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Limitations of Carbon Footprint as Indicator of Environmental Sustainability

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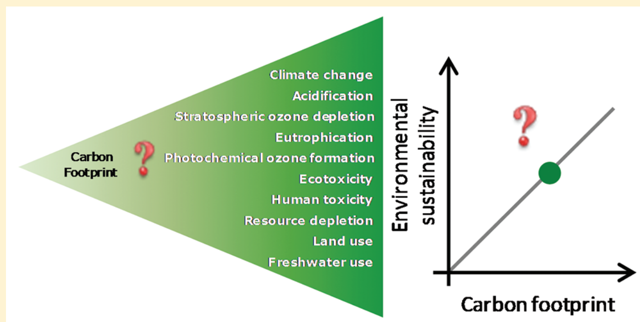
Supporting Information

ABSTRACT: Greenhouse gas accountings, commonly referred to with the popular term carbon footprints (CFP), are a widely used metric of climate change impacts and the main focus of many sustainability policies among companies and authorities. However, environmental sustainability concerns not just climate change but also other environmental problems, like chemical pollution or depletion of natural resources, and the focus on CFP brings the risk of problem shifting when reductions in CFP are obtained at the expense of increase in other environmental impacts. But how real is this risk? Here, we model and analyze the life cycle impacts from about 4000 different products, technologies, and services taken from several sectors, including energy generation, transportation, material production, infrastructure, and waste management. By investigating the correlations between the CFP and 13 other impact scores, we show that some environmental impacts, notably those related to emissions of toxic substances, often do not covary with climate change impacts. In such situations, carbon footprint is a poor representative of the environmental burden of products, and environmental management focused exclusively on CFP runs the risk of inadvertently shifting the problem to other environmental impacts when products are optimized to become more "green". These findings call for the use of more broadly encompassing tools to assess and manage environmental sustainability.



INTRODUCTION

The past two decades have witnessed a growing concern about the impacts of human activities on natural ecosystems, natural resources, and human health.[1−4] As a response to this concern, the field of sustainability science is increasingly solicited in order to understand the interactions between nature and society as well as support the development of adapted management solutions and tools for embracing one or several of the three pillars of sustainability − environmental quality, economic prosperity, and social justice.[5−11]

A recently developed approach to address impacts caused by anthropogenic activities, primarily stemming from consumption and production of goods, systems, and services (commonly termed as "products"), is the Life Cycle Sustainability Assessment (LCSA) framework, which was established by the UNEP/SETAC Life Cycle Initiative.[12] LCSA is defined as the summed outputs from three life-cycle-based assessment tools, each addressing one pillar of sustainability: the environmental Life Cycle Assessment (LCA), the life cycle costing (LCC), and the social LCA (S-LCA). While the latter two are still not broadly accepted due to important shortcomings, e.g. relating to the quantification of impact categories such as human well-being or poverty, the environmental LCA has been used for over two decades to provide decision-makers with recommendations pertaining to the environmental dimension of Sustainable Consumption and Production (SCP).[12−15]

Aiming at a comprehensive quantification of the environmental performances of products, an environmental LCA accounts for all emissions and resource consumptions taken in a life cycle perspective, i.e. from the extraction of the raw materials, such as metal ores or fossil fuels, through the manufacture, the distribution, and the use of the product, up to its potential recycling and ultimate disposal.[16,17] Applying scientifically based characterization models, the inventory of elementary flows between the processes of the product life cycle and the surrounding environment is translated into indicators representing the potential impacts that the product system may have on environment, human health, and resources. LCA covers a broad range of impact categories, typically including climate change, stratospheric ozone depletion, acidification, photochemical ozone formation impacting both ecosystems and human health, aquatic and terrestrial eutrophication, impacts of toxic substances on aquatic and terrestrial ecosystems (i.e., ecotoxicity), impacts of toxic

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substances on human health (i.e., human toxicity), land use, water use, and depletion of both renewable and non-renewable resources. In that setting, LCA aims to provide a comprehensive measure of environmental impact. Coming from a different scientific community, the Millennium Ecosystem Assessment[2] addresses the anthropogenic impacts on Ecosystem Services, which may be seen as concrete dimensions of the areas of protection of Life Cycle Impact Assessment (LCIA). Since the modeling of damages to the areas of protection in LCA is still new and immature,[18] and since some of them are difficult to relate to product systems in a meaningful way, several of the ecosystem service dimensions are thus not represented in LCIA.

Due to the amount of data required for performing a full LCA, several studies have investigated the ability of simplified indicators to act as proxies for environmental performances of a variety of products. The ecological footprint (representing the direct land occupation, such as built-up areas or croplands, as well as indirect land occupation related to nuclear energy use and CO_2 emissions from fossil energy use and cement production in a product life cycle) and the cumulative energy demand (representing the direct and indirect energy use of a product in its life cycle) were found to show significant correlation with other environmental impact indicators and/or the total environmental burden for a majority of products in different sectors, e.g. material production, transport, or energy production.[19−21] Although the need to perform a full LCA is not dismissed, those indicators were recommended for use as screening tools for assessing environmental performances of products/services.

However, none of these studies discusses the consistency and applicability of those indicators in a decision-making context, where the choice between alternatives entails the risk of problem-shifting. Corporations and authorities often aim for simplicity and thus use tools for which data are readily available. Because this might result in environmental policies solely relying on these indicators, it calls for guaranteeing a proper reflection of the whole environmental burden.

In this paper, we chose to focus on greenhouse gas (GHG) accountings, which, besides their full integration in LCA, have known a parallel development. Resting on the work of the Intergovernmental Panel on Climate Change (IPCC), climate change issues have come on top of political agendas, implying the development of stand-alone GHG accounting methods and standards.[22,23] Commonly known as carbon footprint (CFP) methods, these assessments apply a full life cycle perspective and inventorize the six GHGs stated in the Kyoto Protocol.[24,25] Compared to a full LCA addressing all relevant environmental impacts from the product, they are less demanding to perform, and with the strong emphasis on climate change, they have become popular among industries and authorities over the past years.[26,27] The numerous recent initiatives to standardize carbon footprinting, such as the PAS2050 (revised in 2011)[28] and PAS2060,[29] the GHG Protocol Product and Corporate Value Chain Accounting and Reporting Standards (both released in 2011),[30,31] and the forthcoming ISO14067,[32] are strong signals indicating that they are today the main focus of many environmental policies.

It is our goal to (i) investigate the ability of CFP to be representative of the environmental burden embedded in products and (ii) characterize the potential risks of using CFP as a stand-alone indicator of environmental sustainability in decision-making processes. To address those points, the life cycle inventories of ca. 4000 products belonging to a variety of sectors were translated into characterized impact profiles covering a wide range of impact categories for each of these products; all impact categories that are supported by reliable impact assessment methods were addressed, in total covering 13 different environmental impacts (see Methods).

■ METHODS

Impact Assessment Methods. Carbon footprint assesses the six GHGs included in the Kyoto Protocol[24] applying global warming potentials (time horizon of 100 years) from the IPCC to characterize them.[1] To substantiate the aim of the paper, a broad coverage of environmental impact categories was attempted. The impact assessment methods used to characterize each impact pathway were selected from existing Life Cycle Impact Assessment methods according to their viability and reliability with inspiration in recommendations from the EU Commission.[33] For the non-global impact categories, most of the models have been parametrized to represent environmental conditions in continental Europe, although with different levels of accuracy (see references for each impact-specific method described below). Impact assessment methods can be divided in "midpoint" and "endpoint" methods depending on their coverage of the impact pathway that they model. Endpoint methods cover the whole impact pathway from the emissions or consumptions of a substance to its eventual damages on natural environment, human health, and resource depletion, while midpoint methods define their indicators at some intermediary point in the impact pathway, hence stopping before the actual damages. The farther the impact pathway is covered, the higher the modeling uncertainties are.[16] For this reason, only midpoint impact categories were included in the study. Table 1 provides an overview of the assessed impact categories and the sources to which the reader is referred for further methodological details.

Normalization of Impact Categories. The result of the characterization is an indicator result for each impact category. The indicator result is expressed in a metric specific to the impact and its associated assessment method. For example, carbon footprint results are quantified in kg-CO_2eq, while human toxicity impact results are expressed in Comparative

Table 1. Impact Categories Covered in the Study

covered impact categories	LCIA method/ model	sources
climate change (carbon footprint)	IPCC GWP100	1
stratospheric ozone depletion	EDIP1997	34,35
acidification	EDIP2003	36,37
photochemical ozone formation − impacts on vegetation	EDIP2003	36,37
photochemical ozone formation − impacts on human health	EDIP2003	36,37
terrestrial eutrophication	EDIP2003	36,37
aquatic eutrophication (N)	EDIP2003	36,37
aquatic eutrophication (P)	EDIP2003	36,37
freshwater ecotoxicity	USEtox™	38,39
human toxicity − cancer effects	USEtox™	38,39
human toxicity − non-cancer effects	USEtox™	38,39
respiratory inorganics (particulate matters)	−	40,41a
resource depletion (abiotic)	EDIP1997	34,35
land use	−	42,43

[a] Adapted to continental Europe (see the Supporting Methods).

Toxic Unit for human health (CTU_h). To assist a comparison of indicator results across impact categories, normalization was performed,[14] dividing each impact category score by a normalization reference that represents an average person's annual contribution to the impact in a reference region (the impact of society's activities expressed per capita); the resulting common unit for all impact categories is the Person Equivalent (PE). The reference year for the normalization references is 2004 for all impact categories; world was considered the reference region for global impact categories,[44] i.e., climate change, ozone depletion, and non-renewable resource depletion, and the European continent was used as reference region for the regional impacts.[44,45]

Coverage and Classification of Products. Products are "consumable goods or materials or entire infrastructures" (e.g., landfill facility or 1 kg of steel) or "services" (e.g., treatment of 1 m^3 of wastewater or 1MJ of electricity). Their assessments consist of the application of the impact assessment methods to their associated life cycle inventories. Life cycle inventories are aggregates of all the "environmental flows" related to the processes in the product life cycle in terms of inputs from the environment without prior human transformation and outputs to the environment without further human transformation.[17] Long-term emissions (e.g., from landfill leachate) were removed from the assessments because of the current controversies about their inclusion.[46,47] Approximately 4000 life cycle inventories, derived from the Ecoinvent database v2.2,[48,49] were assessed in the study. The products and services that they represent encompass a large diversity of sectors such as energy production, transportation, material production, waste management, agriculture, and infrastructure. To best interpret the results, a classification into categories and subcategories was performed on the basis of the functions or properties shared by the goods or services (Table S2).

It is worth noting that these life cycle inventories are designed as blocks, which LCA practitioners use to build systems to be assessed. Therefore, not all inventories encompass the entire life cycle of the products that they represent. Most of them are in fact "cradle-to-gate" inventories covering the material extraction and the production stage (e.g., production of 1 kg barley) but not the use stage and the disposal stage. The latter is primarily covered by the exclusive waste-management-related services.

Methodological Inconsistencies. Most of the assessed life cycle inventories refer to processes taking place in Europe. A few are global (290) or specific to non-European countries, e.g. United States of America (72), China (55), Brazil (26), Japan (13), or India (12) (Table S2). These life cycle inventories were however assessed using an impact assessment methodology designed for assessing regional impacts primarily at a European scale (EDIP2003 for most regional impact categories). The use of European normalization references for regional impacts also contributes to this inconsistency. Nevertheless, because the number of non-European processes (ca. 12%) is limited and because most of them still refer to activities in industrialized countries, those discrepancies are thought to have negligible effect on the conclusions of the study.

Statistical Analysis. Correlations between CFP and indicator results for other impact categories were analyzed using the nonparametric Spearman rank-order correlation statistics. Statistical software was from the R system.[50] This correlation statistics was selected because of its robustness against outliers. Within a product category or subcategory, impact scores can range up to several orders of magnitude, and the presence of a few outliers in a data set biases non-robust correlation tests (e.g., the Pearson correlation statistics) to give high correlation coefficients (Table S1). To capture the correlation between environmental impacts in a consistent way, a two step procedure was applied. First, the Spearman rank-order correlation coefficients and associated P-values (describing a statistically significant result when $P < 0.05$) were analyzed, and, in case a correlation was indicated, the Pearson correlation coefficients were investigated to ensure a linear relationship (the Spearman correlation test only indicating monotonous correlation), and calculate scaling factors and relative standard deviations (see Tables S1 and S3).

Uncertainties Related to the Use of Normalization. When performing an LCA of products, the incomplete emission data or lack of characterization factors used in the calculation of characterized results bring uncertainties in the impact scores. This predicament is particularly present in the assessment of toxic impacts, for which both emission inventories and characterization factor databases are unable to cover the thousands of chemicals that are released to the environment during the life cycles of products. In contrast, characterized scores of non-toxic impact categories, such as climate change or acidification, are assumed to be relatively accurate, relying as they are on relatively well-reported emission data and a comprehensive set of characterization factors.

The same discrepancies apply to the calculation of the normalization references. A bias may thus appear when normalizing, i.e. when all impact scores are translated into a common unit (PE), because some normalized scores may be overestimated (e.g., toxic impacts, due to underestimated normalization references), while others may be accurately represented (e.g., climate change).[51]

When making comparisons within representative groups or clusters of products (see above), i.e. when investigating for a specific class of products the correlation between CFP and another impact category, the use of normalization does not introduce additional uncertainties to the ones inherent to the characterized results because the relative magnitude of the normalized impact score for a given impact is determined by the same, albeit uncertain, normalization reference for all assessed products. Significant, although not accurately quantifiable, uncertainties may however arise when evaluating the relative magnitudes of the normalized impacts against each other; hence a special care should be taken in this situation.

RESULTS

Discrepancies among Product Categories. Results from the Spearman rank-order correlation tests (Table S1) show that for the whole population of assessed products, correlation coefficients range between 0.7 and 0.8 for all impact categories except land use ($P < 0.05$). This finding suggests a good correlation between CFP and the rest of the environmental impact scores (Figure 1). However, when the full population of products is subdivided into specific product categories, significant underlying miscorrelations are revealed. A separate analysis of the product categories "Energy" and "Infrastructure" reveals large discrepancies between the two, as indicated by color coding in the graphs over all products in Figure 1. The rank-order correlation coefficients toward CFP for the Energy category range below 0.70 for all impact categories, while the

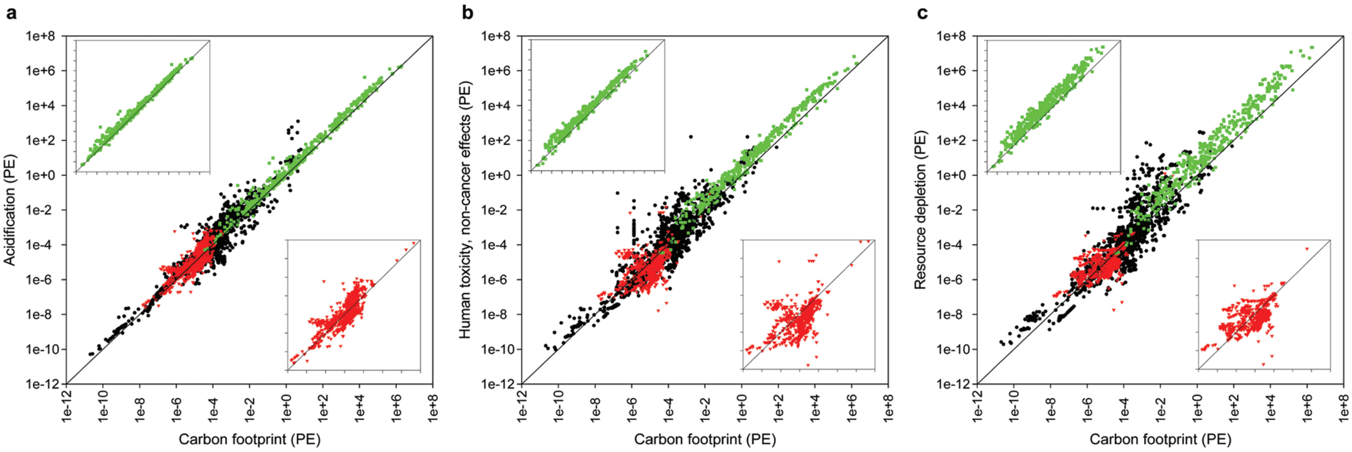

Figure 1. Correlations observed between CFP and a selection of environmental impacts. CFP is plotted against (**a**) acidification, (**b**) human toxicity, non-cancer effects, and (**c**) resource depletion. The graphs illustrate the total assessed products/services (N = 3954), with highlights on infrastructure-related products (green squares, top left insets, N = 487) and energy-related products (red triangles, bottom right insets, N = 1120). Impact scores are expressed in Person Equivalent (PE), reflecting the number of average annual per capita impacts caused by a given assessed product/service (see ref 44); logarithmic scale is used. Dots above the straight line indicate dominance of the compared impact category over carbon footprint. Detailed statistics are available in Table S1. Similar plots are shown for CFP against 10 other environmental impact categories in Figure S1.

Infrastructure category shows correlation coefficients towering above 0.94 for all impact categories ($P < 0.05$; Table S1a,e).

This finding emphasizes the need to differentiate conclusions according to the type of assessed products. The tested products were therefore classified into categories and, where relevant, subcategories to support a more qualified interpretation (Table S2). The correlations found between CFP and other impact indicator scores for different categories of products support identification of two fundamentally different patterns: the genuine correlation, for which CFP serves as a good proxy of the overall environmental impact in a comparison of different products, and the miscorrelation, where CFP is found not to be sufficient as a stand-alone method to represent environmental impact.

When Is CFP an Acceptable Metric? A genuine correlation between carbon footprint and all the other environmental impact indicators can be observed if and only if all impacts from the product life cycle predominantly stem from one or few key processes that covary. For most products contributions to climate change impacts come predominantly from the combustion of fossil fuels used in energy production;[1] the fossil fuel combustion processes present in a product life cycle are therefore always among these key processes. As an illustration, the category of infrastructure-related products (including buildings, wind turbines, pumps, or facilities like power plants) was found to show strong correlations between CFP and all other environmental impact categories (Table S1a-b and Figure S3). For most of the products, the life cycle embraces all emissions and resource consumptions related to the construction and decommissioning of the infrastructure. For nearly all impact categories the impacts were found to be caused predominantly by one or more of three activities: (1) the production and disposal of the steel, (2) the burning of fossil fuels for electricity and heat production and transportation purposes, and (3) the cement production (only relevant for buildings or facilities) (Table S3). The production of the required steel is observed to be highly energy and resource intensive in the assessed systems and thus largely contributes to climate change and other non-toxic impact categories as well as to depletion of resources (via scarce metals like nickel and chromium). Burning of fossil fuels for operations and transportations as well as the clinker production also primarily contribute to non-toxic impacts. Toxic pollutants like heavy metals, released during the production of steel and through its disposal, constitute the major burden for all toxic impact categories. The draw on these identified key processes covaries from one infrastructure-related product to another primarily due to changes in size and mass of the product, e.g. the higher the requirements in steel (with its emissions of toxic substances (metals) during production and disposal of steel), the higher the energy requirements from fossil fuels, used for both the steel production and the subsequent operations, are. With the covariation of these key processes, the indicator scores for all impact categories have thus a propensity to increase or decrease in concert from one product to another within the category, leading eventually to the strength of the observed overall correlation.

When correlation is observed for all impact categories within a determined category of products, scaling factors can be calculated to help predict the magnitude of other impacts when CFP is known for a product. The ratios between the

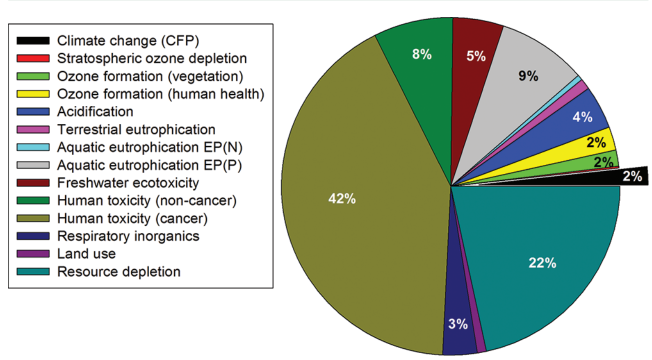

Figure 2. Contributions to total environmental burden for infrastructure-related products and services. Shares of total environmental burden (assuming equal weight of normalized midpoint scores) are provided for the most contributing impacts. Full distributions and background data, including standard deviations, are available in Table S3.

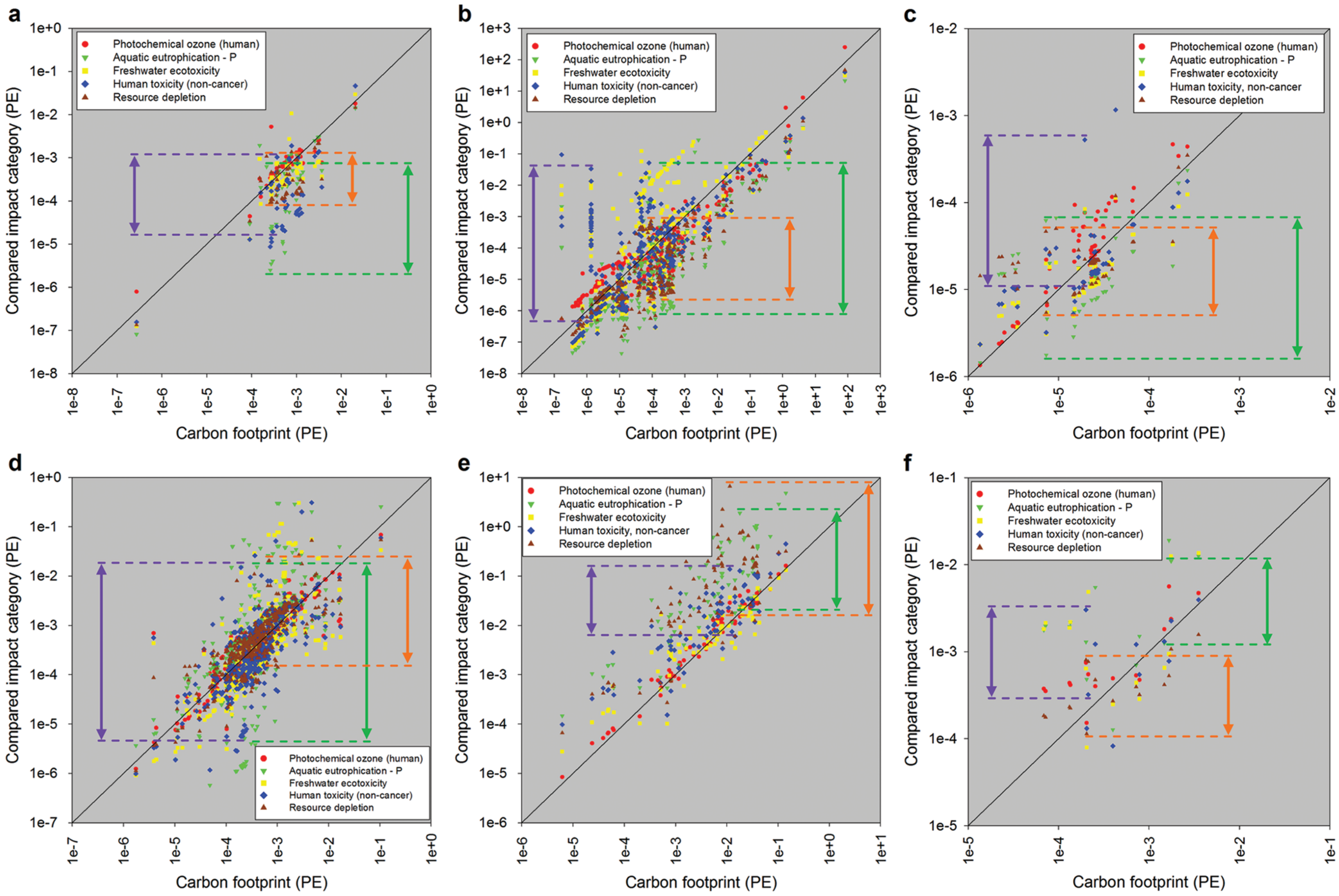

Figure 3. Correlations between CFP and other impact scores for selected product categories. CFP is plotted against scores for five impact categories (see graph legends) for product categories **(a)** "Plastics" ($N = 51$), **(b)** "Waste" ($N = 363$), **(c)** "Road transportation" ($N = 58$), **(d)** "Chemicals" ($N = 510$), **(e)** "Electronics" ($N = 89$), **(f)** "Textiles" ($N = 24$). Impact scores are expressed in Person Equivalent (PE), reflecting the number of average annual per capita impacts caused by a given assessed product/service (see ref 44); logarithmic scale is used. Dots above the straight line show dominance of the compared impact category over carbon footprint. Arrows are for indicative purposes only and reflect the order-of-magnitude difference in impact that may occur between different products with the same CFP for aquatic eutrophication (green), human toxicity (purple), and resource depletion (orange). Detailed statistics are available in Table S1.

normalized scores of each impact and the CFP scores are calculated for each product and averaged over the considered category of products. It is also worth noting that more accurate scaling factors, e.g. with lower standard deviations, could be obtained by further differentiating into subcategories of products, e.g. power plants separated from vehicles in infrastructure-related products (data not shown).

Analyses of the ratios between the individual impact scores and the CFP scores for the infrastructure category (Table S3) indicate that depletion of resources and toxicity-related impacts have a much larger contribution to the averaged environmental burden of infrastructure-related products than non-toxic impacts including climate change. If all normalized environmental impacts are weighted evenly and summed up, CFP scores would thus represent only about 2% of the total average environmental burden, while human toxicity (cancer effects) alone would contribute 42% and resource depletion about 22% (Figure 2). Notwithstanding the methodological uncertainties, particularly in the use of normalization, which leads to overestimated normalized scores for certain impacts such as the toxic impacts (see section Methods), these figures illustrate that, even though carbon footprint serves as a good indicator of environmental impact in comparisons inside this product category, policy-makers should take care not to oversimplify the environmental burden to the sole climate change impacts in their interpretation of environmental sustainability assessments.

When Is CFP a Poor Representative? When disaggregated to subcategory or product level, many product categories show weak correlations between CFP and one or more impact categories (Figure 3; Supporting Information Figures S2, S4–S12). Life cycle assessments typically focus on comparing two or more alternative products, which provide a comparable service and hence belong to the same category of products. The apparent good correlation of CFP and other impact categories across all products (Figure 1 and Figure S1, central panels) is thus of minor importance than the finding that there are many weak correlations when the products are analyzed within their subcategories, and the latter finding counters the suitability of CFP to predict other environmental impact scores when assessing most types of products.

The most deviating impact categories (both in terms of frequency and size of the deviations) were found to be toxicity to ecosystems and humans, depletion of resources, and land use. This is probably due to the fact that these impacts are mainly related to process- or product-specific emissions or inputs, which do not entirely come from energy production processes in the product life cycle. Toxic substances can be emitted through the entire life cycle of the product (e.g.,

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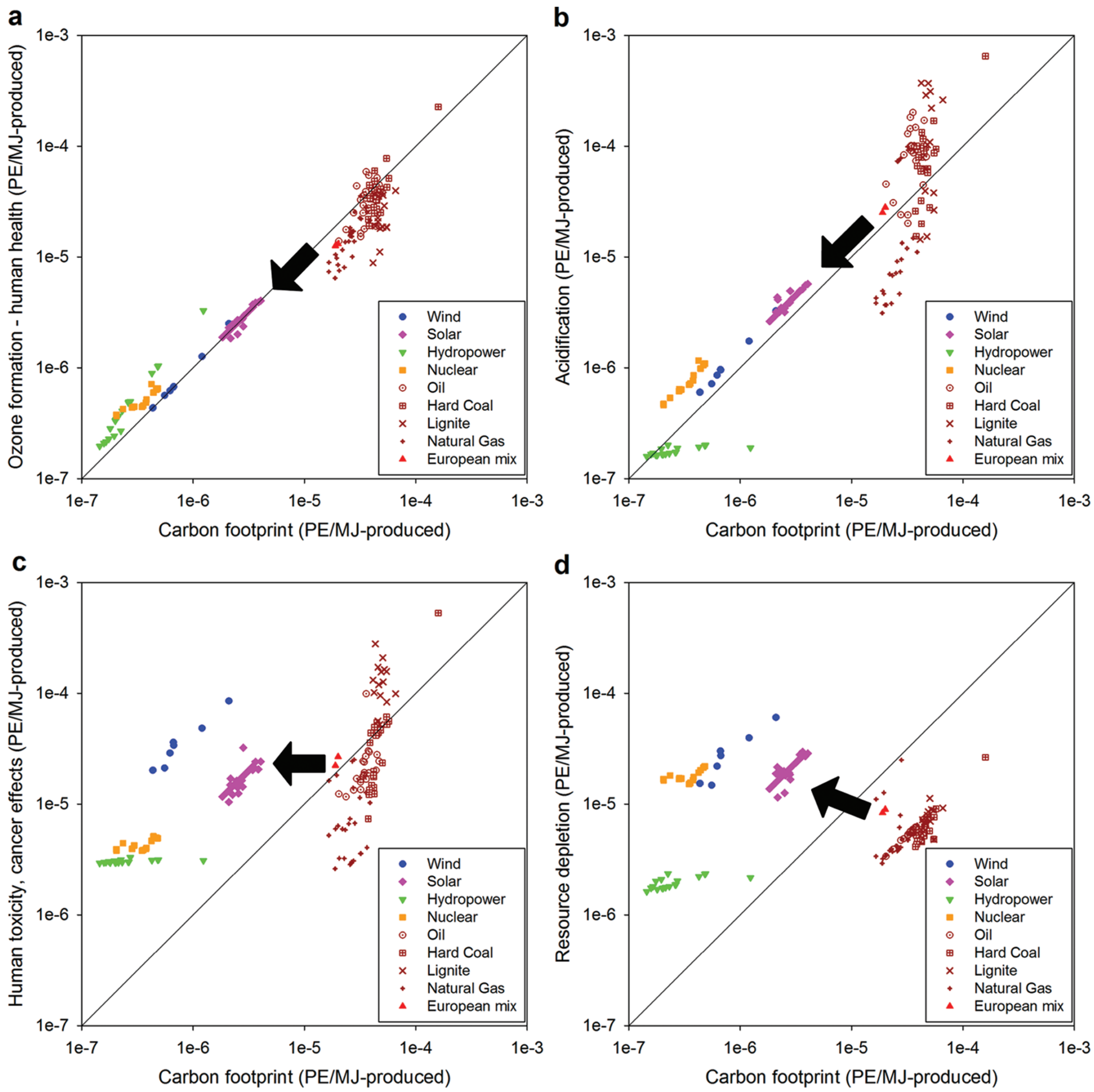

Figure 4. Impact shifts from switching electricity production from use of fossil fuels to use of renewables. CFP is plotted against (**a**) photochemical ozone formation impacts on human health, (**b**) acidification, (**c**) human toxicity associated with cancer effects, and (**d**) resource depletion for 1MJ of electricity produced with different electricity technologies (all marks for fossils are colored in brown). Impact scores are expressed in Person Equivalent (PE) per MJ-produced, reflecting the number of average annual per capita impacts caused by the production of 1MJ of electricity (see ref 44); logarithmic scale is used. Dots above the straight line show the dominance of the compared impact category over carbon footprint.

chemical treatment in production or use stages, incineration or landfilling in disposal stage); depletion of resources is often driven by consumption of scarce metals like copper or nickel; land use is very specific to the type of product and usually shows no direct correlation with energy production. For these impact categories, the indicator score can vary up to several orders of magnitude for the same CFP value (arrows indicating variations in Figure 3).

This finding also remains true for some of the categories that show relatively high Spearman rank-order correlation coefficients, as illustrated in Figure 3d-f, for which some correlation coefficients reach values above ρ = 0.85 (see Table S1). An environmental analyst, comparing two products A or B having the same CFP score, would therefore be unable to distinguish which of the two options is the best with regard to other impact categories such as freshwater ecotoxicity or human toxicity. In a decision-making context, this indicates a real risk of selecting the least environmentally friendly solution, i.e. the one having the largest environmental impact if the decision is based on the CFP alone.

Suboptimization in Electricity Generation. When we worry about environmental sustainability, suboptimization can occur if decisions do not consider the whole life cycle or all relevant categories of environmental impact. Problem shifting may thus occur when changes that lead to a reduction of impacts in one part of the product life cycle are accompanied by increased impacts in another or when reduction in some impacts occur at the cost of increase in other impacts.[15,17]

For the past decade, focus has increasingly been on reducing the burning of fossil fuels, identified as a major contributor to climate change as well as acidification and photochemical ozone formation.[1,52,53] As a mean to substitute the fossil-based energy production, the use of renewable energy sources and nuclear energy has increased.[54] It is tempting to think that the environmental impact of the energy sector is well represented by the CFP score since the energy sector is one of the dominating sources of GHG emissions. Figure 4 presents LCA results for the production of 1MJ of electricity using various fossil-based and renewable energy technologies, plotting indicator results for four impact categories against CFP scores (see results for other impact categories in Figure S4). The results illustrate the changes that occur in the environmental burden of electricity production when switching from the use of fossil fuels to the use of renewables.

When turning away from fossil fuels, the environmental burden related to the burning of the fossils disappears, hence reducing impacts on climate change and other correlated impacts such as acidification and photochemical ozone formation (Figure 4a-b). However, through this technology shift, the impacts stemming from the life cycle of the necessary infrastructure or equipment, notably the depletion of resources (metals) and the impacts on human health from toxic chemicals, still remain present —see black arrows in Figure 4c-d. Depending on the type of infrastructure, they may even increase when switching from fossils to certain types of renewables (e.g., from European mix to wind turbines in Figure 4d).

Therefore, shifting electricity production from the use of fossils to the use of renewables does not make the whole environmental profile "green" in absolute terms. It reduces impacts stemming from the burning of the fossils, primarily climate change, and few other non-toxic impact categories, but it may lead to increased impacts in other categories that are not represented by the CFP score for the energy systems. Even in the energy sector, other impacts on environment and on human health than the climate change impacts are thus still relevant when assessing the environmental sustainability.

DISCUSSION

The analysis tends to corroborate related studies[20,21,55,56] by demonstrating that several categories of products show a poor correlation between CFP and other impact categories, such as toxicity-related impacts or resource depletion, because of different origins in the caused impacts along the product life cycles. Some factors could further increase these observed miscorrelations, e.g. the inclusion of more impact categories (e.g., drinking water scarcity), the application of a full life cycle perspective (see Methods), or a better inventory of releases of toxic emissions.[44]

Our industrial society uses tens of thousands of chemicals and the extent to which they are released into environment is far from being entirely inventoried because large efforts are required to identify and determine each chemical's emissions in a consistent way. For example, nanomaterials are being used increasingly in various products such as electronics, clothing, or personal care products; yet, the resulting releases of nanoparticles and the associated impacts on environment are still not covered in life cycle inventories and LCIA methods, while the relevance of such inclusions has been explicitly proved.[57−59] Likewise, occupational and residential indoor exposures to chemicals and particles, although established as very influential when assessing impacts on human health,[60−62] are still not operational in current LCA practice. For a given category of products, this implies that an environmental analyst may be misled when observing an apparent correlation between all impact categories primarily because specific exposure situations and releases of toxic substances, which are not related to the burning of fossil fuels, are currently not adequately assessed due to the incomplete life cycle inventories and impact assessment methods.

Policy-makers and industries are increasingly using GHG accountings in various contexts, for carbon emission labeling of common goods or as indicators of the environmental performance of novel technologies or products (e.g., biofuels, nanomaterials). As shown in our analysis, products or systems fulfilling similar functions in society's activities may show similar carbon footprints but differ by orders of magnitude with respect to other equally relevant environmental impacts. Therefore, the risk is real in both its magnitude and its breadth that policy-makers and industries solely relying on the information provided by carbon footprinting would overlook those other environmental aspects in their decisions. Ignorance of this risk might, e.g. through suboptimization in technology developments, undermine the global efforts to move toward a more environmentally sustainable society.

Thus, although carbon footprint can be given the credit to have raised environmental awareness among decision makers in politics and business, its limitations in representing the whole 'environmental picture' calls for greater caution. Unless CFP has been demonstrated to function well as overall environmental impact indicator for the product or technology that is being investigated, we strongly encourage decision makers to regard it as a 'transition indicator', i.e. a springboard to move toward a systematic use of more holistic approaches, such as life cycle assessments, in the aim for environmental sustainability.

ASSOCIATED CONTENT

Supporting Information

Figures investigating the correlation analyses between carbon footprint and other impact categories for a selection of product/service categories (Figures S1−S12); supplemental method section describing the characterization and normalization of the impact categories 'respiratory impacts from particulate matters' and 'land use' (Supporting Methods); tables detailing the assessed products/services, the statistical results, and the analysis of results for infrastructure-related products/services (Tables S1−S3). This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Intergovernmental Panel on Climate Change; *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*, Solomon, S., et al.; Eds.; Cambridge University Press: Cambridge, UK, 2007.

(2) Millennium Ecosystem Assessment; *Ecosystems and Human Well-being: Synthesis*; Island Press:Washington, USA, 2005.

(3) Steffen, W.; Sanderson, A.; Tyson, P. D.; Jager, J.; Matson, P. A.; Moore III, B.; Oldfield, F.; Richardson, K.; Schellnhuber, H. J.;

Turner, B. L.; Wasson, R. J. *Global Change and the Earth System: A Planet Under Pressure*; Springer Verlag: Germany, 2004.

(4) Crutzen, P. J. Geology of mankind. *Nature* **2002**, *415*, 23.

(5) Kates, R. W.; Clark, W. C.; Corell, R.; Hall, J. M.; Jaeger, C. C.; Lowe, I.; McCarthy, J. J.; Schellnhuber, H. J.; Bolin, B.; Dickson, N. M.; Faucheux, S.; Gallopin, G. C.; Gruebler, A.; Huntley, B.; Jager, J.; Jodha, N. S.; Kasperson, R. E.; Mabogunje, A.; Matson, P.; Mooney, H.; Moore, B. III; O'Riordan, T.; Svedin, U. Sustainability science. *Science* **2001**, *292*, 641−642.

(6) Clark, W. C.; Dickson, N. M. Sustainability science: The emerging research program. *Proc. Natl. Acad. Sci. U. S. A.* **2003**, *100*, 8059−8061.

(7) Clark, W. C. Sustainability science: A room of its own. *Proc. Natl. Acad. Sci. U. S. A.* **2007**, *104*, 1737−1738.

(8) Seitzinger, S. A sustainable planet needs scientists to think ahead. *Nature* **2010**, *468*, 601.

(9) Rockstrom, J.; Steffen, W.; Noone, K.; Persson, A.; 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, d.L.; Rodhe, H.; Sorlin, 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. A safe operating space for humanity. *Nature* **2009**, *461*, 472−475.

(10) Chapin, F. S.; Carpenter, S. R.; Kofinas, G. P.; Folke, C.; Abel, N.; Clark, W. C.; Olsson, P.; Smith, D. M.; Walker, B.; Young, O. R.; Berkes, F.; Biggs, R.; Grove, J. M.; Naylor, R. L.; Pinkerton, E.; Steffen, W.; Swanson, F. J. Ecosystem stewardship: Sustainability strategies for a rapidly changing planet. *Trends Ecol. Evol.* **2010**, *25*, 241−249.

(11) Elkington, J. *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*; Capstone Publishing Limited, John Wiley & Sons: London, UK, 1999.

(12) Valdivia, S.; Ugaya, C. M. L.; Sonnemann, G.; Hildenbrand, J. *Towards a Life Cycle Sustainability Assessment - Making Informed Choices on Products*; UNEP/SETAC Life Cycle Initiative: Paris, France, 2011.

(13) United Nations Environment Programme (UNEP) & Society of Environmental Toxicology and Chemistry (SETAC); *The Life Cycle Initiative. International Life Cycle Partnership for a Sustainable World*; launched in 2002. http://lcinitiative.unep.fr/ (accessed November 1, 2011).

(14) International Organization for Standardization; *Environmental Management - Life Cycle Assessment - Requirements and Guidelines (ISO 14044:2006)*; ISO: Geneva, Switzerland, 2006.

(15) European Commission − Joint Research Centre − Institute for Environment and Sustainability; *International Reference Life Cycle Data System (ILCD) Handbook − General guide for Life Cycle Assessment - Detailed guidance*, 1st ed.; Publications Office of the European Union: Luxembourg, 2010.

(16) Hauschild, M. Z. Assessing environmental impacts in a life-cycle perspective. *Environ. Sci. Technol.* **2005**, *39*, 81A−88A.

(17) Finnveden, G.; Hauschild, M. Z.; Ekvall, T.; Guinee, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in Life Cycle Assessment. *J. Environ. Manage.* **2009**, *91*, 1−21.

(18) Hauschild, M. Z.; Goedkoop, M.; Guinée, J.; Heijungs, R.; Huijbregts, M. A. J.; Jolliet, O.; Margni, M.; De Schryver, A.; Humbert, S.; Laurent, A.; Sala, S.; Pant, R. Best existing practice for characterization modelling in Life Cycle Impact Assessment. Submitted to the *Int. J. Life Cycle Assess.* (01/2012).

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

(20) Huijbregts, M. A. J.; Rombouts, L. J. A.; Hellweg, S.; Frischknecht, R.; Hendriks, A. J.; Van, d.M.; Ragas, A. M. J.; Reijnders, L.; Struijs, J. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? *Environ. Sci. Technol.* **2006**, *40*, 641−648.

(21) Huijbregts, M. A. J.; Hellweg, S.; Frischknecht, R.; Hendriks, H. W. M.; Hungerbuhler, K.; Hendriks, A. J. Cumulative Energy Demand as predictor for the environmental burden of commodity production. *Environ. Sci. Technol.* **2010**, *44*, 2189−2196.

(22) World Resources Institute (WRI)/World Business Council for Sustainable Development (WBCSD); *The Greenhouse Gas Protocol Initiative − The foundation for sound and sustainable climate strategies*; launched in 1998. http://www.ghgprotocol.org/ (accessed November 1, 2011).

(23) International Organization for Standardization; *Greenhouse gases (ISO 14064:2006)*; ISO: Geneva, Switzerland, 2006.

(24) United Nations; *Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC)*; United Nations: New York, USA, 1998.

(25) European Commission − Joint Research Centre − Institute for Environment and Sustainability; *Carbon Footprint - What it is and how to measure it*; European Commission: Ispra, Italy, 2009.

(26) Weidema, B. P.; Thrane, M.; Christensen, P.; Schmidt, J.; Lokke, S. Carbon footprint - A catalyst for life cycle assessment? *J. Ind. Ecol.* **2008**, *12*, 3−6.

(27) Finkbeiner, M. Carbon footprinting-opportunities and threats. *Int. J. Life Cycle Assess.* **2009**, *14*, 91−94.

(28) British Standards Institution; *PAS 2050:2011 − Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services*; BSI: London, UK, 2011.

(29) British Standards Institution; *PAS 2060:2010 − Specification for the Demonstration of Carbon Neutrality*; BSI: London, UK, 2010.

(30) Greenhouse Gas Protocol; *Corporate Value Chain (Scope 3) Accounting and Reporting Standard*; World Resources Institute and World Business Council for Sustainable Development: USA, 2011.

(31) Greenhouse Gas Protocol; *Product Life Cycle Accounting and Reporting Standard*; World Resources Institute and World Business Council for Sustainable Development: USA, 2011.

(32) International Organization for Standardization; *Carbon footprint of products -- Requirements and guidelines for quantification and communication* (ISO/DIS 14067; under development).

(33) European Commission − Joint Research Centre − Institute for Environment and Sustainability; *International Reference Life Cycle Data System (ILCD) Handbook − Recommendations for Life Cycle Impact Assessment in European context based on existing environmental impact assessment models and factors*; 1st ed.; Publications Office of the European Union: Luxembourg, 2011.

(34) Wenzel, H.; Hauschild, M. Z.; Alting, L. *Environmental Assessment of Products. Vol. 1 - Methodology, Tools and Case Studies in Product Development*; Chapman and Hall: London, UK, 1997.

(35) Hauschild, M. Z.; Wenzel, H. *Environmental Assessment of Products. Vol. 2 - Scientific Background*; Chapman and Hall: London, UK, 1998.

(36) Hauschild, M.; Potting, J. *Spatial Differentiation in LCA Impact Assessment − The EDIP 2003 Methodology*; Environmental News No. 80; Danish Environmental Protection Agency: Copenhagen, Denmark, 2005.

(37) Potting, J.; Hauschild, M. *Background for Spatial Differentiation in LCA Impact Assessment − The EDIP 2003 Methodology*; Environmental Project No. 996; Danish Environmental Protection Agency: Copenhagen, Denmark, 2005.

(38) Hauschild, M. Z.; Huijbregts, M.; Jolliet, O.; Macleod, M.; Margni, M.; Rosenbaum, R. K.; van de Meent, D.; McKone, T. E. Building a model based on scientific consensus for life cycle impact assessment of chemicals: The search for harmony and parsimony. *Environ. Sci. Technol.* **2008**, *42*, 7032−7037.

(39) Rosenbaum, R. K.; Bachmann, T. M.; Gold, L. S.; Huijbregts, M. A. J.; Jolliet, O.; Juraske, R.; Koehler, A.; Larsen, H. F.; MacLeod, M.; Margni, M.; McKone, T. E.; Payet, J.; Schuhmacher, M.; Meent, D; v.d.; Hauschild, M. Z. USEtox-the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int. J. Life Cycle Assess.* **2008**, *13*, 532−546.

(40) Humbert, S.; Marshall, J. D.; Shaked, S.; Spadaro, J. V.; Nishioka, Y.; Preiss, P.; McKone, T. E.; Horvath, A.; Jolliet, O. Intake

fraction for particulate matter: Recommendations for life cycle impact assessment. *Environ. Sci. Technol.* **2011**, *45*, 4808−4816.
(41) Humbert S. Geographically differentiated life-cycle impact assessment of human health. Ph.D. Dissertation, AAT 3402614, University of California, CA, USA, 2009.
(42) Milà i Canals, L.; Cowell, S. J.; Romanyà, J. Method for assessing impacts on life support functions (LSF) related to the use of 'fertile land' in Life Cycle Assessment (LCA). *J. Clean. Prod.* **2007**, *15*, 1426−1440.
(43) Milà i Canals, L.; Muñoz, I.; McLaren, S.; Brandão, M. *LCA methodology and modelling considerations for vegetable production and consumption*; CES Working Papers 02/07; Centre for Environmental Strategy: University of Surrey, UK, 2007.
(44) Laurent, A.; Olsen, S. I.; Hauschild, M. Z. Normalization in EDIP97 and EDIP2003: Updated European inventory for 2004 and guidance towards a consistent use in practice. *Int. J. Life Cycle Assess.* **2011**, *16*, 401−409.
(45) Laurent, A.; Lautier, A.; Rosenbaum, R. K.; Olsen, S. I.; Hauschild, M. Z. Normalization references for Europe and North America for application with USEtox characterization factors. *Int. J. Life Cycle Assess.* **2011**, *16*, 728−738.
(46) Hauschild, M.; Olsen, S. I.; Hansen, E.; Schmidt, A. Gone but not away - addressing the problem of long-term impacts from landfills in LCA. *Int. J. Life Cycle Assess.* **2008**, *13*, 547−554.
(47) Pettersen, J.; Hertwich, E. G. Critical review: Life-cycle inventory procedures for long-term release of metals. *Environ. Sci. Technol.* **2008**, *42*, 4639−4647.
(48) Ecoinvent Centre; *Ecoinvent Data v2.1. Final reports Ecoinvent No. 1−25*; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
(49) PRé; *SimaPro 7.2*; PRé: Amersfoort, Netherlands, 2009.
(50) R Development Core Team; *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing, 2009. http://www.r-project.org/ (accessed March 1, 2011).
(51) Heijungs, R.; Guinee, J.; Kleijn, R.; Rovers, V. Bias in normalization: Causes, consequences, detection and remedies. *Int. J. Life Cycle Assess.* **2007**, *12*, 211−216.
(52) Potter, D. U.; Huber, C. M. *Using the critical load concept to protect ecosystems from acidification*. In *Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18−22 October 2004*; Furniss, M., Clifton, C., Ronnenberg, K.; Eds.; U.S. Department of Agriculture: Washington, USA, 2007.
(53) Derwent, R. G.; Jenkin, M. E.; Saunders, S. M.; Pilling, M. J.; Simmonds, P. G.; Passant, N. R.; Dollard, G. J.; Dumitrean, P.; Kent, A. Photochemical ozone formation in north west Europe and its control. *Atmos. Environ.* **2003**, *37*, 1983−1991.
(54) International Energy Agency; *CO_2 Emissions from Fuel Combustion − Highlights (2009 ed.)*; OECD/IEA: Paris, France, 2009.
(55) Laurent, A.; Olsen, S. I.; Hauschild, M. Z. Carbon footprint as environmental performance indicator for the manufacturing industry. *Annals of CIRP* **2010**, *59*, 37−40.
(56) Berger, M.; Finkbeiner, M. Correlation analysis of life cycle impact assessment indicators measuring resource use. *Int. J. Life Cycle Assess.* **2011**, *16*, 74−81.
(57) Maynard, A. D.; Aitken, R. J.; Butz, T.; Colvin, V.; Donaldson, K.; Oberdoerster, G.; Philbert, M. A.; Ryan, J.; Seaton, A.; Stone, V.; Tinkle, S. S.; Tran, L.; Walker, N. J.; Warheit, D. B. Safe handling of nanotechnology. *Nature* **2006**, *444*, 267−269.
(58) Köhler, A. R.; Som, C.; Helland, A.; Gottschalk, F. Studying the potential release of carbon nanotubes throughout the application life cycle. *J. Clean. Prod.* **2008**, *16*, 927−937.
(59) Xia, T.; Li, N.; Nel, A. E. Potential health impact of nanoparticles. *Annu. Rev. Public Health* **2009**, *30*, 137−150.
(60) Hellweg, S.; Demou, E.; Scheringer, M.; McKone, T. E.; Hungerbuhler, K. Confronting workplace exposure to chemicals with LCA: Examples of trichloroethylene and perchloroethylene in metal degreasing and dry cleaning. *Environ. Sci. Technol.* **2005**, *39*, 7741−7748.
(61) Hellweg, S.; Demou, E.; Bruzzi, R.; Meijer, A.; Rosenbaum, R. K.; Huijbregts, M. A. J.; McKone, T. E. Integrating human indoor air pollutant exposure within Life Cycle Impact Assessment. *Environ. Sci. Technol.* **2009**, *43*, 1670−1679.
(62) Demou, E.; Hellweg, S.; Wilson, M. P.; Hammond, S. K.; McKone, T. E. Evaluating indoor exposure modeling alternatives for LCA: A case study in the vehicle repair industry. *Environ. Sci. Technol.* **2009**, *43*, 5804−5810.