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LIFE CYCLE IMPACT ASSESSMENT

Normalization in EDIP97 and EDIP2003: updated European inventory for 2004 and guidance towards a consistent use in practice

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Abstract
Purpose When performing a life cycle assessment (LCA), the LCA practitioner faces the need to express the characterized results in a form suitable for the final interpretation. This can be done using normalization against some common reference impact—the normalization references—which require regular updates. The study presents updated sets of normalization inventories, normalization references for the EDIP97/EDIP2003 methodology and guidance on their consistent use in practice.
Materials and methods The base year of the inventory is 2004; the geographical scope for the non-global impacts is limited to Europe. The emission inventory was collected from different publicly available databases and monitoring bodies. Where necessary, gaps were filled using extrapolations. A new approach for inventorizing specific groups of substances—non-methane volatile organic compounds and pesticides—was also developed. The resulting inventory was combined with the most updated sets of characterization factors for each impact category in the EDIP methodologies.
Results and discussion Normalization references are provided for global and non-global impact categories for the year 2004, and causes of variations compared to previous versions are identified. For the non-toxic impact categories, they mainly reflect demographic evolution or change in emission intensities. For the toxic impact categories, they are strongly dependent on improvements in the characterization models as well as on the inventory analysis. Differentiation of substance groups into individual substance emissions is an important source, which leads to identification of inconsistencies in the current practice and guidance to ensure compatibility between LCI and LCIA. Uncertainties are not quantified but are mainly expected to lie in the toxic substance inventories, which are known not to encompass all potentially harmful chemicals released in Europe, e.g. omitting some toxic metals.
Conclusions The present study provides the most updated set of publicly available normalization references for the EDIP methodology and emission inventories for Europe that may also serve for the calculation of normalization references for other impact categories. It is believed to be the best estimate available for Europe and is thus recommended for use along with the guidance provided in this study.

Keywords EDIP · European inventory · LCI · LCIA · Life cycle inventory · Normalisation · Normalisation reference

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1 Introduction

With its translation of the product system's environmental flows from the life cycle inventory phase (LCI) into scores that represent their impacts on environment, life cycle impact assessment (LCIA) is essential for the interpretation of the results in relation to the questions posed in the goal definition (Finnveden et al. 2009). Being an optional step in LCIA according to ISO14044:2006 (ISO 2006), normalization of the characterized results gives insight in the relative magnitude of the characterized impacts by relating

them to a common reference situation and expressing them in a unit common for all impact categories. The reference situation is typically the background load from society's total activities, either representing a region (e.g. world or EU25+3 in ReCiPe or CML2001; Sleeswijk et al. 2008; Guinée et al. 2002) or expressed per capita in a given region (e.g. in EDIP or IMPACT2002+; Wenzel et al. 1997; Stranddorf et al. 2005; Lautier et al. 2010). The normalization references are calculated by characterizing the emission inventory for the reference situation in the same way as the inventory for the product system is characterized, and the normalization is performed by dividing the characterized results for the product system by the normalization references. After normalization all impact category results are expressed in the same unit, e.g. in the EDIP case the person equivalent (PE), the number of average annual per capita impacts caused by the product system.

The calculation of the normalization references requires an inventory analysis for the background load, which in itself can be as extensive as a product LCA. Typically, the background load is quantified for a reference year, which should be the same for all impact categories. For a given region the background load may evolve significantly over the years, e.g. because of regulations of chemicals or an increase in pollutant releases. Together with the continuous improvements in the characterization models, this requires that updates of normalization references are performed regularly in order for the LCA practitioner to base his/her interpretation on consistent and reliable results.

While the normalization inventories (see ESM 1) can also be used for calculating normalization references for other LCIA methodologies, the main purpose of this study is to provide an updated emission inventory in support of calculating new normalization references for the Environmental Design of Industrial Products (EDIP) methodology, which is a Danish LCA methodology originally developed in the 90s (Wenzel et al. 1997; Hauschild and Wenzel 1998) and revised in 2003 (Hauschild and Potting 2005). Furthermore the purpose of the paper is to discuss the causes of changes in the normalization references and the main sources of uncertainty in the results.

2 Materials and methods

2.1 LCIA methodologies

The assessment of the impact categories is performed with both the original EDIP97 (Wenzel et al. 1997) and the EDIP2003 methodologies (Hauschild and Potting 2005; Potting and Hauschild 2005), using the most updated sets of characterization factors (LCA Center 2010). Compared to the EDIP97 methodology, the EDIP2003 impact assessment includes a larger part of the impact pathway for the non-global impact categories and supports both a site-generic and a site-dependent assessment on a per-country level within Europe. Emphasis in EDIP2003 is put on including the properties of the emission sources and the receiving environment, which vary significantly within the region. Typically impacts occurring in local areas are partly caused by emissions outside those areas (e.g. dispersion of airborne emissions), hence the need to adopt consistent boundaries; EDIP2003 considers the whole continent of Europe (Potting and Hauschild 2005).

In parallel, the traditional assessment of resource depletion of EDIP97 was also adapted to enable the aggregation of the results—commonly obtained per resource—into one single score (similarly to any other impact category). Details of this adaptation, which requires a new definition of characterization factors, are provided in ESM 2. The consequent normalization reference of this new approach was calculated using existing data for 2004 from the LCA Center (2010).

2.2 Inventory

The inventory study builds on previous works by Potting and Hauschild (2005) and Stranddorf et al. (2005) to establish a comprehensive inventory focusing on emissions that occurred within Europe in 2004; 38 European countries, representing a population of 719 million inhabitants out of the 729 million reported by UNSD (2010) for Europe, were considered. Data quality and availability vary significantly between substances or groups of substances. Data collection for non-toxic impact categories benefits from the fact that the impacts are caused by emissions of few substances, which have been monitored and reported for several years, at least in Europe. Consequently, consistent databases are publicly available through reliable organizations such as the EMEP Centre or EUROSTAT (see ESM 2).

In contrast, toxic impacts may be caused by thousands of substances for which no well-proven systems of monitoring and reporting exist. This issue has previously been discussed (Finnveden et al. 2009; Sleeswijk et al. 2008), and efforts are still on-going to mitigate it. An EU regulation entered into force in 2006 with the aim to establish a publicly available database of emissions of potentially hazardous pollutants released to air, soil and water from industrial facilities in Europe—the European Pollutant Release and Transfer Register, E-PRTR (http://prtr.ec.europa.eu/). Cross-checking with reports from authoritative organizations such as OSPAR or the EMEP Centre revealed, however, that the database is not yet sufficiently comprehensive to serve the purpose of this study (data not shown). To fill the gaps in the emission inventory for the toxic impacts, extrapolations thus had to be performed; details can be found in ESM 2.

Typically, non-methane volatile organic compounds (NMVOCs) are inventorized as a group, and most impact assessment methods provide one or a few generic characterization factors for the human toxicity or photochemical ozone formation impact of the group as such (e.g. EDIP97, CML). While being of minor importance to the photochemical ozone formation, the differentiation of NMVOCs into single substances is highly relevant for the assessment of their human toxicity impact—see Section 4.3. This compelled us to differentiate emissions of NMVOCs into the most important individual substances in this study. An additional benefit of differentiating emissions of NMVOCs lies in the minimization of the risk of double counting in cases where some substances of central interest, such as benzene, are reported as individual emissions alongside the total NMVOC emissions.

For the inventory analysis of European pesticide emissions, the agricultural soil was considered to be part of the technosphere. This means that only those fractions of the applied active ingredients that cross the boundaries of the field and reach the biosphere were included in the inventory, i.e. depositions from the air due to volatilization and wind drift from the field as well as leaching to groundwater and run-off to freshwater ecosystems. Based on estimates using the PestLCI model (Birkved and Hauschild 2006), average fractions of 5% and 0.1% were assumed for modelling direct airborne emissions and waterborne emissions from the field, respectively. Also for the pesticide use, a specification of the applied mixture into active ingredients was performed, using extrapolations from English and Danish pesticide application statistics combined with EUROSTAT reports (see details in ESM 2).

3 Results

The inventory for European normalization references for emission year 2004 is shown in ESM 1 in aggregated form for the whole of Europe. The EDIP97 and EDIP2003 normalization references are provided in Table 1. Where applicable, the old normalization references are also shown in Table 1 for comparison. The normalization references for individual European countries can be viewed in ESM 1.

4 Causes of variations in normalization references

When updating normalization references, changes can result from several causes: (1) change in the substance emissions from the old to the new reference year, (2) change in the size of the population within the reference region, (3) improvements in the characterization models and/or in their coverage of substances with characterization factors and (4) refinement in the inventory modelling such as the extension of emission inventories or specification of groups of substances.

While the normalization references for non-toxic impact categories are typically affected by the first two causes—see Section 4.1, changes in the normalization references for the toxicity-related impact categories are mainly driven by the last two causes—see Sections 4.2 and 4.3.

4.1 Influence of changes in emission and population

Contribution analyses have been performed to identify the dominating contributors for each impact category (Table 2); normalization references for the non-toxic impact categories are typically dominated by a few substances, which have been well monitored for several years (see data sources in ESM 2). Therefore, the inventories can be assumed to be relatively complete. The changes observed in Table 1 between the old set and the new set of normalization references for the impact categories global warming, ozone depletion, acidification, nutrient enrichment/eutrophication and photochemical ozone formation thus tend to reflect actual changes of emissions and/or demography.

The introduction of new potentially harmful chemicals on the market or the regulation or phasing out of others are possible causes of either the increase or decrease in the normalization references. An example is provided by ozone depletion with its normalization reference dropping by a factor of 5 between 1994 and 2004 (cf. Table 1), and by a factor of 15, when comparing with more recent figures from 2008 (not shown here).

At the same time, changes in population figures within the reference region can also affect the normalization references, when they are expressed on an annual per capita basis as is the case in EDIP. In the case of an increasing population, this factor tends to lower the normalization reference. Taking the impact category “global warming”, between 1994 and 2004, emissions of greenhouse gases increased by 1.6%, while the demographic growth was much higher, i.e. 15%, leading to an overall decrease of the normalization reference, from 8.7 to 7.7 t-CO_2eq/capita/year (data for 1994 are based on Stranddorf et al. 2005).

4.2 Influence of characterization models

For the toxic impact categories, it is updates of the characterization models as well as changes in the substance coverage that together with inventory choices discussed in Section 4.3 constitute the main causes for the changes observed in the normalization references in Table 1. This is visible from the contribution analyses in Table 3. Taking human toxicity via air (HTA) from both EDIP97 and

Table 1 Normalization references for the 22 EDIP impact categories (emission year 2004)

Impact categories	Symbols	Method	Geographical scope	Norm. ref. (NR)	Old NR (1994)	Unit
Global warming	GW	EDIP97/2003	World	7.73E+03	8.70E+03	kg CO_2eq/person/year
Ozone depletion	OD	EDIP97/2003	World	2.05E−02	1.03E−01	kg CFC11eq/person/year
Acidification	AC97	EDIP97	Europe	5.48E+01	7.40E+01	kg SO_2eq/person/year
Nutrient enrichment	NE	EDIP97	Europe	4.59E+01	1.19E+02	kg NO_3^-eq/person/year
–N-equivalents	–	EDIP97	Europe	8.32E+00	2.40E+01	kg Neq/person/year
–P-equivalents	–	EDIP97	Europe	2.82E−01	4.00E−01	kg Peq/person/year
Photochemical ozone formation (low-NO_X)	PO	EDIP97	Europe	1.58E+01	2.50E+01	kg C_2H_4eq/person/year
Photochemical ozone formation (high-NO_X)	PO	EDIP97	Europe	1.34E+01	2.50E+01	kg C_2H_4eq/person/year
Acidification	AC03	EDIP2003	Europe	3.93E+02	2.20E+03	m²UES/person/year
Terrestrial eutrophication	TE	EDIP2003	Europe	1.37E+03	2.10E+03	m²UES/person/year
Aquatic eutrophication	AE	EDIP2003	Europe	4.59E+01	5.80E+01	kg NO_3^-eq/person/year
–N-equivalents	–	EDIP2003	Europe	8.32E+00	1.20E+01	kg Neq/person/year
–P-equivalents	–	EDIP2003	Europe	2.82E−01	4.10E−01	kg Peq/person/year
Photochemical ozone formation–impacts on vegetation	PO_{veg}	EDIP2003	Europe	5.97E+04	1.43E+05	m² ppm hr/person/year
Photochemical ozone formation–impacts on human health	PO_{hum}	EDIP2003	Europe	2.84E+00	1.01E+01	m² ppm hr/person/year
Chronic ecotoxicity in aquatic ecosystems (ETWC)	ETWC-97	EDIP97	Europe	2.96E+06	3.52E+05	m^3 water/person/year
Acute ecotoxicity in aquatic ecosystems (ETWA)	ETWA-97	EDIP97	Europe	5.25E+05	2.91E+04	m^3 water/person/year
Chronic ecotoxicity in terrestrial ecosystems (ETSC)	ETSC-97	EDIP97	Europe	2.22E+05	9.64E+05	m^3 soil/person/year
Chronic ecotoxicity in aquatic ecosystems (ETWC)	ETWC-03	EDIP2003	Europe	3.66E+06	–	m^3 water/person/year
Acute ecotoxicity in aquatic ecosystems (ETWA)	ETWA-03	EDIP2003	Europe	6.65E+05	–	m^3 water/person/year
Chronic ecotoxicity in terrestrial ecosystems (ETSC)	ETSC-03	EDIP2003	Europe	7.32E+04	–	m^3 soil/person/year
Human toxicity, via air	HTA-97	EDIP97	Europe	3.58E+10	3.06E+09	m^3 air/person/year
Human toxicity, via air	HTA-03	EDIP2003	Europe	4.73E+08	1.71E+08	$year^{-1}$
Human toxicity, via water	HTW-97	EDIP97	Europe	4.72E+04	5.22E+04	m^3 water/person/year
Human toxicity, via soil	HTS-97	EDIP97	Europe	8.06E+03	1.27E+02	m^3 soil/person/year
Resource depletion	RD	EDIP97	World	8.17E−01	–	PR/person/year

EDIP2003 assessments as an example, it can be seen that whereas formaldehyde and butadiene appear to dominate the impact potential when using EDIP97 (31% and 19%, respectively), benzene is by far the largest contributor to the impact in the EDIP2003 assessment (55%) where exposure is more realistically represented.

The coverage of substances is not responsible for the differences between the old and the new normalization references in Table 1 since the CFs are available for the same chemicals in both calculations. However, the methodological advances, represented here by the introduction of a more geographically explicit exposure modelling, tend to modify the distribution of the impact potentials significantly as visible from Table 3. Although arising from a specific improvement within the same methodology, these discrepancies demonstrate the well-known issue that the use of different characterization methods for an impact category can lead to large inconsistencies in the obtained results (Dreyer et al. 2003; Pant et al. 2004).

4.3 Influence of inventory modelling

In parallel to continuous improvements in characterization models, the development of inventory analysis can also be a significant source of changes in normalization references as they aim to increase accuracy and representativeness of the estimated impact scores. The inventory modelling related to NMVOCs and pesticides—see Section 2.2—is discussed below with respect to influences on the normalization references.

Table 2 Main contributors to the normalization references for the EDIP non-toxic impact categories

Substances	Emission compartment	GW (%)	OD (%)	AC97 (%)	NE (%)	PO (%)	AC03 (%)	TE (%)	AE (%)	PO_{veg} (%)	PO_{hum} (%)
Carbon dioxide	Air	**67**	–	–	–	–	–	–	–	–	–
Carbon monoxide	Air	3	–	–	–	*20*	–	–	–	5	8
Total NMVOCs	Air	–	–	–	–	**77**	–	–	–	*24*	**36**
Nitrous oxide	Air	6	–	–	–	–	–	–	–	–	–
Methane	Air	*18*	–	–	–	2	–	–	–	–	1
Total ODS	Air	4	–	–	–	–	–	–	–	–	–
CFCs	Air	–	**53**	–	–	–	–	–	–	–	–
HCFCs	Air	–	*24*	–	–	–	–	–	–	–	–
Methyl bromide	Air	–	*11*	–	–	–	–	–	–	–	–
Carbon tetrachloride	Air	–	*10*	–	–	–	–	–	–	–	–
Halons	Air	–	1	–	–	–	–	–	–	–	–
Nitrogen oxides (NO_X)	Air	–	–	**37**	–	–	*22*	**42**	–	**70**	**55**
Ammonia	Air	–	–	**35**	–	–	*28*	**58**	–	–	–
Sulphur oxides (SO_X)	Air	–	–	*28*	–	–	**50**	–	–	–	–
Total-N	Water	–	–	–	**84**	–	–	–	**80**	–	–
Total-P	Water	–	–	–	*16*	–	–	–	*20*	–	–
TOTAL		99	100	100	100	100	100	100	100	99	100

The cut-off of the substance contribution reported here is 1%; contributions 10–30% are marked in italics; contributions above 30% are marked in bold

GW global warming, *OD* ozone depletion, *AC97* acidification (EDIP97), *NE* nutrient enrichment (EDIP97), *PO* photochemical ozone formation (EDIP97), *AC03* acidification (EDIP 2003), *TE* terrestrial eutrophication (EDIP 2003), *AE* aquatic eutrophication (EDIP 2003), PO_{veg} photochemical ozone formation impacts on vegetation (EDIP 2003), PO_{veg} photochemical ozone formation impacts on human health (EDIP 2003), *ODS* ozone-depleting substances

4.3.1 Issues related to NMVOC and pesticide inventories

In their update of the normalization references for EDIP toxic impacts, Stranddorf et al. (2005) demonstrated that the specification of individual substances unveils underestimations caused by the widely used simplifying approach to characterize groups of substances, e.g. NMVOCs, as a whole. The specifications of NMVOCs in the current inventory (see details in ESM 2) tend to confirm those assertions: NMVOCs turn out to govern the human toxic impacts, via air and via soil, inducing the EDIP97 normalization references to increase by factors of ca. 12 and 63, respectively, compared to their previous values (see Table 1).

Similar results occur from a more substance-specific treatment of the emissions of pesticides, but the differences observed in Table 1 between the EDIP97 normalization references calculated by Stranddorf et al. (2005) and those calculated in this study are not only explained by the specification into active ingredients but also by the change in emission modelling—see Section 2.2. In this study, the pesticides are modelled as direct emissions from the field to either air or water. As a result, the contribution to the terrestrial ecotoxic potential becomes much lower than what is typically obtained when the applied quantities of pesticides are modelled as emissions to agricultural soil (e.g. in Stranddorf et al. 2005).

Despite the specification of the NMVOCs, which tends to increase the impact potential (cf. above), the overall result for the EDIP97 normalization reference for terrestrial ecotoxicity is a drop by a factor of 4.3. Conversely, the impact potentials for aquatic ecotoxicity increase due to the inclusion of direct emissions of pesticides to the freshwater environment, for chronic effects by a factor of around 8.4.

As a consequence, using the old set of normalization references in combination with the substance-specific treatment of NMVOCs and pesticides and the consideration of agricultural fields as a part of the technosphere could introduce a considerable bias in the obtained results. For the ecotoxic impact categories presented above, the discrepancy between the two normalized impact scores could be as large as a factor of 36 compared to the use of the updated set of normalization references (Fig. 1). This could lead to improper recommendations based on the results of the study. The need to keep regular updates in phase with the development of the LCA methodology itself, both at the characterization and at the inventory levels, is strongly supported by these findings.

4.3.2 Guidance for improving inventories of NMVOCs and pesticides

As it was found that the differentiation of substance groups into individual substances can have a significant influence on

Table 3 Main contributors to the normalization references for the EDIP 97 and 2003 toxic impact categories

Substances	Emission compartment	ETWC-97 (%)	ETWA-97 (%)	ETSC-97 (%)	ETWC-03 (%)	ETWA-03 (%)	ETSC-03 (%)	HTA-97 (%)	HTA-03 (%)	HTW-97 (%)	HTS-97 (%)
1,3-Butadiene	Air	–	–	–	–	–	–	*19*	8	–	–
Acrolein	Air	–	–	–	–	–	–	3	–	–	–
Benzene	Air	–	–	–	–	–	–	*14*	**55**	2	**88**
Benz(a)pyrene	Fresh water	4	2	–	4	2	–	–	–	–	–
Butanol	Air	–	–	–	–	–	–	*12*	5	–	–
Benzene	Marine water	4	2	–	4	2	–	–	–	–	–
Chlorpyrifos	Fresh water	**53**	8	–	**56**	9	–	–	–	–	–
Copper	Fresh water	8	4	–	6	3	–	–	–	–	–
Cypermethrin	Fresh water	3	–	–	4	–	–	–	–	–	–
Dioxins	Air	–	–	–	–	–	–	–	–	3	–
Ethene	Air	–	–	5	–	–	5	–	–	–	–
Formaldehyde	Air	–	–	**82**	–	–	**82**	**31**	*13*	–	–
Hexanes	Air	2	–	–	2	–	–	–	–	–	–
Iron	Fresh water	5	3	–	4	2	–	–	–	–	–
Lead	Fresh water	–	–	–	–	–	–	–	–	2	–
Lead	Air	–	–	–	–	–	–	–	6	–	–
Mercury	Agricultural soil	–	–	–	–	–	–	–	–	3	–
Mercury	Air	–	–	–	–	–	–	–	–	**43**	–
Mercury	Fresh water	–	–	–	–	–	–	–	–	**38**	–
Parathion-methyl	Fresh water	*14*	**77**	–	*14*	**79**	–	–	–	–	–
Zinc	Fresh water	2	–	–	2	–	–	–	–	3	–
VOC, unspecified [c]	Air	–	–	9	–	–	9	*16*	7	–	7
TOTAL		95	96	96	96	97	96	95	94	94	95

The cut-off of substance contribution reported here is 2%; contributions 10–30% are marked in italics; contributions above 30% are marked in bold

ETWC ecotoxicity, water chronic (EDIP97 or 2003); *ETWA* ecotoxicity, water acute (EDIP97 or 2003); *ETSC* ecotoxicity, soil chronic (EDIP97 or 2003); *HTA* human toxicity via air (EDIP97 or 2003); *HTW* human toxicity via water (EDIP97); *HTS* human toxicity via soil (EDIP97); *VOC* volatile organic compounds

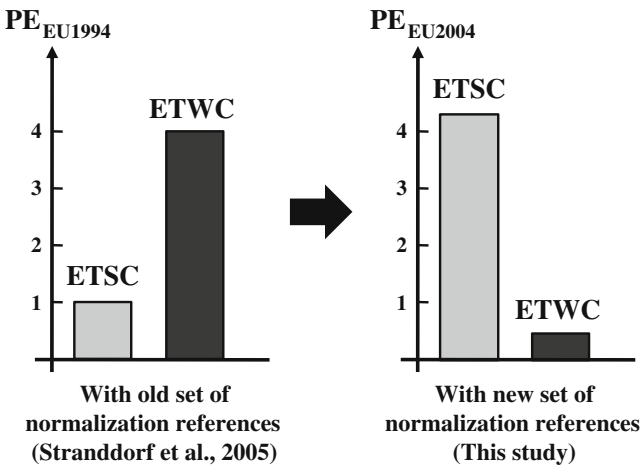

Fig. 1 Example of normalized results obtained when using an old set and a new set of normalization references for EDIP97 to assess the same product system. *ETSC* ecotoxicity, soil chronic; *ETWC* ecotoxicity, water chronic; PE_{EU2004} Person Equivalent based on Europe 2004

the resulting normalization references, a default approach to apply generic characterization factors by grouped emission sources was developed for the situation where the data needed to support a substance-specific inventory are not available to the LCA practitioner (for physical reasons, e.g. measurements, or for legal reasons, e.g. confidentiality), or uncertainties associated with the specifications are too high. Following the approach presented in Hauschild and Wenzel (1998), NMVOC characterization factors, differentiated according to their emission source and sector and applicable to Europe, were calculated for the EDIP toxic impact categories for 80 different source types (see ESM 1). No default factors were calculated for pesticides since the emissions have a very strong dependency on local conditions of application, e.g. the applied agricultural practice.

Another issue highlighted in this study lies in the setting of boundaries between the technosphere and the biosphere, which is often improperly done in the current practice of pesticide emission modelling. Today, several databases and LCA software still inventorize the full applied quantity of

pesticides as direct emissions to agricultural soil, whereas the latter shall be part of the technosphere (see Section 2.2). The 68 pesticides included in the Ecoinvent database are thus considered as emissions to agricultural soil, taking 100% of the applied active ingredients and letting the characterization model deal with their fate (Nemecek and Kägi 2007).

However, most impact assessment models are not able to distinguish the fates of pesticides from those of other compounds, which are unintentionally released (e.g. metals in sewage sludge applied to agriculture). Generally, a large fraction of pesticides is taken up by plants or degraded in the field or on the leaves, and this fraction does not affect the environment outside the field. A sensitivity analysis was performed on the EDIP97 normalization references in order to evaluate the divergence arising from using an improper pesticide inventory. The inventory described in this study (see Section 2.2) was used, but pesticide emissions to air (5%) and water (0.1%) were substituted by 100% emissions to soil. Results show that human toxicity is overall not affected since pesticides play a negligible role in the assessment whereas impact potentials are ca. 3–7 times lower to what they should be for aquatic ecotoxicity and more than 165 times too high for terrestrial ecotoxicity. These large discrepancies for ecotoxicity impacts support the recommendation that product life cycle inventories must be corrected to include only emissions from the field before using the normalization references reported in this study.

5 Uncertainty and sensitivity analysis in relation to inventory settings

5.1 Uncertainty and bias

Only a qualitative assessment of uncertainties was deemed possible, identifying the main sources of uncertainties. Normalization references for the non-toxic impact categories generally have a reasonable reliability due to considerable experience with reporting inventories for the associated emissions at the national and European levels, and the relatively stable characterization models. However, considerable efforts are still required to reach such a level of quality for the toxic impacts because of (1) the absence of characterization factors for relevant organic substances additional to those presently covered, (2) the modelling uncertainties related to the determination of the existing characterization factors, and (3) the incompleteness of the European emission inventory used to calculate the normalization references.

The former two refer to uncertainties inherent to the EDIP methodology. Currently, the EDIP97 methodology has factors for a few hundred chemicals, and although these include many priority chemicals, it is expected that a number of toxic substances of relevance for the human and ecotoxic impacts at a European level may still be without characterization factors in this methodology. In addition, characterization factors for individual substances are strongly dependent on the availability of data on substance characteristics, and they may thus change in time as new knowledge about a substance is generated. However, the largest uncertainties in this study are likely to reside in the latter of the above identified uncertainty sources because only a limited number of substances could be inventorized, and the reliability of the data for some of the most contributing substances is questionable due to the extrapolations applied to arrive at the data.

The influence of this issue was observed when applying the normalization references on a few distinct life cycle inventories from the Ecoinvent database (not shown here). Upon normalization, a number of metals (e.g. iron, thallium, strontium, chromium (+VI)), initially not included in the normalization inventory, turned out to contribute significantly to the toxic impact categories. The omission of these metal emissions in the inventory of the normalization references lead to a bias in normalization with too high toxic impacts, which might threaten the validity of the interpretation. It was therefore chosen to expand the normalization inventory by including emissions of these metals from the energy generation through a combination of European energy figures with emission factors from the Ecoinvent database (EUROSTAT 2010; Ecoinvent Centre 2007) (already accounted for in the references given in Table 1).

5.2 Sensitivity analysis on inventory robustness

To further investigate the sensitivities of the inventory built in this study, normalization references for EDIP97 toxic impact categories were calculated using a different European inventory from Sleeswijk et al. (2008; revised, Sleeswijk, 2010, personal communication), which is based on the emission year 2000. Table 4 summarizes the most influential differences between the approaches taken by Sleeswijk et al. and by this study.

Table 4 illustrates that the deviations in the calculated normalization references (ratio shown) arise from differences in the inventory of a very limited number of substances. The modelling of pesticides is thus entirely responsible for the deviation observed for the terrestrial ecotoxicity normalization reference and partly explains the deviation for aquatic ecotoxicity. The deviations in the other impact categories can typically be assigned to a few other inconsistencies in the inventory choices, viz. the selection of the data sources and the type of extrapolations applied when inventorizing NMVOCs and waterborne releases of heavy metals and dioxins.

Considering the rather different inventory approaches taken in the two studies, it is interesting that the

Table 4 Inventory discrepancies between Sleeswijk et al. (2008; revised, Sleeswijk, 2010, personal communication) and this study that influence the EDIP97 normalization references for the toxic impact categories

Impact category	Inventory aspect	Sleeswijk et al. (2008; revised, Sleeswijk, 2010, personal communication)[a]	This study	Ratio[b]	Influence on the impact potential
Chronic ecotoxicity in aquatic ecosystems [c]	Pesticide modelling	Pesticides as 100% emitted to soil	Pesticides as 0.1% emitted to freshwater and 5% to air	45.9	Contribution of pesticides equals ca. 70% with inventory from this study whereas no pesticide contributes in the assessment with inventory from Sleeswijk et al. where nothing is emitted to water nor to air.
		Extrapolations based on GDP or areas	Extrapolations based on consumption data and agriculture modes in the UK and DK		
	Heavy metals (HM) to freshwater	EPER database used for EU-15, complemented by extrapolations with GDP	OSPAR and HELCOM reports complemented by GDP extrapolations		Higher emissions in this study (factors 46 and 35 for Cu and Zn, respectively), leading to higher impact potentials from HM emitted to aquatic ecosystems in this study compared to Sleeswijk et al.
	Dioxins emitted to freshwater	Emissions to water extrapolated from USA, Japan and Canada	Not included		Waterborne dioxins accounting for 10% with inventory from Sleeswijk et al. The extrapolated emission data for Europe was found to be too uncertain to include in this study, so there is no contribution to the normalization reference.
	Iron (and some other metals, e.g. Cr(+VI) and Sr) to freshwater	Not included	Rough estimates for iron (and these other metals) based on energy production in Europe		Significant contribution of iron (and strontium to a lesser degree) in this study (5.5%).
Chronic ecotoxicity in terrestrial ecosystems	Pesticide modelling	Pesticides as 100% emitted to soil	Pesticides as 0.1% emitted to freshwater and 5% to air	0.007	Terrestrial ecotoxicity potential is dominated at ca. 100% by pesticide contributions in Sleeswijk et al., while main contributors are NMVOCs in the present study (99%)
		Extrapolations based on GDP or areas	Extrapolations based on consumption data in Europe and agriculture practices in UK and DK		
Human toxicity, via air	NMVOC emissions (specified)	Most emissions of NMVOCs to air extrapolated from Canada, US and Japan data (incl. formaldehyde)	Differentiation of NMVOCs based on emission data and sector-specific distributions	9.1	NMVOCs dominant in both assessments (62% in Sleeswijk et al. and 96% in this study, both driven by formaldehyde and butadiene contributions) but lower NMVOC emissions are considered in the inventory of Sleeswijk et al. (hence the lower normalization reference resulting from the latter)
Human toxicity, via water	Dioxins emitted to freshwater	Emissions to water extrapolated from USA, Japan and Canada	Not included	1.1	Waterborne dioxins accounting for 6% with inventory from Sleeswijk et al.
	Thallium (and some other metals, e.g. Cr(+VI), Fe and Sr) to freshwater	Not included	Rough estimates for thallium (and these other metals) based on energy production in Europe		Contribution of thallium (1.2%) to impact potential in this study
Human toxicity, via soil	NMVOC emissions (specified)	Most emissions of NMVOCs to air extrapolated from Canada, US and Japan reports (incl. formaldehyde)	Differentiation of NMVOCs based on emission data and sector-specific distribution	23.2	NMVOCs dominant in both assessments (40% in Sleeswijk et al. and 97% in this study, both driven by benzene contributions) but lower NMVOC emissions are considered in the inventory of Sleeswijk et al. (hence the lower normalization reference resulting from the latter)

[a] Inventory of (Sleeswijk et al. 2008) revised by the authors (Sleeswijk, 2010, personal communication)

[b] Ratios of normalization references (this study)/(Sleeswijk, 2010, personal communication)

[c] Acute ecotoxicity on aquatic ecosystems not reported as comparisons are similar to the ones for chronic ecotoxicity

normalization references end up within 1–2 orders of magnitude for all the toxic impact categories. On the other hand, this finding documents that the normalization contributes to increasing the uncertainty of the toxic impact categories compared to the non-toxic categories, and they emphasize the need to concentrate efforts to better inventorize central substances or groups of substances, such as dioxins and some specific heavy metals.

6 Conclusions

The study provides the most updated set of publicly available normalization references for the EDIP method (both EDIP97 and EDIP2003) and a set of inventory data covering all the common midpoint categories to be applied in the calculation of European normalization references for other LCIA methodologies. The references are calculated for the emission year 2004, and for the non-global impact categories, they represent the European background load. For the toxic impact categories, emphasis was put on including recent developments in inventory modelling. The differentiation of emissions of groups of chemicals, such as NMVOCs and pesticides, into individual substance emissions was performed, and pesticide emissions were modelled to the ecosphere rather than to the technosphere to ensure compatibility with characterization models. The outcome helped highlight the inconsistencies still inherent in current LCI practices, where the harmonization of the approaches followed appears as an important challenge to take up in the field of LCA.

Furthermore, important sources of uncertainties were identified for the toxic impact categories, both at the characterization and at the inventory levels. For the latter, the most significant issues are related to incompleteness in the coverage of substances. Practical trials and comparisons with other inventory information were performed to quantitatively estimate these gaps. The findings clearly demonstrate the need to complement inventories with reliable information on key substances such as heavy metals or dioxins.

References

Birkved M, Hauschild MZ (2006) PestLCI-a model for estimating field emissions of pesticides in agricultural LCA. Ecol Model 198(3–4):433–451

LCA Center (2010) Expected to provide updated characterization factors for the EDIP methodology. www.lca-center.dk Accessed Apr 2010

Dreyer LC, Niemann AL, Hauschild MZ (2003) Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99 – does it matter which one you choose? Int J Life Cycle Assess 8(4):191–200

Ecoinvent Centre (2007) Ecoinvent data. Swiss Centre for Life Cycle Inventories. Dübendorf. www.ecoinvent.ch

EUROSTAT (2010) Tables, section Environment and Energy–expected to contain yearly updated data (both national and European). http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main_tables Accessed Mar 2010

Finnveden G, Hauschild MZ, Ekvall T, Guinee J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in life cycle assessment. J Environ Manage 91 (1):1–21

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, Koning Ad, Oers Lv, Wegener Sleeswijk A, Suh S, de Haes HA Udo, Bruijn Hd, Duin Rv, Huijbregts MAJ (2002) Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer, Dordrecht, p 692

Hauschild M, Potting J (2005) Spatial differentiation in LCA impact assessment – the EDIP 2003 methodology. Environmental news No. 80 2005. Danish Environmental Protection Agency. Copenhagen, Denmark. http://www2.mst.dk/udgiv/publications/2005/87-7614-579-4/pdf/87-7614-580-8.pdf Accessed Mar 2010

Hauschild M, Wenzel H (1998) Environmental assessment of products. Volume 2 – scientific background. Chapman and Hall, Thomson Science, London, 0-412-80810-2

ISO (2006) ISO 14044 International Standard. In: Environmental management – life cycle assessment – requirements and guidelines. International Standard Organization, Geneva

Lautier A, Rosenbaum RK, Margni M, Bare J, Roy P, Deschênes L (2010) Development of normalization factors for Canada and the United States and comparison with European factors. Sci Total Environ 409(1):33–42

Nemecek T, Kägi T (2007) Life cycle inventories of Swiss and European agricultural production systems. Final report Ecoinvent V2.0 No. 15a. Agroscope Reckenholz-Taenikon Research Station ART, Swiss Centre for Life Cycle Inventories. Zurich and Dübendorf, Switzerland. www.ecoinvent.ch Accessed May 2010

Pant R, Van Hoof G, Schowanek D, Feijtel TCJ, de Koning A, Hauschild M, Pennington DW, Olsen SI, Rosenbaum R (2004) Comparison between three different LCIA methods for aquatic ecotoxicity and a product environmental risk assessment – insights from a detergent case study within OMNIITOX. Int J Life Cycle Assess 9(5):295–306

Potting J, Hauschild M (2005) Background for spatial differentiation in LCA impact assessment–the EDIP 2003 methodology. Environmental project no. 996 2005. Danish Environmental Protection Agency. Copenhagen, Denmark. http://www2.mst.dk/Udgiv/publications/2005/87-7614-581-6/pdf/87-7614-582-4.pdf Accessed Mar 2010

Sleeswijk AW, Huijbregts MAJ, van Oers LFCM, Guinée JB, Struijs J (2008) Normalisation in product life cycle assessment: an LCA of the global and European economic systems in the year 2000. Sci Total Environ 390(1):227–240

Stranddorf HK, Hoffmann L, Schmidt A (2005) Update on impact categories, normalisation and weighting in LCA–selected EDIP97 data. Environmental Project Nr. 995 2005. Danish Environmental Protection Agency, Copenhagen

UNSD (2010) Demographic Yearbooks (years 2004, 2005, 2006, 2007) – available on the UNSD website. http://unstats.un.org/unsd/demographic/products/dyb/2000_round.htm Accessed Mar 2010

Wenzel H, Hauschild M, Alting L (1997) Environmental assessment of products. Volume 1–methodology, tools and case studies in product development. Chapman and Hall, Thomson Science, London, 0-792-37859-8