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ANALYSIS

Ecological footprint accounting in the life cycle assessment of products

Mark A.J. Huijbregts[a,*], *Stefanie Hellweg*[b], *Rolf Frischknecht*[c], *Konrad Hungerbühler*[d], *A. Jan Hendriks*[a]

[a] *Department of Environmental Science, Faculty of Science, Radboud University Nijmegen, 6500 GL Nijmegen, The Netherlands*
[b] *Institute of Environmental Engineering, ETH Zurich, 8093 Zurich, Switzerland*
[c] *ecoinvent Centre, Empa, 8600 Duebendorf, Switzerland*
[d] *Institute for Chemical- and Bioengineering, ETH Zurich, 8093 Zurich, Switzerland*

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ABSTRACT

We present and discuss ecological footprint (EF) calculations for a large number of products and services consumed in the western economy. Product-specific EFs were calculated from consistent and quality-controlled life cycle information of 2630 products and services, including energy, materials, transport, waste treatment and infrastructural processes. We formed 19 homogeneous product/process subgroups for further analysis, containing in total 1549 processes. Per group, the average contribution of two types of land occupation (direct and energy related) to the total EF was derived. It was found that the ecological footprint of the majority of products is dominated by the consumption of non-renewable energy. Notable exceptions are the EFs of biomass energy, hydro energy, paper and cardboard, and agricultural products with a relatively high contribution of direct land occupation. We also compared the ecological footprint results with the results of a commonly used life cycle impact assessment method, the Ecoindicator 99 (EI). It was found that the majority of the products have an EF/EI ratio of around 30 m^2-eq. yr/ecopoint ± a factor of 5. The typical ratio reduces to 25 m^2 yr/ecopoints by excluding the arbitrary EF for nuclear energy demand. The relatively small variation of this ratio implies that the use of land and use of fossil fuels are important drivers of overall environmental impact. Ecological footprints may therefore serve as a screening indicator for environmental performance. However, our results also show that the usefulness of EF as a stand-alone indicator for environmental impact is limited for product life cycles with relative high mineral consumption and process-specific metal and dust emissions. For these products the EF/EI ratio can substantially deviate from the average value. Finally, we suggest that the ecological footprint product data provided in this paper can be used to improve the footprint estimates of production, import and export of products on a national scale and footprint estimates of various lifestyles.

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[*] *Corresponding author*. Tel.: +31 24 365 28 35; fax: +31 24 365 30 30.
E-mail address: m.huijbregts@science.ru.nl (M.A.J. Huijbregts).

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1. Introduction

The need for more sustainable products, processes, and ultimately lifestyles, has triggered the development of a large number of environmental assessment tools (e.g. Azar et al., 1996; Hertwich et al., 1997; Robèrt, 2000; Robèrt et al., 2002). These tools measure environmental performance and identify improvement potentials from an environmental point of view. One group of assessment methods focuses on the direct and indirect resource inputs and/or emissions from the "cradle to grave" of products. The underlying philosophy is to take into account all environmental impacts during the whole life cycle of products. These environmental product assessment methods are also called life cycle assessment (LCA) methods.

For the interpretation of product-specific life cycle resource use and emissions, two classes of LCA methods can be identified that produce one single score for every product assessed. The first class of indicator methods aims at analysing all potential environmental impacts occurring during the life cycle of a product. A commonly applied single-score impact assessment method in LCA is the Ecoindicator 99 (EI; Goedkoop et al., 1998; Goedkoop and Spriensma, 2000). The EI-method focuses on quantifying impacts on human health, ecosystem quality and resources. A single score per product is obtained by applying weighting factors based on panel preferences. The second class of methods produce input-related indicators, for instance based on the cumulative use of land, energy and materials. Inputs can be assessed with relatively high confidence and is considered to be indicative of total environmental performance. One example of this class is the cumulative energy demand (Chapman, 1974; Hirst, 1974) quantifying the energy required during the life cycle of a product.

As shown by Huijbregts et al. (2006), fossil cumulative energy demand (CED) is indeed an important driver of several environmental impacts and thereby indicative for many environmental problems. Although fossil cumulative energy demand (CED) is strongly linked to emission-related impacts as global warming and acidification, correlations of CED to land use are relatively low. Land use plays an important role in relation to the production of renewable energy carriers and less for fossil fuel extraction (Hischier et al., 2005; Jungbluth et al., 2005). In this context, the ecological footprint (EF) may be an appropriate alternative for the CED as a proxy single-score indicator in LCA. The EF integrates (i) the area required for the production of crops, forest products and animal products, (ii) the area required to sequester atmospheric CO_2 emissions dominantly caused by fossil fuel combustion, and (iii) the area required by nuclear energy demand (Wackernagel et al., 2002; Monfreda et al., 2004). The EF has been commonly used to assess human pressure in geographical context, for instance on the level of nations, regions or cities (see e.g. Folke et al., 1997; Wackernagel et al., 2002; Nijkamp et al., 2004). Furthermore, the EF of a number of products, mainly energy carriers and food products, have been calculated (Kautsky et al., 1997; Folke et al., 1998; Chambers et al., 2000; Simmons et al., 2000; Deumling et al., 2003; Stöglehner, 2003; Holdren and Høyer, 2005). Up to now, however, the EF methodology has not been comprehensively applied to assess environmental burdens by a wide range of products (Wackernagel and Yount, 2000).

The current paper fills this information gap by calculating ecological footprints of 2630 products and services in the western economy, including energy generation, material production, transport, waste treatment processes and infrastructure. We formed 19 rather homogeneous product/process subgroups for further analysis, containing in total 1549 processes. Per group, the average contribution of the three types of land occupation (direct, CO_2 and nuclear) to the total EF was derived. Instead of producing another theoretical critical assessment of the ecological footprint method (e.g., van de Bergh and Verbruggen, 1999), we compared the ecological footprint results with the results of a more sophisticated impact assessment method, i.e. the Ecoindicator 99. This helps to identify for which product categories the two approaches will lead to a different ranking of products in practice.

2. Methodology

2.1. Ecological footprint

The ecological footprint is defined as the biologically productive land and water a population requires to produce the resources it consumes and to absorb part of the waste generated by fossil and nuclear fuel consumption (Wackernagel and Rees, 1996; Wackernagel et al., 2002; Monfreda et al., 2004). The focus on biologically productive land and water for humans reflects the anthropogenic perspective of the ecological footprint accounts (Wackernagel et al., 2005). In the context of LCA, the ecological footprint of a product is defined as the sum of time-integrated direct land occupation and indirect land occupation, related to nuclear energy use and to CO_2 emissions from fossil energy use and cement burning:

$$\mathrm{EF} = \mathrm{EF}_{\mathrm{direct}} + \mathrm{EF}_{\mathrm{CO_2}} + \mathrm{EF}_{\mathrm{nuclear}} \quad (1)$$

For the products included in the analysis, direct land occupation over time (m^2 yr) is defined by (i) built-up area, (ii) forest, (iii) cropland, (iv) pasture and (v) hydropower area. The direct ecological footprint, related to the five land occupation types identified, is calculated by

$$\mathrm{EF}_{\mathrm{direct}} = \sum_a A_a \cdot \mathrm{EqF}_a \quad (2)$$

where $\mathrm{EF}_{\mathrm{direct}}$ is the ecological footprint of direct land occupation (m^2 yr), A_a is the occupation of area by land use type a (m^2 yr) and EqF_a is the equivalence factor of land use type a (–). One important difference with the original ecological footprint approach as described in Wackernagel et al. (2005) is that we apply product-specific yield figures for forestry, pasture and crops to obtain the direct land occupation A_a instead of global average yields (ecoinvent Centre, 2004). As argued by Wiedmann and Lenzen (2007), actual yields better reflect gains in product efficiency which is considered an important aspect in the life cycle assessment of products.

Table 1 – Parameter settings for the calculations of ecological footprints (Wackernagel et al., 2005)

Parameter	Abbreviation	Unit	Value
Equivalence factor forest	EqF_f	–	1.4
Equivalence factor built-up area	EqF_b	–	2.2
Equivalence factor primary cropland	EqF_c	–	2.2
Equivalence factor hydropower area	EqF_h	–	1.0
Equivalence factor pasture	EqF_p	–	0.5
Equivalence factor marine area	EqF_p	–	0.4
Fraction CO_2 absorbed by the ocean	F_{CO_2}	–	0.3
Sequestration rate of CO_2	S_{CO_2}	kg CO_2 m^{-2} yr^{-1}	0.4
Fossil fuel emission intensity of CO_2	I_{CO_2}	kg CO_2 MJ^{-1}	0.07

Equivalence factors (EqF), taken from Wackernagel et al. (2005), adjust each type of land for bioproductivity. One area unit (m^2) is equal to one area unit with productivity equal to the average productivity of all the bioproductive area on Earth. High-productivity lands, such as cropland, have a high EqF, and low-productivity lands, like pastures, have a low EqF (Table 1). It could be argued that using actual yields for the calculation of land-use requirements in combination with global average Equivalence factors for assessing bioproductivity is not consistent (see Wiedmann and Lenzen, 2007). However, in the context of life cycle impact assessment, equivalence factors can be seen as characterisation factors to aggregate different types of land use in terms of 'bioproductive area'. Characterization factors are generally average factors without further regional differentiation (e.g. Pennington et al., 2004). Table A1 in the Appendix gives further details of the conversion of ecoinvent land types in land types as specified in the EF-calculations.

The CO_2 footprint estimates the additional biologically productive area required to sequester atmospheric fossil CO_2 emissions and calcination CO_2 from cement burning through afforestation (Monfreda et al., 2004; Wackernagel et al., 2005). The sequestration area to be occupied is calculated by:

$$EF_{CO_2} = M_{CO_2} \cdot \frac{1 - F_{CO_2}}{S_{CO_2}} \cdot EqF_f \tag{3}$$

where EF_{CO_2} is the ecological footprint of indirect land occupation by fossil- and cement-related CO_2 emissions (m^2 yr), M_{CO_2} is the product-specific emission of CO_2 (kg CO_2), F_{CO_2} is the fraction of CO_2 absorbed by oceans (–), S_{CO_2} is the sequestration rate of CO_2 by biomass (kg CO_2 m^{-2} yr^{-1}) and EqF_f is the equivalence factor of forests (–). This results in an EF of 2.7 m^2 yr kg^{-1} CO_2 emitted.

Following Monfreda et al. (2004), the nuclear energy footprint is calculated as if it were fossil energy:

$$EF_{nuclear} = E_{nuclear} \cdot I_{CO_2} \cdot \frac{1 - F_{CO_2}}{S_{CO_2}} \cdot EqF_f \tag{4}$$

where $EF_{nuclear}$ is the ecological footprint of indirect land occupation by the use of nuclear fuels (m^2 yr), $E_{nuclear}$ is the product-specific nuclear energy use (MJ) and I_{CO_2} is the average fossil fuel emission intensity of CO_2 (kg CO_2 MJ^{-1}). This results in an EF of 0.2 m^2 yr MJ^{-1} consumed nuclear primary energy. Parameter settings of F, S, I and EqF are specified in Table 1.

2.2. *Life cycle inventory database*

The ecoinvent database v1.2 (ecoinvent Centre, 2004; Frischknecht et al., 2005), containing consistent and quality-controlled life cycle information for 2630 products and services consumed in the western economy, has been used to derive product-specific ecological footprints and ecoindicator scores. Table 2 provides an overview of the product groups and the corresponding number of products considered. A subset of the total number of products and services in ecoinvent (1549 processes) was included in the data analysis to maintain homogeneity within the product groups. Ecological footprints of all 2630 products and services are included as supporting information (Appendix B). Energy production includes both heat and electricity production processes by non-renewable energy sources (oil, hard coal, lignite, natural gas, and nuclear) and renewable energy sources (hydropower, photovoltaic, wood, and wind). Material production comprises many different product types, including plastics, chemicals, metals, agricultural products, and building materials. Transport includes transport of products and persons by road, ship, train, airplane, and pipelines. Waste treatment represents

Table 2 – Product groups, derived from ecoinvent Centre (2004)

Product group	Number of services
Fossil energy[a] (MJ)	113
Nuclear energy (MJ)	11
Biomass energy (MJ)	37
Wind and solar energy (MJ)	21
Hydro energy (MJ)	31
Plastics (kg)	50
Paper and cardboard (kg)	59
Packaging glass (kg)	14
Metals (kg)	98
Chemicals[b] (kg)	351
Building products[c] (kg)	96
Agricultural products[d] (kg)	75
Goods transport (tkm)	28
Passengers transport (pkm)	12
Incineration[e] (kg)	73
Landfill[f] (kg)	113
Recycling[g] (kg)	28
Waste water (m^3)	23
Infrastructure (unit)	317

[a] Hard coal, lignite, natural gas, and oil.
[b] Chemicals, paintings, pesticides, fertilizers, and washing agents.
[c] Construction materials, construction glass, insulation, mortar and plaster.
[d] Feed production, seed production, and agricultural products.
[e] Municipal waste incineration and hazardous waste incineration.
[f] Inert material landfill, land farming, residual material landfill, sanitary landfill, and underground deposit.
[g] Direct recycling and recycling (partly) after sorting plant.

various types of land fill, incineration, recycling, and wastewater. Finally, infrastructural processes include all types of infrastructure, such as power plants, furnaces, and lorries.

2.3. *Data analysis*

The ecological footprint results were analysed in two ways. First, the average relative contribution to the total ecological footprint of (i) direct land occupation (summation of land used for forestry, hydropower, pasture, crops and build up), (ii) indirect land occupation due to CO_2 emissions and (iii) indirect land occupation due to nuclear energy consumption were derived and compared for all the product groups included.

In order to quantify the relationship between the ecological footprint as a relative simple environmental indicator and the ecoindicator 99 (EI; Goedkoop and Spriensma, 2000) as a relative complex environmental indicator, we calculated per product x the ratio R of the EF-score and EI-score:

$$R_x = \frac{EF_x}{EI99_x} \tag{5}$$

The ratio can be understood as a potential conversion factor between the Ecoindicator results (in ecopoints) and the ecological footprint results (in m^2 yr). If the ratio of the two impact scores is approximately equal for all products, this will imply that the two methods do not differ in their gross ranking of products.

3. Results

3.1. *Ecological footprints*

Fig. 1 gives the range of the ecological footprint scores of all the product groups involved. The ranges can be clarified by the fact that not every product within a product group has the same EF. For fossil and nuclear energy generation, the EF is around 0.5 m^2 yr MJ^{-1}. The typical EF of energy produced by biomass, solar and wind, and water is respectively about a factor of 5, 10 and 100 lower compared to non-renewable energy generation. Transport of goods and persons have typical EFs of 0.1 m^2 yr tkm^{-1} and 0.3 m^2 yr pkm^{-1}, respectively. The EF of material production is around 1–10 m^2 yr kg^{-1}. Very high EF values ($>10^4$ m^2 yr kg^{-1}) are found for the production of metals, such as Platinum. Relatively low EF values are reported for the production of building materials, such as clay and limestone (<0.01 m^2 yr kg^{-1}). Incineration of waste has a typical EF equal to the production of materials (5 m^2 yr kg^{-1}), while EFs of landfill and recycling are generally lower (around 0.05 m^2 yr kg^{-1}). Finally, infrastructure, such as

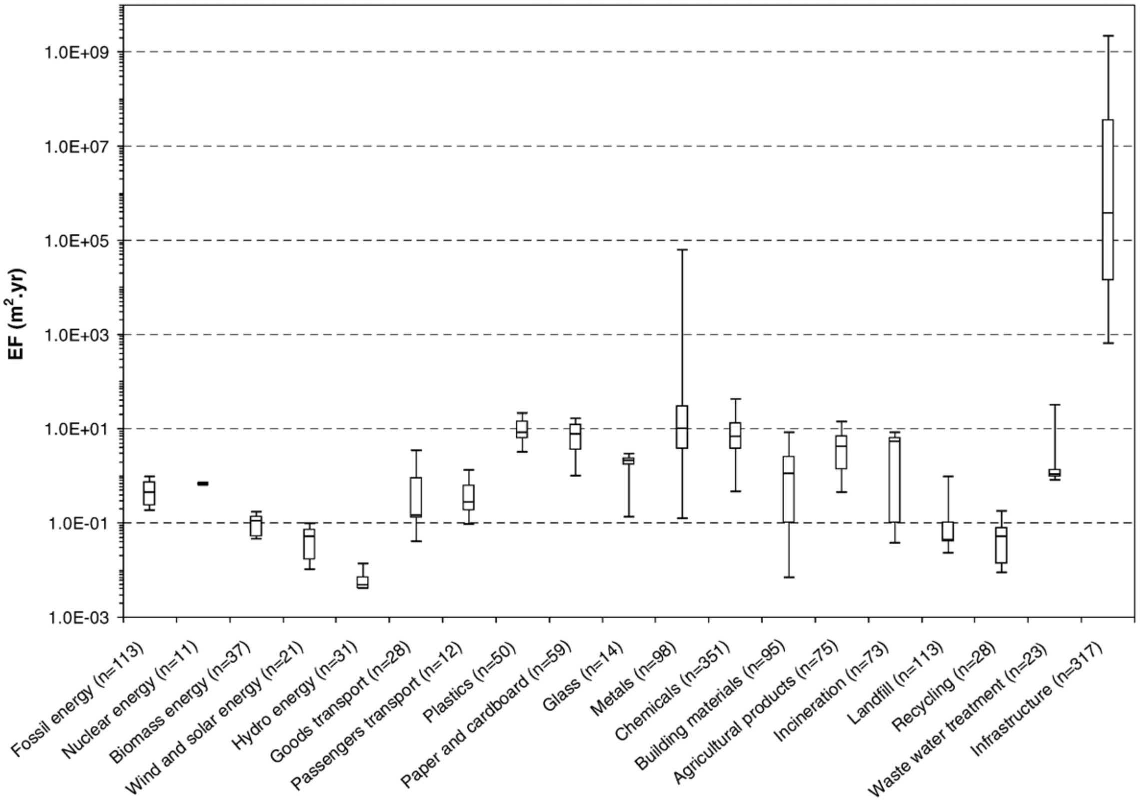

Fig. 1 – Box plots of the ecological footprint scores (EF). The energy production processes (fossil, nuclear, biomass, wind and solar, hydro) are given in m^2 yr MJ^{-1}, goods transport in m^2 yr tkm^{-1}, passenger transport in m^2 yr pkm^{-1}, infrastructure in m^2 yr $unit^{-1}$, and material production and waste treatment (plastics, paper and cardboard, glass, metals, chemicals, building materials, agricultural products, incineration, landfill, recycling) in m^2 yr kg^{-1}, except for waste water treatment which is in m^2 yr m^{-3}. The centre of the box represents the median value, the edges of the box indicates the 25th and 75th percentiles and the whiskers represent the 5th and 95th percentiles of the distributions.

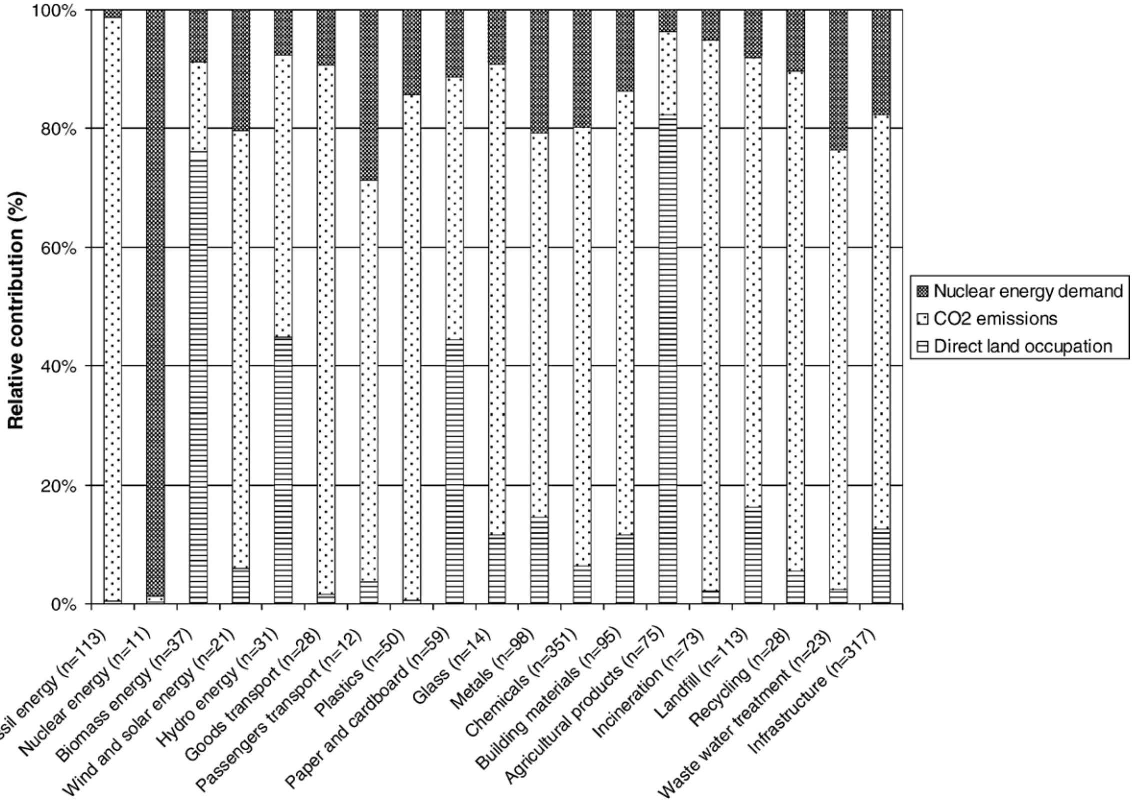

Fig. 2 – Relative contribution to the ecological footprint of respectively direct land occupation, land occupation due to CO_2 emissions and land occupation due to nuclear energy demand; n = number of processes.

lorries, typically shows EFs around 10^5 m^2 yr $unit^{-1}$. EFs higher than 10^9 m^2 yr $unit^{-1}$ are also reported, for instance, for the construction of power plants.

Fig. 2 shows that in energy generation processes as well as transport, the ecological footprint is mainly dominated by CO_2 emissions. One main exception is the production of nuclear energy which is fully dominated by the EF of nuclear energy demand. Other exceptions are the production of biomass energy and hydro energy with an average relative contribution of direct land occupation of respectively 76% (forestry) and 45% (hydropower area). In material production the typical domination of CO_2 emissions is also visible with notable exceptions of the product groups ‘paper and cardboard’ and ‘agricultural products’ with relatively high contributions of direct land occupation, i.e. respectively forestry and cropland. Fig. 2 also indicates that for waste-treatment processes and infrastructure, CO_2 emissions dominantly contributes to the total ecological footprint (typically 84% to 98%).

3.2. *Method comparison*

Fig. 3 shows the ratios of the ecological footprint and ecoindicator scores and their confidence intervals per product group. The overall median product ratio R is around 30 m^2 yr/ecopoints and varies between 8 and 80 m^2 yr/ecopoints for the product categories identified, except nuclear energy. The typical EF–EI ratio for the production of nuclear energy shows a strong deviation from the typical product ratio of 30 m^2-eq. yr/ecopoints (a factor of 50 higher). In terms of uncertainty, the 50th confidence interval (25/75 percentile) and 90th confidence interval (5/95 percentile) is respectively within a factor of 2 and 5 for the majority of the product groups involved, with notable exceptions for the production of metals and building materials and all waste treatment processes. For these product groups, the spread between the products is found to be larger (respectively up to a factor of 60 and 500 for the 50th and 90th confidence interval).

4. Discussion

The ecological footprint quantifies the demand of humans put on natural capital in terms of biological productive area required to support current consumption levels (Wackernagel et al., 2002). Compared to non-renewable (fossil and nuclear) CED, EF provides a more differentiated and complete picture of environmental impact due to the combination of fossil CO_2 emissions, nuclear energy use and direct land occupation in one common metric ‘global hectares’. First, it appeared that the forest EF is particularly important for the production of biomass-based energy and paper and cardboard (respectively 74% and 42% of the total EF). For biomass-based energy and paper and cardboard this can be explained by the fact that the direct material input is based on wood itself (Hischier, 2004). For agricultural products typically 80% of the total EF is clarified by the occupation of land by crops, while for hydropower the use of land by water reservoirs typically account for 45% of the total EF. For the other product

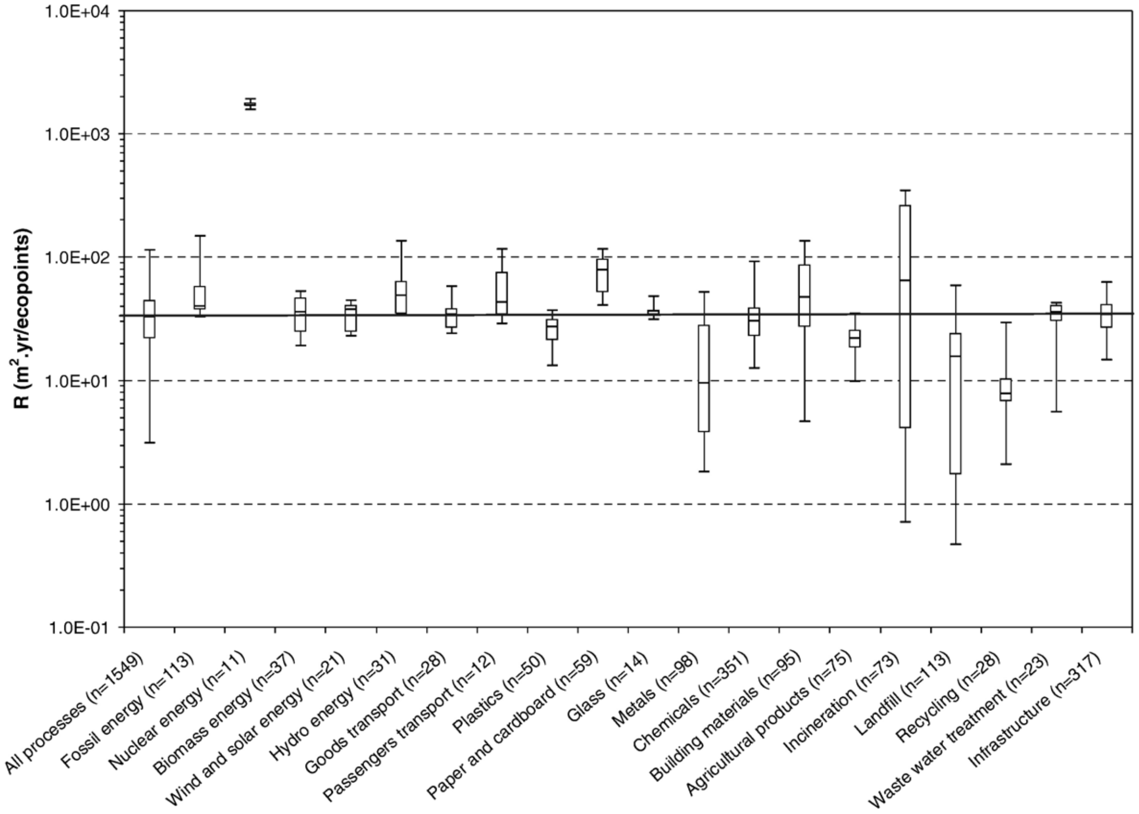

Fig. 3 – Box plots of the ratios *R* of the ecological footprint (EF in m^2 yr) and the EcoIndicator (EI in ecopoints) scores. The centre of the box represents the median value, the edges of the box indicates the 25th and 75th percentiles and the whiskers represent the 5th and 95th percentiles of the distributions. The horizontal line indicates the typical ratio of 30 m^2 yr/ecopoints including all 1549 products.

categories, CO_2 emissions, mainly due to the burning of fossil fuels, dominate the total EF. In these cases, the larger number of interventions assessed may not improve the results compared to the application of fossil CED as a proxy indicator for environmental impacts (Huijbregts et al., 2006).

A consistent comparison of the EF and EI methodologies has been assured by applying a comprehensive life cycle inventory dataset as derived from ecoinvent. Comparing ecological footprints with ecoindicator scores, it should first be acknowledged that EF deliberately includes environmental interventions that can be potentially sustainable only, i.e. the use of potentially renewable functions and services of nature. For instance, environmental contamination by persistent compounds are excluded from the analysis (Holmberg et al., 1999; Wackernagel et al., 2005). There are cases that may therefore not be assessed in an adequate way in terms of environmental impact. For example, a farmer switching from organic to intensive farming would benefit by a smaller footprint for using less land, while the environmental burdens from applying more chemicals would be neglected. In contrast, the ecoindicator methodology aims to include all relevant impacts, including toxicity and ozone depletion (Goedkoop et al., 1998). Although the two methods follow a different philosophy, the comparison shows that the majority of the 1549 products have an EF/EI ratio around 30 m^2 yr/ecopoint. This implies that both methods will typically produce the same type of gross ranking results. An advantage of the ecological footprint method is that relatively low uncertainty is attached to the interventions included, such as land occupation, fossil energy use and CO_2 emission factors, and equivalency factors of different land use types (Monfreda et al., 2004). In contrast, impacts addressed by the Eco-indicator methodology involve large methodological and technical uncertainties (Goedkoop and Spriensma, 2000; Lenzen, 2006). However, for a number of product categories clearly different ranking results are obtained by EF and EI. First, the production of nuclear energy gives a systemically higher relative ranking by EF compared to EI (about a factor of 50). This can be clarified by the fact that the EF method artificially assesses the production of nuclear energy in the same way as production of fossil energy with corresponding CO_2 emissions. In contrast, the EI method assesses the actual burden of radioactive emissions in terms of loss of life years in the population, based on Frischknecht et al. (2000). It appears that the burden caused by radioactive emissions, as calculated by Goedkoop and Spriensma (2000), is systemically lower compared to the burden attached to the burning of fossil fuels. This difference in starting point between the two assessment methods clarifies the relatively high ranking of nuclear energy production processes in EF compared to EI. Exclusion of the rather arbitrary nuclear energy demand EF from the footprint calculations indeed results in an average EF/EI ratio for nuclear energy production processes which is comparable to other product categories (Fig. 4). Further note that the typical EF/EI ratio reduces from about 30 to 25 m^2 yr/ecopoints by excluding nuclear energy demand from the EF-calculations.

Second, the production of metals and the recycling of building materials result in a typically higher relative ranking by EI compared to EF. For these production categories, the impact of (i) non-energy related emissions, such as process-specific particulate matter and metal emissions by industry, and (ii) resource consumption of metals have a relatively large share in the total impact scores of the EI method (Frischknecht and Jungbluth, 2004). These emissions and extractions, however, are not assessed by the current EF method. Third, it was found that the production of metals, building materials and all waste treatment categories, particularly incineration and land fill, have a large spread in EF–EI ratios. Particularly, the metal and building products delivered by the mining industry, such as bauxite and gypsum, have relatively high EI-scores due to mineral consumption and process-specific metal and dust emissions which are not accounted for in the EF-method, resulting in relatively low EF–EI ratios as explained above. However, for metal and building products which are further processed, such as steel and insulation materials, fossil energy consumption has a much larger share in the overall EI-score. For these types of products, EF–EI ratios are more in line with the typical ratio of around 30 m^2 yr/ecopoints.

Landfill and incineration of inorganic materials, such as metals and ashes, result in relatively high emissions of metals that cause carcinogenic and ecotoxic effects. These emissions are not related to the use of non-renewable energy consumptions or land occupation, causing a relatively low EF/EI ratio for these types of waste treatment processes. On the other hand, relatively high EF/EI ratios were found for disposal of organic materials, particularly incineration of plastics. The EF- and EI-scores for these incineration processes are fully determined by CO_2 emissions. Apparently, the conversion factor of around 30 m^2 yr/ecopoints based on a typical combination of direct land use, CO_2 emissions and nuclear energy consumption is lower than the conversion factor based on CO_2 emissions only. This implies that indirect land occupation due to CO_2 emissions results in a relatively higher burden in the EF-method compared to the EI-method in relation to direct land occupation and nuclear energy consumption.

We expect that the relative ranking of product systems by EF and EI will come even closer if a number of additional impacts will be taken into account without violating the concept of the EF-method. First, the land occupation due to the emission of CO_2 can be expanded by including also other greenhouse gases in the calculation routine. This can be readily implemented in the EF calculations by taking global warming outcomes in terms of CO_2-equivalents, as based on the Global Warming Potential concept, as a starting point (see e.g. Lenzen and Murray, 2001; Holdren and

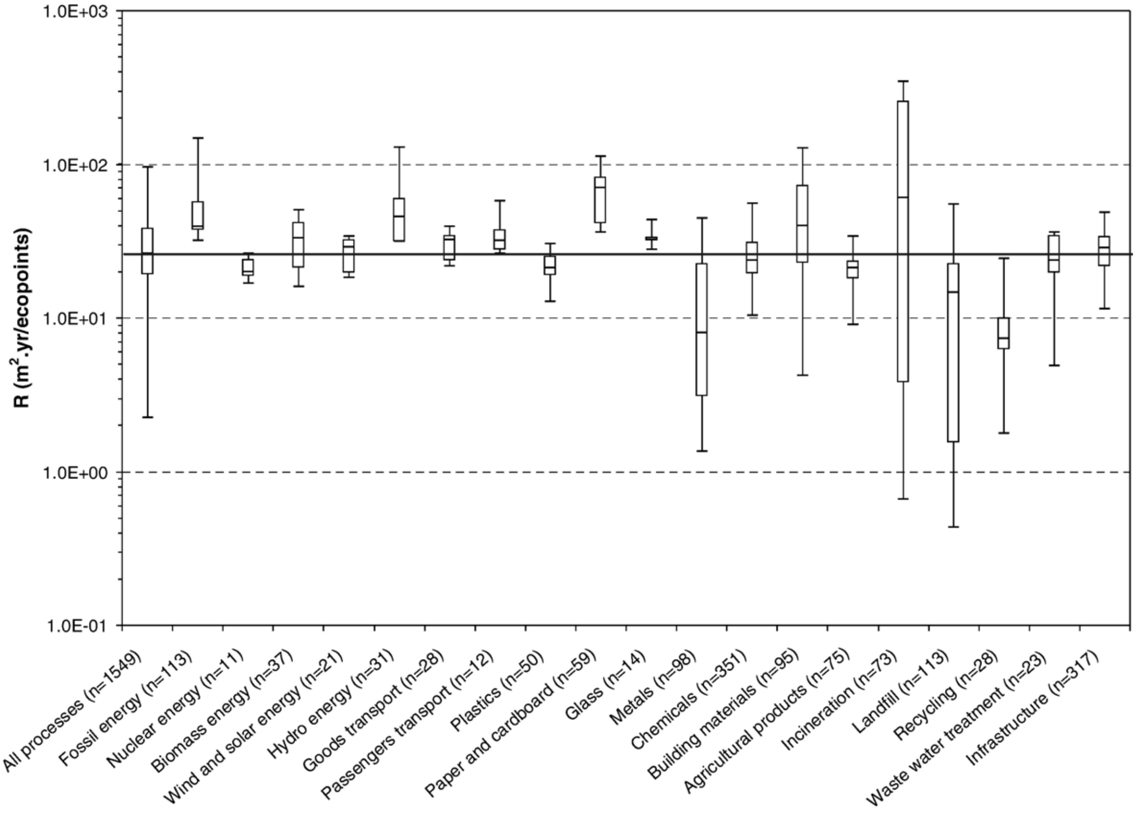

Fig. 4 – Box plots of the ratios *R* of the ecological footprint without nuclear energy demand (m^2 yr) and the EcoIndicator (Ecopoints) scores. The centre of the box represents the median value, the edges of the box indicates the 25th and 75th percentiles and the whiskers represent the 5th and 95th percentiles of the distributions. The horizontal line indicates the typical ratio of 25 m^2 yr/ecopoints for all 1549 products, excluding nuclear energy demand in the EF calculations.

Hoyer, 2005). Second, the land required to absorb the emissions of key nutrients, nitrogen (N) and phosphorus (P), by wetlands and agricultural ecosystems can be added to the ecological footprint results (Folke et al., 1997). Third, the area occupied by acidifying and toxic pollutants can be included by the critical load concept (Holmberg et al., 1999). With the critical load concept, the total area exceeding critical loads for acidifying pollutants (Potting et al., 1998; Hettelingh et al., 2005), metals (Hall et al., 2006) and even persistent organic pollutants (van den Hout et al., 1999) can be included in the current ecological footprint calculations. Fourth, the use of equivalence factors that refer to impacts on biodiversity instead of bioproductivity can be considered more relevant from an ecological point of view for the aggregation of various land use types into an ecological footprint (Lenzen and Murray, 2001; Lenzen et al., 2007). Characterisation factors applied in the life cycle impact assessment of various land use types may be well suited for this purpose (e.g. Koellner and Scholz, 2007a,b).

Ecological footprint calculations can also benefit from our footprint results for more than 2500 product systems. For instance, it is common practice to base the consumption part of the national scale footprint calculations on the energy embodied in traded goods (Monfreda et al., 2004). These rather crude ecological footprint estimates for traded goods could be replaced by our more comprehensive product-specific ecological footprints. Furthermore, the underpinning of ecological footprint calculations of lifestyles, including households and tourists (e.g. Simmons and Chambers, 1998; Hunter, 2002; Hunter and Shaw, 2005; Hunter et al., 2006), can be enhanced with our product-specific footprints. Combining our footprint estimates of material production, modes of transport, energy production and waste treatment with lifestyle information, e.g. from consumer surveys, can give a more complete and detailed picture of lifestyle ecological footprints. Finally, we were able to represent the footprint of products in a more appropriate way by applying actual yields instead of global average yields in our calculations (see e.g. also Wiedmann and Lenzen (2007) for a detailed discussion on this topic).

5. Conclusion

Ecological footprints of a large number of products consumed in the western economy have been calculated by combining fossil CO_2 emissions, nuclear energy use and direct land occupation in terms of global hectares. It was shown that the ecological footprint provides a more complete picture of environmental pressure compared to non-renewable CED which is particularly important for the product groups ‘biomass-based energy’, ‘hydro energy’, ‘paper and cardboard’ and ‘agricultural products’. Comparing ecological footprints with ecoindicator scores, it was found that the majority of the products have an EF/EI ratio of around 30 m^2 yr/ecopoint±a factor of 5. The relatively small variation of this factor implies that both methods may produce rather similar gross ranking results. Based on this observation, we conclude that the use of land and use of fossil fuels are important drivers of overall environmental impact. Ecological footprints may therefore serve as a screening indicator for environmental performance. However, our results also show that the usefulness of EF as a stand-alone indicator for environmental impact is limited for product life cycles with relative high mineral consumption and process-specific metal and dust emissions. For these products the EF/EI ratio can substantially deviate from the average. In addition to applying the ecological footprint philosophy in a product context, ecological footprint data on a product basis can in turn be used to improve the ecological footprint calculations. Particularly, the footprint estimates of production, import and export of products on a national scale and footprint estimates of various lifestyles can benefit from our assessment.

Acknowledgements

We thank Thomas Wiedmann and Manfred Lenzen for their valuable comments on the use of yield factors and equivalence factors in the footprint calculations.

Appendix A

Table A1– Conversion of ecoinvent land occupation classification, as based on the CORINE land cover classes, in classification categories related to global equivalence factors (EqF), based on Wackernagel et al. (2005)

Ecoinvent classification	CORINE classification	Footprint classification	EqF (–)
Occupation, arable, non-irrigated	CORINE 211	Cropland	2.2
Occupation, construction site	CORINE 133	Built-up area	2.2
Occupation, dump site	CORINE 132	Built-up area	2.2
Occupation, dump site, benthos	CORINE 132a	Fisheries	0.4
Occupation, forest, intensive	CORINE 31b	Forest	1.4
Occupation, forest, intensive, normal	CORINE 31b1	Forest	1.4
Occupation, industrial area	CORINE 121	Built-up area	2.2
Occupation, industrial area, benthos	CORINE 121c	Fisheries	0.4
Occupation, industrial area, built up	CORINE 121a	Built-up area	2.2
Occupation, industrial area, vegetation	CORINE 121b	Built-up area	2.2
Occupation, mineral extraction site	CORINE 131	Built-up area	2.2
Occupation, pasture and meadow, extensive	CORINE 231b	Pasture	0.5
Occupation, pasture and meadow, intensive	CORINE 231a	Pasture	0.5
Occupation, permanent crop, fruit, intensive	CORINE 222a	Cropland	2.2
Occupation, shrub land, sclerophyllous	CORINE 323	Forest	1.4
Occupation, traffic area, rail embankment	CORINE 122d	Built-up area	2.2
Occupation, traffic area, rail network	CORINE 122c	Built-up area	2.2
Occupation, traffic area, road embankment	CORINE 122b	Built-up area	2.2
Occupation, traffic area, road network	CORINE 122a	Built-up area	2.2

(continued on next page)

Table A1 (*continued*)

Ecoinvent classification	CORINE classification	Footprint classification	EqF (–)
Occupation, urban, discontinuously built	CORINE 112	Built-up area	2.2
Occupation, water bodies, artificial	CORINE 512a	Hydropower	1
Occupation, water courses, artificial	CORINE 511a	Hydropower	1

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolecon.2007.04.017.

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