Ecological Indicators 24 (2013) 240–245

Contents lists available at SciVerse ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

EcoTime—An intuitive quantitative sustainability indicator utilizing a time metric

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ARTICLE INFO

Article history:
Received 29 December 2011
Received in revised form 18 June 2012
Accepted 24 June 2012

Keywords:
Sustainability
Indicators
Footprint
EcoTime
Time

ABSTRACT

Sustainability indicators strive to convey the impacts of human activities on natural resource utilization, yet many fail to express these impacts in a simple relatable manner. We introduce a new sustainability indicator, EcoTime, which recasts an environmental burden of a process or item (e.g., the emission of 10 kg CO_2 associated with a car trip) in time units (seconds, days, etc.). The EcoTime units represent the burden's share of a benchmark quota calculated according to location or context. For example, a developed country's average yearly CO_2 emissions of 11 ton per capita would translate to 365 EcoTime days in which case the 10 kg CO_2 mentioned above would equal ≈8 EcoTime hours. Since time units are commonly used the EcoTime indicator is easy to communicate to a varying audience alleviating challenges often associated with existing sustainability indicators. It leverages our innate ability to easily grasp contrasting time units over several orders of magnitude, ranging from seconds to years. Another key advantage of EcoTime is that its value shifts attention from the absolute environmental impact, which may not be meaningful to most people, to impact magnitude relative to world resource availability or usage, thus giving the burden an intuitive, intrinsic context. In addition, EcoTimes of different impact types can be conveniently and succinctly grouped as a vector (e.g., GHG emissions, water, or land footprints), or, because of the similar units, as a composite scalar. We provide several case study examples of the methodology.

1. Introduction

The efficacy of efforts to mitigate growing human demand for natural resources can increase significantly by novel methods for effectively and intuitively communicating consumption costs. While some of those efforts (e.g., carbon caps) are top-down, the bottom-up approach emphasizes individual voluntary choices, which collectively can have significant impacts. Incorporating sustainability considerations in individuals' decision making requires conveying to consumers the environmental impacts of products and services, through text, label, or qualitative indices (Gallastegui, 2002). Any delivery mechanism comprises of two stages. The first tallies the environmental burdens exerted by the evaluated process or item. In the second stage, the information is distilled into a representation that simultaneously retains the meaningful quantitative information gathered in the first stage and casts it in a format that can be readily understood by an average, scientifically uninitiated person. In this paper, we focus on the latter, recasting resource consumption estimates obtained by any methodology into a quantitative yet intuitive indicator.

Life Cycle Analysis (LCA) (ISO 14040; Baumann and Tillman, 2004) inclusively considers the production, active use, and end of life stages of a product, assembling the natural resource inventory utilized in the product's full life cycle, tracking and summing those burdens into an aggregate value. Parallel efforts at carbon footprint calculations (Weidmann and Minx, 2008) emphasize the overall greenhouse gas (GHG) emissions associated with a product or service. Efforts to expand the scope of footprint indicators have yielded the concept of ecological footprint (Wackernagel and Rees, 1996). The ecological footprint expresses humanity's environmental pressure in terms of required land resources relative to available land. The ecological footprint thus calculates impacts in units of area, namely global hectares (gha), a hypothetical hectare featuring global mean productivity. The ecological footprint had been mostly used for calculating national footprints but has also been applied for specific consumption items (Collins and Fairchild, 2007). A similar concept underlies water footprint estimates (Hoekstra, 2009), where costs, in liters or m^3, account for the full production and consumption life cycle. While some human activities, such as agriculture, lend themselves naturally to ecological footprint-like methodology, recasting other resources, such as GHG emissions, in terms of equivalent land resources is very challenging.

The indicators developed so far suffer from a common limitation in communicating the results to consumers. Costs of 1.2 kg

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http://dx.doi.org/10.1016/j.ecolind.2012.06.018

of carbon, 0.014 m^2 or 730 L of water are easy to dismiss with respect to the overall world resources; is 1.2 kg of carbon a lot or negligible? Dealing with very large or very small values is far from intuitive for most people. In addition, using unique units for each impact type creates another barrier in dissemination, further limiting these indicators' utility. Approaches such as the EcoIndicator (PRe consultants, 2000a), or the Swiss Scarcity Methodology (Frischknecht et al., 2006) try to address those issues by normalization to a standard resource usage or pollution. Monetary value as a composite indicator can overcome some of these difficulties, but entails other fundamental difficulties such as the issue of substitutability (weak and strong sustainability (Gutés, 1996)) as well as establishing the exact direct (market) and indirect (non-market) costs of services and goods (Costanza et al., 1997).

Because of the limitations of existing indicators, we set out to develop a metric that will have intuitive units, will be generic for different sectors, and will give a sense of intrinsically available world resources, a metric that conveys a clear sense of whether a given impact is small or large relative to available natural resource.

Used regularly by most, time is intuitively comprehended over >7 orders of magnitude (seconds to years). The obvious finality of time engenders an intuitive sense of the available resources, making time an appealing impact metric that rises above the aforementioned limitations of existing metrics. Indeed, time has been used as a proxy for resource depletion, well-being, or societal progress (Sicherl, 2007). For environmental health implications, DALY, Disability Adjusted Life Year, is a widespread indicator that uses time units to measure disease burden. Based on detailed information on the prevalence and timing of specific diseases, DALY is an estimate of years lost to illness or premature death (Gold et al., 2002).

In presenting the ecological footprint, Wackernagel and Rees (1996) used resource usage associated with reading a newspaper, or drinking a glass of orange juice, cast in time equivalents, as examples. Similarly, the idea of the overshoot day (Williams, 2006), the day within a year when humanity has consumed the available resources for that year, strives to convey the immediacy of resource depletion, forming a tractable and easily understood metric.

The ultimate aim of our approach is to devise a clear measure of the environmental consequences of products and services used daily. We set out to achieve this objective by converting current and future indicators' values into a metric based on a time basis, forming the EcoTime indicator. Below we explain the methodology, apply it to several case studies, and discuss EcoTime's strengths and limitations.

2. Results

2.1. EcoTime methodology

The methodology we suggest is based on transforming environmental burdens (e.g. resource consumption) to a time unit (EcoTime minutes, hours, days, etc.), which conveys the magnitude of consumption in relation to a benchmark quota (Fig. 1). The benchmark quota can be for example an estimate of the per capita sustainable renewable resource amount or a value representing a 'business-as-usual' scenario (see Appendix A).

The suggested metric, termed EcoTime, uses as input prior estimates of the environmental burdens incurred during production of a given product or service (Fig. 1, steps 1 and 2). The estimations can be the result of a detailed LCA or any other similar approach. Any specific methodology for these calculations has its limitations but our methodology focuses on a way to represent the output of such analysis agnostic of the discussion on the best way to perform the tallying of the natural costs. The resource consumption

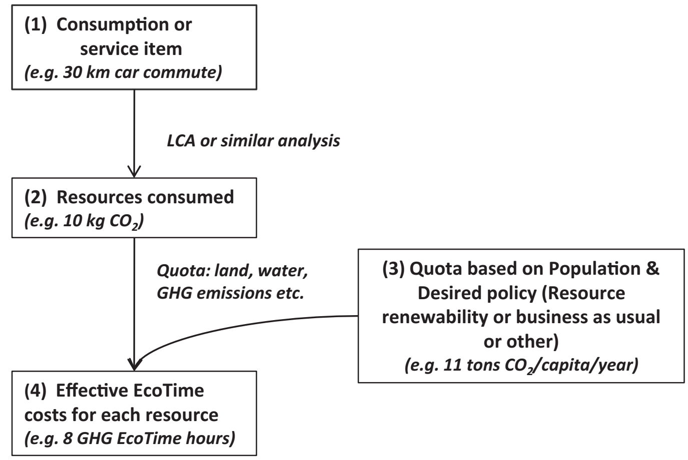

Fig. 1. EcoTime methodology flowchart: items used or activities (1) are analyzed in terms of the resources consumed (2) through life-cycle analysis or any other quantitative method and then compared to a renewable benchmark quota (3). Quotas are derived from resource renewability (renewable quota), or from alternative scenarios such as 'business-as-usual' or other policy. This results in an effective time cost for each resource (4), defined as the EcoTime of that item or activity in that resource. A numeric example using the characteristic GHG emission of a 30 km car commute and 'business-as-usual' developed country per capita GHG emission quota is given in parenthesis.

is compared to a benchmark quota (Fig. 1 step 3), which depicts either the resource's renewability or some other scenario, e.g. its per capita 'business-as-usual' consumption. The quota chosen is based on the target use of EcoTime: if for instance the quota chosen is a per capita average consumption of the resource, then the resulting EcoTime is the time cost compared to an average person's consumption; if the quota is the renewability of the resource, then the EcoTime is an effective time cost relating to the sustainable usage of that resource (Fig. 1 step 4).

As a simplified illustrative example consider a 30 km car commute to work. For a moderate car efficiency scenario this incurs a carbon footprint of about 10 kg CO_2 (Fig. 1, step 2) (Lenzen, 1999). Assuming a 'business-as-usual', developed world average emission of 11 ton per capita per year (Fig. 1, step 3) this is equal to about one thousandth of the yearly quota. With 8800 h per year this will be represented in the EcoTime methodology as 8 GHG emissions EcoTime hours (Fig. 1, step 4). In this example the costs of car production and similar indirect aspects are also included (Lenzen, 1999). The value in terms of time gives a concrete evaluation on the intensity of this activity in the personal fraction of natural resources utilization. In other words, the EcoTime units of time intrinsically contain a reference/benchmark that enables assessing the magnitude of impact in a specified context. This solves the problem that to many people the environmental impact in absolute values of kg CO_2 or squared meters are tough to put in the context of the available world resources.

Table 1 presents the carbon footprint of three representative activities: daily use of a computer, a 30 km car drive, and a one way flight from NY to London. For each activity we use a previously estimated value for its carbon footprint (see Appendix B section 1) and we calculate their associated EcoTime based on an 11 ton/year/per-capita quota ('business-as-usual'). Using a laptop for 10 h incurs a GHG emission of 0.11 kg, which for a 'business-as-usual' quota of 11 ton per year per capita represents a fraction of $0.11/11000 = 1 \times 10^{-5}$ of a year, or about 5 min. A one way trip from London to New York has an EcoTime value of 1.5 months, a high impact activity (Lenzen, 1999). The exact impact of a flight depends on many conditions such as type of aircraft used, number of passengers or what type of climatic forcings are effectively taken into account (Chester and Horvath, 2009) (see also Appendix

Table 1
CO_2 emissions and EcoTime of three illustrative activities using the "business as usual" quota (11 ton per capita per year): using a personal computer for 10 h, a 30 km drive to work and a one way flight from New York to London. The leftmost column presents the activity; the second column on the left – the CO_{2eq} emissions incurred during the activity; the third column on the left is the fraction of the yearly quota, basically the CO_{2eq} emissions divided by the quota (assuming 'business-as-usual' annual quota per capita of 11 ton GHG). The rightmost column presents the result of the fraction of the yearly quota in useable time units. For more details see the Appendix B section 1.

Activity	CO_{2eq} emission (kg)	Fraction of yearly quota	GHG EcoTime
Laptop computer (10 h)	0.11	1×10^{-5}	5 min
30 km drive to work	10	9.3×10^{-4}	8 h
One way flight NY-London	1400	0.13	1.5 months

B section 1). For consistency and clarity, all of our numerical examples use the "business as usual" quotas to derive EcoTime values. In the future we envision adapting the quota to the relevant context, such as geographical location. In the Appendix B we give an example employing a different quota.

2.2. Case study: energy consumption of two different households in the USA

We further clarify the approach through a schematic EcoTime accounting of the activities of two different hypothetical households described in Jones and Kammen, 2011 (Figure 6 in their paper). These authors conducted a survey of the carbon footprint of about 2000 US households. Based on their survey, they identified two archetypical households. The first (household A) is a two person, high income San Francisco household, whereas household B houses a middle class family of 5 in St. Louis. We convert the Jones and Kammen results to EcoTime using the mean US per capita annual GHG footprint, ≈20 ton CO_{2eq} (Jones and Kammen, 2011). Using this average as a benchmark yields Fig. 2, giving the two households' respective GHG related EcoTimes. The activities presented in Fig. 2 are categorized into the five shown groups: transportation, housing, food, goods and services. The EcoTime values obtained present the categories' GHG burdens relative to average per capita annual emissions marked as the 12 EcoTime months baseline (dashed green). For more information on the categories and calculations see Appendix B section 1. Household A (San Francisco) GHG emissions are predominately from motor

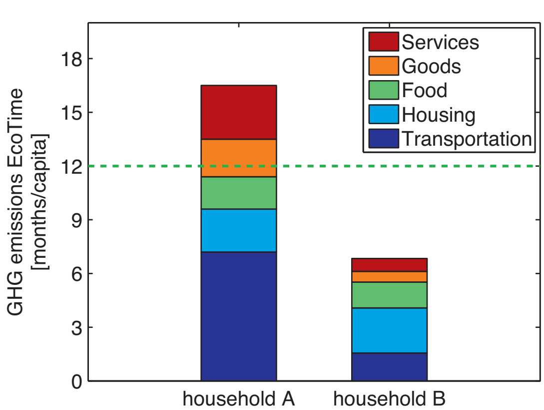

Fig. 2. GHG EcoTime months for activities of two individuals, one from a high income San Francisco household (household A), and the other from a middle class St. Louis household. EcoTime calculations are based on the annual Carbon footprint results of Jones & Kammen (2011) and the 20 ton CO_{2eq} per person per year mean American carbon footprint benchmark quota. Results are divided into the 5 shown categories for comparison. See text and SI section 1 for more details.

vehicles and air travel, with energy consumption of about half of the average American's, thanks to the Bay area's comfortable weather and clean fuel mix used for power generation. Conversely, Household B's GHG emissions are dominated by electricity use due to St. Louis' characteristic high per kWh emissions and cooling and heating requirements. On an annual per capita basis, household A's total sum of activities exceeds the average American value by 4.5 EcoTime months, while household B's activity sum is 5.2 EcoTime months below that mean. This yields values above and below the 12 EcoTime months reference line, respectively. The transformation into time units gives a concrete sense of the contribution of each category to the personal 12 EcoTime months equivalent quota. For instance the transportation GHG emissions of the two households (A and B) map into ≈7 and ≈1.5 EcoTime months (≈12 and ≈2.6 ton of CO_{2eq} per person per year), respectively.

2.3. Accounting for several natural resources in parallel – case study of comparing meals using EcoTime

To illustrate handling of more than one impact type, we analyze two schematic meals: a plant-based meal, and an animal-based meal. Both meals have similar caloric contents of ≈500 kcal. Table 2 compares the environmental burdens of the two meals in terms of carbon footprint, land usage measured by the ecological footprint, and water footprint, where EcoTime values (in hours) are derived by scaling the environmental burdens of each ingredient (Appendix B Section 2 and 3) by the corresponding 'business-as-usual' benchmark quota.

The plant-based meal has an EcoTime cost of ≈1 GHG hour, 3 land hours and 11 water hours relative to the 'business-as-usual' scenario. This is lower in all dimensions than the animal-based meal, whose EcoTime values are 2 GHG hours, 12 land hours and 13 water hours. Stated differently, one animal-based meal consumes 1/12, 1/2 and ∼1/2 of the daily per capita resources of fossil fuel, land and water respectively. Table S3 of the Appendix B presents the results relative to 'renewable' benchmark quotas.

2.4. Merging the EcoTime vector into a single scalar cost

Can we combine the EcoTime values for GHG, land and water into a single indicator, aggregating the multi-dimensional representation (Hák et al., 2007) into a scalar? While it can be argued that it is best to give a detailed, multi-dimensional depiction of the impacts, easy communication may be better served by converting all dimensions into a single integrative value (Costanza, 2000). The EcoIndicator methodology (PRe consultants, 2000b) met this challenge by merging based on predefined weights representing subjective personal values, emphasizing, e.g., human health, resource depletion, climate, or biodiversity. In the EcoTime methodology all impacts assume time units (GHG EcoTime, water EcoTime, etc.), and can be kept as separate categories having similar units. Alternatively, one can naturally aggregate them, either

Table 2
Environmental burdens (ecological footprint, carbon footprint, and water footprint) converted to EcoTime hours of a plant-based and an animal-based meal of about 500 kcal. To obtain EcoTime 'business-as-usual' benchmark quotas were used for all three environmental burdens. The water EcoTime calculation is divided into a local component and a global component because some items are locally produced and some are imported (see Appendix B section 3 for further explanations and derivation).

Consumption option	GHG EcoTime [h]	Ecological footprint EcoTime [h]	Water EcoTime [h]
Plant-based meal	1	3	11
Animal-based meal	2	12	13

Table 3
Aggregation of the EcoTime values for the two meal options (Table 2) (using the 'business-as-usual' quotas) into a composite indicator using three different weighting schemes.

Consumption options	Equal based weighting [h]	Local water-centric weighting [h]	Carbon-centric weighting [h]
Plant-based meal	3	8	2
Animal-based meal	7	4	4

via a simple summation, or by assigning weights to each environmental impact, reflecting the perceived relative importance. As noted before, aggregation is based on personal value judgments, and poses pitfalls that merit caution (Bohringer and Jochem, 2007). Because of the unit uniformity, under EcoTime the aggregation step is relatively transparent. We exemplify several possible weighting profiles: equal weighting, where each of the three environmental burdens previously presented receive the same weight (33%), a local water-centric weighting and a carbon-centric weighting, in which water and carbon receive the largest weight, respectively, with the remainder distributed uniformly (see Appendix B section 4 for more details).

Table 3 presents the composite indicator results for the two meal options in the 'business-as-usual' scenario (Table 2) using the three discussed weighting schemes. The animal-based meal has a higher EcoTime value than the plant-based meal, except in the local-water-centric weighting. This is because in our example meat is an imported product and while its total water footprint is high, its local component is relatively low making it the option with least overall weighted EcoTime.

3. Discussion

3.1. Advantages of using a time basis

The time units proposed here have several benefits. First, any proposed metric must address the challenge of conveying very disparate values, sometime orders of magnitude apart. By analogy to finance, one must be able to handle any sum from cents to millions. Everyday intuition is not experienced at dealing with widely disparate scales, e.g., in summing squared centimeters to hectares, or how the use of a hectare compares with world resources. On the other hand, most people can intuitively comprehend disparate timespans from seconds to centuries without further explanation. Moreover, people are accustomed to the finality of time, that one only gets 24 h a day. For those reasons, time is an effective and intuitive metric.

In the framework of sustainability, addressing the balance between resources left for wild habitats versus humanity appropriation, the EcoTime methodology naturally represents this dichotomy as the time left unused out of a day or a year and thus available for nature. In the context of the DSPIR (Driving Force-Pressure-State-Impact-Response) framework, EcoTime lends itself well as a 'pressure indicator' within an array of development alternatives.

Once a scalar value is reached there could be more ways to represent it. For example, utilizing the fact that calories are a metric highly recognized and referred to by the public, the methodology of EcoTime lends itself to a similar representation in which people can have a given set of 'environmental' calories per day, that is, a gauge presenting their daily consumption activities.

For some activities, EcoTime can be compared with the actual time the activity takes for a measure of the sustainability of the activity, with the understanding that in order to "leave something for Nature", one should strive to use less than 24 effective EcoTime hours per day or 365 EcoTime days per year.

3.2. Limitations of the EcoTime metric

There are many gaps in making the proposed method an ideal system. The estimations of quotas are problematic as they aim to give a single value to a complex resource that can always be better characterized. Here we choose a preliminary coarse grained perspective that can be further refined in the future. In addition, the suitability of some quotas as benchmarks is debatable. For example, the GHG 'renewable' quota (0.8–1 ton per capita per year (Stern and HM Treasury, 2006; Metz et al., 2007)) is very restrictive compared to western lifestyles, which create about an order of magnitude more emissions. As an alternative, the 'business-as-usual' scenario compares the consumption resources to current use. It can similarly be used on a national basis, or adjusted for various income levels. The 'renewable' quotas impartially convey world resource availability, and thus leave any moral decisions to individuals. Developing quota estimation methodology that takes better note of earth's resources is an open challenge. Modern technology permits a concentrated, transparent and detailed documentation process that can enable monitoring and updating of the calculations associated with EcoTime. Despite limited availability of accurate absolute input values, relative comparisons are more tractable, and can yield quantitative indicators of sustainability naturally consistent with human cognition.

EcoTime shares some characteristics with the EcoIndicator formalism (PRe consultants, 2000b), which is widely used to interpret LCA results. By normalizing the results of each emission type by its annual per capita extent in Europe (PRe consultants, 2000a), EcoIndicator reports total environmental impacts dimensionlessly, representing the total impact in multiples of the average European's annual environmental impacts. EcoIndicator can thus be interpreted in terms of time units, and its approach of presenting the results relative to the European mean benchmark is similar to EcoTime. However, differences exist between EcoIndicator and our methodology as detailed in the Appendix B Table S6.

3.3. Implementation and dissemination

The presented approach lends itself to widespread use. For example, items (a car, a laptop, a jug of milk) can have an associated label, akin to food ingredients labels, that will detail its EcoTime, both for different individual categories and as an aggregate weighted EcoTime. Different suppliers can then convey their environmental efforts via their effective EcoTime. In any implementation, calculated EcoTimes should always be presented with access to full documentation of the underlying data used, and intermediate steps performed, en route to the final values (as exemplified in the Appendix B section). Such transparency is readily facilitated by modern information infrastructure.

By simplifying and expanding availability of information that quantifies adverse environmental impacts, and by rendering environmental impacts of competing options straightforwardly comparable, the EcoTime methodology stands to promote the essential yet currently slow or nonexistent process of internalizing externalities (Mayeres et al., 1996; Pretty et al., 2001). For instance, an electric company utility bill can include, along with the financial cost, also an EcoTime value for the electricity used. This value will vary from supplier to supplier, reflecting each supplier's energy sources and production efficiency. Food items can be similarly labeled with their EcoTime values, reflecting the items' environmental burdens relative to a daily recommended load similar to present nutritional labeling that highlights food items' contribution to the recommended daily allowance (RDA). In a world of increasing information availability we envision credit card monthly statements that report all consumed items' EcoTime costs, giving an easy overview of resources used.

We suggest EcoTime as a methodology that can alleviate some of the limitations of current sustainability indicators and serve as a tool in humanity's challenging path toward sustainability.

Acknowledgments

This study benefited from discussions with Uri Alon, Hadas Bar-Or, David Cahen, Daniel Diaz, Ram Fishman, Avi Flamholz, Hezi Gildor, Noam Gressel, Tamar Israeli, Avi Levi, Steve Morse, Elad Noor, Oren Shoval, and Mathis Wackernagel.

This work was supported by the Wolfson Family Charitable Trust; Mr. and Mrs. Yossie Hollander, Israel and the Lerner Family Plant Science Research Endowment Fund.

Appendix A.

A.1. Setting a quota for different natural resources as a benchmark for EcoTime

Efforts to determine earth's renewable or sustainable capacities are varied and inconclusive (Cohen, 1995; Rees, 1996), and depend sensitively on how those terms are defined. Although unique values do not exist, estimates under specific and clearly stated assumptions are sufficient for the proposed EcoTime methodology. Representative 'renewable' and 'business as usual' quotas are given in Table A1.

Devising a sustainable GHG emission quota is a contentious subject that depends on estimating both earth's carbon sequestration capacity (Schimel, 1995; Falkowski et al., 2000) as well as on the allowable target atmospheric concentrations, both vigorously researched and publicly debated. For demonstrating the EcoTime approach, we use estimates of the earth's GHG sequestration ability that yield permissible emission quota of 0.8 (Stern and HM Treasury, 2006) to 1 ton CO_{2eq} per capita per year (IPCC report, (Metz et al., 2007)).

Similarly, using the Ecological footprint network, we obtain an estimate of earth's land resources of 1.8 global hectares (gha) per person per year (Ewing et al., 2010), where a gha is a hectare with global mean bioproductivity (Wackernagel and Rees, 1996). As we are interested in land resources per se, not in C sequestration capacity, we subtract from the total available ghas the global mean per capita forest land, the key factor in carbon sequestration, obtaining the ≈1 gha per person shown in Table A1. Note that a suitable benchmark choice depends on the objectives of the analysis; using a global or national mean availability (e.g., national effective productive land divided by national population) are viable alternative references, each with its unique numerical results and possible interpretations.

Table A1
'Business-as-usual' and 'renewable' annual per capita quotas of natural resource usage, which are used as benchmarks for determining the different EcoTime values. These include GHG emissions (in ton), ecological footprint (global hectares) and water footprint (cubic meters). References for the values appear in Appendix B.

Annual quota per capita	'Business-as-usual' value (developed world)	'Renewable' global value
GHG emissions	11 ton	1 ton
Ecological footprint (without energy component)	1.3 gha	1 gha
Water footprint – global	1300 m^3	7600 m^3
Water footprint – local (Israel)	360 m^3	270 m^3

A.2. Global and local quotas

An important distinction must be drawn between local and global resources. For example, GHG absorption is sensibly discussed globally. Water and land, on the other hand, are inherently local, not easily transferrable, resources. One approach is to distinguish locally used resources from transferrable (exported-imported) uses. For example, water used for household consumption is considered local, while water used agriculturally, or by industries, whose products can be readily shipped, is considered global. A finer resolution (e.g. at the regional level) of the origin of the products and direct water consumption patterns can give a more detailed picture of the water's environmental pressure. We split water use into direct local (national) consumption (e.g., residential use), and consumption of imported items that embody water consumed elsewhere (e.g., sugar from Brazil consumed in the UK), also termed virtual water (Allan, 1993, 1994). Taking into consideration the regional differences in water scarcity (Frischknecht et al., 2006), we analyze local and global consumption separately. A similar approach can be developed for land and other local/global resources.

To analyze national water EcoTime, we take the example of relatively arid Israel. The 'business-as-usual' water consumption in Israel is 2.2 billion $m^3\,yr^{-1}$ (Hoekstra and Chapagain, 2008), or about 360 m^3 $person^{-1}\,yr^{-1}$, while, available renewable water is 1.7 billion $m^3\,yr^{-1}$ (Hoekstra and Chapagain, 2008) or 270 m^3 per capita annually, indicating that in Israel water demand outpaces sustainable supply. Considering the global scale, and allocating all available water for human use (disregarding for argument sake the potentially catastrophic outcome of this approach), the global water footprint is estimated at 9087 $Gm^3\,yr^{-1}$ (Mekonnen and Hoekstra, 2011) or 1300 m^3 $person^{-1}\,yr^{-1}$. Dividing global renewable water resources ($52 \times 10^3\,km^3$) (Hoekstra and Chapagain, 2008) by global population yields a quota of ≈7600 m^3 $person^{-1}\,yr^{-1}$. While in our analysis sustainable usage is implicitly defined as aligning usage with renewable quotas, a stricter approach (OECD Secretariat, 2004) may be to define sustainable usage as, say, 40% of available renewable sources.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2012.06.018.

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