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Guidance on how to move from current practice to recommended practice in Life Cycle Impact Assessment

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Abstract

This report provides guidance on how to move from current practice to recommended practice in Life Cycle Impact Assessment. It is composed of three complementary parts elaborated in the first task force (TF1) of the LCIA programme, with contribution of the other three task forces:

1. The first part concentrates on midpoint categories. It defines a consistent and systematic process to evaluate different category indicators within an LCIA midpoint category, and to recommend an adequate indicator or set of indicators. It then applies this process to provide recommendations for acidification modeling: Six currently used methods are compared to provide a practical illustration and to demonstrate its applicability. This application on acidification will serve as a template to provide guidance for the selection of indicators for other midpoint categories.

2. Based on the analysis of impact pathways in individual midpoint impact categories, the second part describes some possible damage categories and indicators. It constitutes a starting point to assess environmental relevance across the different midpoint impact indicators and a preliminary basis to ensure a consistent and common approach to damage modelling. It aims covering all emission related damages categories, where there is sufficient knowledge available.

3. The third part focuses on aspects of location and time as they affect impact modeling, i.e. spatial and temporal differentiation. This section first establishes basic principles determining a) the need for spatial or archetype differentiation in the different impact categories, b) possible ways to address this, and c) the consequences for LCI and LCIA modelling.

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1 Evaluation of category indicators and characterization models: application to acidification

1.1 Introduction

Life cycle impact assessment (LCIA) serves to evaluate the character and relative importance of the environmental and human health interventions contained in a life cycle inventory (LCI). Its purpose is to aggregate the long list of interventions typically found in practice into a small set of indicators, or even to a single indicator. This is done in order to identify processes that contribute most to the overall impact, to compare products, or to garner support for promising technological innovations (Hertwich et al. 2002).

It was recognized early on in the methodological development of LCA that cause-and-effect relationships are sometimes difficult, if not impossible to prove. Therefore, in contrast to more absolute approaches, such as environmental risk assessment (ERA), LCIA is a tool for comparing relative measures of impact using surrogate methods (e.g., stressors effects concepts) (Fava et al. 1992, Barnthouse et al., 1997). Nearly fifteen years later, the identified methods and models have grown significantly, and user needs continue to drive necessary advances in more comprehensive approaches and further improvements in the relative accuracy of characterization factors (Stewart and Jolliet 2004, Bare and Gloria 2006).

The goal of this document is to evaluate current characterization indicators and methods and put forth recommendations on appropriate use, and likewise inform practitioners of known practical limitations. This process aims to provide guidance and recommendations for further improvement. Work has been carried out within the Life Cycle Impact Assessment Programme of the UNEP/SETAC Life Cycle Initiative, by an adhoc subtask force composed of individual members of **Task Force 1 – LCIA Information system and framework**, and **Task Force 4 – Transboundary impacts**.

The second generation of international standards pertaining to LCA and LCIA[1] aims to set only general compliance requirements for applicable methods. Therefore, there is substantial latitude in the choice of evaluation methods when conducting impact assessment.

In consideration of the variety of impact assessment methods, that is, the category indicators and associated models that practitioners may choose from, the present chapter aims to increase transparency and to offer recommendations regarding the choice of category indicators and models when conducting a LCA study. In addition, this paper offers guidance on identified areas requiring further development.

The approach proposed by this working group includes the development of a set of criteria to evaluate category indicator and characterization model and an evaluation procedure to make these criteria fully operational (Chapter 1.2). It was developed with the goal to ensure consistency in the evaluation among the different impact categories, building on previous efforts such as work within SETAC (Udo de Haes et al. 2002) and the UNEP-SETAC Life Cycle Initiative Impact Assessment

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[1] ISO/FDIS:2006 14040 Environmental Management – Life Cycle Assessment – Principles and Framework and ISO/FDIS/2006 14044 Environmental Management – Life Cycle Assessment – Requirements and guidelines.

Definition Study (Jolliet et al. 2004). It then applies the evaluation procedure to acidification (Section 1.3), comparing six currently used methods, providing recommendations for this impact category (Section 1.3.6) and a practical illustration of the procedure applicability.

1.2 Method

The methodology has been developed in two complementary steps. In a first step, a general list of criteria has been developed to evaluate category indicator and characterization model. An evaluation procedure has then been developed to make these criteria fully operational and relevant for a given impact category, based on evaluation statements that are category specific.

1.2.1 Development of evaluation criteria

What makes a good choice of a category indicator and characterization model, or a set of indicators and models?

In this section, the development of a set of evaluation criteria is outlined.

- ISO 14044 has specified a number of **requirements** for the selection of impact categories, category indicators and characterization models. Whenever impact categories, category indicators and characterization models are selected in an LCA, the related information and sources shall be referenced. This also applies when new impact categories, category indicators or characterization models are defined.
- Accurate and descriptive names shall be provided for the impact categories and category indicators.
- The selection of impact categories, category indicators and characterization models shall be both justified and consistent with the goal and scope of the LCA.
- The selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration.
- The environmental mechanism and characterization model that relate the LCI results to the category indicator and provide a basis for characterization factors shall be described.
- The appropriateness of the characterization model used for deriving the category indicator in the context of the goal and scope of the study shall be described.
- LCI results other than mass and energy flow data included in an LCA (e.g. land use) shall be identified and their relationship to corresponding category indicators shall be determined.

In addition to the requirements, the following **recommendations** apply:

- the impact categories, category indicators and characterization models should be internationally accepted, i.e. based on an international agreement or approved by a competent international body;
- the impact categories should represent the aggregated impacts of inputs and outputs of the product system on the category endpoint(s)[2] through the category indicators;
- value-choices and assumptions made during the selection of impact categories, category indicators and characterization models should be minimized;

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[2] Attribute or aspect of natural environment, human health, or resources, identifying an environmental issue giving cause for concern

- the impact categories, category indicators and characterization models should avoid double counting unless required by the goal and scope definition, for example when the study includes both non carcinogenic human health and carcinogenic human health;
- the characterization model for each category indicator should be scientifically and technically valid, and based upon a distinct identifiable environmental mechanism and reproducible empirical observation;
- the extent to which the characterization model and the characterization factors are scientifically and technically valid should be identified;
- the category indicators should be environmentally relevant.

Building upon the ISO requirements and recommendations, this working group derived a more specific set of criteria resulting for the following five aspects:

(1) *comprehensiveness of the impact category to related endpoint(s)*[3],
(2) *environmental relevance and reproducibility,*
(3) *transparency - easy of understanding and applicability,*
(4) *scientific validity and reliability,* and
(5) *inclusion and compatibility with weighting and normalization.*

Each group includes a list of detailed criteria to evaluate the category indicators, characterization models and sets of indicators and models. The structure and the detailed criteria are given in Appendix I and II, the latter being the preliminary set of criteria developed within TF1 and the first one the improved set of criteria obtained through an iterative process analyzing the acidification impact category. A scoring procedure was proposed to evaluate the compliance with the criteria by the working group:

a – full agreement
b – compliance in all essential points
c – compliance or passable agreement made
d – little compliance
e – no compliance

It is important to note that not all the proposed criteria are equally important, but the aim is to qualitatively compare the different methods, highlighting their performances and limitations in respect to each criterion. This set of criteria and the evaluation procedure presented below set the basis for 1) evaluating the overall consistency of the characterization models and indicators between all the impact categories and over the LCIA midpoint-damage framework and 2) evaluating characterization indicators and models within a midpoint impact category. The present work focuses on the second point. The comprehensiveness across the impact categories, i.e. the coverage of all significant impacts in each LCIA method is not the scope of this exercise and should be addressed in a later step.

1.2.2 Evaluation procedure

A hierarchical evaluation procedure was developed with the purpose to customize the selection criteria identified in Appendix I to the considered impact category and to make them fully operational through a series of positive statements against which the degree of compliance of the methods can be tested. This effort brings together science and pragmatism to provide recommended practices that are scientifically defendable, relevant to the identified damages, and as

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[3] How far is the midpoint indicator representative to all the endpoints relevant for this impact category?

important, practical. As such, the following procedure, which shall be later applicable to the evaluation of all the impact categories, was proposed and employed:

1. *Comprehensiveness:* Evaluate the comprehensiveness of the midpoint category indicators in relationship with the damage categories as defined in the Midpoint-damage document for the whole framework (Jolliet et al. 2004)) (see also Table 2.1, part 2).
2. *Environmental relevance:* Evaluate the environmental relevance of the category indicator to the subject(s) to protect within a given impact category prior to evaluating the scientific validity of the model.
3. *Model framework analysis:* Analyze the models according to the general LCIA framework (Udo de Haes et al. 2002): fate & transport, exposure, dose-response curve in regard to the damage. This step is necessary to make model choices explicit and to improve transparency. A quantitative analysis is made wherever possible to facilitate the identification of substantive differences between methods.
4. *Identification of evaluation statements:* Based on the model analysis, define a limited series of main statements characterizing how the five evaluation criteria apply to the impact category evaluated, starting with comprehensiveness to the defined common damages and environmental relevance. Some statements apply to all impact categories (e.g., feasibility to provide calculation for different continents or for main archetypical situations (or patterns) leading to important variations, whereas other need to be adapted to the specificity of the environmental issue addressed by the category).
5. *Methods evaluation:* Apply the five evaluation criteria and related main evaluation statements to the selected models and evaluate the category indicator and characterization model accordingly (see Appendix I):
6. *Final recommendations*: Summarize the learning of the evaluation via a set of recommendations on the characterization model and category indicator, including practicability in relationship to the data availability to derive characterization factors.

This methodology applies for all emission related impact categories, as such, step 3 should be adapted to assess impact categories, such as land use and resource depletion, that are fundamentally different in structure.

1.3 Evaluation of the acidification impact category

The initial evaluation commences with a review of state-of-the-science acidification methodologies as documented by TF4 of the LCIA Programme of the SETAC-UNEP Life Cycle Initiative (Potting et al., 2006). The following methods with their related indicators were evaluated: CML 92 traditional H+ method (Heijungs et al. 1992), TRACI (Bare et al. 2003), original Area of unprotected ecosystems method (UA) (Potting et al. 1998) and the improved Area of unprotected ecosystems method (UA) (Hettelingh et al. 2005), Accumulated exceedance (AE) (Seppälä et al. 2006) Hazard index (HI) (Huijbregts et al. 2001), and Base Saturation (BS) (van Zelm et al. 2007).

1.3.1 Comprehensiveness of the impact category regarding its related damages

Relying on the midpoint-damage framework (Table 2.1) three possible damages have been identified as having a strong link to terrestrial acidification: Decrease or disappearance of species (biodiversity), decrease in biotic productivity (bioproductivity) and physical destruction of objects (materials). The first two damage areas, biodiversity & bioproductivity, are strongly correlated and could be grouped for this evaluation (Wilson 1988). Damages of human life of acidifying substances, such as SO_x are to be considered when assessing human respiratory impacts. Direct damages of substances on crops, such as effect of SO_2 on biomass production, should be considered separately in the ecotoxicity impact category.

The methods analyzed in this comparison may include impacts of acidifying emissions on land and inland waters. In CML 92 depositions of acidifying emissions include also sea area. In TRACI, UA, AE and HI sea areas are omitted and only depositions to land and inland waters are taken into account. In European methods, in addition, the sensitivity of the ecosystem to acidifying deposition (see Section 1.3.2) is determined for the terrestrial ecosystems (forest, grassland, wetland and shrub) and the most important/sensitive lake and river ecosystems (Hettelingh et al. 1995; Hettelingh et al. 2005). Acidification in ocean caused by increasing atmospheric carbon dioxide concentrations (Orr et al. 2005) is not taken into account in this paper. Finally, the BS method has only been applied to forest ecosystems in Europe (van Zelm et al. 2007).

1.3.2 Environmental relevance of the category indicator to the damage

Environmental relevance of category indicators for acidification is important at the midpoint, endpoint, and damage level. In a combined midpoint, endpoint or damage method it seems wise to choose a midpoint indicator as close as possible in the environmental model where all substances are unified in an indicator to satisfy the five criteria (comprehensiveness, relevance/reproducibility, transparency, validity and compatibility). Even though the remainder of the environmental mechanism from midpoint to damages describes the link to environmentally relevant endpoint indicators, this sometimes occurs at the expense of reducing the comprehensive nature of the midpoint, and likely resulting in higher uncertainty.

Environmental relevance is also important for the midpoint category. For example, in the case of acidification, considering only the change in area above critical load is not representative enough as additional damages in areas already above the critical load are not considered. This indicator cannot describe environmental benefits if the deposition remains higher than the critical load after emission reductions, i.e. no change in the unprotected area of ecosystems occurs. Similarly, disregarding fate assessment and assuming all areas are sensitive generates an indicator that may not be relevant enough to describe potential damages of acidifying emissions, particularly when assessing emission taking place in different continents. In addition, fate factors may differ between acidifying substances with different chemical properties.

The actual acidification is a consequence of many contributions from large geographical areas and time periods. The allocation of the acidification effects to single contributors can be done in several ways and the choice of allocation principle is a subjective choice. As the dose-response curve for most category indicators is not linear, there is a difference between marginal and average impacts.

The carrying capacity of an ecosystem is its ability to bear an environmental load without significant damage (EEA, 1999). Damage to biological life from the deposition of acidifying substances depends mainly on the species living in that area and the buffering capacity of the receiving body. Additionally, there are receiving bodies that have a stock of cationic buffering substances that can counteract acidification up to a certain deposition rate. A large part of this buffering capacity is tied up in soil minerals and released by weathering. If the deposition of acidifying substances is larger than what can be neutralized by cationic release, acidification will rise and the so called critical load is exceeded. This critical load therefore expresses the maximum load that a given system can tolerate before failing (ref:ETC/CDS. General Environmental

Multilingual Thesaurus (GEMET 2000)). The critical load is therefore the highest deposition of a compound that will not cause chemical changes leading to long-term harmful effects on ecosystem structure and function.

For Integrated Assessment studies, the exceedance of the critical load is very important because one may aim to calculate the area which is above this value. In LCA, we prefer to introduce the distinction between sensitive area (with low cation buffer capacity and sensitive ecosystems) and insensitive area (with high cation buffer capacity or insensitive ecosystems). On the one hand, it makes sense to disregard insensitive area, i.e. with high cation buffer capacity. On the other hand, depositions to sensitive area with low cation buffer capacity are relevant in LCA even if effect will only be visible in the future. This implies that LCIA methods shall consider area above the critical load **and** below the critical load showing low cation buffer capacity. We believe that this distinction will hold true for several impact categories.

All of the acidification characterization methodologies considered in this comparison, with the exception of Heijungs et al. (1992), relate to some extent, to sensitive areas. Damage in terms of decreased biodiversity and bioproductivity is complex and the dose-response curve is non-linear However, linear approximations may be feasible for isolated parts of the dose-response curve and for areas where the soil and species are well known. Difficult challenges arise for estimating acidification potential at the global level, as soil composition and sensitive species present are less well known.

1.3.3 Model framework analysis

The model frameworks are analyzed according to the general life cycle impact assessment framework proposed by the SETAC (Udo de Haes et al. 2002). For emission related impact categories, the characterization factor(CF) can be expressed as a fate factor (FF), multiplied by an effect factor (EF), as per Equation 1:

$$CF_{i,ar} = FF \cdot EF = \underbrace{f_{i,ar} \cdot \theta_{i,r\ sensitivity}}_{\text{FF}} \cdot \underbrace{\beta_{dose-response}}_{\text{EF}} \qquad (1)$$

where:

- $f_{i,ar}$ represents the fate factor for substance *i* representing the transport in air (a) and the transfer to receptor-environment (r). It models the change in deposition of acidic substances due to change in emission [dimensionless (kg/kg)].
- $\theta_{i,r\ sensitivity}$ is the fate sensitivity factor in the receptor-environment. It models the change in soil parameters such as acidity potential or base saturation due to change in acid deposition. It can be calculated as the number of mol H+ released per kg of pollutant [mol H+/kg] multiplied by the soil sensitivity [-] or the change in base saturation over a unit area and unit time per kg deposited [m2 year/kg] (van Zelm et al. (2007)).
- $\beta_{dose-response}$ expresses the effect factor, i.e. the response of the ecosystem to the change in cation capacity (or base saturation) e.g. [Impact/mol H+] or [-].

Interestingly, this framework is analogous and compatible to the terrestrial and aquatic ecotoxicity framework retained at the 2003 Lausanne workshop of the Life Cycle Initiative (Jolliet et al. 2006), where the cause-effect chain is characterized as the product of a transfer factor to soil or water × fate factor in soil or water × exposure and effect factor.

Characterization factors for acidification are traditionally calculated at midpoint level, as it is the case for the LCIA methods considered in this analysis. Some damage oriented LCIA method relates emissions of acidifying substances to the damage biodiversity (Steen 1999; Goedkoop et al. 2000; Hayashi et al. 2004; van Zelm et al. 2007) Both midpoint and damage approaches follow the same cause-effect chain up to changes in soil parameters ($f_{i,ar} \cdot \theta_{i,r\ sensitivity}$), but differ in the effect factor.

Figure 1 describes fate of acidifying emissions linking the source up to the change of parameters in the receptor compartment ($f_{i,ar} \cdot \theta_{i,r\ sensitivity}$). This includes (1) the emission, (2) the transport into the air, (3) the deposition to the land area and (4) the change of parameters in the receptor-environment. The receptor compartment could show different degrees of sensitivity with respect to the damage categories. In the following we will focus on the impacts on biodiversity & bioproductivity, keeping in mind that while the transport and deposition would follow similar pathways, different effect factors would apply to the prediction of potential effects on the physical destruction of objects. If needed, a similar structure could be applied on bioproductivity with the soil sensitivity factor and the effect factor that can show different values

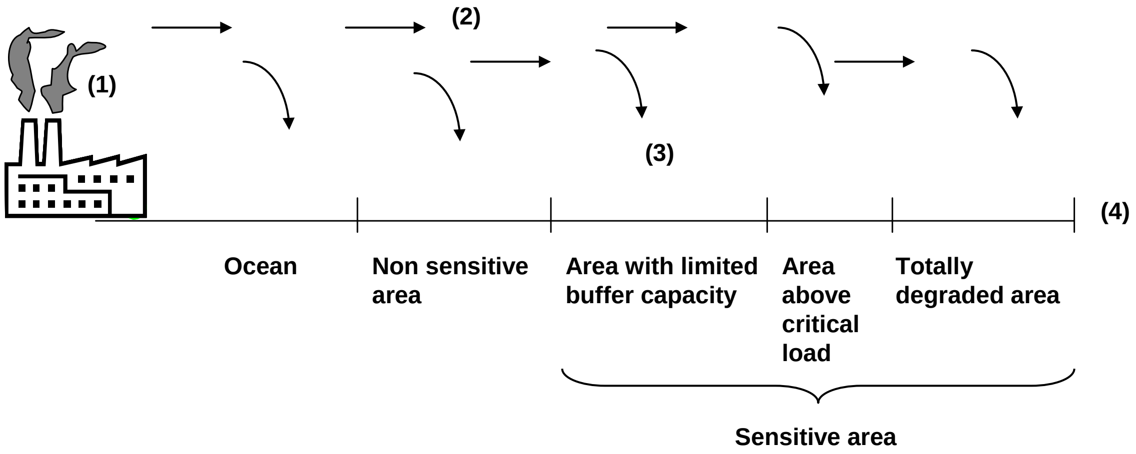

Figure 1 Fate & exposure transport of acidifying substances. Deposition can take place in Ocean or Land Area, which distinguish between non sensitive area (ns), and sensitive area (sa). This latter can further be distinguished between area with limited buffer capacity (bc), area above critical load (cl) and totally degraded area (da)

Figure 1 accounts for acid deposition on areas with a different degree of sensitivity: ocean, non sensitive area (e.g. in 60’000 yr) and sensitive area. This latter includes areas with limited buffer capacity (that could become sensitive in a future time period, e.g. 100, 50, or 10 yrs depending on the magnitude of the deposition), areas at critical load and totally degraded areas. Table 1 analyses the 5 methods considered in this paper, decoupling and explaining the different models and indicators according to the parameters of Equation 1.

The CML 92 method only considers the sensitivity factor in term of its acidification potential (AP), representing the release of mole H+ in the environment (Heijungs et al. 1992). TRACI also introduces the fate transport as the fraction deposited on land (Bare et al. 2003). The Area of unprotected ecosystems method (UA) (in its original (Potting et al. 1998) and improved version, (Hettelingh et al. 2005), the Accumulated Exceedance (AE), (Seppälä et al. 2006) and the Hazard (HI) methods, (Huijbregts et al. 2001) all adopt a sensitivity factor, $\theta_{i,r\ sensitivity}$ based on critical load approach. The UA and AE methods and the so-called only above critical load approach of the HI methods disregard the fraction of proton deposited in non sensitive areas where the acidity critical load is not exceeded. The base saturation method, (van Zelm et al. 2007) characterizes acidification at midpoint level through the change in soil base saturation. It then links it to damages on forest ecosystems in term of changes in Potentially Not Occurring Fraction of plant species.

Table 1: Characterization models decoupled and explained according to the parameters of Equation 1. The indexes denote ocean (o), non sensitive area (ns) and sensitive area (sa), which includes: buffer capacity area for a given time frame (bc), critical load area (cl) and totally degraded area (da). AP is the acidity potential, AE is the accumulated exceedance of critical load, CLecos is the critical load for the terrestrial and inland water ecosystems (ecos) of land area, BS is the degree to which the adsorption complex of a soil in forest area is saturated with base cations and PNOF is a potentially not occurring fraction of plant species in forest area.

	$f_{i,ar}$	$\theta_{i,r\ sensitivity}$	$\beta_{dose-response}$
CML 92	$1 \cdot A_{ocean+land+inland\ water}$	$\theta_{i,o} = \theta_{i,ns} = \theta_{i,sa} = AP_i \cdot$[H$^+$/kg]	1
TRACI	Source to deposition matrix proportional to $A_{land+\ inland\ water}$	$\theta_{i,o} = 0$; $\theta_{i,ns} = \theta_{i,bc} = \theta_{i,cl} = \theta_{i,da} = AP_i$ [H$^+$/kg]	1
UA	Source to deposition matrix proportional to A_{ecos}	$\theta_{i,o} = \theta_{i,ns} = \theta_{i,bc} = \theta_{i,da} = 0$ $\theta_{i,cl} = \Delta_{critical\ area}$ [m2/kg] in which AP_i and CL_{ecos} are used	1
AE	Source to deposition matrix proportional to A_{ecos}	$\theta_{i,o} = \theta_{i,ns} = \theta_{i,bc} = 0$ $\theta_{i,cl} = \theta_{i,da} = AE[eq/kg]$ in which AP_i and CL_{ecos} are used	1
HI	Source to deposition matrix proportional to A_{ecos}	$\theta_{i,ns} = \theta_{i,sa} = AP_i$ [H+/kg] or $\theta_{i,cl} = \theta_{i,da} = AP_i$[H+/kg] and $\theta_{i,bs} = \theta_{i,ns} = 0$	$1/CL_{ecos}$ $1/CL_{ecos}$
BS	Source to deposition matrix proportional to A_{forest}	$\frac{dBS_{forest}}{dDEP_{forest}}$ [m^{2}year/kg]	$dPNOF_{forest}/dBS_{forest}$

Method specificities can be characterized as follows:

The CML92 method of (Heijungs et al. 1992) accounts for a full deposition of all emissions, whether deposited on land or ocean area. The fate sensitivity factor only considers the acidification potential in term of H+ releases and does not make any differentiation between deposition to a sensitive area or to an insensitive area, i.e. all the deposition on the entire area has acidification potential. The dose-response curve implicitly equals 1.

The TRACI method (Bare et al. 2003) provides generic and spatially differentiated characterization factors for the US. A fate model links the emission to the deposition on land area while intentionally disregarding emissions to the ocean. The characterization model utilizes spatially specific atmospheric and transport modeling in the United States (NAPAP: National Acid Precipitation Assessment Program). TRACI's detailed fate and transport analysis is empirically based and validated to allow site dependent analysis for North America. TRACI considers the fate sensitivity factor having acidification potential on the entire land and inland water area whether soil and ecosystems are sensitive or not. The dose-response curve implicitly equals 1.

The Unprotected Area method (UA: Potting et al., 1998; Hettelingh et al., 2005) is based on a category indicator measuring changes in area of unprotected ecosystems due to emission reductions at country level within Europe. The original version (Potting et al. 1998) is based on emission reduction of 10% together with a European critical load database (Hettelingh et al. 1995). The improved version provides more stable characterization factors using 50% reductions of national emission, since CFs may be unstable for small changes in emission (Hettelingh et al. 2005). UA also considers a fate transport model linking the emission to the deposition to land area using the RAINS European model (Potting et al. 1998) and the Lagrangian version (150 x 150 km^2 grid cells) of the EMEP model (Hettelingh et al. 2005). Only the fraction of deposition in areas that change from below to above critical load is considered being sensitive to acidification, disregarding deposition in already sensitive areas. The indicator thus measures the increase in areas of unprotected ecosystem that become over critical load. The dose-response curve implicitly equals 1.

The method of Accumulated Exceedance (AE) (Seppälä et al. 2006) provides European Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication. The atmospheric transport and deposition model to land area is determined using the Lagrangian version of the EMEP together with a new European critical load database (Hettelingh et al. 2004). The fate sensitivity factor only accounts for acidification potential for the deposition to sensitive area at and above critical load. The acidification potential is expressed in absolute accumulated exceedance. The dose-response curve implicitly equals 1.

The method of Hazard index (HI) (Huijbregts et al. 2001) also provides European spatially-specific characterization factors for acidifying and eutrophying air pollutants. CFs express the marginal change in the hazard index of all ecosystems in Europe, comparing the actual load to the critical load (Hettelingh et al. 1995) weighted over ecosystems and region. Atmospheric transport and deposition is determined using the RAINS European model accounting only for the fraction of deposition to area at critical load and totally degraded area. The HI method assumes a dose-response slope inversely proportional to the critical load itself. Two indicator approach are proposed 1) assuming a fate sensitivity factor proportional to the acidification potential on the entire land area and 2) assuming acidification potential only on area above critical load.

It is important to notice that characterisation factors calculated by the first indicator approach of the HI methods do not change due to the changes in (European) emissions, whereas the UA, AE and the second HI method do. In the new emission situation (in Europe) area above critical loads will change. It is important to notice that the change in area above critical load is mainly due to changes in emissions whereas the value of the critical load for a given area is approximately constant during the considered time horizon. For example, if European emissions will decrease by 10%, the area above critical loads will decrease, too. Thus, new critical loads and emissions have separate effects on the determination of characterisation factors.

The Base saturation method (Van Zelm et al, 2007) calculates the transfer coefficient of acidifying substances from source to European forest area using the EUTREND model. It uses the simulation model for acidification's regional trends (SMART 2) to characterize soil sensitivity at midpoint level as a change in soil base saturation. Adapting van Zelm et al. (2007) to the above framework, the fate sensitivity factor becomes the number of mol H+ released per kg of pollutant [mol H+/kg] multiplied by the change in base saturation over a unit area and unit time per mol H+ deposited [m2 year/mol H+]. The fate-sensitivity factor therefore represents the change in base saturation over a unit area and unit time per kg deposited [m2 year/kg]. The change in Base Saturation per unit deposition is presently only available for Europe. It is the only method that has a physiologically based dose-response. Based on Monte-Carlo simulations for 240 plant species, it expresses the change in potentially not occurring fraction of plant species per change base saturation [dimensionless].

1.3.4 Definition of evaluation statements

From the model framework analysis and the initial list of criteria from Appendix II, we derived the following statements characterizing how the criteria apply to this category.

(1-2) comprehensiveness, *environmental relevance and reproducibility,*

- Atmospheric fate and factor linking emissions to the receptor environment must be considered.
- Acidification should disregard transfer to ocean compartment and consider the fraction transferred to land, including surface waters (continental surface area when adopting the simplification grouping terrestrial and aquatic environment). However, some oceanic sensitive area such as reefs could be still included.
- For damages on materials, transfer factor for land and built area matters (no buffer capacity for a building is considered).
- For damages on biodiversity expressed in term of loss of species, it is useful to consider a fate sensitivity factor in the receptor environment discriminating between sensitive and insensitive areas.
- The fate sensitivity factor account for sensitive area, which includes area with limited buffer capacity.
- The fate sensitivity factor accounts for sensitive area, which includes totally degraded area (area already above critical load), implying that the magnitude of deposition in sensitive areas also matters, (not only the change in sensitive areas) even if the buffer capacity has already been exceeded

(3) *transparency - easy of understanding and applicability,*

- The model should cover the main inventory flows with conventional LCA and be able to work with generic data (at least at the continental level).

(4) *scientific validity and reliability*

- For evaluations covering larger than one continental area, it is essential to be able to consider the variations in sensitivity between continents and to cover all continents. In addition, regional differentiation could also be relevant (see chapter 3)
- Model should include documentation regarding scientific validity and reliability with some estimate of uncertainty propagation.

(5) *inclusion and compatibility with weighting and normalization.*

- The method should be consistent with normalization and weighting procedures which may be applied.

An evaluation matrix (see appendix I) is then derived based on the above statements and a set of main evaluation criteria relevant to this evaluation. The full list of evaluation criteria refers to Appendix I.

1.3.5 Application of main evaluation criteria and statements to the existing acidification impact methods

A detailed evaluation of the 5 methods is made in Table I.1 (see enclosed Excel spreadsheet Appendix I) based on the main evaluation criteria and statements derived in the above chapter. The evaluation accounts for the geographical context where the methods are developed. In addition, we also evaluate the feasibility to extend each method to produce worldwide generic factors for the other continents than that of origin.

- The CML92 traditional H+ method determines characterization factors disregarding fate, transport, or any geographical differentiation to sensitive area. It is therefore not relevant enough for differentiating the large differences between continents. (see below)
- TRACI is specifically developed to determine characterization factors for North America. It includes a fate and transport model linking the emission to the deposition on land and freshwater area with intentional disregard to the ocean. Considering deposition to land area has the advantage to cover in a generic way both biodiversity & bioproductivity and man-made material damages. TRACI could be complemented by a fate sensitivity factor to sensitive areas if a focus on biodiversity & bioproductivity damages is desired and similarly, an explicit transfer factor to built area if the damage man-made environment is desired.
- The change in area above critical load in the original UA method is not relevant enough in the LCA context as the increase in deposition in sensitive area (i.e. area already above the critical load) is discounted and does not meet the 4th statement above. In addition the feasibility to obtain average estimates worldwide would be difficult for the methods proposed by Potting et al. (1998). This could be slightly easier for the improved method of Hettelingh et al. (2005). Finally this method is difficult to make compatible with further damage modeling.
- The *AE* method is likely the best available midpoint method for biodiversity & bioproductivity to be used to determine worldwide characterization factors. Initially developed considering the latest emission and sensitive area in Europe, it could potentially be applicable to obtain continental values worldwide using more comprehensive models or expert estimates. For biodiversity damages it considers area with limited buffer capacity being sensitive area. One has to be conscious that it needs to be complemented by evaluation of acidification damages on materials/built environment or at least study the correlations between damages. The *AE* method is potentially compatible with further damage modeling.
- The same conclusions for load to sensitive areas made for *AE* apply for the *HI* method. For the HI method, however, some doubts exist on the relevance of the dose-response curve, as the slope over buffer capacity depends on the buffer capacity itself. The *HI* method is potentially compatible with further damage modeling.
- Alternative base saturation factor and dose-response slopes recently proposed by the same team (van Zelm et al. 2007) is likely to provide an interesting basis for the next generation of acidification methods. The possibility to determine proxy of the changes in base saturation and in dose-response for various continents need to be further explored.

1.3.6 Learning and recommendations for a method providing worldwide generic factors

A method to determine indicators for acidifying substances reflecting the state of the art and in line with LCA should propose a framework that includes:

- a fate and model linking emission to the receptor environment (soil, water or build area), disregarding the transfer to ocean and considering at least the transfer to land
- A load to the receptor environment expressed in terms of cation capacity, N-corrected (see above)
- average fate sensitivity factors to sensitive areas, for impacts focusing on biodiversity & bioproductivity damages; this could be determined at least at continental level by a model or by expert judgment, the fate sensitivity is expected to be non zero in areas over critical load
- improved methods on better dose-response is needed for impacts focusing on biodiversity & bioproductivity damages; a dose-response slope is non zero in areas over critical load
- an average transfer to built area for impacts focusing on materials
- the latest changes in acidifying emission levels (this is strength and weakness at the same time as the magnitude of emission is changing with the time)

As a result of this evaluation of the six acidification methodologies, the following possibilities could be explored to better derive methods that include worldwide characterization factors for a global situation.

A simplistic model for biodiversity/bioproductivity could combine results from an existing atmospheric fate factor and use expert judgment to estimate the fraction of land being sensitive area in combination with a load to the receptor environment expressed in terms of cation capacity. To link emission to deposition for Europe start from Seppälä et al. (2006) or related model, for North America, start from TRACI. For other continents, or even all continents, use global model, such as the York model[4] (Kuylenstierna et al. 2001) or equivalent to derive average transfers to land and sensitive areas.

For derivation of a more sophisticated method to include worldwide characterization factors of all impacts it would be necessary to model the different cause-effect chain including biodiversity, bioproductivity, and material modification.

Atmospheric fate factors: use a global fate model such as such Kuylenstierna et al. (2001) Bouwman et al., (2002) ; Dentener et al., (2006) , GEOSCHEM or equivalent to derive emission to deposition matrices consistently among all the continents.

For biodiversity & bioproductivity impacts determine the soil fate sensitivity factors, by modeling the changes in key soil parameters (base saturation and/or pH) on the global scale for a number of ecosystem types, such as forests (as Huijbregts and colleagues did for Europe), natural grasslands, aquatic ecosystems etc. Identify the available models that would fit the scope of this task. For example, one can use the European steady state version of Smart 2 model (Van Hinsberg and Kros 2001; Kros 2002) available for forests. This model can be used both for critical load and for damage approaches. For this latter develop then an effect model for the various ecosystem types and response parameters (e.g. dose-response for pH in heath lands) as suggested by van Zelm and colleagues (2007). Combining the different models one can then calculate a global set of characterization factors for critical load and for damage approaches and evaluate the possibility of generating a generic compartment and set of characterization factors.

When considering aquatic acidification one should consider the direct deposition on surface water and the indirect transfer via the soil. Further area of development is also required to assess temporal

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[4] http://www.york.ac.uk/inst/sei/rapidc2/sens/risktext.html

changes, to assess changes in sensitive area due to changes in emission level (dynamic modeling). Finally for damage on man-made environment a fraction of built area should be considered.

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2 Midpoint to damages modeling and indicators

2.1 Context

The Life Cycle Initiative, a joint project between UNEP and SETAC, has proposed a comprehensive LCA framework to combine midpoint-oriented and damage-oriented approaches in a common and consistent framework (Jolliet et al., 2004). The present discussion focuses on the second part of the assessment from midpoint to damages for all LCIA impact categories. Although this intends to stimulate developments both for midpoint and damage modeling, users may choose to stop at any intermediary level, as a function of model uncertainty and easiness for further interpretation and possibly weighting (if desired and appropriate). Since the LCIA work of the UNEP-SETAC mainly focused on midpoint indicators and modeling, this part only constitutes a starting point to assess environmental relevance across the different midpoint impact indicators and a preliminary basis to ensure a consistent and common approach to damage modelling.

2.2 Objective and process

To enable a good coordination between the different UNEP-SETAC LCIA task forces, it is important to have from the start a consistent and common approach to damage modelling across the different impact categories.

To achieve this, two complementary approaches have been conducted during 2004:

- Based on a common template, all taskforces have described the different impact pathways relating LCI results - emissions and extractions - to midpoint and eventually damage categories. (bottom-up approach: see zip file "Midpoint to Damages all TF.zip" containing all templates).
- The updated UNEP/SETAC LCIA framework has been published in the Int J. of LCA (Jolliet et al., 2004). Table 1 and chapter 5 of this paper especially describe in detail the damage categories and their relation to midpoint categories, in a top-down damage to midpoint approach.

Based on these two inputs, an updated table has been produced to identify and compare the different proposals from the task forces with the Int. J of LCA paper. The present working document summarizes the result of this discussion as a preliminary input to the different task forces and as a starting point towards a consistent and common approach to damage modelling across the different impact categories. This section starts with some general statements on the potential, limitations, and role of damage modelling in LCIA as inspired by the 2004 Portland LCIA meeting. It then specifically addresses the following questions:

- Which common damage indicator(s) could be retained as a default basis for a given damage category (e.g. damage on human health, biotic natural environment, abiotic resources)?
- What is the best way to structure and eventually group damage categories to enable the easiest midpoint to damage modelling?

2.3 General statements on midpoint and damage/endpoint modelling

Based on the analysis of impact pathways in individual midpoint impact categories, we first list a series of statements to guide further development of recommendations and comparisons for midpoint to damage modeling. We then describe some possible damage categories and indicators where there is sufficient knowledge available.

Choice of midpoint and damage indicators

As discussed by Jolliet et al. (2004) and Bare and Gloria (2006) impact categories can be divided into two groups.

The first group includes relatively well-established midpoints (e.g. global warming) based on common impact mechanisms and for which further modelling does not differentiate between various substances. This type of impact categories is illustrated in Figure 2.1 in Bare and Gloria (2006). Examples of the first type of traditional midpoint categories include: ozone depletion, global warming, acidification, eutrophication, and smog formation. In practice many methods do not report the endpoint level (case of skin cancer), which is an interim result but reported in a damage units. These damage models can have units of Disability Adjusted Life Years (DALYs), an aggregation of environmental impacts, monetary value, or other aggregated damage units.

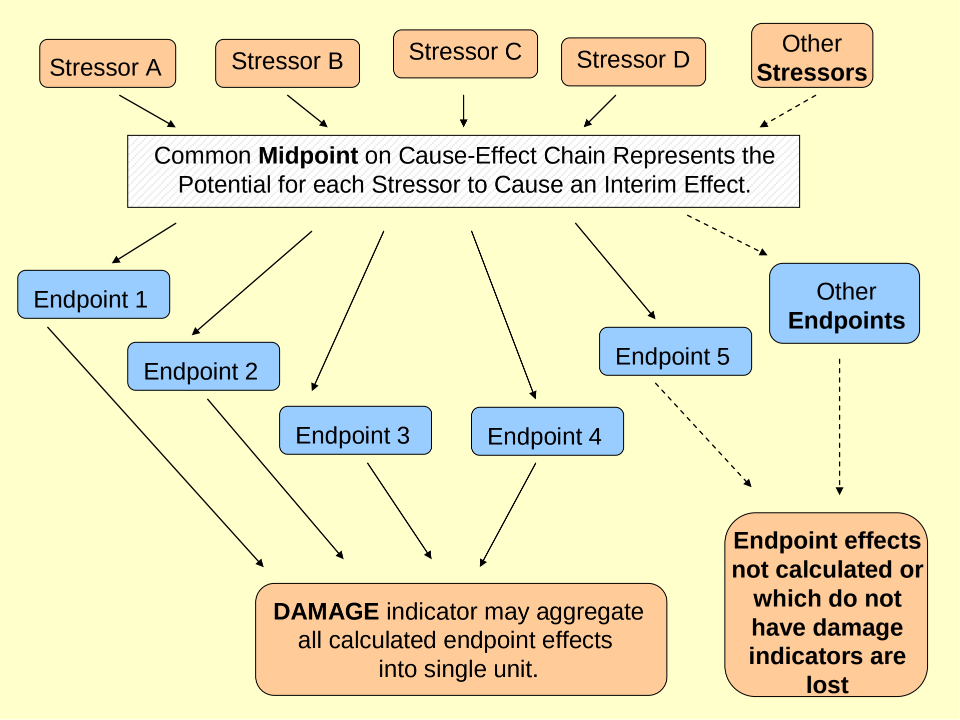

Figure 2.1. Progression from Inventory flow to Damage for Classic Midpoint Impact Categories. Note that endpoints not included in the damage indicators are lost. (Excerpted from Bare and Gloria, 2006)

Even though the remainder of the environmental mechanism from midpoint to endpoint to damages describes the link to environmentally relevant endpoint indicators, this sometimes occurs at the expenses of the comprehensive nature of the midpoint, and likely resulting in higher uncertainty. In certain categories, providing methodological approaches that characterize the environmental mechanism closer to endpoints and damages does not provide additional distinction of differences in impact between substances. However, a model between damage and midpoint may add relevance (either in a quantitative or qualitative manner – in cases where quantification of endpoints is difficult to impossible), and this relevance may be added for all substances in the same way. This could also enable us to compare the outcomes of different midpoint categories using models based on natural science instead of weighting factors based on social science. In a midpoint model it seems wise to minimize the unnecessary uncertainty by choosing a midpoint indicator as early as possible in the environmental chain where all substances are unified in an indicator yet the five criteria are still satisfied: comprehensiveness, relevance/reproducibility, transparency, validity and compatibility (see Section 1).

The second group of impact categories which is illustrated in Figure 2.2 in Bare and Gloria (2006) may not have a common midpoint and are comprised of different environmental mechanisms. Examples of the second type of impact categories which are almost always represented at an aggregated level (either at damage or midpoint level) include human toxicity and ecotoxicity, where interim human health endpoints that may be aggregated include neurological, reproductive, respiratory, and cardiovascular health endpoints. The aggregation may be in units of DALYs, monetary value, or a unitless score which is based on the relative human toxicity potency after including the fate, transport, and toxicity of the substances and comparing to a reference substance.

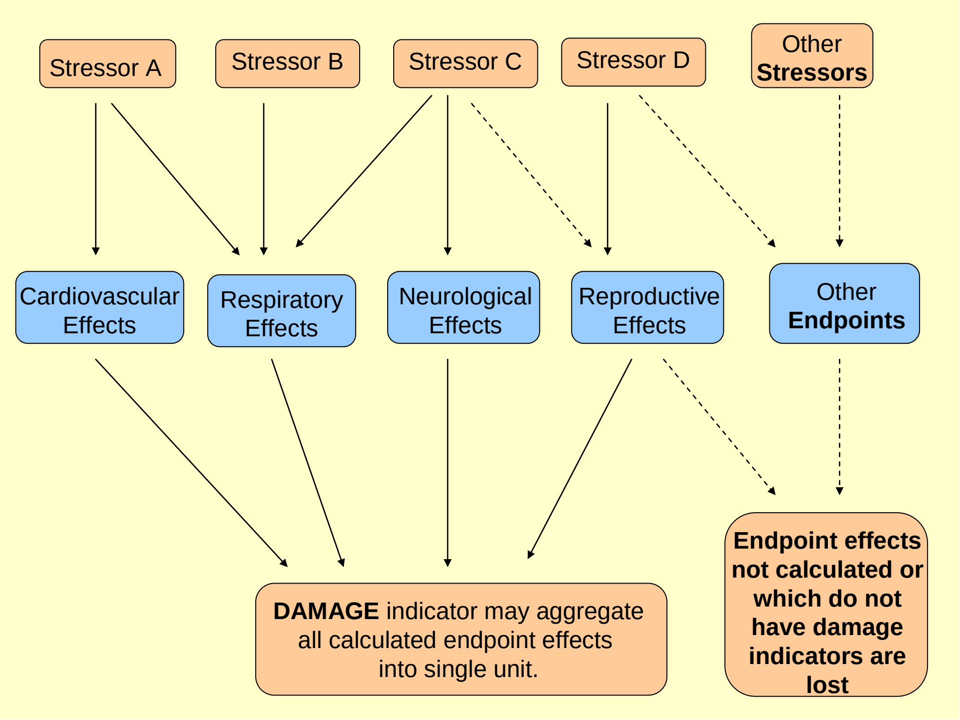

Figure 2.2. Progression from Inventory flows to Damage for Human Health. Note that endpoints not included in the damage indicators are lost. (Excerpted from Bare and Gloria, 2006)

The following points should be considered:

1) For the first group of impact categories described above, the goal of damage modelling is to make results in different midpoint categories comparable, and sometimes to arrive to a single score, or smaller number of environmental scores. It can then replace or

support weighting practices in the midpoint approaches. **The choice to stay at the midpoint level or go to the damage level is left to the user.**

2) When the decision has been made to go to the damage level on an impact category of the first type (e.g., global climate change), **care must be taken to ensure comprehensiveness.** For example, while it may be relatively easy to quantify some impacts (e.g., malaria), other impacts (e.g., the impact on biodiversity) may not be so easily quantified and thus may be lost.

3) **Intermediary steps should be made explicit and reported separately.** For example, if number of cases, Years of Life Lost (YLL) and Years of Life Disabled (YLD) are utilized then these should be considered first separately for impacts on human health. Disability weighting could then be explicitly considered if desired to group diseases together to arrive to DALY.

4) **All modelling (midpoint and damage) should be properly documented on data and modelling uncertainty and reliability. Value choices should be made explicit and properly documented (implicit and explicit in midpoint and damage modelling).** As a matter of fact, it is important to be more specific about these values choices to decrease the uncertainty. **There is no unique universal set of values.**

In addition to the above points, the following specified subcriteria are presented:

(1) *comprehensiveness relative to various Area of Protection*[5]*:*
    Are all possible impacts included? Is double counting avoided? If occurring, it should be identified.
(2) *environmental relevance and reproducibility,*
    Are all the category indicators and characterisation models consistently attributional or consequential?
(3) *transparency - easy of understanding and applicability,*
    Are value choices and assumptions explicit? Please list them.
(4) *scientific validity and reliability,* and
    Do all category indicators and characterisation models linking midpoint to damage fulfill the requirements on being science based?
    Are the temporal and spatial system borders consistent and defined for corresponding category indicators and characterisation models?
(5) *inclusion and compatibility with weighting and normalization*.

Further guidance is required on the following: 1) what is the best technique to develop weighting factors consistently for midpoint or damage assessment results?, 2) How does one differentiate between value based weighting and modelling assumptions and what is allowed for comparative assertions within ISO 14044? (Hertwich, 2002, Marsmann et al, 1999, and Hertwich et al., 1998).

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[5] how far is the indicator representative to all the endpoints relevant for this impact category?
In some LCA methods, YLL have been based on an implicit weighting (a death at 20 years old is equivalent to 3 deaths at 60 years old for a life expectancy of 80. In Murray et al., xxx, the unaggregated DALY and YLL are named the DALY [0,0] and the YLL [0,0]

2.4 Proposal for initial indicator at damage level

Regarding the remaining divergences of opinions on the use of damage indicators and the high uncertainty associated with their calculation, care must be taken before making recommendations in this domain to avoid loss of credibility in the approach. The main use of the proposed table below at present time is therefore to assess environmental relevance across the different midpoint impact categories in a consistent and common approach.

Table 2.1 summarizes many of the main damage types as well as an initial default indicator that is based on the cause-effect chain. Additional details in the damage description are defined in the section 5 of Jolliet et al., 2004.

Table 2.1 Damage categories and possible damage indicators (N°: number; YLL: year of life lost; YLD: year of life disabled; DALY: disability adjusted life years, PDF; percentage of disappeared fraction of species)

Subjects considered	**Damages related to intrinsic values**	**Damages related to functional values**	**Damage measured**	**Possible damage indicators as a default**
Human life	Human health (intrinsic)		Both mortality and morbidity	N° and age of death, N° and duration of diseases, YLL, YLD, DALY
		Human health (labour and productivity)	Loss in productivity	usually not considered, related to indicators for intrinsic damage on human health
Biotic environment	Biotic natural environment (biodiversity)		Loss or disappearance of species	PDF-m^2-year
		Biotic productivity, grouping biotic nat. resources (e.g. tuna) and man-made biotic	Biotic productivity loss	Net Primary Production or $ of productivity losses
Abiotic environment	Abiotic natural env. (e.g.rapids)		--	Biotic natural env. as proxy
		Abiotic nat. resources (e.g.water,miner.)	intermediary towards damages on biodiversity and human welfare	MJ surplus energy
	Man-made abiotic envir. cultural objects	Man-made abiotic envir. (e.g. houses)	Physical destruction or impairment of objects	Cost for repair or loss in monetary units

1. **Human health**: For damages on human health, the aim is clearly to measure both mortality and morbidity. It is important to keep distinct and separate the different steps of the dose-response and severity assessments. One option is to first characterize and report damages separately in terms of the following indicators: number (or risks) and age of death, number and duration of morbidity for different types of illness. This can then lead to a calculation of the Years of Life Lost and Years of Life Disabled for different types of morbidities. Disability weighting could then be explicitly considered if desired to group diseases together to arrive to DALY. Note that the value choice of assuming equal severity for different diseases is often implicitly made when performing human toxicity characterization modeling based on No Observable Effect Level (NOEL), Lowest Observable Effect Level (LOEL) or similar toxicity measures and expressing the human health units in substance equivalents (e.g., benzene equivalents, toluene equivalents).

Specific issues: As dose-response information often relies on animal bioassays, the type of morbidity could be difficult to establish for a given chemical. This means that the present damage oriented approaches are likely to rely on morbidity classes (e.g., for carcinogens and non-carcinogens as proposed by Crettaz et al. 2002 and Huijbregts et al. 2005). Also note that for many substances the toxicity testing is often conducted to the Lowest Observable Effect Level (LOEL). This means that additional effects may occur above this concentration for different effects at various levels. Consistently calculating the severity of each of these possible effects at different effect levels is seldom done because of lack of data to support the calculation for the full array of health impacts for each substance.

2. Biotic natural environment (biodiversity), At present time, we are aiming to measure decrease or disappearance of species from the local area (not necessarily from the globe), also linked to the biotic environment. Note that measure of potentially (?) affected fraction of species, such as PAF, is an intermediary measure of species decrease. Fraction of disappeared species, such as PDF is more suited to characterize the loss of species. It has then to be integrated over a certain area and time to yield a damage indicator that can be related to a unit emission in kg. Further research is needed in order to extend indicators for the terrestrial ecosystem to disappearance of species in aquatic ecosystems.

Specific issues: In the determination of the loss of species, a weighting of the “importance” of species could eventually introduce severity to ecotoxicological impacts, for instance based on the categories of the IUCN red list. Complexity will be difficult to handle in this context, not only due to different ecological functions and related importance of species in an ecosystem, but also linked to different substitutability of a species to retain the ecological function of the ecosystem.

3. Biotic natural resources and **man-made biotic environment** are difficult to distinguish in practice. As impact pathways consider both these area (a forest is often both a natural resource and a man-made biotic environment), these could be grouped under the term of e.g. **biotic productivity**. Net Primary Production can be considered as an interesting indicator, but to our knowledge, addresses mostly algae and vascular plants. Further studies are required to see how this can be extended to cover fish stocks, etc. A possible alternative is to measure and express damages in term of monetary productivity loss.

4. Abiotic nat env. (e.g. rapids). So far there is no intention to model this damage category in LCIA. It is suggested to keep the biotic natural environmental indicator as a proxy.

5. Whether **Abiotic natural resources** is an intrinsic endpoint or has an intermediary status towards damages on biodiversity and human health is still debated and needs further clarification. So far additional MJ to close the Life Cycle could be retained, but the exact status of this indicator needs to be further defined. Stewart and Weidema (2005) chose to present their modelling for future backup technologies as part of impact assessment, mainly because there is a tradition to treat resources as an impact category in LCA.

Weidema et al. (2005) discuss that it would be preferable to place it as part of the inventory analysis, in parallel to for example future waste treatment processes. This would make it easier to ensure that the same inventory procedures for data collection and forecasting would be applied, thus increasing the overall consistency of the LCA modelling. Weidema et al. also broadened the need for further assessment as follows: " It is generally agreed (e.g. Jolliet et al. 2004) that resources have mainly an instrumental value, i.e. resources are valuable because they enable us to produce or protect other things that have intrinsic value to us, although different people may have different opinions concerning the intrinsic values. We believe that, over and above the current and future biophysical impacts of resource use, there are also other economic and social impacts of relevance such as distributional impacts and impacts on human productivity which, as higher order effects, will also have impacts on human health and well-being. This implies that, even if the biophysical impacts of future resource extractions are included in the inventory analysis as suggested above, there are other impacts which still needs to be accounted for."

Specific issues: While being beyond the scope of the present work, it is important to note that an additional link to environment via social life cycle impacts can be foreseen as an indirect effect: If resources are fully extracted from the South to the North, poverty will increase and thus unsustainable use of potentially renewable resources will also increase leading to further damages.

6. For man-made biotic environment, the damage consists of a physical destruction or impairment of the object, with the consequence of a loss of market value in the case of market-able objects. In the case of non-marketable goods like historical sites, the impairment reduces their intrinsic values. It is proposed to consider the cost of repair or the losses in monetary values.

Complementary to these considerations, Table III.1 in appendix III presents an overview of damage categories and their link to midpoint categories, adapted from Jolliet et al., 2003b on the basis of received templates from the different task forces. An additional line summarizes the indicators retained as a default starting basis.

7. The notion of 'Life Support Function' (LSF) could also be introduced in the context of Table 2.1, as an additional concept to help understanding of the value judgment inherent in some midpoint categories. According to Udo de Haes et al. (2002), LSFs are major regulating functions within the environment that enable a life on earth that could also deserve to be protected. Particular LSFs are: climate regulation, hydrological cycles and soil fertility. For example, climate equilibrium can be considered as having an intrinsic value deserving to be protected from damage. As suggested by Heijungs et al.(2003), LSFs then play a role at midpoint level similar to areas of protection at damage level: LSFs could be considered as safeguard subjects at midpoint level, representing operational groups of items of value to human society for some midpoint categories. While the exact status and role of LSFs needs to be further clarified (for further explanations refer to Udo de Haes et al. 2002), it can presently be recognised that the LSF concept helps to make explicit the values behind some of the midpoint categories, as global warming, and therefore aids the performing of a proper weighting exercise at that level, if appropriate and desired. It can further be acknowledged that LSFs have an intermediary character compared to human health and natural environment, as damage to climate regulation, for example, could generate further damages to human and non-human life.

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3 Spatial and temporal differentiation in LCI and LCIA modeling

3.1 Context

An initial discussion was carried out at the SETAC Portland meeting in 2004, followed by exchanges with members of the LCI programme and in the LCIA steering committee. On this basis, an initial document is presented below setting basic principles determining a) the need for spatial and temporal differentiation, b) the way to address spatial and temporal differentiation and an initial attempt to apply c) the consequences for LCI and LCIA modelling and d) the next steps to be taken.

3.2 Need for spatial differentiation

The definition study in the Terms of Reference of the task forces defined that where relevant; the need for spatial and temporal differentiation will be identified. The following way to address spatial differentiation was suggested: "Generic situation dependency[6] can be introduced to account for those main archetypical situations (or patterns) leading to important variations in characterisation factors and therefore justifying a differentiation.

Building on this and on discussions in several LCIA workgroup meetings, the following pragmatic approach is suggested:

1. As a default, a generic situation should be defined corresponding to the most likely situation at continental level (e.g. mean population density in Europe; most likely values of pH and DOC-dissolved organic carbon concentrations in waters for copper toxicity)

2. Differentiation should be considered if sensitivity studies show that high variations in characterization factors for a given category are observed, that is,,at least a factor 2 to 10 depending on the uncertainty in the category.

3.3 Ways to address spatial differentiation in modelling, including initial application

Two different options have been identified to address spatial differentiation, with a possibility to combine them:

2a) *Archetype differentiation:* Based on sensitivity studies, a restricted set (e.g. 5) of archetypical situations could be defined for specific impact categories (e.g. desertic area, low population densities - rural area, medium population densities, highly populated urban center; 5, 25, 75 and 95 percentile conditions of DOC (dissolved organic carbon) and pH corresponding to variations in ecotox characterization factor). Sets of factor are determined for these archetypical situations. This mainly makes sense for archetypical situations for which the characterization factors are equal or

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[6] Generic situation dependency: different situations where LCA is used in different types of application are identified. The different situations may pose different requirements to the LCIA methodology. For each of these situations, generic recommendations on LCIA methodology are given.

have similar fate and exposure behaviours. This is not always the case for categories like acidification involving a fate component where the transfer fraction to sensitive areas has to be considered.

This means that the inventory should be differentiated in terms of these archetypical situations (emissions in highly densely populated area), enabling the application of the respective factors. A possibility is also to associate certain industry sectors or emission types with given archetypes: for example, road traffic is associated to emission at ground level, whereas electricity generation power plants usually involve high stacks.

2b) *Geographical differentiation:* Alternatively, a direct geographical differentiation could be performed by providing directly characterization factors as a function of the location of emission that need to be recorded in the inventory. This differentiation could take place at continental, national, regional or local levels depending on the magnitude and scale of the expected variations.

2c) *Combined archetype-geographical approach:* When relevant maps could show the spatial repartition over region, continent or worldwide of the archetypical situations defined in 2a) to help the practitioner to select the right archetype when the location of emission is known and to look at the necessary resolution to provide reliable factors. For acidification, for example, emission on a given continent can be associated to a given archetype. Tables could also be developed to relate, for example, very localized zip codes, with given archetypes.

The advantage of the archetype based approach is that there are only a restricted number of archetypes that need to be reported. The potential problem is that these archetypes will differ between impact categories, meaning that several archetypes should be reported for the emissions of a given process. An alternative is to report the fraction of emissions for a given process that is emitted for the different conditions.

Table 3.1 presents an initial attempt to propose main spatial archetypes for different impact categories, with most relevant spatial differentiation in bold red characters. This template will need to be further refined in parallel with the development of guidance for each midpoint category, e.g. for categories such as land use and related issues of salinization and erosion.

Table 3.1: definition of main spatial archetypes situations to differentiate in priority

Midpoint categories:	**Factors of very high influence and differentiation criteria**	**Proposed archetypes**	**Characteristic scale**
Human toxicity **Particulate matter** **Respiratory inorganics**	Population density	High population density - urban Medium population density Low population density-rural	Regional scale for short life substances and continental scale for PBT
	+ Dilution volume	+ Indoor emissions	indoors vs outdoors
	Emission height above ground	Height of emission or ground-pipe/stack/plane	process type (car/plane travel, industrial combustion processes)
Acidification	Fate & transport factor marginally / sensitive area Buffering capacity and sensitivity	fraction of emission to sensitive areas (to be further refined)	Large differences within continent and between continents
Aquatic and terrestrial Eutrophication	Fate & transport factor to P-limited and to N-limited area for freshwater and marine coastal water	fraction of P-limited area for freshwater/marine water fraction of N-limited area for freshwater/marine water	Continental level or very localized data (e.g., stream fate analysis)
Ecotoxicity	Fate & Transport: residence time of water to ocean	Emission to river water basin Emission to lake water basin	large regions in continent
	Sensitivity of eco populations which are exposed.	Deserts, lakes, forests, grasslands, etc.	Localized
Freshwater use	To be framed further	To be defined for physical impacts of water depletion	Highly local

3.4 Temporal differentiation

Temporal differentiation can play an important role in a variety of impact categories. Time is important when quantifying the impacts of persistent substances and long term impacts such as global warming or impacts of metals which can take place over years. The specific timing of the emission can also be important in short term categories such as smog formation where the magnitude of the resulting problem can be dependent upon the season of the emission and even the time of day of the emission. The interaction with Life Cycle Inventory is essential as the emissions themselves can take place over decades, centuries (e.g. building disposal) or even thousands of years in the case of landfill emissions.

On the one hand, LCA system boundaries are usually selected while considering a functional unit, and are often covering broad temporal and geographical boundaries. In these cases, short, midterm, and long term impact should all be addressed. Overall impact with integration over milleniums may significantly enhance assessment uncertainties.

Temporal discounting is a value choice which may be imposed on an LCA system, but it should only be applied if both inventory and impacts are consistently temporally differentiated. It could be used to address functional damage categories such as man-made environment or biotic productivity. If the idea of equity across generation, it could be less suitable for intrinsic damages on human life where a discount is debatable.

As a pragmatic solution it is proposed that calculations for impacts in all LCIA midpoint and damage categories be conducted for two time horizons (Udo de Haes et al. 1999):
- Best estimate for overall impacts as a baseline (integration up to infinite or very long term)

- 100 years as an alternative to study the impact of temporal criteria.

3.5 Consequences for LCI modelling and reporting

An archetype differentiation requires in practice that a limited number of these archetypes is well defined and broadly accepted to have LCI results differentiated per archetype at a process level. Inventory result then need to be specified by the type of emission condition (e.g. emission in high/low density populated area or in urban area).

For spatial differentiation, the location of emission could be characterized by latitude/longitude and continent/country/region/location. We will hence need a hierarchy (e.g. GIS code, continent, country) that need to be reported in the LCI to be useful. The connection between a coordinate and the receiving environment can be automated in GIS but still has many subjective aspects according to different scales, precisions and accuracies in spatial data. A set of data to describe the location information will be needed and should already be available in the geo-data community.

The continental differentiation represents a minimal resolution. Additional requirements on the inventory should be restricted to most important variations as defined above.

3.6 Consequences for LCIA modeling

For time differentiation, we propose that all characterization factors be reported when relevant for both 100 years and very long term effects.

For spatial differentiation, all methods should be able to differentiate impact at least as a function of continental characteristics in an initial step.

Appendix I: Comparison of five methods for acidification

See worksheet "Acidification" in file "Comparison analysis acidification TF1-v21.xls"

Appendix II: General evaluation criteria

See worksheet "General criteria" in file "Comparison analysis acidification TF1-v21.xls"

Appendix III Analysis of damage to midpoint category indicators

Table III.1: Overview of damage categories, midpoint categories and their links, adapted from Jolliet et al., 2003b. '⊗' indicate relevant links that could be quantitatively modelled, 'x' other relevant links, '()' indicate that these links are only relevant if the corresponding damage category were included in LCA[7]

Subjects considered	**Human life**		**Biotic environment**			**Abiotic environment**		
Damages related to intrinsic values	Human health (intrinsic)		Biotic natural environment (species)			Abiotic natural env. (e.g.rapids)		
Damages related to functional values		Human health (labour)		Biotic nat. resources (e.g. tuna)	Man-made biotic envir. (e.g. crops)		Abiotic nat. resources (e.g.water,miner.)	Man-made abiotic envir. (e.g. houses)
Proposed damage indicators chapter 5 of Jolliet et al.	N° and age of death N°diseases & disease duration DALY, substance equivalents	-	to be defined or PAF-m^2-year PDF-m^2-year	- *to be defined with biotic & abiotic natur. environment*	*not represented so far, if needed: prevention cost or loss or Biotic natural env. as proxy ?*	- *Biotic natural env. as proxy ?*	MJ surplus energy for future procurement	- cost for repair or loss in monetary units
Midpoint categories:								
Human toxicity for particulate conc PM2.5	⊗ YLL, YLD, DALY, substance equivalents	(x)						
Casualties	⊗	(x)	x	(x)				
Noise	⊗	(x)	x	(x)	(x)			
Photooxidant formation	⊗ YLL, YLD, DALY	(x)	⊗	(x) NPP	(x) NPP, crop losses in $			relatively small but significant effect
Ozone depletion (skin cancer, cataract, not human immune system ?)	⊗ YLL, YLD, DALY	(x)	x Phytoplankton, terrestr.plants NPP ?	(x) NPP ?	(x)			
Climate change also beneficial effects !	x high uncertainties to go to DALY	(x)	x high uncertainties to go to PAF or PDF	(x)	(x)			(x)
Acidification	also indirect mobilization of metals		⊗ direct and indirect	(x)	(x)			(⊗) direct effects
Eutrophication aquatic terrestrial: fraction N depos. or area of exceedence ?	via algal blooms		⊗ N marine, P for freshwater PDF ?	(x)	(x)			-
Ecotoxicity			⊗ loss of species, substance equivalents	(x) substance equivalents	(x)			
Land use impacts (arable land)			⊗ to be consider.	(x)	(x)	x	⊗ effects on quality of land as a resource	
Species and organism dispersal			x	(x)	(x)			
Abiotic resource depletion Metallic minerals . Other minerals Energy Freshwater (%reduction of waterbody volume)	x indirect impact on humans	(x)	x x PAF	(*) (x) (x)	Unclear distinction between man-made biotic env. and biotic natural resources(*) (x) (x)	x x	energy to recover the metal only factor ? ⊗ ⊗ ⊗ ⊗	
Biotic resources depletion			⊗	(⊗)	(x)			

([7] The names of the damage categories have been abbreviated. Strictly speaking, the damage categories are **damages to** human health, **to** the biotic natural environment, etc.)