Cumulative energy demand as predictor for the environmental burden of commodity production

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Brief

Cumulative energy demand is a good screening indicator for the overall life cycle environmental impact of many non-agricultural goods.

Abstract

Cumulative energy demand has been used as a methodology to assess life cycle environmental impacts of commodity production since the early seventies, but has also been criticized because it focuses on energy only. During the past 30 years there has been much research into the development of more complex single-score life cycle impact assessment methodologies. However, a comprehensive analysis of potential similarities and differences between these methodologies and cumulative energy demand has not been carried out so far. Here we compare the cumulative energy demand of 498 commodities with the results of six frequently applied environmental life cycle impact assessment methodologies. Commodity groups included are metals, glass, paper and cardboard, organic and inorganic chemicals, agricultural products, construction materials, and plastics. We show that all impact assessment methods investigated often provide converging results, in spite of the different philosophies behind these methodologies. Fossil energy use is identified by all methodologies as the most important driver of environmental burden of the majority of the commodities included, with the main exception of agricultural products.We conclude that a wide range of life cycle environmental assessment methodologies point into the same environmental direction for the production of a wide range of commodities.

Introduction

Changing society in the direction of large-scale application of more sustainable production technologies and life styles is one of the most challenging tasks faced by humanity. To evaluate the environmental performance of human activities and to identify improvement potentials, a large number of assessment methodologies and corresponding indicators have been proposed *(1-3)*. One distinct group of methodologies assesses the resource extractions and emissions caused by the making, use and disposal of products, also called life cycle assessment (LCA) methodologies. The underlying philosophy is to take into account all relevant pressures during the complete life cycle of a material, product or service *(4-6)*.

For the interpretation of resource use and emissions of commodities, a large number of LCA-methodologies are used to assess the environmental performance. These methodologies can be subdivided into two classes *(7-15)*. The first class of assessment methodologies produces relatively simple resource-oriented indicators, such as demand of energy or area. Resource-related methodologies considered here are, apart from Cumulative Energy Demand (CED; *8*), the Ecological Footprint (EF; *9, 10*) and the Cumulative Exergy Extraction from the Natural Environment (CEENE; *11, 12*). The CED represents the direct and indirect energy use, including the energy consumed during the extraction, manufacturing and disposal of the raw and auxiliary materials *(8)*. EF quantifies the demand of humans on natural capital in terms of biological productive area *(9)*. CEENE depicts total exergy deprived from nature to provide a material, summing up the exergy of all energy resources, non-energy resources and land required *(11)*. Exergy accounts for the maximum amount of work when bringing the resource's components to its reference state *(12)*.

The second class of assessment methodologies aims at analyzing emissions and resource extractions related to the life cycle of a product in terms of environmental impacts, producing 'impact-related' indicators *(7)*. For instance, the climate footprint is a measure of the total amount of carbon dioxide equivalent greenhouse gas emissions over the life cycle of a material, assessing the impact of a product to global warming *(16-18)*. Methodologies that address a wide range of different stressors are the Environmental Priority Strategy (EPS), Ecological Scarcity (ES) and Eco-Indicator 99 (EI) *(13-15)*. These three methodologies differ with regard to the types and number of resources and emissions they assess as well as to the underlying environmental models. Moreover, the final weighting step between the various impact categories considered (e.g. acidification, climate change and abiotic resource depletion) is based on different principles:

EPS uses a Willingness-to-Pay monetarization approach, Ecological Scarcity measures the "distance to political targets" (e.g. regulatory thresholds or political goals) and Eco-indicator uses expert enquiries to set up a weighting scheme.

As the various assessment methodologies have fundamentally different starting points and require different data input, it is not known how the results relate to each other. There is also no agreement on which methodology should be considered as the 'golden standard', as every environmental assessment methodology has its own strong and weak points. Here we analyze the outcome and the underlying relationships between CED and the six environmental assessment methodologies mentioned above based on the results for production life cycles of 498 commodities. We selected CED as a benchmark, as it is the life cycle methodology with the longest scientific history, the lowest number of environmental interventions required (see Table S3) and the lowest data uncertainty involved.

Methodology

Inventory database. To allow for a meaningful method comparison, quality-controlled emission and extraction data for the production of commodities are required. The ecoinvent database v1.3 combined with up-to-date inventory data from the European Plastics Industry was used for this purpose *(19-21)*. Ecoinvent applies consistent system boundaries with coherent background processes, such as transport, electricity, heat and infrastructure, for all commodities included. The database also includes a relatively large set of environmental interventions: 148 resources and 844 emissions to soil, air, and water *(19)*. A large coverage of environmental interventions was necessary to adequately compare different types of environmental assessment methodologies, of which some assessed a wide range of emissions and resources. Table 1 provides an overview of the total number of resource extractions and emissions taken into account in the various environmental assessment methodologies included in the comparison.

We defined two inventory sets to be used in the method comparison. The first set includes the complete supply chain for the commodity life cycles considered. This is the standard selection, called "default scenario" in the following, and resembles all emissions and extractions of the production of the commodities. A second inventory set was developed to demonstrate for every assessment method the importance of fossil fuel use. In this dataset, we systematically excluded processes from the supply chain that are fuelled by fossil energy, i.e. transport, electricity and heat production processes. Fossil feed stocks, as applied in the production of organic chemicals and plastics, were excluded in this database as well. The difference between this and the first inventory dataset resembles the impact of fossil fuel use for all commodities investigated. Two ways to exclude fossil-related process data were employed. First, the underlying processes of electricity production, heat production and transport based on fossil energy carriers, included as specific processes, were removed from the database. This also included the infrastructure connected to these processes, such as the plant for electricity generation and the truck for road transport. Second, for 88 commodities the process sheets were adapted by removing fossil heat related emissions, as in these cases the emissions for heat production were directly assigned to the commodity production process (Table S1).

The inventory data for a number of commodities was available in ecoinvent on a fully aggregated level only. In these cases, the emissions and extractions could not be directly subdivided in fossil-related and non fossil-related emissions and extractions as mentioned above. For 40 commodities, mainly organic chemicals and plastics, we were able to update the ecoinvent database with inventory data from the European Plastics Industry (20). This new dataset sample enabled us to subdivide the inventory outcomes of these commodities in respectively fossil and non-fossil related interventions. The single scores for the remaining commodities with aggregated data only were excluded from further analysis but maintained as background processes in the database. Because of the inter-linkage between the process data in the inventory analysis, the aggregated data can also indirectly influence the results of other commodities. For this reason, we also excluded commodities from the statistical analysis in the case that the remaining fossil CED in the non-fossil scenario was larger than 1% compared to the fossil CED in the default scenario.

For commodities that have unit processes that hardly differ from one another, such as the production of the pesticide Glyphosate in respectively Switzerland and Europe, only the product with the largest geographical coverage was further included in the analysis. This minimizes the interdependency between the production processes. Ultimately, we performed the statistical analysis with inventory data for production life cycles of 498 commodities (Table S2).

Cumulative energy demand. The Cumulative energy demand (CED) of a product represents the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing and disposal of the raw and auxiliary materials *(8, 22-23)*. The total CED is comprised of the fossil cumulative energy demand CEDfossil in units of MJ (i.e. from hard coal, lignite, peat, natural gas, and crude oil) and the CED of nuclear, biomass, water, wind and solar energy in the life cycle. Typical upper heating values for the primary energy resources required in the CED calculations were taken from the ecoinvent database *(24)* and are listed in Table S3

Ecological footprint. The Ecological Footprint (EF) is a method for estimating the biologically productive area necessary to support human consumption patterns *(9)*. The EF deliberately includes activities that are potentially sustainable only, i.e. the use of potentially renewable functions and services of nature. Contamination of nature by persistent compounds, for instance, is excluded from the analysis *(25, 26)*. In the context of LCA, the ecological footprint is defined as the sum of direct land occupation and indirect land occupation, related to fossil and nuclear energy use, over time by human society. For the products included in the analysis, direct land occupation over time (m^2-Eq.yr) is defined by (i) built-up area, (ii) forest, (iii) cropland, (iv) pasture and (v) hydropower area. Equivalence factors (EqF), taken from Wackernagel *et al. (26)*, adjust each type of land for bioproductivity. One global 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 *(26)*. The fossil energy footprint estimates the additional biologically productive area required to sequester atmospheric fossil CO_2 emissions through afforestration *(26)*. Following Wackernagel *et al. (26)*, the nuclear energy footprint is calculated as if it were fossil energy. More details about the characterization factors used can be found in Huijbregts *et al. (10)* and Table S4

Cumulative exergy extraction. Exergy analysis assesses the quality and quantity of a resource, representing the upper limit of the portion of the resource that can be converted into work, given the ambient environmental conditions *(12)*. The cumulative exergy extraction from the natural environment (CEENE) quantifies the exergy “taken away” from natural ecosystems over the life cycle of a commodity. The CEENE method sums eight categories of resources withdrawn from the natural environment: renewable resources, fossil fuels, nuclear energy, metal ores, minerals, water resources, atmospheric resources and land resources *(11)*. Exergy data on reference flows were all taken from Dewulf *et al. (11)* and listed in Table S5

Climate footprint. The climate footprint is a measure of the total amount of carbon dioxide equivalent emissions over the production life cycle of a commodity *(27)*, using the Global Warming Potential for a 100 year time horizon (kg CO_2-Eq/kg), as a weighting factor. Global Warming Potentials were taken from Forster *et al. (28)* and can be found in Table S6.

Ecoscarcity. The EcoScarcity 97 method (ES) is based on the “distance-to-target” principle *(14)*. It compares the existing flow of a substance with the critical flow defined by political targets. The ecofactors calculated from the current and critical flows are a measure of the ecological relevance of the emission and resource use concerned and permit the calculation of a single product-specific environmental score. The types of emissions and resource use included in the ES-method can be found in Table S7.

Environmental Priority Strategy. The Environmental Priority Strategy method (EPS) addresses the environmental impacts related to the development of products *(13)*. For the weighting of environmental effects a monetary approach is chosen, based on the principle of Willingness to Pay *(13)*. The EPS-method defines overall environmental impacts in terms of environmental load units (ELU), equal to the monetary unit 'Euro'. The types of impacts included in the EPS-method are specified by Steen *(13)* and listed in Table S8

Ecoindicator. The EcoIndicator 99 method (EI) calculates damages towards a small set of comprehensive protection targets, i.e. human health, ecosystem quality and resources. These damages can be further aggregated to obtain an overall impact score for a product. Weighting factors for the three protection targets are defined by a panel procedure *(15, 29)*. The types of impacts included in the EI-method can be found in Goedkoop and Spriensma *(15)*. Fundamental uncertainties in the methodology are quantified by calculating scores for three different world perspectives (Egalitarian, Hierarchist, and Individualist). The Ecoindicator method based on the hierarchic perspective and average weighting set, recommended by Goedkoop and Spriensma *(15)* as the default method, is used here (see Table S9).

Statistical analysis. Log-linear regression analysis was performed to correlate cumulative energy demand to the impact scores of the other six methodologies included. The regression analysis was performed using the standard and non-fossil inventory set, respectively. Results are provided for all commodity groups together as well as per individual commodity group. All results were normalized to 1 kg commodity to avoid distortions in the statistical analysis due to largely different (and arbitrary) sizes of the functional units. Furthermore, for each commodity group and method we calculated the average reduction for the score of all materials included in that group after excluding fossil energy from the inventory analysis. For the non-fossil part of the scores, we derived which fraction of the remaining impact was caused by respectively (i) the emission of pollutants, (ii) the use of resources and (iii) the occupation and/or transformation of land.

Results

Figure 1 indicates that cumulative energy demand correlated well to other indicators ($R^2 = 0.61$-0.83; $P < 0.001$) in the default scenario. The uncertainty in the predictability of the regression equations of the cumulative energy demand is +/- a factor of 3 to 4 covering all commodity groups (Figure 1; 90% confidence interval), except for the EPS methodology. For the EPS-regression the uncertainty is higher (+/- a factor of 11; 90% CI) due to the relatively high EPS impact scores for particular metals, such as mercury, platinum, rhodium and palladium production. For metal production, resource scarcity of minerals has a prominent contribution to the EPS-scores. Further note that the CF-score of the plastic tetrafluoroethylene and the ES-score of liquid mercury production are relatively high compared to the CED of these commodities (respectively Figure 1C and 1D). HCFC-22 emissions in the production of tetrafluoroethylene and mercury emissions to air in the production of liquid mercury explain the relatively high indicator scores. In contrast, the indicator scores of the construction material cob are found to be relatively low compared to the CED of this commodity. This commodity has a relatively high biomass CED, while the underlying production processes cause relatively low environmental impacts.

Table S10 in the Supporting Information shows that the explained variance of the commodity-specific CED regressions is high for all commodity groups and methods included ($R^2 > 0.6$), except for agricultural products for all methods included ($R^2 = 0.36$-0.47), paper and cardboard for EPS and CF ($R^2 < 0.05$) and plastics for EF ($R^2 = 0.21$). For agricultural products, the low explained variance by CED can be explained by the fact that for this commodity group the CED is dominated by the biomass feedstock CED which is rather constant per unit of commodity produced. Environmental impacts, however can substantially differ between the various agricultural practices due to differences in land use intensity, nutrient emissions and pesticide application. For paper and cardboard, the CED is generally dominated by the use of biomass feedstock as well. The EPS scores within this commodity group are, however, mainly determined by a combination of fossil fuel related impacts and depletion of mineral resources. The CF scores for paper and cardboard production are mainly determined by CO_2 emissions caused by burning fossil fuels. As the use of biomass feedstock has no specific relation with the use of fossil fuels and mineral resources, this difference clarifies the low explained variance of the CED towards EPS and CF for paper and cardboard production. For plastics, the low explained variance by the CED for the EF can be clarified by the fact that the CED of this commodity group is mainly determined by the use of fossil feedstock, while the EF is mainly explained by CO_2 emissions caused by burning fossil fuels.

Figure 2 shows that in the non-fossil energy scenario the explained variance of the CED-based regression equations is much higher for the resource-oriented methodologies (CEENE, EF) compared to the impact-oriented methodologies (CF, EPS, EI and ES), i.e. $R^2 = 0.73\text{-}0.84$ versus $R^2 = 0.23\text{-}0.47$. These regression results indicate that non-fossil CED has relatively little connection to non-fossil related environmental impacts with regard to the methods CF, EPS, ES and EI, while non-fossil exergy extraction and non-fossil ecological footprints are more closely related to the non-fossil CED. This finding implies that the life cycle use of fossil energy is an important explaining variable for the correlation between CED and the impact-related methodologies CF, EPS, EI and ES.

Figure 3 indicates that within all methodologies assessed fossil energy use is dominant (> 50% contribution) for the majority of the commodity groups included, with a small number of exceptions. For agricultural products, the use of fossil resources is classified as less relevant than other interventions, according to the majority of methods applied. This is primarily due to nutrient emissions for ES, emissions of non-fossil related greenhouse gases in the case of CF, i.e. methane (CH_4) and nitrous oxide (N_2O), and land use for CEENE, EF, and EI. A similar picture is seen for paper and cardboard, though the importance of fossil resources tends to be higher than for agricultural products. Furthermore, for the impact-oriented methodologies (ES, EPS, EI), fossil-related impacts make up less than 50% of the weighted impact for metals and inorganic chemicals, except for the EI evaluation of inorganic chemicals. Figure 3 also indicates that the relative importance of the remaining non-fossil impacts between the stressor categories pollution, resource use and land use widely differs between the methodologies. For instance, in the Ecoscarcity methodology pollution of nutrients and metals is weighted rather strongly. On the contrary, according to Ecological Footprint, Cumulative Exergy Extraction and Ecoindicator, land use is the most important non-fossil stressor.

Discussion

In the present paper, cumulative energy demand accounting was compared with six other single-score environmental assessment methodologies. A coherent comparison of the methodologies has been assured by applying a consistent life cycle inventory dataset sample consisting of 498 materials. Although we applied state-of-the-art life cycle inventory and environmental assessment methodologies in our analysis, there are inherent uncertainties connected to the information employed. First, cradle-to-gate interventions in commodity production are inventoried, excluding emissions during the use phase and disposal phase of the commodity life cycles. Emissions during commodity application and disposal may, however, be relevant in some cases, particularly for construction materials *(30)*. Second, lacking information on toxic emissions and corresponding impact factors is a common problem in LCA studies *(31)*. Trace emissions may not always be known for all production facilities and not all toxic emissions have an impact factor within the impact-oriented assessment methodologies employed. Another shortcoming in the current study is that we evaluated the usefulness of CED with the environmental impacts assessed by other single-score methodologies, but not with observed environmental impact. This implies that in the current work, impacts that are generally missing in LCA have not been tested with regard to the CED either. For instance, water scarcity, thermal pollution and indoor exposure to chemicals are neglected by the single-score methodologies included in the comparison *(32, 33)*. Whether these impacts have a good correlation with the CED remains to be tested. Finally, our analysis is based on a process-based life cycle inventory database that contains potential errors associated with the truncation towards higher-order upstream data requirements. Combining process-based data with input-output-data in a hybrid LCA environment has been suggested to obtain accurate and complete results *(e.g. 34, 35)*. Whether the correlation structure between CED and other assessment methodologies, as found in the current study, will change by increasing the completeness of the current dataset with input-output data, remains to be tested.

With regard to the portfolio of environmental assessment methodologies, we were not able to include all single-score methodologies available. For instance, indicators focusing on total mass flows *(36)* and emergy flows *(37)* were not included in this analysis due to the lack of compatible inventory information. Further broadening the scope towards the inclusion of socio-economic indicators may also give new insights *(38)*. Including such other methodologies in the comparison is possible and recommendable, but requires the inclusion of extra physical and financial inventory flows in the database employed here.

The high correlation between the various methodologies included and cumulative energy demand reveals that, in spite of the fundamentally different philosophies and complexity of the assessment methodologies compared, they produce a comparable ranking of commodity production impacts. The results of the regression analysis clearly demonstrates a tendency that cumulative energy demand as well as other simplified indicators are often representative indicators of overall environmental impact, as based on best available life cycle inventory and impact information. The uncertainty range reported for the regression equations is well within the uncertainty estimates provided for the more complex impact assessment methods, such as the

Ecoindicator *(15)*. Comparisons between specific environmental impacts and energy *(39)*, exergy versus energy *(40)*, and Ecoindicator versus ecological footprint *(10)* also point into this direction. It appears that fossil-energy related impacts are weighted strongly by all seven methodologies for the majority of the commodities included, although the motivation for doing so varied between the methods used, such as resource scarcity versus greenhouse gas emissions. This finding confirms the results of other studies, suggesting that the burning of fossil fuels is a major contributor to various environmental problems *(41-43)*. It also stresses that increasing energy efficiency and switching to renewable energy sources should be a top priority in environmental policy.

There are, however, a number of exceptions. First, for agricultural products non-fossil energy related impacts dominate in six out of the seven methodologies included, but for different reasons. For CED it is the biomass energy stored in the agricultural products itself that dominates, while in the EF it is the requirement of bioproductive land, in CEENE the amount of exergy that nature is deprived of by land use, and Ecoindicator the loss of biodiversity by the use of agricultural land. The Ecoscarcity methodology showed high importance of nitrogen and phosphorus emissions for agricultural products, while for the climate footprint N_2O emissions from the use of fertilizers are important contributors for agricultural products *(44)*. Second, the resource-oriented indicators (CED, CEENE, and EF) indicate that renewable energy demand and land use are typically most relevant for paper and cardboard production. Third, with respect to the impact-oriented indicators (ES, EPS, and EI), non-fossil environmental impacts are important in the case of metals and inorganic chemicals. Mineral resource depletion, toxicity by metal emissions, and fine particulate matter impacts were considered important by the Ecoindicator for these product groups. In the Ecoscarcity methodology, a relatively high impact of metal emissions has been found, while the Environmental Priority System assigned high importance to the depletion of mineral resources for these product groups. The differences in prioritizing the importance of underlying drivers of non-fossil environmental interventions imply that recommendations for impact reductions within these product categories may indeed depend on the impact assessment methodology employed.

Following best available life cycle inventory and impact information, the overall evidence suggests that for the majority materials included in the present study, the environmental assessment methodologies provide similar results and that the use of fossil energy is a major driver of environment impacts. In this context, cumulative energy demand, the methodology with the lowest data requirements, can serve as a screening indicator for environmental performance.

This information is particularly relevant in LCA studies focusing on early product development for which generally only little information is available on environmental interventions.

Supporting Information Available

Additional information on commodities which are specifically adapted in the 'without fossil energy scenario', commodities included in the method comparison, environmental interventions and related impact factors for all the methodologies assessed, and regression results for the individual commodity groups applying the default life cycle inventory selection. This material is available free of charge via the Internet at http://pubs.acs.org.

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Table 1. Overview of the environmental assessment methods analyzed in this paper and number of resource extractions and emissions assessed by the various methods from the elementary flows reported in the ecoinvent database (v1.3).

Method	**Unit**	**Key characteristic**	**Number of resource extractions**	**Number of emissions**	**Total number of interventions**
Cumulative Energy Demand (CED)	MJ-eq	Life cycle total energy use	11	0	11
Ecological Footprint (EF)	m^2.yr	Life cycle area use	23	1	24
Cumulative Exergy Extraction in the Natural Environment (CEENE)	MJ_{ex}-eq	Life cycle total exergy use	112	0	112
Climate Footprint (CF)	CO2-eq.	Life cycle greenhouse gas emissions	0	20	20
Ecological Scarcity (ES)	UBP	“Distance-to-political target” weighing; resource and emission oriented	13	156	169
Environmental Priority Strategy (EPS)	ELU	Monetarization of life cycle impacts; damage oriented	67	60	127
Eco-Indicator (EI)	Ecopoints	Panel weighing of life cycle impacts; damage oriented.	94	161	255

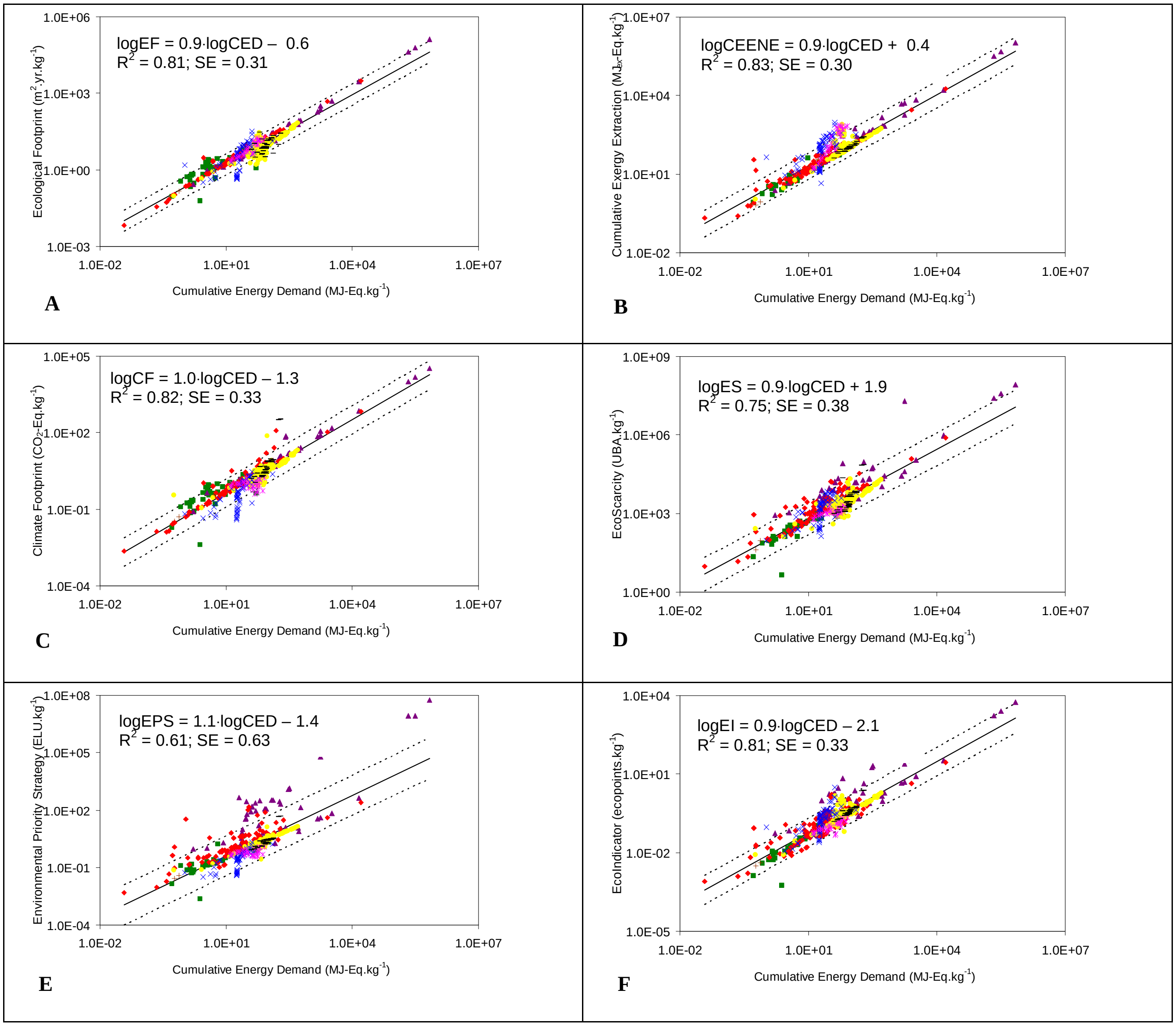

Figure 1: Linear regression plots with 90-percentile confidence intervals (dotted lines) for the default scenario, based on 65 agricultural products (x); 42 construction materials (■),11 glass materials (+); 121 inorganic chemicals (♦); 146 organic chemicals (●); 33 plastics (-); 51 metals (▲); and 29 paper and cardboard materials (*) for the Cumulative Energy Demand and respectively Ecological Footprint (A), Cumulative Extraction of Exergy from the Natural environment (B), Climate Footprint (C), EcoScarcity (D), Environmental Priority Strategy (E), and EcoIndicator (F).

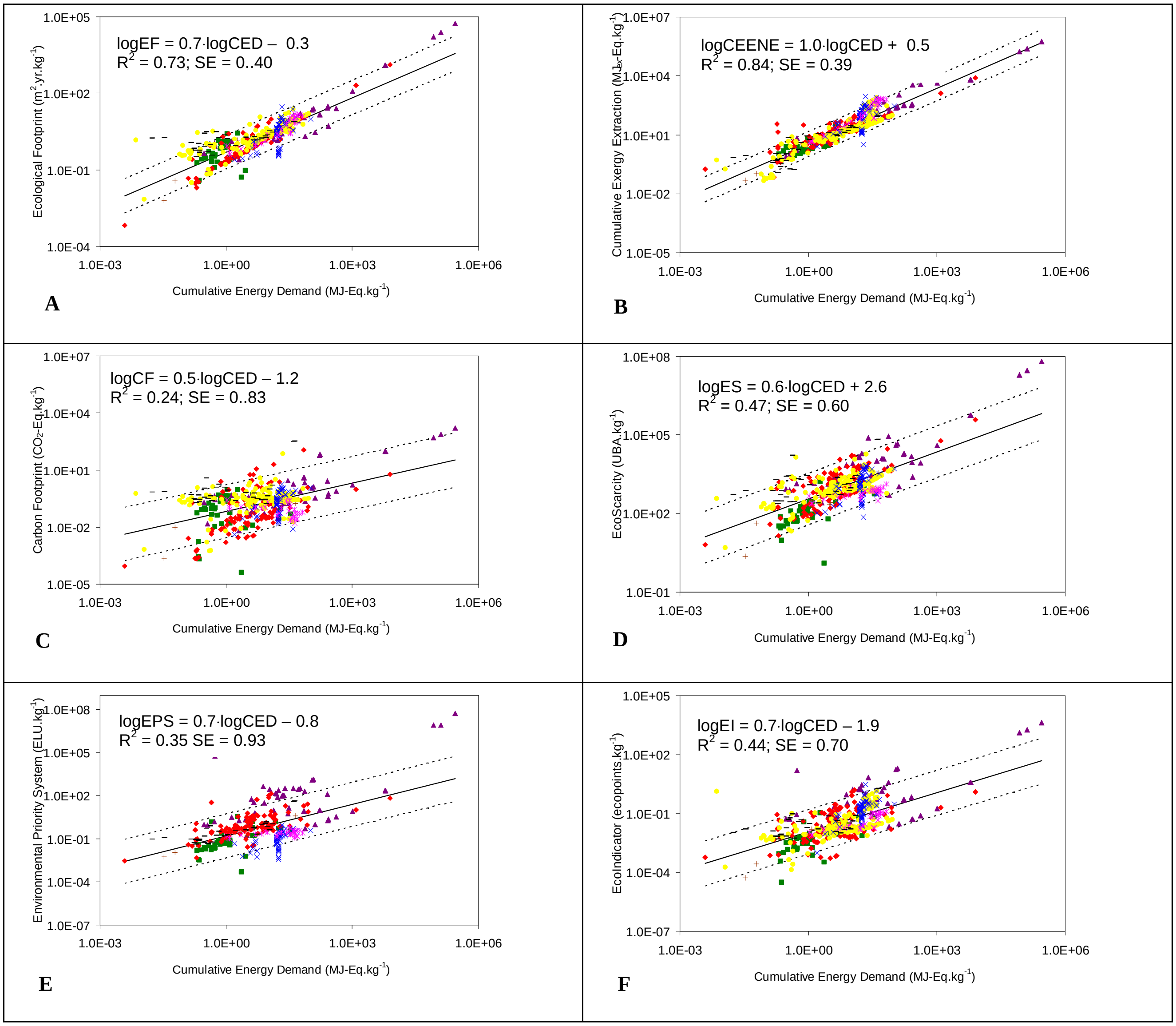

Figure 2: Linear regression plots with 90-percentile confidence intervals (dotted lines) for the non-fossil energy scenario, based on 65 agricultural products (x); 42 construction materials (■),11 glass materials (+); 121 inorganic chemicals (♦); 146 organic chemicals (●); 33 plastics (-); 51 metals (▲); and 29 paper and cardboard materials (*) for the Cumulative Energy Demand and respectively Ecological Footprint (A), Cumulative Extraction of Exergy from the Natural environment (B), Climate Footprint (C), EcoScarcity (D), Environmental Priority Strategy (E), and EcoIndicator (F).

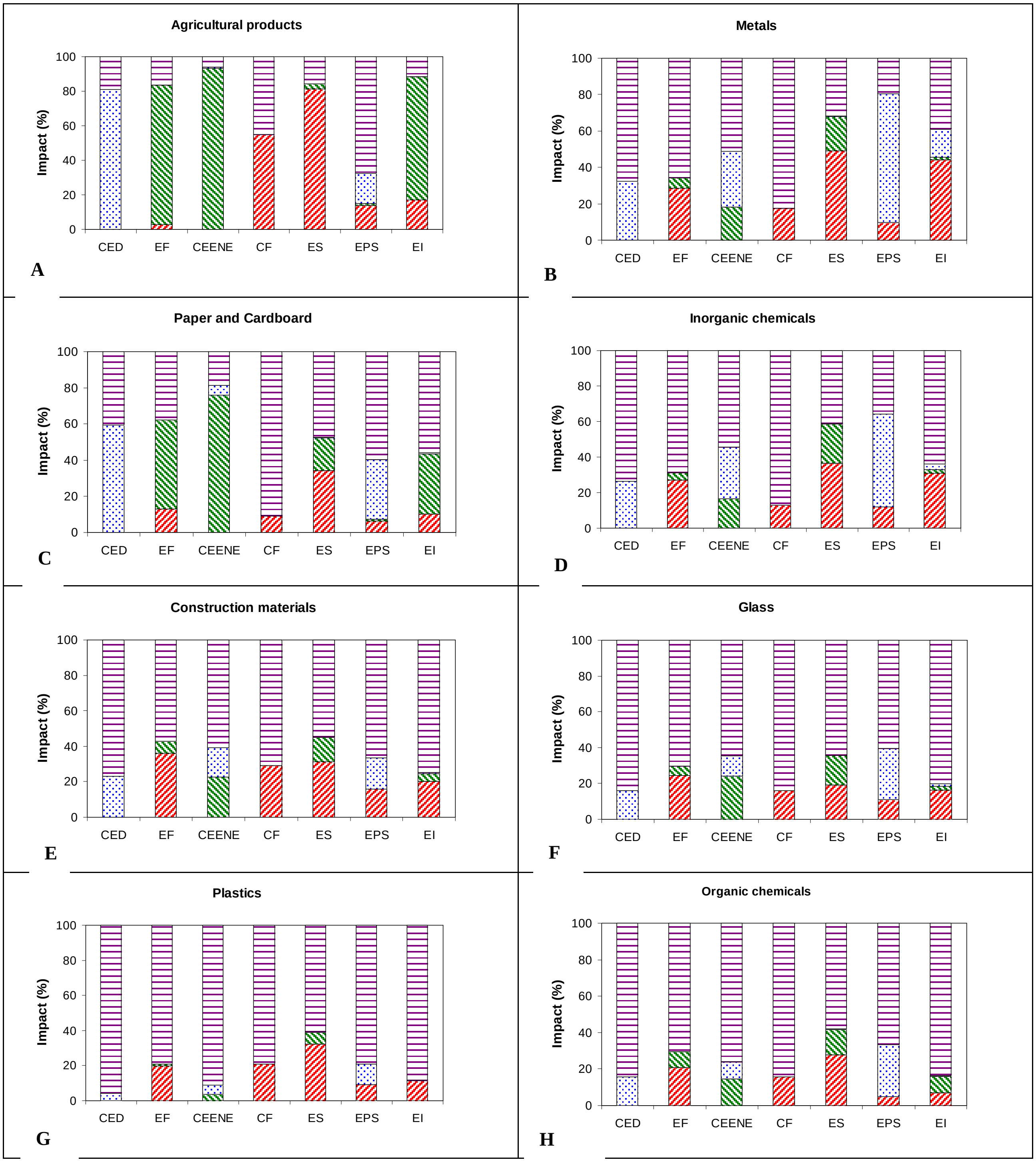

Figure 3: Fossil (▤) and non-fossil contribution to the total impact. The non-fossil impact is subdivided into three categories: pollution (▨), resource use (░), and land use (▧). The commodity groups included are agricultural products (A, n = 65); metals (B, n = 51); paper and cardboard (C, n = 29); inorganic chemicals (D, n = 124); construction materials (E, n = 39); glass (F, n = 11); plastics (G, n = 33); and organic chemicals (H, n = 146). CED = Cumulative Energy Demand; EF = Ecological Footprint; CEENE = Cumulative Exergy Extraction from the Natural Environment; CF = Climate Footprint; ES = Environmental Scarcity method; EPS = Environmental Priority System; EI = Ecoindicator.