overshoot or ecological deficit stands for usage of more resources that Earth can renew, and can persist only for some	Very limited impact in terms of policy lessons because EF is an aggregated indicator (van den Bergh and Grazi, 2014)	– Carbon capture and storage (CCS) – Carbon offsetting – Reduced energy and water consumption – Improved energy efficiency – Renewable energy utilization – Responsible and efficient use or products – Reducing, reusing, and recycling of products

	time. The human economy can deplete stocks and fill waste sinks (Ewing et al., 2010). It is a difference between biocapacity and EF (Global Footprint Network, 2012)		– Reducing waste – Using more sustainable transportation
Energy footprint (ENF)	ENF is currently superficially defined. It is suggested that it stands for the specific energy usage per functional unit when considering fossil-based and renewable-based energy (Sobhani et al., 2012)	Efficient energy use and renewable energy are the main pillars of sustainable energy policies. Various countries around the world have adopted different energy policies. The European Union set binding targets by 2020 to reduce GHG emissions by 20% from 1990 levels, raising the share of energy production from renewable resources to 20%, improvement in energy efficiency, and a minimum target of 10% of the renewable energy in the transportation sector (European Commission, 2009a). The United States established several energy management goals and requirements due to economic and energy security considerations. Among the acts, the more important are Energy Policy Act of 2005 (Energy Policy Act, 2005) and Energy Independence and Security Act of 2007 (Energy independence and Security Act, 2007). China's twelfth 5-year plan (2011–2015) set a compulsory target of non-fossil fuels proportion of 11.4% by 2015 and 15% by 2020, energy intensity reduction by 16%, and carbon intensity reduction by 17% (Li and Wang, 2012). Renewable Energy Target scheme in Australia requires 20% of Australia's electricity coming from renewable sources by 2020 (Australian Government and Department of the Environment, 2014), etc.	– Technological developments – Reduced energy consumption – Improved energy efficiency as one of the larger and least costly opportunities – Using more sustainable transportation – Renewable energy production and consumption

(*Continued*)

Table 5.2 Key Environmental Footprints: Definitions, Policies, and Ways for Footprint Reduction or Prevention *Continued*

Footprint	Definition	Policy	How to Reduce It
Nitrogen footprint (NF)	NF is the total amount of reactive nitrogen released into the environment as a result of an entity's resource consumption, expressed in mass units of reactive nitrogen (Leach et al., 2012). It represents disruption of the regional to global nitrogen cycle and its consequences due to human activities (Čuček et al., 2012b)	Several directives are related to reactive nitrogen and phosphorus emissions in air and water bodies to address the problem of nutrient build-up in ecosystems. The European Union's main directives on nitrogen and phosphorus in the atmosphere are: directive 2001/81/EC, National Emission Ceilings; 2008/1/EC, Integrated Pollution, Prevention, and Control (IPPC); and 2008/50/EC, Ambient Air Quality. The European Union's main directives related to nutrient emissions in water bodies are: 2006/118/EC, Groundwater Directive; 208/56/EC, Marine Strategy Framework Directive; 91/676/EEC, Nitrates Directive; 91/271/EEC, Urban Waste Water Treatment Directive; and 2000/60/EC, Water Framework Directive (Oenema et al., 2011). The main legislations in the United States related to nutrient emissions are Clean Water Act. (2002) and The Clean Air Act (2004)	(Čuček et al., 2012b): – Reducing energy consumption – Changing diets to more sustainably prepared food and fish – Consuming less meat, particularly beef – Reducing food waste – Crop genetic engineering to create symbiotic Rhizobium bacteria – Traditional or enhanced breeding techniques – Precision farming based on soil analysis – Cover crops (Smil, 1997): – Stabilization of population – Recycling of organic waste – Crop rotation – Legume cultivation (European Commission DG Environment News Alert Service, 2012): – Using more sustainable transportation – Improving wastewater treatment

Phosphorus footprint (PF)	PF represents disruption of phosphorus cycle. It is expressed in mass units of phosphorus per functional unit	See policies for NF reduction	– Reducing food waste – Crop genetic engineering – Search for new phosphorus sources (Smil, 2000): – Stabilization of population – Consuming less meat and dairy products – More efficient fertilization (e.g., terracing, no-till agriculture, cover crops) – Precision farming – Removal of phosphorus from sewage and industrial waste Reduce, reuse, and recycle (Vaccari, 2009): – Improving wastewater treatment by removing pollutants, especially heavy metals – Using agricultural residues and animal waste, including bones as fertilizer – Halt excreted phosphorus
Biodiversity footprint (BF)	BF is defined as "the summation of all the pressures that have potential consequences for biodiversity" (de Bie and van Dessel, 2011)	Several biodiversity-related legislations have been developed, and approximately 170 countries now have national biodiversity strategies and action plans (Secretariat of the Convention on Biological Diversity, 2010). Among them are the EU Biodiversity Strategy to 2020 (European Commission, 2011b), Australia's Biodiversity Conservation Strategy 2010–2030 (Natural Resource Management Ministerial Council, 2010), Canada Species at Risk Act (Minister of	– CF, NF, WF, and PF mitigation (Secretariat of the Convention on Biological Diversity, 2010): – Careful land-use planning – Sustainably produced and harvested food (Hooper): – Reduce (avoid), reuse, and recycle

(*Continued*)

Table 5.2 Key Environmental Footprints: Definitions, Policies, and Ways for Footprint Reduction or Prevention *Continued*

Footprint	Definition	Policy	How to Reduce It
Biodiversity footprint (BF)		Justice, 2014), Biological Diversity Act of India (National Biodiversity Authority, 2014), National Policy of Biological Diversity of Malaysia (Ministry of Science Technology and The Environment Malaysia, 1998), etc.	– Opt for renewable energy and energy efficiency – Reducing the use of pesticides and fertilizers – More resource-efficient economy (European Commission, 2011a): – Protecting areas (both in land and in coastal waters) to conserve the native habitats and biodiversity – Conservation of particular species – Restoration of terrestrial, inland water and marine ecosystems and their services, and conserve biodiversity – Combating invasive alien species – Ensuring the sustainable use of fisheries resources
Land footprint (LF)	LF, also termed actual land demand, is related to land requirement and is defined as the summation of all the areas directly and indirectly required to satisfy the consumption (Giljum et al., 2013a)	Agricultural policies should support the implementation of sustainable agricultural practices. Policies related to CF, ENF, and BF also affect LF. Biofuel policies (Sorda et al., 2010) could have significantly negative impact on LF	– Careful land-use planning (Giljum et al., 2013b): – Reduce consumption of meat and other animal products – Opt for renewable energy that has low LF and, therefore, avoid the use of biofuel

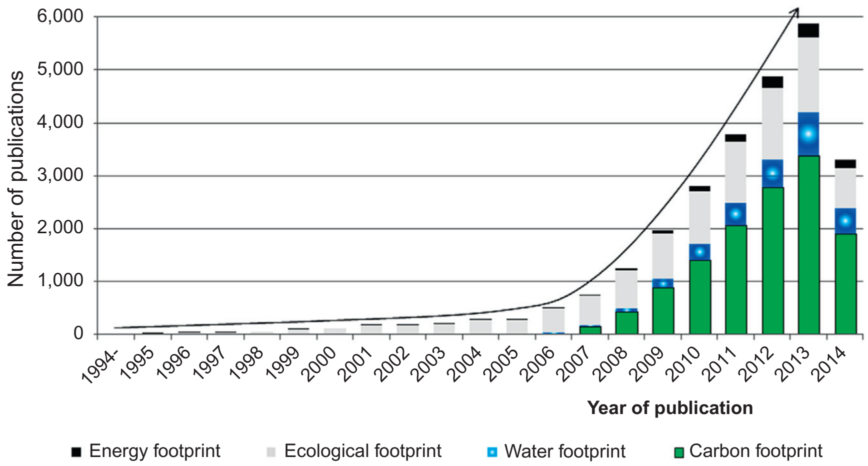

FIGURE 5.7

Increasing number of scientific publications related to evaluation of the footprint family of indicators in Science Direct and Scopus (to June 2014).

CARBON FOOTPRINT

Over the past few years, CF, has become one of the more important environmental protection indicators (Wiedmann and Minx, 2008). It has been widely used in scientific literature. Several research studies have analyzed the CF, its impact, minimization, mitigation, and even sequestration (Klemeš et al., 2006). Five-thousand fifty articles in Science Direct and 7,500 articles in Scopus (May 2014) address the CF. The more quoted definitions, policies, and methods regarding CF reductions are presented in Table 5.2.

CF is related to human-induced climate change and global warming, which are recognized by many as the greatest environmental threat for the twenty-first century (Abbott, 2008). The term “global warming” considers the continuing increase in the average temperature of the Earth’s atmosphere and oceans. Many researchers assume that it is caused by increased concentrations of GHGs in the atmosphere, resulting (most likely) from human activities such as deforestation, other land use changes, and the burning of fossil fuels. The main GHGs, the concentrations of which are increasing, are CO_2, CH_4, N_2O, hydrochlorofluorocarbons (HCFCs), hydro-fluorocarbons (HFCs), and ozone in the lower atmosphere (World Meteorological Organization, 2014). CO_2 is the single most important human-emitted GHG in the atmosphere, contributing approximately 63.5% to the overall global radiative forcing, not considering water vapor, which is continuously within the Earth’s climatic circulation (World Meteorological Organization, 2009). The burning of fossil fuels releases additional (not released by natural processes) CO_2 into the atmosphere. Approximately half of this excess CO_2 is absorbed by the land and oceans, but the remainder accumulates within the atmosphere and enhances the natural greenhouse effect (Dilling et al., 2003). Global emissions from the burning of fossil fuels, the clearing of forests, and agricultural activities have led to the release of more than 1,100 Gt of CO_2 into the atmosphere since the mid nineteenth century (Sims et al., 2007).

It has been declared that the global average near-surface atmospheric temperature had already increased by 0.78°C during the twentieth century, with much of this warming (0.61°C) occurring over the past 30 y (Staudt et al., 2008). Temperatures are predicted to increase by at least an additional 1.1−6.4°C over the next 100 y. This warming would cause significant changes in sea levels (an increase of 0.18−0.59 m), ecosystems, the melting of glaciers, the extent of ice and snow, precipitation, water availability, and the probable expansions of subtropical deserts. Other consequences would include higher maximum temperatures, fewer colder days, changes in agricultural yields, and an increase in infectious diseases. Global warming and climate change may also be associated with deterioration in the health of humans, more intense hurricanes, tropical cyclone activity, flooding, drought, wildfires, the insect populations, and ocean acidification (Staudt et al., 2008).

CF is, in general, a consumption-based indicator (Gleick et al., 2014). It usually represents the amount of CO_2 and other GHGs emitted over the full life cycle of a process or product (UK Parliamentary Office of Science and Technology (POST), 2011). CF is quantified using indicators such as the GWP (European Commission, 2007), which represents the quantities of GHGs that contribute to global warming and climate change. A specific time horizon is considered, usually 100 y (Intergovernmental Panel on Climate Change, 2009). A similar definition indicates that the CF is a result of life cycle thinking applied to global warming (climate change) (European Commission, 2007).

The land-based definition of the CF is that it represents the land area required for the sequestration of fossil fuel CO_2 emissions from the atmosphere through afforestation (De Benedetto and Klemeš, 2009). Wiedmann and Minx (2008) proposed that the CF is a measurement of the exclusive direct (on-site, internal) and indirect (off-site, external, embodied, upstream, and downstream) CO_2 emissions of an activity or over the life cycle of a product, measured in mass units. Wright et al. (2011). suggested that only two carbon-based gases, CO_2 and CH_4, the data collection of which is relatively straightforward, should be used when determining a CF. It includes the activities of individuals, populations, governments, companies, organizations, processes, and industrial sectors (Galli et al., 2012).

Other different terms relating to GHG emissions have been suggested and/or used, such as climate footprint (Wiedmann and Minx, 2008), CO_2 footprint (Huijbregts et al., 2008), GHG footprint (Downie and Stubbs, 2013), methane footprint (Wiedmann and Barrett, 2011), and GWP footprint (Meisterling et al., 2009).

CF is calculated using LCA or input−output analysis (Hertwich and Peters, 2009). It can be calculated using various tools. The simplest are CF calculators that are aimed at reducing emissions related to individual lifestyles (Jones and Kammen, 2011). They have become relatively common on the Internet and can

Table 5.3 List of Selected CF Calculators

Application	Unit	Developer	Website
Calculates the CF for different countries from mobility and from options for living with carbon offsets	t/y and €/y	Carbon Footprint Ltd	www.carbonfootprint.com
For the United States, calculates the CF from transportation, housing, and shopping with actions to reduce the CF, possibly to zero	$t_{CO2eq.}$/y	University of California, Berkeley	coolclimate.berkeley.edu
For the United States, calculates the CF based on the state average and compares it with the United States and global average CF per person	$t_{CO2eq.}$/y	The Nature Conservancy	www.nature.org
For the United States, calculates the household CF and compares it to the average CF	lb_{CO2}/y	US EPA	www.epa.gov

promote public awareness of carbon emissions from the behavior of individuals. However, these calculators can generate varying results, even for the same individual activity (Čuček et al., 2012c). Overall, these calculators lack consistency and furnish insufficient information about their methods and estimates. Several of the CF calculators also promote methods for mitigating CO_2 emissions through offsets or investments in renewable energy technology (Padgett et al., 2008). The similarities and differences among 10 US-based calculators were reviewed by Padgett et al. (2008). CF calculators are intended primarily for individuals and households but can also be applied to businesses. Table 5.3 contains a list of CF calculators selected from several currently available CF calculators (Chait, 2009).

WATER FOOTPRINT

In recent decades, the need for measuring the WF has appeared to be attributable to freshwater security and pollution. The qualities and quantities of surface and groundwater resources are being affected by the impact of population growth, migrations to cities, increasing resource consumption, and climate change (United Nations Environment Programme, 2007). Over the next decade (by 2025), it is estimated that two-thirds of the world's population will be subjected to a shortage of water (United Nations Environment Programme, 2007), mainly attributable to water pollution (Conserve Energy Future, 2014). It is seen by many as a water crisis (Holden, 2014). Therefore, WF evaluation and minimization are priorities for sustainability. The good news is that reducing the WF to a sustainable level is possible with consumption pattern change, even with an increasing population (Ercin and Hoekstra, 2014).

WF was introduced in 2002 by Hoekstra and Hung (2002). It has also attracted significant and increased attention within the scientific community, but much lower than that of the CF (Figure 5.7).

WF is an indicator of direct and indirect water usage by an individual, community, business, or nation (Hoekstra, 2008). It is considered a consumption-based metric because it attributes the water usage to the consumer rather than the producer (Gleick et al., 2014). It is closely linked to the concept of virtual water (Hoekstra and Chapagain, 2007) and represents the total volume of direct and indirect freshwater used, consumed, and/or polluted. Table 5.2 presents the definition, policies, and possibilities regarding how to decrease WFs.

WF consists of (Hoekstra et al., 2011):

- Blue WF: Indicator of consumption of freshwater (surface and groundwater) to produce the goods and services by the individual or community. It includes evaporated water, water incorporated within products, water not returned to the same catchment area, and water not returned during the same period.
- Green WF: Consumption of rainwater that does not run-off or recharge the groundwater but is stored within the soil as soil moisture. For crops and wood, it is the sum of production-related evapotranspiration and incorporation of water into the harvested products.
- Gray WF: Indicator of pollution. It is defined as the volume of freshwater that is required to dilute pollutants to such an extent that the quality of the water remains above agreed water quality standards.

WF is a method for quantifying water usage for a particular product for any well-defined group of consumers (e.g., an individual, city, province, state, or nation) or producer (e.g., a public organization, private enterprise, or economic sector). It can also reflect the embodied or virtual water in imports and exports (Dong et al., 2013). A WF is measured in terms of water volumes consumed (evaporated or incorporated within the product) and polluted per unit of time or per functional unit (Galli et al., 2012).

The strength of the WF concept is that it provides a broad perspective on the water management of the system and allows for a deeper understanding of water usage. The WF integrates water usage and pollution over the complete supply chain (Galli et al., 2011). It measures water usage of different types, such as blue, green, and gray waters. It also connects water uses to specific places and times, and evaluates the hydrological sustainability of a system (Dourte and Fraisse, 2012).

The weaknesses of the WF are that it represents just the quantity of water used without an estimation of the related environmental impacts, the lack of required data, the estimation of gray WF is subjective (Jeswani and Azapagic, 2011), and no uncertainty studies are available even though uncertainty can be significant (Galli et al., 2011). There is still greater potential for improvement regarding accounting standards as well as data coverage, disaggregation, and quality (Giljum et al., 2013a).

There is a huge WF associated with some products. Table 5.4 shows the WF of some selected products and of primary energy carriers.

Table 5.4 Average WF of Some Products and Primary Energy Carriers

Product (Hoekstra and Chapagain, 2007)	Virtual Water (L)	Primary Energy Carrier (1 GJ[a]) (Gerbens-Leenes et al., 2008)	Virtual Water (m^3)
1 glass of beer (250 mL)	75	Natural gas	0.11
1 cup of coffee (125 mL)	140	Coal	0.16
1 slice of bread (30 g)	40	Crude oil	1.06
1 cotton t-shirt (250 g)	2,000	Uranium	0.09
1 egg (140 g)	135	Wind energy	≈ 0
1 hamburger (150 g)	2,400	Solar thermal energy	0.30
1 kg of rice	2,500	Hydropower	22.3
1 kg of beef (Water Footprint Network, 2014)	15,400	Biomass energy	10–250

[a] *277.8 kWh.*

Table 5.5 List of Selected WF Calculators

Application	Unit	Developer	Website
For different countries, it calculates the water required to produce the goods and services consumed by humans	m^3/y	Hoekstra, Chapagain, Mekonnen (Water Footprint Network, 2014)	www.waterfootprint.org
For different countries, it calculates the water required to produce the goods and services consumed by humans	L/d, gal/d	Kemira (2014)	www.waterfootprintkemira.com
For the United States, it individually calculates the WF relating to water used in homes and yards, food consumption, transportation and energy, and purchased products	L/d, gal/d	National Geographic (2014a)	environment.nationalgeographic.com
For US individuals and households, it calculates the WF, compares it with that of the average American user, and provides water-saving tips	L/d, gal/d	GRACE Communications Foundation (2014)	www.gracelinks.org

WF can also be calculated using various tools, such as WF calculators, graph-based tools, mathematical programming tools, and input−output analysis. The simplest are WF calculators, which have become common tools for evaluating WF. Table 5.5 contains a list of a few selected WF calculators.

ECOLOGICAL FOOTPRINT

The EF was developed in 1992 by Rees (1992). It answers the question: "How much of the biological capacity of the planet is required by a given human activity or population?" (Global Footprint Network, 2011). The average world citizen has an EF of approximately 2.7 global average hectares, but there are only 2.1 global average hectares of bioproductive land and water per capita on Earth (Rees, 2010). According to Sadik (Motavalli, 1999), many environmentalists think that the carrying capacity of the Earth is a maximum of 4 billion. Currently, the world population exceeds 7.2 billion people (Worldometers—Real Time World Statistics, 2014), and it is estimated that it will reach and stabilize at 10 billion (Worldometers—Real time World Statistics, 2014).

Humanity had already overshot global biocapacity by 50% during approximately 2007 (Ewing et al., 2010), which means that humanity used approximately 1.5 Earths to support its consumption (Galli et al., 2014). The increase in global demands is mainly attributable to CF, fishing ground footprint, and agricultural footprint (Galli et al., 2014). This overshoot, if it continues, will put global ecosystems at serious risk for degradation or collapse (Kitzes et al., 2007). For these reasons, EF evaluation is also attracting increased interest within the scientific community (Figure 5.7). Furthermore, Table 5.2 offers definitions of EFs, biocapacity, and ecological overshooting. In terms of policy, there are only limited measures; however, there are several possibilities for decreasing EFs.

EF has emerged as the world's primary measurement of humanity's demands on nature (Wackernagel and Rees, 1996) and is now widely used as an indicator for measuring environmental sustainability. EF is defined as a measurement of the human demand for land and water areas and compares the human consumption of resources and absorption of waste with the Earth's ecological capacity to regenerate (Global Footprint Network, 2010). EF provides an aggregated assessment of multiple anthropogenic pressures (Galli et al., 2012). It is a composite indicator that combines (Toderoiu, 2010):

- Built-up area (built-up land footprint)—Area covered by human infrastructure for housing, transportation, and industrial production (settlements, roads, hydroelectric dams, etc.). By best estimates approximately 0.2×10^9 ha or 1.3% of the total land is built-up land.
- Land for carbon absorption or uptake (CF)—Biologically productive area required to absorb the CO_2 not sequestered by the oceans (Kitzes et al., 2007). It is calculated using the carbon absorption potential of the world

average of forests. The footprint is primarily attributable to fossil fuel burning, international trade, and land use practices (Borucke et al., 2013).

- Fishing grounds (fishing ground footprint)—Area of inland and marine waters necessary for primary production of fish, seafood, and other marine products. Approximately 2.3×10^9 ha (6.4% of total water surface) of fishing ground exist (only continental shelves and inland waters are included).
- Forest area (forest land footprint)—Area of forest required to support the annual harvest of timber products, fuel wood, and pulp. Approximately 3.9×10^9 ha (26.2% of total land) of forest are available worldwide.
- Grazing land (grazing land footprint)—Area of grassland used in addition to crop feeds required to raise livestock for meat, hides, wool products, milk, and dairy. It comprises all grassland used to provide feed for animals, including cultivated pastures as well as wild grasslands and prairies. There are approximately 3.5×10^9 ha (23.5% of total land) of grassland and pasture worldwide.
- Cropland (cropland footprint)—Area required to grow all crop products required for human consumption (food and fiber) and to grow livestock feeds, fish meals, oil crops, and rubber. There are approximately 1.5×10^9 ha (10.1% of total land) of cropland worldwide.

The main strength of the EF concept is that it is attractive and intuitive (Schaefer et al., 2006), and that its methodology is continuously improving. It is especially useful in raising the awareness of environmental loading imposed by humanity (Ferng, 2002). The EF helps in the understanding of the complex relationships between the many environmental problems by exposing humanity to a “peak everything” situation (Galli et al., 2011). However, it should be noted that the EF measures only one major aspect of sustainability, namely, the environmental aspect, and not all environmental concerns (Galli et al., 2012). EF excludes economic or social indicators.

EF is, in general, a consumption-based indicator and includes all biologically productive areas worldwide for satisfying consumption at specific local levels, including those embodied in import and export (Giljum et al., 2013a). EF’s balance for local consumption (e.g., within a country), EF_C is calculated as follows (Galli et al., 2014):

$$EF_C = EF_P + EF_I - EF_E \tag{5.12}$$

where

EF_P—ecological footprint of production
EF_I—footprint embodied in imported commodity flows
EF_E—footprint embodied in exported commodity flows

The EF of each single product i, EF_i, locally produced, imported, or exported is defined as (Galli et al., 2014)

$$EF_i = \frac{P_i}{Y_{W,i}} \cdot EQF_i \tag{5.13}$$

where

P_i—amount of each primary product i harvested, amount of CO_2 emitted
$Y_{W,i}$—annual world average yield for the production of commodity i, carbon uptake capacity
EQF_i—equivalence factor for the land use type producing product i

Local biocapacity, BC, is defined in Eq. (5.14) and provides an assessment of the capacities of assets to produce renewable resources and ecological services (Galli et al., 2014):

$$BC = \sum_i A_{N,i} \cdot YF_{N,i} \cdot EQF_i \tag{5.14}$$

where

$A_{N,i}$—bioproductive area that is available for the production of each product i at the local level
$Y_{W,i}$—specific yield factor for the land producing product i

EF and biocapacity can be applied at scales ranging from single products to households, cities, regions, and countries or to humanity as a whole; however, it is most effective, meaningful, and robust at aggregate levels (Wackernagel et al., 2006). National footprint accounts (nation-level EF assessments) are regarded as the most complete (Kitzes et al., 2009).

EF is usually measured in global area units as the amount of bioproductive space (Hoekstra, 2008) and in global area units per person (Ewing et al., 2010). Each global hectare represents the same fraction of the Earth's total bioproductivity and is defined as one hectare of land or water normalized to the world average productivity from all of the biologically productive land and water within a given year. The total biologically productive area available on the Earth is approximately 12 billion hectares (Galli et al., 2011). Biologically productive areas include cropland, forests, and fishing grounds but exclude deserts, glaciers, or the open ocean (Kitzes and Wackernagel, 2009). However, converting the data to area units can be problematic. It also has limited data availability, uncertainty of data, and geographic specificity.

EF can also be calculated using various tools. The simplest are EF calculators, which have become common tools. Table 5.6 contains a list of a few selected EF calculators.

ENERGY FOOTPRINT

Population and income growth are the two more powerful driving forces behind the demand for energy (British Petroleum, 2011). Consequently, insecure energy supply, high energy prices, and ever-increasing energy demand are among the more important issues in today's society (Brandi et al., 2011). Most likely, the global energy usage will continue to increase by using predominantly fossil fuels (British Petroleum, 2011). In 2012, the global primary energy consumption was

Table 5.6 List of Selected EF Calculators

Application	Unit	Developer	Website
For 17 countries, it calculates how many planets and how much land area is required to support a human's lifestyle, including food, shelter, mobility, goods, and services	$N_{\text{Planet Earths}}$ and global hectares	Global Footprint Network	www.footprintnetwork.org
It calculates how many planets are required to support a human's lifestyle, including food, travel, home, and staff	$N_{\text{Planet Earths}}$	World Wide Fund for Nature	footprint.wwf.org.uk
For various countries, it calculates EF and provides suggestions for reducing carbon, food, housing, and goods and services footprints	$N_{\text{Planet Earths}}$ and global hectares	Center for Sustainable Economy	myfootprint.org

522 EJ (12.47 Gtoe) (British Petroleum, 2013) and grew by 1.8% per year. Oil remained the world's leading fuel with 33.1% of global energy consumption, natural gas's share of global primary energy consumption was 23.9%, global coal's consumption was 29.9%, and nuclear global energy consumption was 4.5%. The renewable's share in global energy consumption was 8.6%, of which 6.7% was attributable to hydroelectricity. It should be noted that those numbers include only commercially traded fuels (British Petroleum, 2013).

Humankind is rapidly exhausting fossil fuels and, as a consequence, people are going to depend on non-fossil energy sources in future. The timing of a global peak regarding oil production is less certain, although there is a growing view that maximum production will occur between 2010 and 2020 (Maggio and Cacciola, 2012). The global peak for coal extraction from the existing coalfields was predicted by Patzek and Croft (2010) to occur approximately during 2011. Some other estimates predicted peak coal later, generally between 2010 (Mohr and Evans, 2009) and 2062 (Maggio and Cacciola, 2012). Natural gas is performing slightly better, with the world's natural gas production peak being predicted between 2025 (Maggio and Cacciola, 2012) and 2066 (Mohr and Evans, 2011). An energy crisis will be an urgent challenge handled within the twenty-first century. Developing clean and renewable energy resources ranks as one of the greatest challenges facing humankind in the medium-term to long-term (Mata et al., 2011). No single energy technology or combination of technologies exists that can address all challenges in a sustainable manner (Ma et al., 2011). ENFs are therefore of significant importance. The suggested definition, various policies, and possibilities for reducing ENFs are shown in Table 5.2.

In general, various definitions of an ENF have been offered. The global footprint network (Global Footprint Network, 2012) defined it as the sum of all areas used to provide non-food and non-feed energy. ENF is the sum of the areas of carbon uptake land, hydropower land, forested land for wood fuel, and cropland for fuel crops. Palmer (1998) defined an ENF as a measurement of the land required to absorb those CO_2 emissions originating from energy usage. Another definition of an ENF is that it represents the area required to sustain energy consumption and is measured as the area of forest that would be required to absorb the resulting CO_2 emissions, excluding the proportion absorbed by the oceans and the area occupied by hydroelectric dams and reservoirs for hydropower (World Wide Fund for Nature, 2002). De Benedetto and Klemeš (2009) calculated an ENF by multiplying the final energy usage of different energy carriers by their land indices and adding the results to the footprint of the whole supply chain. Yet another definition of an ENF is that it corresponds to the demand for non-renewable energy resources (Schindler, 2013), such as cumulative fossil and nuclear energy demand in terms of primary non-renewable energy use, such as energy content of a material as well as the non-renewable energy spent on its extraction (Hermann et al., 2011). It is also defined as the specific energy usage per functional unit (Sobhani et al., 2012) considering fossil-based and renewable-based energy (Vujanović et al., 2014). Because of differences in the qualities of heat and electrical energies, ENF can be divided into electricity−transportation footprint and heat footprint (Vujanović et al., 2014).

ENF can be measured in local (the surface area of a specified region's average biologically productive land and sea over a given year) (Global Footprint Network, 2012) or global (the surface area of the Earth's average biologically productive land and sea over a given year) (Wiedmann and Lenzen, 2007) area units or in units of energy (higher or lower heating value (Hermann et al., 2011) per functional unit.

ENF includes sub-footprints, such as the fossil or fossil ENF (Stoeglehner and Narodoslawsky, 2009), nuclear ENF (Stoeglehner et al., 2005), renewable ENF (Chen and Lin, 2008), wind footprint (Magoha, 2002), solar footprint (Denholm and Margolis, 2008), heat footprint (Vujanović et al., 2014), and others.

NITROGEN FOOTPRINT

Nitrogen is essential for life and it is a critical limiting element for food production (Smil, 1997). It is the most common element in the Earth's atmosphere and a primary component of crucial biological molecules, including proteins and nucleic acids such as DNA (deoxyribonucleic acid) and RNA (ribonucleic acid). It plays a key role in helping to feed the growing populations. Smil (2001) estimated that in the mid 1990s, 40% of the global population was dependent on crops fertilized with reactive nitrogen. In 2008, an updated estimate was that 48% of the world's population was fed by Haber−Bosch nitrogen (Erisman et al., 2008). Since 1970, the world's population has increased by 78% and production of reactive nitrogen, N_r (all N species except N_2), increased by 120% (Galloway et al., 2008). Crops need large amounts of N to grow, but only N_r can be readily used by most organisms, including crops.

However, the world's nitrogen cycle has been dramatically altered because of human activities (Galloway et al., 2008). The amount of human-caused reactive or biologically available N_r within the global environment has increased by a factor of 12.5 (187 Mt N/y in 2005) since the nineteenth century (15 Mt N/y in 1860), in association with the increased use of fertilizers (Galloway et al., 2008). Agriculture is responsible for approximately 80% of the N_r produced worldwide (Union of Concerned Scientists, 2009). More than half of the synthetic N fertilizer ever used on the planet has been used since 1985 (Millennium Ecosystem Assessment, 2005). N_r is also created by the burning of fossil fuel and biomass, by manure run-off, and by the planting of legumes. The primary nitrogen emission sources are transportation, agriculture, power plants, and industry.

Much anthropogenic nitrogen is lost in the air, water, and soil, and has a destructive effect on the ecosystem and human health (Galloway et al., 2008). Approximately 80% of nitrogen used in food production is lost before the consumption and the remainder is lost after consumption as human waste. In biofuel production, all of the nitrogen used is lost to the environment (N-Print Team, 2014). Nitrogen deposition significantly alters the global nitrogen cycle, reduces the biodiversity, pollutes and degrades waters, impacts the human health (shortness of breath, blue baby disease (U.S. Environmental Protection Agency (EPA), 2014), and some cancers (Smil, 1997)), and affects the global environment (Vitousek et al., 1997). It contributes to the eutrophication of coastal rivers and bays (non-potable water, blooms of cyanobacteria and algae, fish kills, and consequently dead zones), formation of smog, soil acidification (Smil, 1997), depletion of ozone in the upper atmosphere, and global warming (European Commission DG Environment News Alert Service, 2012).

NF is a measurement of the amount of reactive nitrogen released into the environment as a result of human activities, expressed in total units of N_r (Čuček et al., 2012b) (see also the NF website) (N-Print Team, 2014). The definition, policies, and NF reduction suggestion paths are represented in Table 5.2. NF mainly covers the N_r emissions NO_x, N_2O, NO_3^-, and NH_3, and they can be rapidly interconverted from one N_r form to another (Galloway et al., 2003). An N_r atom that starts out as part of NH_3 in the Haber–Bosch process is used to produce fertilizer. N_r is then partly incorporated within the crops and then is partly released as NH_3, NO, N_2O, N_2, or NO_3^-. The N_r species can be rapidly interconverted from one N_r form to another (Galloway et al., 2003). NF represents disruption of the regional to global nitrogen cycle and its consequences. The weakness of the NF is the lack of data, its uncertainty (Leach et al., 2012), and high data demand (Gu et al., 2013).

NF can be calculated using various tools. The better-known tools are NF calculators. Table 5.7 contains a list of available NF calculators.

Table 5.7 List of NF Calculators

Application	Unit	Developer	Website
For the United States, United Kingdom, Germany, and the Netherlands, it determines an individual's contribution to nitrogen losses to the environment from resource uses. It focuses on four main areas of consumption: food, housing, transportation, and goods and services (Leach et al., 2012)	mass unit/y	N-PRINT Team	n-print.org (N-Print Team, 2014)
For Chesapeake watershed, it calculates average household NF and provides tips to reduce the footprint	lb/y	Chesapeake Bay Foundation	www.cbf.org (Chesapeake Bay Foundation, 2014)

PHOSPHORUS FOOTPRINT

Phosphorus is a fossil mineral found in rocks that accumulates as a result of geological processes. In addition to nitrogen, phosphorus is a critical element in food security. Today, food could not be produced at current global levels without the use of processed mineral fertilizers; therefore, humanity has become addicted to phosphate rock (Cordell et al., 2009).

Phosphorus is a finite resource that might become scarce and might peak within the next decades (Cordell, 2010). It is predicted that current global reserves may be depleted during the next decades (Cordell et al., 2009). However, depletions and peaks in mineral resources are difficult to forecast (Carpenter and Bennett, 2011) because of changes in production costs, data reliability, changes in demand and supply (Cordell et al., 2009), and possible future extraction technologies. Nonetheless, peak phosphorus is worthy of careful consideration because declines in phosphorus availability could significantly decrease agricultural yields (Carpenter and Bennett, 2011). The PF is therefore of significance. It may even be more important in the future because of a growing global population and biofuels. The main definition, policies, and potential ways to reduce PF are shown in Table 5.2.

The PF addresses the phosphorus imbalance within crops (Lott et al., 2009). Leakage of phosphorus leads to eutrophication of surface freshwater and some coastal waters (Carpenter and Bennett, 2011), which spurs blooms of cyanobacteria depleting fish and creating dead zones. More than 400 dead zones have been reported worldwide, affecting an area of more than 245,000 km^2 (Diaz and Rosenberg, 2008).

BIODIVERSITY FOOTPRINT

Humans have transformed 40–50% of the ice-free land surface, changing prairies, forests, and wetlands into agricultural and urban systems (Chapin et al., 2000).

They are destroying biological diversity (biodiversity) at an alarming rate (Purvis and Hector, 2000) and causing changes in the global distribution of organisms (Chapin et al., 2000).

The main drivers of biodiversity loss are (Sodhi et al., 2009):

- Landscape modification, habitat loss or change, fragmentation, human infrastructure, and deforestation, especially tropical humid forests that are the more species-rich
- Spread of invasive non-native species or genes outcompeting endogenous species and the spread of disease (Galli et al., 2014)
- Overharvesting and overexploitation of specific species, especially attributable to fishing and hunting. The global trading system for food, cosmetics, and pharmaceuticals is related to it
- Pollution that affects the health of species, particularly in aquatic ecosystems, such as excess nutrient (nitrogen and phosphorus) loading in waters, pesticide use in farming, and dumping of garbage at sea
- Climate change and the greenhouse effect

Ultimately, the main drivers are human activities (European Commission, 2011a) and the size, growth, and resource demands of the human population (Nag, 2008). As the world population and economy grow, so do the pressures on biodiversity (Galli et al., 2014).

Extinction is the most common way biodiversity is lost or reduced (Treat and Callahan, 2013). When a species becomes endangered or extinct, usually more than just that species is affected. According to some studies, humanity has already caused the extinction of 5–20% of species (Chapin et al., 2000) in many groups of organisms, and current rates of extinction are estimated to be 100 times to 1,000 times faster than natural extinction rates (Pimm et al., 1995). Some estimates are that the extinction rate is up to 140,000 species per year, and a much larger number of species are endangered (Nag, 2008).

BF is defined as "the summation of all the pressures that have potential consequences for biodiversity" (de Bie and van Dessel, 2011). It is related to reduction in biodiversity and, therefore, to the rate of biodiversity loss (Hanafiah et al., 2012). BF is also measured as a global area required to compensate for the mean species abundance loss caused by direct land use and by fossil-based CO_2 emissions for the life cycle of a product (Hanafiah et al., 2012). Definition, policy, and BF reduction options are summarized in Table 5.2.

Biodiversity loss threatens the well-being of humans (Díaz et al., 2006). It is estimated that between 50,000 and 70,000 plant species are used in medicine worldwide (Schülke, 2008), and approximately 1×10^8 t of aquatic life, including fish, molluscs, and crustaceans, are taken from the wild every year. Extinctions can disrupt vital ecological processes such as pollination and seed dispersal, leading to cascading losses, ecosystem collapse, and a higher extinction rate overall (Sodhi et al., 2009). The risks related to biodiversity and loss of ecosystem services are already impacting agriculture, forestry, and fisheries (European

Commission, 2011a). According to the European Commission (2011a), biodiversity loss is the most critical global environmental threat along with climate change. Pereira et al. (2012) stated that "global biodiversity change is one of the more pressing environmental issues of our time." Also, the Aldesgate Group (2011) pointed out that "the protection of biodiversity and ecosystem services, while complex to value and quantify accurately, is essential for future well-being and economic development." There are also strong ethical arguments for protecting biodiversity (European Commission, 2009b). BF is therefore very important.

However, unlike the presented footprints, the BF is complicated to assess and cannot be calculated easily for the products, businesses, activities, and reporting (Burrows, 2011). A global observation system for monitoring biodiversity changes does not exist yet (Pereira et al., 2012). There is still limited awareness of biodiversity issues among the general public and decision-makers (Secretariat of the Convention on Biological Diversity, 2010). Several attempts have been made to measure the BF, such as using land area appropriated by human activity, the number of threatened species (Burrows, 2011), extinction rate, and the population trend of species (Butchart et al., 2010). Currently, it might be impossible to evaluate the BF at satisfactory levels, but it is possible to identify the hot spots (Burrows, 2011). Standards and frameworks of the BF are currently undergoing development (BIQ Forum, 2014).

LAND FOOTPRINT

Population growth and economic income have been identified as the more important drivers for the LF (Giljum et al., 2013b). More than 75% of the Earth's land (excluding Greenland and Antarctica) is already used by humans (Haberl et al., 2011). Land use ranges from very intensive to very extensive. Approximately 1% of the land is used as infrastructure and urban areas, approximately 10−12% is used as cropland, approximately 26% is used as forestry land, and between 23% (Toderoiu, 2010) and 36% (Haberl et al., 2011) is used as grazing land. Of the remaining land, approximately half is unproductive or covered by rocks, snow, or deserts. The other half includes pristine forests (4.6% of total area), including tropical rainforests and all other forests with almost no signs of human use (Haberl et al., 2011).

The LF usually assesses those land areas that are directly and indirectly required to satisfy the consumption either for specific product(s) or for total consumption (Giljum et al., 2013a). It is a powerful method of illustrating the dependencies of local areas (regions or countries) on foreign land, which is embodied in imports and exports ("virtual land") (Giljum et al., 2013b). Another definition and usage of land footprint is that it is equivalent to EF excluding carbon uptake land, because this is directly related to CO_2 emissions already captured by the CF (Steen-Olsen et al., 2012). Furthermore, it is defined as the amount of biologically productive land required to satisfy the consumption (Weinzettel et al., 2013). Currently, no harmonized definition of the LF exists (Giljum et al., 2013a). It is important to note that LF approaches differ from calculations of the EF, because no weighting of land areas by different bioproductivities is applied.

Because of data restrictions, LF studies have often focused on the agricultural and forestry areas (Giljum et al., 2013a). The summary of LF definition, policies, and reduction options is presented in Table 5.2.

OTHER ENVIRONMENTAL FOOTPRINTS

In addition to footprints that are recognized as key, several other environmental footprints have been introduced to date (June 2014). These footprints are briefly described in this section.

MATERIAL FOOTPRINT

Material footprint is a consumption-based indicator of resource use. It is defined as a global allocation of used raw material extraction to the final demand of an economy (Wiedmann et al., 2013). The material footprint does not record the actual physical movement of materials within and among countries but, instead, enumerates the link between the beginning of a production chain (where raw materials are extracted from the natural environment) and its end (where a product or service is consumed). It opens a new perspective on global material supply chains and on the shared responsibility for the impacts of extraction, processing, and consumption of environmental resources (Wiedmann et al., 2013). It illustrates the global life cycle-wide material extraction and the final consumption of material within a region, occurring either within a country or beyond borders of countries (Giljum et al., 2013a). Material footprint is a newer term for "ecological rucksacks" (Giljum et al., 2013a). Another definition of material footprint is that it is an indicator for measuring and optimizing the resource consumption of products and their ingredients and the production processes along the whole value chain (Lettenmeier et al., 2012).

EMISSION FOOTPRINT

The emission footprint represents the quantities of product or service-created emissions into the air (e.g., SO_2, particles, CO, CO_2), water (e.g., chemical oxygen demand (COD), nitrogen, and phosphorus), and soil (through spillage in the soil). Emission footprints are calculated on a per-area basis. The conversion of emissions is calculated according to the principle that anthropogenic mass flows must not alter the qualities of local compartments. Maximum flows are defined based on the naturally existing qualities of the compartments and their replenishment rate per unit area. For emissions to soil, the replenishment rate is given by the decomposition of biomass to humus (measured by the production of compost by biomass). For groundwater, this is the seepage rate (given by local precipitation). For emissions into the air, the natural exchange of substances between forests and air per unit area is taken as a basis of comparison between natural and anthropogenic flows. Different emissions to air are not weighted, because only the largest dissipation areas are to be considered. Lower area consumption emissions may be dissipated without violating the principle that anthropogenic mass flows must not alter the qualities of local compartments (Sandholzer and Narodoslawsky, 2007).

HUMAN FOOTPRINT

The human footprint measures energy quantities, resources, and products consumed by a human during his/her lifetime and includes, for example, the number of food "pieces," the volumes of fuel and water, and the mass of waste (National Geographic, 2014b). Human footprint evaluates everything humans eat, use, wear, buy, and discard during their lifetime (Kirk, 2011). Human footprint is also a measure of transformation, integrating information regarding human access, settlement, transformation of land use/land cover, and development of energy infrastructure (Trombulak et al., 2010).

WASTE FOOTPRINT

Waste footprint is the amount of waste produced by sourcing ingredients and materials, manufacturing and processing, and transportation (Thinking Ahead, 2011). It also represent the environmental, economic, and social impacts that result from waste that humans create (HEC Global Learning Centre, 2009).

EMERGY FOOTPRINT

Emergy footprint combines the EF calculation and emergy analysis (Zhao et al., 2005). Emergy is calculated by the following equation:

$$\text{Emergy (seJ)} = \text{exergy (J)} \cdot \text{transformity (seJ/J)} \tag{5.15}$$

The concepts of emergy, exergy, and transformity are briefly presented in Table 5.8.

Biocapacity is estimated as a function of the renewable resources available (Brown et al., 2009). Consumption data can be converted into emergy flows and are grouped into the following categories: cropland; forestry; animal husbandry; and energy resources. All the energy flows (J) are transformed into solar emergy (seJ/y) through transformity. Emergy flows are divided by the global emergy density (seJ/gha) to obtain the global average productive hectares—emergy footprint (e.g., gha/capita) (Brown et al., 2009).

Table 5.8 Emergy, Exergy, and Transformity

	Description
Emergy	Ability of energy (exergy) of one kind or another is that it is used in transformations directly and indirectly when making a product or creating a service (Odum, 1996). It measures quality differences between forms of energy. It accounts for different forms of energy and resources, such as natural resources, renewable and non-renewable energy flows, economic goods, labor, and information, and it describes the amount of one kind of energy required to make another form of energy or resource. The unit of emergy is emjoule (emJ)—available energy of one kind consumed in transformations. It is usually expressed in a unit of solar emergy – embodied solar equivalent joules or solar emjoules (seJ) – all direct and indirect solar energy inputs that have been used in creating a service or product. Other units used are coal emjoules, electrical emjoules, and others. The greatest strength of emergy is that all energy and resources are put on a common scale that is objective and scientific (Brown and Angelo, 2010)
Exergy	Exergy is the energy that is available to be used for work. It quantifies maximal theoretical work that can be delivered by bringing an energy source into equilibrium with its environment. Exergy is always destroyed when a process involves a temperature change because energy conversion processes are irreversible. This destruction is proportional to the entropy of the system and its surroundings. The destroyed energy is also called anergy
Transformity	Transformity or energy quality ratio is the emergy (usually solar emergy) required to make a unit of available energy of the product or service, expressed in (seJ)/J. It aims to quantify energy quality and is defined as the ratio of emergy (work put into a product) and useful energy or exergy (value received from the product). Transformities are obtained through the analysis of a production process or by other empirical means (Campbell et al., 2005)

$$\text{Emergy footprint (gha)} = \frac{\text{emergy (seJ)}}{\text{global emergy density (seJ/gha)}} \tag{5.16}$$

The most important feature of emergy footprint is that it enables a comparison of all resources on a fair basis. Emergy footprint calculations also include deserts, glaciers, and open oceans, which are excluded in EF analyses. However, there are several disadvantages: environmental services and negative externalities are excluded from analyses and calculations of transformities are difficult and should be estimated (Brown et al., 2009).

EXERGY FOOTPRINT

The exergy footprint includes the following resource consumption categories: materials; water; energy; food; and, with the additional research underway, human and monetary capital (Caudill et al., 2010). By using exergy, the need to define, normalize, and aggregate various impact categories is avoided. It uses national-level exergy consumption on a per-capita basis as the normalization factor and compares it to a national baseline value (Caudill et al., 2010).

CHEMICAL FOOTPRINT

The chemical footprint is an indication of potential risk posed by a product based on its chemical composition, the human and ecologically hazardous properties of the ingredients, and the exposure potential of the ingredients during its life cycle. Its analysis should include a comprehensive quantification of the chemicals used, consumed, produced, or modified throughout the life cycle of the product of interest and the risks posed (Panko and Hitchcock, 2011).

POLLUTION FOOTPRINT

Pollution footprint is an EF based on pollution absorption. It accounts for pollutants incurred by human activities and is clarified in terms of different classes or types of pollutants (Min et al., 2011). It is based on input−output analysis for measuring the discharge coefficients and amounts of pollutants for the system (Gao and Fan, 2009).

RADIOACTIVE FOOTPRINT

Radioactive footprint is defined as the total geographical area contaminated by radioactive isotopes, including the quantity and radioisotope composition dispersed both on land and water, as a result of a nuclear power plant disaster, atomic bomb blast, or depleted uranium munitions event (Urban Dictionary, 2014).

FOOD FOOTPRINT

Food footprint is also called the material footprint of food production. It includes those areas needed to grow crops, fish, and graze animals, and to absorb carbon emissions from food processing and transportation (Sokoli, 2014); it is expressed in hectares/capita. The global average food footprint is 0.79 ha/capita (Neset and Lohm, 2005). A person's food footprint (foodprint) is also defined as all the emissions that result from the production, transportation, and storage of the food supplied to meet their consumption needs. Focus is especially placed on food supply and is expressed in $t_{CO_2,eq}$/capita (Shrink That Footprint Ltd, 2014). Furthermore, it includes the land required to produce the food and to sequester CO_2 emissions from the food production process (Zeev et al., 2014).

NUTRITIONAL FOOTPRINT

Nutritional footprint is a concept that links environmental, health, and social issues of nutrition and food products together. Nutritional footprint assessment is a quantitatively based approach and evaluates the levels of health and environmental impacts from the life cycle's perspective. It can provide a more environmentally friendly and healthier choice of food products (Lukas et al., 2013). The methodology for evaluating the nutritional footprint consists of two preparation steps and three main steps. The preparation steps include assessment of relevant health (calorie and salt content, content of dietary fiber and saturates, nutrient density, etc.) and environmental indicators (material, CF, WF and LF, biodiversity, erosion and earth movement, etc.), and reference data and assessment levels. Furthermore, the main steps include (i) estimation of health and environmental issues related to food products; (ii) allocation and evaluation of the selected indicators during the life cycle phases; and (iii) identification and quantitative comparison of results. All the indicators have allocated ranges from 1 to 3 to approximately identify hot spots, health and environmental indicators have equal weights, and the overall assessment consists of one number (the lower the better) (Lukas et al., 2013). It is a tool that enables a detailed overview, and it is relatively easy to compare different impacts of food products (Lucas et al., 2013).

CONCLUDING REMARKS

Humanity is in the middle of one of the largest experiments in the history of the Earth (Chapin et al., 2000). In an increasingly resource-constrained world, accurate and effective accounting systems are needed to map supply and demand for ecosystem services (Galli et al., 2014). Regretfully, it seems that humanity is moving further and further away from sustainability (Zhao et al., 2005). Moving toward sustainability requires the redesigning of production, consumption, and waste management, as well as the will to implement it. Reliable definitions and measurements are necessary for achieving these goals. Several tools for measuring sustainability have been developed to evaluate the (un)sustainability of humans, nations, processes, products, or activities. Nevertheless, the definition of a suitable environmental and/or sustainability metric for supporting objective environmental and/or sustainability assessments is still an open issue within the literature.

This chapter briefly presented the metrics for measuring environmental sustainability such as indicators of potential environmental impact, eco-efficiency, eco profit and total profit, eco NPV and total NPV and other combined criteria, sustainability indexes, and environmental footprints. Furthermore, key environmental footprints, such as CF, WF, EF, ENF, NF, PF, BF, and LF have been presented in detail. Finally, other environmental footprints have been assessed that are not widely known and used, and that are not recognized as key environmental footprints.

Key environmental footprints pose significant pressure to the Earth. Several options regarding how to reduce key environmental footprints have been recognized. The importance of evaluating total footprints (burdening and unburdening) instead of only direct (burdening) footprints has been pointed out. However, it should be noted that reducing one footprint can negatively impact other footprints. One such example is biofuel production, which has the potential for improving CF and ENF but could negatively impact the WF, NF, PF, BF, and LF.

The negative consequences of increasing specific footprints have been recognized by governments, businesses, researchers, and the public in general; therefore, the number of footprint evaluations has significantly increased over the past decade. Several policies and targets have been adopted throughout the world to move toward more sustainable development and to mitigate or prevent harmful impacts on the environment, such as climate change, biodiversity loss, eutrophication of water bodies, and many others. It should be noted, however, that measuring environmental footprints and their consequences on the environment is a relatively young discipline; therefore, it is expected that more researchers will join the effort and more frameworks and concepts will be found in the near future with the developed tools.

ACKNOWLEDGMENT

The authors are grateful for financial support from the Slovenian Research Agency (Programs P2-0032 and P2-0377) and from the Hungarian State and the European Union under project TÁMOP-4.2.2/A-11/1/KONV-2012-0072 “Design and optimisation of modernisation and efficient operation of energy supply and utilisation systems using renewable energy sources and ICTs.”

REFERENCES

Abbott, J., 2008. What is a carbon footprint? Edinburgh, UK: The Edinburgh Centre for carbon management. <www.timcon.org/CarbonCalculator/Carbon%20Footprint.pdf> (accessed 20.02.2014).

Aldesgate Group, 2011. Pricing the Priceless, The business case for action on biodiversity. <www.aldersgategroup.org.uk/asset/download/472/Business%20and%20Biodiversity.pdf> (accessed 02.05.2014).

Allen, T., 2008. Life cycle tools for sustainable change. Prodesign (96), 52–54.

Attorre, F., 2014. Soqotra Archipelago (Yemen): Toward Systemic and Scientifically Objective Sustainability in Development and Conservation. Edizioni Nuova Cultura, Rome, Italy.

Australian Government, 2013. Water Act 2007, No. 137, 2007 as amended. <www.comlaw.gov.au/Details/C2014C00043> (accessed 02.06.2014).

Australian Government; Department of the Environment, 2014. The Renewable Energy Target (RET) scheme. <www.environment.gov.au/climate-change/renewable-energy-target-scheme> (accessed 05.06.2014).

Azapagic, A., Clift, R., 1999. Life cycle assessment and multiobjective optimisation. J. Clean. Prod. 7, 135–143.

Bertok, B., Barany, M., Friedler, F., 2012. Generating and analyzing mathematical programming models of conceptual process design by P-graph software. Ind. Eng. Chem. Res. 52, 166–171.

Bhaskar, V., Gupta, S.K., Ray, A.K., 2000. Applications of multiobjective optimization in chemical engineering. Rev. Chem. Eng. 16, 1–54.

BIQ Forum, 2014. Biodiversity & Ecosystem Service Footprint Project. <www.biofootprint.org/> (accessed 02.05.2014).

Bojarski, A.D., Laínez, J.M., Espuña, A., Puigjaner, L., 2009. Incorporating environmental impacts and regulations in a holistic supply chains modeling: an LCA approach. Comput. Chem. Eng. 33, 1747–1759.

Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., Lazarus, E., Morales, J.C., Wackernagel, M., Galli, A., 2013. Accounting for demand and supply of the biosphere's regenerative capacity: The National Footprint Accounts' underlying methodology and framework. Ecol. Indic. 24, 518–533.

Brandi, H.S., Daroda, R.J., Souza, T.L., 2011. Standardization: an important tool in transforming biofuels into a commodity. Clean Technol. Environ. Policy 13, 647–649.

British Petroleum, 2011. BP Energy Outlook 2030. <www.bp.com/content/dam/bp/pdf/Energy-economics/Energy-Outlook/BP_Energy_Outlook_Booklet_2011.pdf> (accessed 28.04.2014).

British Petroleum, 2013. BP Statistical Review of World Energy June 2013. <www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf> (accessed 28.04.2014).

Brown, M., Sweeney, S., Campbell, D.E., Huang, S.-L., Ortega, E., Rydberg, T., Tilley, D. and Ulgiati, S., 2009. Emergy synthesis: Theory and applications of the emergy methodology. Proceedings from the Fifth Biennial Emergy Conference, Gainesville, FL, USA.

Brown, M.T., Angelo, M.J., 2010. Valuing nature, the challenge of the National Environmental Legacy Act. In: Flournoy, A.C., Driesen, D.M. (Eds.), Beyond Environmental Law: Policy Proposals for a Better Environmental Future. Cambridge University Press, New York, USA.

Burrows, D., 2011. How to measure your firm's biodiversity footprint: the Guardian. <www.theguardian.com/sustainable-business/biodiversity-footprint-new-carbon-measurement-management> (accessed 29.04.2014).

Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, J.E.M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G.M., Chanson, J., Chenery, A.M., Csirke, J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway, J.N., Genovesi, P., Gregory, R.D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M.A., McRae, L., Minasyan, A., Morcillo, M.H., Oldfield, T.E.E., Pauly, D., Quader, S., Revenga, C., Sauer, J.R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S.N., Symes, A., Tierney, M., Tyrrell, T.D., Vié, J.-C., Watson, R., 2010. Global biodiversity: indicators of recent declines. Science 328, 1164–1168.

Campbell, D.E., Brandt-Williams, S.L., Meisch, M.E., 2005. Environmental Accounting Using Emergy: Evaluation of the State of West Virginia. US Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Atlantic Ecology Division, Narragansett, USA.

Carbonfund.org, 2014. How to reduce your carbon footprint. <www.carbonfund.org/reduce> (accessed 15.03.2014).

Carpenter, S.R., Bennett, E.M., 2011. Reconsideration of the planetary boundary for phosphorus. Environ. Res. Lett. 6 (1), 1−12.

Carson, R., 1962. Silent Spring. Houghton Mifflin, New York, USA.

Caudill, R.J., Olapiriyakul, S., Seale, B., 2010. An Exergy Footprint Metric Normalized to US Exergy Consumption per Capita. 2010 IEEE International Symposium on Sustainable Systems and Technology (ISSST), 1−6.

Chait, J., 2009. The 15 best carbon calculators. <www.mnn.com/earth-matters/climate-weather/stories/the-15-best-carbon-calculators> (accessed 19.03.2014).

Chakrabortty, R., Hasin, M., 2013. Solving an aggregate production planning problem by using multi-objective genetic algorithm (MOGA) approach. International Journal of Industrial. Engineering Computations 4, 1−12.

Chapin III, F.S., Zavaleta, E.S., Eviner, V.T., Naylor, R.L., Vitousek, P.M., Reynolds, H. L., Hooper, D.U., Lavorel, S., Sala, O.E., Hobbie, S.E., Mack, M.C., Díaz, S., 2000. Consequences of changing biodiversity. Nature 405, 234−242.

Chen, C.-Z., Lin, Z.-S., 2008. Multiple timescale analysis and factor analysis of energy ecological footprint growth in China 1953−2006. Energy Policy 36, 1666−1678.

Chesapeake Bay Foundation, 2014. Nitrogen Calculator, Your Bay Footprint. <www.cbf.org/news-media/multimedia/nitrogen-calculator> (accessed 28.04.2014).

China.org.cn, 2014. Policies & Announcements. <www.china.org.cn/environment/node_7076102.htm> (accessed 02.05.2014).

Clean Water Act., 2002. Federal Water Pollution Control Act. As Amended Through PL 107-133.

Conserve Energy Future, 2014. Water Pollution Facts. <www.conserve-energy-future.com/various-water-pollution-facts.php> (accessed 10.04.2014).

Cordell, D., 2010. The Story of Phosphorus, Sustainability implications of global phosphorus scarcity for food security (PhD Thesis). Institute for Sustainable Futures, University of Technology, Sydney, Australia, and Department of Water and Environmental Studies, Linköping University, Sweden.

Cordell, D., Drangert, J.-O., White, S., 2009. The story of phosphorus: global food security and food for thought. Global Environ. Change 19, 292−305.

Čuček, L., 2013. Synthesis of sustainable bioprocesses using computer-aided process engineering (PhD Thesis). Maribor, Slovenia University of Maribor; Faculty of Chemistry and Chemical Engineering. <dkum.uni-mb.si/Dokument.php?id = 55146> (accessed 08.05.2013).

Čuček, L., Drobež, R., Pahor, B., Kravanja, Z., 2012a. Sustainable synthesis of biogas processes using a novel concept of eco-profit. Comput. Chem. Eng. 42, 87−100.

Čuček, L., Klemeš, J., Kravanja, Z., 2012b. Carbon and nitrogen trade-offs in biomass energy production. Clean Technol. Environ. Policy 14, 389−397.

Čuček, L., Klemeš, J.J., Kravanja, Z., 2012c. A review of footprint analysis tools for monitoring impacts on sustainability. J. Clean. Prod. 34, 9−20.

Čuček, L., Klemeš, J.J., Varbanov, P.S., Kravanja, Z., 2012d. Reducing the dimensionality of criteria in multi-objective optimisation of biomass energy supply chains. Chem. Eng. Trans. 29, 1231−1236.

Čuček, L., Varbanov, P.S., Klemeš, J.J., Kravanja, Z., 2012e. Total footprints-based multi-criteria optimisation of regional biomass energy supply chains. Energy 44, 135–145.

Čuček, L., Klemeš, J.J., Kravanja, Z., 2013a. A novel concept of eco- and total-net present value applied to the synthesis of biogas processes. Conference ECCE9/ECAB2, The Hague, Netherlands, Number 1250. <www.ecce2013.eu/documenten/wednesday_april_24.pdf> (accessed 04.06.2014).

Čuček, L., Klemeš, J.J., Varbanov, P.S., Kravanja, Z., 2013b. Dealing with high-dimensionality of criteria in multiobjective optimization of biomass energy supply network. Ind. Eng. Chem. Res. 52, 7223–7239.

Čuček, L., Klemeš, J.J., Varbanov, P.S., Kravanja, Z., 2013c. Dimensionality reduction approach for multi-objective optimisation extended to total footprints. Sixth International Conference on Process Systems Engineering (PSE ASIA), Kuala Lumpur, Malaysia. <www.sps.utm.my/download/PSEAsia2013-128.pdf> (accessed 30.04.2014).

Čuček, L., Klemeš, J.J., Kravanja, Z., 2014. Objective dimensionality reduction method within multi-objective optimisation considering total footprints. J. Clean. Prod. 71, 75–86.

Daimler, 2011. Well-to-wheel. <www2.daimler.com/sustainability/optiresource/index.html> (accessed 21.05.2014).

De Benedetto, L., Klemeš, J., 2008. LCA as environmental assessment tool in waste to energy and contribution to occupational health and safety. Chem. Eng. Trans. 13, 343–350.

De Benedetto, L., Klemeš, J., 2009. The environmental performance strategy map: an integrated LCA approach to support the strategic decision-making process. J. Clean. Prod. 17, 900–906.

De Benedetto, L., Klemeš, J., 2010. The environmental bill of material and technology routing: an integrated LCA approach. Clean. Technol. Environ. Policy 12, 191–196.

de Bie, S., van Dessel, B., 2011. Compensation for Biodiversity Loss, Advice to the Netherlands' Taskforce on Biodiversity and Natural Resource. De Gemeynt, Klarenbeek, the Netherlands, <www.gemeynt.nl/en/component/docman/doc_view/8-compensation-for-biodiversity-loss> (accessed 03.05.2014).

de Haes, H.A.U., Heijungs, R., Suh, S., Huppes, G., 2004. Three strategies to overcome the limitations of life-cycle assessment. J. Ind. Ecol. 8, 19–32.

Delft University of Technology, 2012. The Model of the Eco-costs/Value Ratio (EVR). Delft, the Netherlands. <www.ecocostsvalue.com/> (accessed 22.01.2014).

Denholm, P., Margolis, R.M., 2008. Land-use requirements and the per-capita solar footprint for photovoltaic generation in the United States. Energy Policy 36, 3531–3543.

Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321, 926–929.

Díaz, S., Fargione, J., Chapin III, F.S., Tilman, D., 2006. Biodiversity loss threatens human well-being. PLoS Biol. 4, 277.

Dilling, L., Doney, S.C., Edmonds, J., Gurney, K.R., Harriss, R., Schimel, D., Stephens, B., Stokes, G., 2003. The role of carbon cycle observations and knowledge in carbon management. Annu. Rev. Environ. Resour. 28, 521–558.

Dong, H., Geng, Y., Sarkis, J., Fujita, T., Okadera, T., Xue, B., 2013. Regional water footprint evaluation in China: a case of Liaoning. Sci. Total Environ. 442, 215–224.

Dourte, D.R., Fraisse, C.W., 2012. What is a Water Footprint?: An Overview and Applications in Agriculture. <edis.ifas.ufl.edu/pdffiles/AE/AE48400.pdf> (accessed 20.04.2014).

Downie, J., Stubbs, W., 2013. Evaluation of Australian companies' scope 3 greenhouse gas emissions assessments. J. Clean. Prod. 56, 156–163.

Energy Independence and Security Act, 2007. <www.gpo.gov/fdsys/pkg/STATUTE-121/pdf/STATUTE-121-Pg1492.pdf> (accessed: 01.06.2014).
Energy Policy Act, 2005. <www.gpo.gov/fdsys/pkg/STATUTE-119/pdf/STATUTE-119-Pg594.pdf> (accessed 01.06.2014).
Ercin, A.E., Hoekstra, A.Y., 2014. Water footprint scenarios for 2050: a global analysis. Environ. Int. 64, 71–82.
Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z., Winiwarter, W., 2008. How a century of ammonia synthesis changed the world. Nat. Geosci. 1, 636–639.
European Commission, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. Official Journal of the European Communities; Luxembourg.
European Commission, 2007. Carbon footprint—what it is and how to measure it. <lca.jrc.ec.europa.eu/Carbon_footprint.pdf> (accessed 15.02.2014).
European Commission, 2009a. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union, Brussels, Belgium.
European Commission, 2009b. The Message from Athens. Athens, Greece. <ec.europa.eu/environment/nature/biodiversity/conference/pdf/message_final.pdf> (accessed 02.05.2014).
European Commission, 2011a. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions, Our life insurance, our natural capital: an EU biodiversity strategy to 2020 Brussels, Belgium. <ec.europa.eu/environment/nature/biodiversity/comm2006/pdf/2020/1_EN_ACT_part1_v7%5B1%5D.pdf> (accessed 02.05.2014).
European Commission, 2011b. The EU biodiversity strategy to 2020. Brussels, Belgium. <ec.europa.eu/environment/nature/info/pubs/docs/brochures/2020%20Biod%20brochure%20final%20lowres.pdf> (accessed 02.06.2014).
European Commission, 2014. Policies. <ec.europa.eu/environment/policies_en.htm> (accessed 02.05.2014).
European Commission DG Environment News Alert Service, 2012. SCU; The University of the West of England; Bristol, Online calculator measures consumers' "nitrogen footprint". <ec.europa.eu/environment/integration/research/newsalert/pdf/278na3.pdf> (accessed 29.04.2014).
Ewing, B., Moore, D., Goldfinger, S., Oursler, A., Reed, A., Wackernagel, M., 2010. Ecological Footprint Atlas 2010. Global Footprint Network, Oakland, New Zeeland, <www.footprintnetwork.org/images/uploads/Ecological_Footprint_Atlas_2010.pdf> (accessed 28.04.2014).
Fang, K., Heijungs, R., de Snoo, G., 2013. The footprint family: comparison and interaction of the Ecological, Energy, Carbon and Water footprints. Metallurgical Res. Technol. 110, 77–86.
Fang, K., Heijungs, R., de Snoo, G.R., 2014. Theoretical exploration for the combination of the ecological, energy, carbon, and water footprints: overview of a footprint family. Ecol. Indic. 36, 508–518.
Ferng, J.-J., 2002. Toward a scenario analysis framework for energy footprints. Ecol. Econ. 40, 53–69.
Finkbeiner, M., 2009. Carbon footprinting—opportunities and threats. Int. J. Life Cycle Assess. 14, 91–94.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manage. 91, 1−21.

Fuel-Cell e-Mobility, 2014. Well-to-Wheel—Integral Efficiency Analysis. <www.fuel-cell-e-mobility.com/h2-infrastructure/well-to-wheel-en/> (accessed 21.05.2014).

Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B., Giljum, S., 2011. Integrating Ecological, Carbon and Water Footprint: Defining the "Footprint Family" and its Application in Tracking Human Pressure on the Planet. Technical Document, Surrey, UK.

Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B., Giljum, S., 2012. Integrating ecological, carbon and water footprint into a "Footprint Family" of indicators: definition and role in tracking human pressure on the planet. Ecol. Indic. 16, 100−112.

Galli, A., Weinzettel, J., Cranston, G., Ercin, E., 2013. A footprint family extended MRIO model to support Europe's transition to a One Planet Economy. Sci. Total Environ. 461−462, 813−818.

Galli, A., Wackernagel, M., Iha, K., Lazarus, E., 2014. Ecological footprint: implications for biodiversity. Biol. Conserv. 173, 121−132.

Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B., Cosby, B.J., 2003. The nitrogen cascade. BioScience 53, 341−356.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., et al., 2008. Transformation of the Nitrogen cycle: recent trends, questions, and potential solutions. Science 320, 889−892.

GAMS Development Corporation, 2013. GAMS—A User's Guide. Washington, DC. <www.gams.com/dd/docs/bigdocs/GAMSUsersGuide.pdf> (accessed 05.11.2013).

Gao, J.-x., Fan, X.-s., 2009. Pollution footprint contrastive analysis on industrial import and export in China. China Environ. Sci. 1, 030.

Gerbens-Leenes, W., Hoekstra, A., van der Meer, T., 2008. The Water Footprint of Bio-Energy and Other Primary Energy Carriers, Value of Water Report Series No. 29. UNESCO-IHE, Delft, the Netherlands, <www.waterfootprint.org/Reports/Report29-WaterFootprintBioenergy.pdf> (accessed 02.09.2013).

Giljum, S., Lutter, S., Bruckner, M., Aparcana, S., 2013a. State-of-Play of National Consumption-Based Indicators, A Review and Evaluation of Available Methods and Data to Calculate Footprint-Type (Consumption-Based) Indicators for Materials, Water, Land and Carbon. Sustainable Europe Research Institute (SERI), Vienna, Austria, <ec.europa.eu/environment/enveco/resource_efficiency/pdf/FootRev_Report.pdf> (accessed 03.05.2014).

Giljum, S., Wieland, H., Bruckner, M., de Schutter, L., Giesecke, K., 2013b. Land Footprint Scenarios, A Discussion Paper Including A Literature Review and Scenario Analysis on the Land Use Related to Changes in Europe's Consumption Patterns. Sustainable Europe Research Institute (SERI), Vienna, Austria, <www.foeeurope.org/sites/default/files/publications/seri_land_footprint_scenario_nov2013_1.pdf> (accessed 03.05.2014).

Glavič, P., Lukman, R., 2007. Review of sustainability terms and their definitions. J. Clean. Prod. 15, 1875−1885.

Glavič, P., Lesjak, M., Hirsbak, S., 2012. European training course on eco-efficiency. 15th European Roundtable on Sustainable Consumption and Production, Bregenz, Austria. <vbn.aau.dk/files/66744447/European_Training_Course_on_Eco_Efficiency.pdf> (accessed 03.06.2014).

Gleick, P.H., Ajami, N., Christian-Smith, J., Cooley, H., Donnelly, K., Fulton, J., Ha, M.-L., Heberger, M., Moore, E., Morrison, J., Orr, S., Schulte, P., Srinivasan, V., 2014. The World's Water Volume 8: The Biennial Report on Freshwater Resources. Island Press, Washington, USA.

Global Footprint Network, 2010. Footprint Basics—Overview. <www.footprintnetwork.org/en/index.php/GFN/page/footprint_basics_overview/> (accessed 21.02.2014).

Global Footprint Network, 2011. Frequently asked questions—What is the Ecological Footprint? <www.footprintnetwork.org/en/index.php/gfn/page/frequently_asked_questions/> (accessed 21.04.2014).

Global Footprint Network, 2012. Glossary. <www.footprintnetwork.org/en/index.php/gfn/page/glossary/> (accessed 20.02.2014).

Goodland, R., 1995. The concept of environmental sustainability. Annu. Rev. Ecol. Syst. 26, 1–24.

Government of Canada, 2013. What is eco-efficiency? <www.ic.gc.ca/eic/site/ee-ee.nsf/eng/h_ef00010.html> (accessed 15.04.2014).

GRACE Communications Foundation, 2014. Water footprint calculator. <www.gracelinks.org/1408/water-footprint-calculator> (accessed 07.06.2014).

Grossmann, I.E., Guillén-Gosálbez, G., 2010. Scope for the application of mathematical programming techniques in the synthesis and planning of sustainable processes. Comput. Chem. Eng. 34, 1365–1376.

Gruener, O., 2010. The water footprint: water in the supply chain. Environmentalist 1, 12.

Gu, B., Leach, A.M., Ma, L., Galloway, J.N., Chang, S.X., Ge, Y., Chang, J., 2013. Nitrogen Footprint in China: food, energy, and nonfood goods. Environ. Sci. Technol. 47, 9217–9224.

Guillén-Gosálbez, G., 2011. A novel MILP-based objective reduction method for multi-objective optimization: application to environmental problems. Comput. Chem. Eng. 35, 1469–1477.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., de Haes, H.A.U., de Bruijn, H., van Duin, R., Huijbregts, M.A.J., Lindeijer, E., Roorda, A.A.H., van der Ven, B.L., Weidema, P.P., 2002. Handbook on Life Cycle Assessment, Operational Guide to the ISO Standards. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Haberl, H., Erb, K.-H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C., Plutzar, C., Steinberger, J.K., 2011. Global bioenergy potentials from agricultural land in 2050: sensitivity to climate change, diets and yields. Biomass Bioenergy 35, 4753–4769.

Haggar, S.E., 2007. Sustainable Industrial Design and Waste Management: Cradle-to-Cradle for Sustainable Development. Elsevier Academic Press, NY, USA.

Haimes, Y.Y., Lasdon, L.S., Wismer, D.A., 1971. On a bicriterion formulation of the problems of integrated system identification and system optimization. IEEE Trans. Syst. Man Cybern. SMC-1, 296–297.

Hanafiah, M.M., Hendriks, A.J., Huijbregts, M.A.J., 2012. Comparing the ecological footprint with the biodiversity footprint of products. J. Clean. Prod. 37, 107–114.

HEC Global Learning Centre, 2009. Waste Footprint. <www.globalfootprints.org/waste> (accessed 22.05.2014).

Hendrickson, C.T., Horvath, A., Joshi, S., Klausner, M., Lave, L.B., McMichael, F.C., 1997. Comparing two life cycle assessment approaches: a process model vs. economic input-output-based assessment. Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment, ISEE-1997, 99. 176–181.

Hermann, B.G., Debeer, L., De Wilde, B., Blok, K., Patel, M.K., 2011. To compost or not to compost: carbon and energy footprints of biodegradable materials' waste treatment. Polym. Degrad. Stabil. 96, 1159–1171.

Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: a global, trade-linked analysis. Environ. Sci. Technol. 43, 6414–6420.

Hoekstra, A., 2009. Human appropriation of natural capital: a comparison of ecological footprint and water footprint analysis. Ecol. Econ. 68, 1963–1974.

Hoekstra, A.Y., 2008. Water Neutral: Reducing and Offsetting the Impacts of Water Footprints, Value of Water Research Report Series No. 28. UNESCO-IHE Institute for Water Education, Delft, the Netherlands, <doc.utwente.nl/77202/> (accessed 06.06.2014).

Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: water use by people as a function of their consumption pattern. Water Resour. Manag. 21, 35–48.

Hoekstra, A.Y., Hung, P.Q., 2002. Virtual Water Trade: A Quantification of Virtual Water flows Between Nations in Relation to International Crop Trade. UNESCO-IHE Institute for Water Education, Delft, the Netherlands.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard: Water Footprint Network. <www.waterfootprint.org/downloads/TheWaterFootprintAssessmentManual.pdf> (accessed 02.09.2013).

Holden, J., 2014. Water Resources: An Integrated Approach. Routhledge, New York, NY.

Hooper, D., 10 Things you can do to help Biodiversity. Western Washington University, Bellingham, WA, USA. <fire.biol.wwu.edu/hooper/10thingsforbiodiversity.pdf> (accessed 18.07.2014).

Huang, H., Lu, J., 2014. Identification of river water pollution characteristics based on projection pursuit and factor analysis. Environ. Earth Sci., 1–9.

Huijbregts, M.A., Hellweg, S., Frischknecht, R., Hungerbühler, K., Hendriks, A.J., 2008. Ecological footprint accounting in the life cycle assessment of products. Ecol. Econ. 64, 798–807.

Hundal, M., 2000. Life Cycle Assessment and Design for the Environment. International Design Conference—Design 2000, Dubrovnik, Croatia. <www.cem.uvm.edu/~mhundal/defrec/lcadfe.pdf> (accessed 06.06.2014).

Hunt, R., Franklin, W., Hunt, R.G., 1996. LCA—How it came about. Int. J. Life Cycle Assess. 1, 4–7.

Huppes, G., Ishikawa, M., 2005. Eco-efficiency and its xsterminology. J. Ind. Ecol. 9, 43–46.

Integrated Sustainability Analysis (ISA), 2014. About BottomLine3. <www.isa.org.usyd.edu.au/consulting/BL3.shtml> (accessed 21.05.2014).

Intergovernmental Panel on Climate Change, 2009. IPCC Expert Meeting on the Science of Alternative Metrics, Meeting report. Oslo, Norway.

International Organisation for Standardisation (ISO), 2006a. ISO 14040, Environmental Management—Life Cycle Assessment—Principles and Framework. Geneva, Switzerland.

International Organisation for Standardisation (ISO), 2006b. ISO 14044, Environmental Management—Life Cycle Assessment—Requirements and Guidelines. Geneva, Switzerland.

Jeswani, H.K., Azapagic, A., 2011. Water footprint: methodologies and a case study for assessing the impacts of water use. J. Clean. Prod. 19, 1288–1299.

Jeswani, H.K., Azapagic, A., Schepelmann, P., Ritthoff, M., 2010. Options for broadening and deepening the LCA approaches. J. Clean. Prod. 18, 120–127.

Jones, C.M., Kammen, D.M., 2011. Quantifying carbon footprint reduction opportunities for U.S. Households and communities. Environ. Sci. Technol. 45, 4088–4095.

Jørgensen, A., Le Bocq, A., Nazarkina, L., Hauschild, M., 2008. Methodologies for social life cycle assessment. Int. J. Life Cycle Assess. 13, 96–103.

Juhász, C., Szőllősi, N., 2008. Environmental management. <www.tankonyvtar.hu/en/tartalom/tamop425/0032_kornyezetiranyitas_es_minosegbiztositas/ch03.html> (accessed 10.04.2014).

Kemira, 2014. Kemira Water Footprint Calculator. <www.waterfootprintkemira.com/> (accessed 07.06.2014).

Kirk, E., 2011. Human Footprint: Everything You Will Eat, Use, Wear, Buy, and Throw Out in Your Lifetime. National Geographic Kids, Washington, DC.

Kitzes, J., Wackernagel, M., 2009. Answers to common questions in ecological footprint accounting. Ecol. Indic. 9, 812–817.

Kitzes, J., Peller, A., Goldfinger, S., Wackernagel, M., 2007. Current methods for calculating national ecological footprint accounts. Sci. Environ. Sustainable Soc. 4, 1–9.

Kitzes, J., Galli, A., Bagliani, M., Barrett, J., Dige, G., Ede, S., Erb, K., Giljum, S., Haberl, H., Hails, C., Jolia-Ferrier, L., Jungwirth, S., Lenzen, M., Lewis, K., Loh, J., Marchettini, N., Messinger, H., Milne, K., Moles, R., Monfreda, C., Moran, D., Nakano, K., Pyhälä, A., Rees, W., Simmons, C., Wackernagel, M., Wada, Y., Walsh, C., Wiedmann, T., 2009. A research agenda for improving national Ecological Footprint accounts. Ecol. Econ. 68, 1991–2007.

Klemeš, J., Cockerill, T., Bulatov, I., Shackely, S., Gough, C., 2006. Engineering Feasibility of Carbon Dioxide Capture and Storage. Carbon Capture and its Storage: An Integrated Assessment. Ashgate Publishing Ltd., Ashgate, UK, 43–82.

Klemeš, J., Friedler, F., Bulatov, I., Varbanov, P., 2010. Sustainability in the Process Industry: Integration and Optimization: Integration and Optimization. McGraw-Hill Companies, New York, NY, USA.

Koskela, M., Vehmas, J., 2012. Defining eco-efficiency: a case study on the finnish forest industry. Bus. Strat. Env. 21, 546–566.

Krajnc, D., Glavič, P., 2003. Indicators of sustainable production. Clean. Technol. Environ. Policy 5, 279–288.

Kravanja, Z., 2010. Challenges in sustainable integrated process synthesis and the capabilities of an MINLP process synthesizer MipSyn., Comput. Chem. Eng. 34, 1831–1848.

Kravanja, Z., 2012. Process systems engineering as an integral part of global systems engineering by virtue of its energy—environmental nexus. Curr. Opin. Chem. Eng. 1, 231–237.

Kravanja, Z., Čuček, L., 2013. Multi-objective optimisation for generating sustainable solutions considering total effects on the environment. Appl. Energy 101, 67–80.

Kravanja, Z., Ropotar, M., Pintarič, Z.N., 2005. Incorporating Sustainability into the Superstructural Synthesis of Chemical Processes. The conference on Industrial pollution and sustainable development—CIPSD, Maribor, Slovenia.

Krotscheck, C., Narodoslawsky, M., 1996. The Sustainable Process Index a new dimension in ecological evaluation. Ecol. Eng. 6, 241–258.

Leach, A.M., Galloway, J.N., Bleeker, A., Erisman, J.W., Kohn, R., Kitzes, J., 2012. A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment. Environ. Dev. 1, 40–66.

Lettenmeier, M., Göbel, C., Liedtke, C., Rohn, H., Teitscheid, P., 2012. Material footprint of a sustainable nutrition system in 2050—Need for dynamic innovations in production, consumption and politics. Proc. Food Syst. Dyn., 584–598.

Li, J., Wang, X., 2012. Energy and climate policy in China's twelfth five-year plan: a paradigm shift. Energy Policy 41, 519–528.

Lott, J.N.A., Bojarski, M., Kolasa, J., Batten, G.D., Campbell, L.C., 2009. A review of the phosphorus content of dry cereal and legume crops of the world. Int. J. Agric. Resour. Governance Ecol. 8, 351–370.

Lucas, M., Palzkill, A., Rohn, H., Liedtke, C., 2013. The nutritional footprint: an innovative management approach for the food sector. In: Brebbia, C.A., Popov, V. (Eds.), Food and Environment II: The Quest for a Sustainable Future. WIT Press, Southampton, UK.

Lukas, M., Liedtke, C., Rohn, H., 2013. Food Chain Management, The Nutritional Footprint—Assessing Environmental and Health Impacts of Foodstuffs. World Resources Forum, Davos, Switzerland, <www.worldresourcesforum.org/files/WRF2013/Scientific%20Sessions/Melanie.Lukas-Holger.Rohn_.pdf> (accessed 21.05.2014).

Lygoe, R.J., 2010. Complexity Reduction in High-Dimensional Multi-Objective Optimisation. University of Sheffield, Sheffield, UK.

Ma, L., Liu, P., Fu, F., Li, Z., Ni, W., 2011. Integrated energy strategy for the sustainable development of China. Energy 36, 1143–1154.

Maggio, G., Cacciola, G., 2012. When will oil, natural gas, and coal peak? Fuel 98, 111–123.

Magoha, P., 2002. Footprints in the wind?: Environmental impacts of wind power development. Refocus 3, 30–33.

Martineau, R.J., Novello, D.P., 2004. The Clean Air Act Handbook. American Bar Association, Chicago, IL, USA.

Mata, T.M., Martins, A.A., Sikdar, S.K., Costa, C.A.V., 2011. Sustainability considerations of biodiesel based on supply chain analysis. Clean Technol. Environ. Policy 13, 655–671.

McManus, M., 2010. Life Cycle Assessment: An Introduction. University of Bath, Institute for Sustainable Energy and the Environment, Bath, UK, <www.bath.ac.uk/i-see/posters/Life_Cycle_Assessment_An_Introduction_MM_ppp_ISEE_Website.pdf%3e> (accessed 08.02.2013).

Meisterling, K., Samaras, C., Schweizer, V., 2009. Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. J. Clean. Prod. 17, 222–230.

Mekonnen, M.M., Hoekstra, A.Y., 2010. The Green, Blue and Grey Water Footprint of Farm Animals and Animal Products. UNESCO-IHE Institute for Water Education, Delft, the Netherlands, <doc.utwente.nl/76912/> (accessed 22.01.2013).

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, DC, USA.

Min, Q., Jiao, W., Cheng, S., 2011. Pollution footprint: a type of ecological footprint based on ecosystem services. Resour. Sci. 2, 003.

Minister of Justice, 2014. Species at Risk Act. Canada. <laws-lois.justice.gc.ca/PDF/S-15.3.pdf> (accessed 02.06.2014).

Ministry of Science Technology and The Environment Malaysia, 1998. National Policy on Biological Diversity. Institut Terjemahan Negara Malaysia Berhad, Kuala Lumpur, Malaysia.

Mohr, S.H., Evans, G.M., 2009. Forecasting coal production until 2100. Fuel 88, 2059–2067.

Mohr, S.H., Evans, G.M., 2011. Long term forecasting of natural gas production. Energy Policy 39, 5550–5560.

Motavalli, J., (1999). Dr. Nafis Sadik, The UN's Prescription for Family Planning. <www.emagazine.com/includes/print-article/magazine-archive/8090/> (accessed 28.04.2014).

Munasinghe, M., 2004. Sustainable development: basic concepts and application to energy. In: Cleveland, C.J. (Ed.), Encyclopedia of Energy. Elsevier, New York, NY, USA, pp. 789–808.

Nag, A., 2008. Textbook of Agricultural Biotechnology. PHI Learning Private Limited, New Delhi, India.

National Biodiversity Authority, 2014. The Biological Diversity Act 2002. <www.nbaindia.org/> (accessed 02.06.2014).

National Geographic, 2014a. What is Your Water Footprint? <environment.nationalgeographic.com/environment/freshwater/change-the-course/water-footprint-calculator/> (accessed 07.06.2014).

National Geographic, 2014b. Human Footprint. <www.nationalgeographic.com/xpeditions/lessons/14/g68/HumanFootprint.pdf> (accessed 02.05.2014).

Natural Resource Management Ministerial Council, 2010. Australia's Biodiversity Conservation Strategy 2010–2030. Commonwealth of Australia Canberra, Australia, <www.cbd.int/doc/world/au/au-nbsap-v2-en.pdf> (accessed 02.06.2014).

Neset, T.-S., Lohm, U., 2005. Spatial imprint of food consumption: a historical analysis for Sweden, 1870–2000. Hum. Ecol. 33, 565–580.

Niemetz, N., Kettl, K.H., Eder, M., Narodoslawsky, M., 2012. RegiOpt conceptual planner—Identifying possible energy network solutions for regions. Chem. Eng. Trans. 29, 517–522.

N-Print Team, 2014. Welcome to the N-Print website! <www.n-print.org/> (accessed 12.02.2014).

Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. Wiley, New York, NY, USA.

Oenema, O., Bleeker, A., Braathen, N.A., Budňáková, M., Bull, K., Čermák, P., Geupel, M., Hicks, K., Hoft, R., Kozlova, N., Leip, A., Spranger, T., Valli, L., Velthof, G., Winiwarter, W., 2011. Nitrogen in current European policies,. In: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Greenfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment: Sources, Effects and Policy Perspectives. Cambridge University Press, Cambridge, UK.

Padgett, J.P., Steinemann, A.C., Clarke, J.H., Vandenbergh, M.P., 2008. A comparison of carbon calculators. Environ. Impact Assess. Rev. 28, 106–115.

Palmer, A.R.P., 1998. Evaluating ecological footprints. Electron. Green J. 1 (9), <escholarship.org/uc/item/05k183c9> (accessed 03.03.2014).

Panko, J., Hitchcock, K., 2011. Chemical footprint: ensuring product sustainability. Air Waste Manag. Assoc., 12–15.

Patzek, T.W., Croft, G.D., 2010. A global coal production forecast with multi-Hubbert cycle analysis. Energy 35, 3109–3122.

Pereira, H.M., Navarro, L.M., Martins, I.S., 2012. Global biodiversity change: the bad, the good, and the unknown. Annu. Rev. Environ. Resour. 37, 25–50.

Perry, S., Klemeš, J., Bulatov, I., 2008. Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors. Energy 33, 1489–1497.

Pezzey, J., 1989. Economic Analysis of Sustainable Growth and Sustainable Development, Environment Department Working Paper No. 15. World Bank, Washington, DC, USA.

Pieragostini, C., Mussati, M.C., Aguirre, P., 2012. On process optimization considering LCA methodology. J. Environ. Manage. 96, 43–54.

Pimm, S.L., Russell, G.J., Gittleman, J.L., Brooks, T.M., 1995. The future of biodiversity. Science 269, 347–350.

Pozo, C., Ruíz-Femenia, R., Caballero, J., Guillén-Gosálbez, G., Jiménez, L., 2012. On the use of principal component analysis for reducing the number of environmental objectives in multi-objective optimization: application to the design of chemical supply chains. Chem. Eng. Sci. 69, 146–158.

Procter & Gamble Science-in-the-Box, 2014. Life Cycle Assessments (LCAS). <scienceinthebox.com/life-cycle-assessment> (accessed 15.03.2014).

Purvis, A., Hector, A., 2000. Getting the measure of biodiversity. Nature 405, 212–219.

Quantis Sustainability counts, 2009. What is Life Cycle Assessment? <www.quantis-intl.com/life_cycle_assessment.php> (accessed 12.05.2014).

Rao, S.S., 2009. Engineering Optimization: Theory and Practice, fourth ed. John Wiley & Sons, Inc., Hoboken, NJ, USA.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment. Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environ. Int. 30, 701–720.

Rees, W.E., 1992. Ecological footprints and appropriated carrying capacity: what urban economics leaves out. Environ. Urban. 4, 121–130.

Rees, W., 2010. The human nature of unsustainability. In: Heinberg, R., Lerch, D. (Eds.), The Post Carbon Reader: Managing the 21st Century's Sustainability Crises. Watershed Media in collaboration with Post Carbon Institute, Healdsburg, US, pp. 194–206.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., De Wit, C.A., Hughes, T., Van Der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475.

Sabio, N., Kostin, A., Guillén-Gosálbez, G., Jiménez, L., 2012. Holistic minimization of the life cycle environmental impact of hydrogen infrastructures using multi-objective optimization and principal component analysis. Int. J. Hydrogen Energy 37, 5385–5405.

Sandholzer, D., Narodoslawsky, M., 2007. SPIonExcel—Fast and easy calculation of the sustainable process index via computer. Resour. Conserv. Recycl. 50, 130–142.

Saur, K., 1997. Life cycle impact assessment. Int. J. Life Cycle Assess. 2, 66–70.

Schaefer, F., Luksch, U., Steinbach, N., Cabeça, J., Hanauer, J., 2006. Ecological Footprint and Biocapacity, The World's Ability to Regenerate Resources and Absorb Waste in a Limited Time Period. Office for Official Publications of the European Communities, Luxembourg.

Schindler, 2013. Energy and GHG Footprint, A Big Step Forward. <www.schindler.com/com/internet/en/about-schindler/corporate-citizenship/site-ecology/energy-and-ghg-footprint.html> (accessed 13.02.2013).
Schülke, A., 2008. Biodiversity in German Development Cooperation. Kasparek Verlag, Heidelberg, Germany.
Secretariat of the Convention on Biological Diversity, 2010. Global Biodiversity Outlook 3. Montréal, Canada. <www.cbd.int/doc/publications/gbo/gbo3-final-en.pdf> (accessed 02.05.2014).
Shrink That Footprint Ltd., 2014. Shrink Your Food Footprint. <shrinkthatfootprint.com/shrink-your-food-footprint> (accessed 22.05.2014).
Sims, R.E.H., Schock, R.N., Adegbululgbe, A., Fenhann, J., Konstantinaviciute, I., Moomaw, W., Nimir, H.B., Schlamadinger, B., Torres-Martínez, J., Turner, C., Uchiyama, Y., Vuori, S.J.V., Wamukonya, N., Zhang, X., 2007. Energy supply. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK; New York, NY, USA.
Smil, V., 1997. Global population and the nitrogen cycle. Sci. Am. 277, 76–81.
Smil, V., 2000. Phosphorus in the environment: natural flows and human interferences. Annu. Rev. Energy Environ. 25, 53–88.
Smil, V., 2001. Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. The MIT Press, Cambridge, USA.
Sobhani, R., Abahusayn, M., Gabelich, C.J., Rosso, D., 2012. Energy footprint analysis of brackish groundwater desalination with zero liquid discharge in inland areas of the Arabian Peninsula. Desalination 291, 106–116.
Sodhi, N.S., Brook, B.W., Bradshaw, C.J., 2009. Causes and consequences of species extinctions. Princet. Guide Ecol., 514–520.
Sokoli, L., 2014. Sustainable development as the imperative of the twenty-first century; towards alternative approaches on measuring and monitoring. Acad. J. Interdiscipl. Stud. 3, 105–109.
Sorda, G., Banse, M., Kemfert, C., 2010. An overview of biofuel policies across the world. Energy Policy 38, 6977–6988.
Staudt, A., Huddleston, N., Kraucunas, I., 2008. Understanding and Responding to Climate Change: Highlights of National Academies Reports. <www.tribesandclimatechange.org/documents/nccc/nccc20110504_229.pdf> (accessed 10.03.2014).
Steen-Olsen, K., Weinzettel, J., Cranston, G., Ercin, A.E., Hertwich, E.G., 2012. Carbon, land, and water footprint accounts for the European Union: consumption, production, and displacements through international trade. Environ. Sci. Technol. 46, 10883–10891.
Stoeglehner, G., Narodoslawsky, M., 2009. How sustainable are biofuels? Answers and further questions arising from an ecological footprint perspective. Bioresource Technol. 100, 3825–3830.
Stoeglehner, G., Levy, J.K., Neugebauer, G.C., 2005. Improving the ecological footprint of nuclear energy: a risk-based lifecycle assessment approach for critical infrastructure systems. Int. J. Crit. Infrastructures 1, 394–403.
Tallis, B., Azapagic, A., Howard, A., Parfitt, A., Duff, C., Hadfield, C., Pritchard, C., Gillett, J., Hackitt, J., Seaman, M., Darton, R., Rathbone, R., Clift, R., Watson, S.,

Elliot, S., 2002. The Sustainability Metrics, Sustainable Development Progress Metrics Recommended for use in the Process Industries. IChemE, Rugby, UK.

The Central People's Government of the People's Republic of China. 2002. Water Law of the People's Republic of China. <www.gov.cn/english/laws/2005-10/09/content_75313.htm> (accessed 01.06.2014).

The Clean Air Act, 2004. <www.epw.senate.gov/envlaws/cleanair.pdf> (accessed 02.06.2014).

Thinking Ahead, 2011. Waste Footprint and Sustainable Suppliers. <www.usbthinkingahead.com/2011/09/waste-footprint-and-sustainable-suppliers.html> (accessed 02.05.2014).

Toderoiu, F., 2010. Ecological footprint and biocapacity—methodology and regional and national dimensions. Agric. Econ. Rural Dev. 2, 213–238.

Treat, S., Callahan, N.B., 2013. Drivers of Biodiversity Loss: Environmental Literacy Council. <enviroliteracy.org/subcategory.php/352.html> (accessed 29.04.2014).

Trombulak, S., Baldwin, R., Woolmer, G., 2010. The human footprint as a conservation planning tool. In: Trombulak, S.C., Baldwin, R.F. (Eds.), Landscape-scale Conservation Planning. Springer, the Netherlands, pp. 281–301.

U.S. Environmental Protection Agency (EPA), 2014. Basic Information about Nitrate in Drinking Water. <water.epa.gov/drink/contaminants/basicinformation/nitrate.cfm> (accessed 28.04.2014).

UK Parliamentary Office of Science and Technology (POST), 2011. Carbon footprint of electricity generation. London, UK. <www.parliament.uk/documents/post/postpn_383-carbon-footprint-electricity-generation.pdf> (accessed 22.01.2013).

UNEP/SETAC, 2009. Life Cycle Management: How Business Uses it to Decrease Footprint, Create Opportunities and Make Value Chains More Sustainable. <www.unep.org/pdf/DTIE_PDFS/DTIx1208xPA-LifeCycleApproach-Howbusinessusesit.pdf> (accessed 21.01.2013).

Union of Concerned Scientists, 2009. NO SURE FIX, Prospects for Reducing Nitrogen Fertilizer Pollution through Genetic Engineering. <www.ucsusa.org/assets/documents/food_and_agriculture/no-sure-fix.pdf> (accessed 20.03.2014).

United Nations Environment Programme, 2007. Water, Section B, State-and-Trends of the Environment: 1987–2007, Global Environment Outlook 4: Environment for Development, Valetta, Malta, pp. 115–156.

United Nations Framework Convention on Climate Change, 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change. <unfccc.int/resource/docs/convkp/kpeng.pdf> (accessed 12.04.2014).

Urban Dictionary, 2014. Radioactive Footprint. <www.urbandictionary.com/define.php?term=radioactive%20footprint> (accessed 28.05.2014).

Vaccari, D.A., 2009. Phosphorus: a looming crisis. Sci. Am. 300, 54–59.

van den Bergh, J.C.J.M., Grazi, F., 2014. Ecological footprint policy? Land use as an environmental indicator. J. Ind. Ecol. 18, 10–19.

Vitousek, P.M., Aber, J.D., Howarth, R.W., Likens, G.E., Matson, P.A., Schindler, D.W., Schlesinger, W.H., Tilman, D.G., 1997. Human alteration of the global nitrogen cycle: sources and consequences. Ecol. Appl. 7, 737–750.

Vogtländer, J.G., Bijma, A., Brezet, H.C., 2002. Communicating the eco-efficiency of products and services by means of the eco-costs/value model. J. Clean. Prod. 10, 57–67.

Vogtländer, J.G., Baetens, B., Bijma, A., Brandjes, E., Lindeijer, E., Segers, M, et al., 2010. LCA-Based Assessment of Sustainability: The Eco-costs/Value Ratio (EVR). VSSD, Delft, the Netherlands.

von Blottnitz, H., Curran, M.A., 2007. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. J. Clean. Prod. 15, 607–619.

Vujanović, A., Čuček, L., Pahor, B., Kravanja, Z., 2014. Multi-objective synthesis of a company's supply-network by accounting for several environmental footprints. Process Saf. Environ. Prot. 92 (5), 456–466.

Wackernagel, M., Rees, W.E., 1996. Our Ecological Footprint: Reducing Human Impact on the Earth. New Society Publishers, Gabriola Island, British Columbia, Canada.

Wackernagel, M., Schulz, N.B., Deumling, D., Linares, A.C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., Randers, J., 2002. Tracking the ecological overshoot of the human economy. Proc. Natl. Acad. Sci. 99, 9266–9271.

Wackernagel, M., Kitzes, J., Moran, D., Goldfinger, S., Thomas, M., 2006. The ecological footprint of cities and regions: comparing resource availability with resource demand. Environ. Urban. 18, 103–112.

Water Footprint Network, 2014. Water Footprint. <www.waterfootprint.org/?page = files/home> (accessed 15.02.2014).

Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A., 2013. Affluence drives the global displacement of land use. Global Environ. Change 23, 433–438.

Wiedmann, T., Barrett, J., 2011. A greenhouse gas footprint analysis of UK Central Government, 1990–2008. Environ. Sci. Policy 14, 1041–1051.

Wiedmann, T., Lenzen, M., 2007. On the conversion between local and global hectares in ecological footprint analysis. Ecol. Econ. 60, 673–677.

Wiedmann, T., Minx, J., 2008. A definition of "carbon footprint". In: Pertsova, C.C. (Ed.), Ecological Economics Research Trends. Nova Science Publisher, Hauppauge, NY, USA, pp. 1–11.

Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2013. The material footprint of nations. Proc. Natl. Acad. Sci. <www.pnas.org/content/early/2013/08/28/1220362110> (accessed 26.10.2014).

World Commission on Environment and Sustainable Development (WCED), 1987. Our Common Future (The Brundtland Report). Oxford University Press, Oxford Bungay, Suffolk, UK.

World Meteorological Organization, 2009. WMO Greenhouse Gas Bulletin, The State of Greenhouse Gases in the Atmosphere Using Global Observations through 2008. <www.wmo.int/pages/prog/arep/gaw/ghg/documents/GHG-bulletin2009_en.pdf> (accessed 21.03.2014).

World Meteorological Organization, 2014. GAW Greenhouse Gas Research. <www.wmo.int/pages/prog/arep/gaw/ghg/ghgbull06_en.html> (accessed 21.03.2014).

World Wide Fund for Nature, 2002. Living planet report. <www.footprintnetwork.org/images/uploads/lpr2002.pdf> (accessed 20.02.2014).

Worldometers—Real Time World Statistics, 2014. Current World Population. <www.worldometers.info/world-population/wpc.php?utm_expid=4939992-7.scuhn054Q5WXvFD9uRG9Xw.2&utm_referrer=http%3A%2F%2Fwww.google.si%2Furl%3Fsa%3Dt%26rct%3Dj%26q%3D%26esrc%3Ds%26source%3Dweb%26cd%3D2%26ved%3D0CDgQFjAB%26url%3Dhttp%253A%252F%252Fwww.worldometers.info/world-population/

wpc.php?utm_expid=4939992-7.scuhn054Q5WXvFD9uRG9Xw.2&utm_referrer=http%3A%2F%2Fwww.google.si%2Furl%3Fsa%3Dt%26rct%3Dj%26q%3D%26esrc%3Ds%26source%3Dweb%26cd%3D2%26ved%3D0CDgQFjAB%26url%3Dhttp%253A%252F%252Fwww.worldometers.info%252Fworld-population%252F%26ei%3Dp9ViU7mROfLH7Aan0oHwAw%26usg%3DAFQjCNErbPyUCHWnx-PRFhnobEtJRV06Mg%26sig2%3DCnTCiGUgjkEdU5NefXkphA%26bvm%3Dbv.65788261%2Cd.ZGU> (accessed 28.04.2014).

Wright, L.A., Kemp, S., Williams, I., 2011. Carbon footprinting": towards a universally accepted definition. Carbon Manage. 2, 61–72.

Zaccai, E., 2012. Over two decades in pursuit of sustainable development: influence, transformations, limits. Environ. Dev. 1, 79–90.

Zeev, S., Meidad, K., Avinoam, M., 2014. A multi-spatial scale approach to urban sustainability— An illustration of the domestic and global hinterlands of the city of Beer-Sheva. Land Use Policy. 41, 498–505.

Zhao, S., Li, Z., Li, W., 2005. A modified method of ecological footprint calculation and its application. Ecol. Model. 185, 65–75.