# ILCD handbook

International Reference Life Cycle Data System


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# Recommendations for Life Cycle Impact Assessment in the European context

## - based on existing environmental impact assessment models and factors

First edition

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## Preface

To achieve more sustainable production and consumption patterns, we must consider the environmental implications of the whole supply-chain of products, both goods and services, their use, and waste management, i.e. their entire life cycle from “cradle to grave”.

In the Communication on Integrated Product Policy (IPP), (EC, 2003), the European Commission committed to produce a handbook on best practice in Life Cycle Assessment (LCA). The Sustainable Consumption and Production (SCP) Action Plan (EC, 2008) confirmed that *“(…) consistent and reliable data and methods are required to assess the overall environmental performance of products (…)”*. The International Reference Life Cycle Data System (ILCD) Handbook, based on the existing international standards on LCA, ISO 14040/44, provides governments and businesses with a basis for assuring quality and consistency of life cycle data, methods and assessments.

This guidance document provides recommendations on models and characterisation factors that should be used for impact assessment in applications such as Life Cycle Assessment (LCA). This supports the analyse of emissions into air, water and soil, as well as the natural resources consumed in a single integrated framework in terms of their contributions to different impacts on human health, natural environment, and availability of resources. It supports the calculation of indicators for different impacts such as climate change, ozone depletion, photochemical ozone formation, respiratory inorganics, ionising radiation, acidification, eutrophication, human toxicity, ecotoxicity, land use and resource depletion.

# Executive Summary

## Overview

Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) are scientific approaches behind a growing number of environmental policies and decision support in business in the context of Sustainable Consumption and Production (SCP). The International Reference Life Cycle Data System (ILCD) provides a common basis for consistent, robust and quality-assured life cycle data, methods and assessments. These support coherent and reliable business and policy instruments related to products, natural resources, and waste management and their implementation, such as eco-labelling, eco-design, and green procurement.

This guidance document provides recommendations on the methods to apply for modelling of the most common impact categories, linking emissions and resources consumed over the life cycle to the impact indicators.

## About Life Cycle Impact Assessment (LCIA)

In a Life Cycle Assessment, the emissions and resources consumed linked to a specific product are compiled and documented in a Life Cycle Inventory (LCI). An impact assessment is then performed, generally considering three areas of protection: human health, natural environment, and issues related to natural resource use.

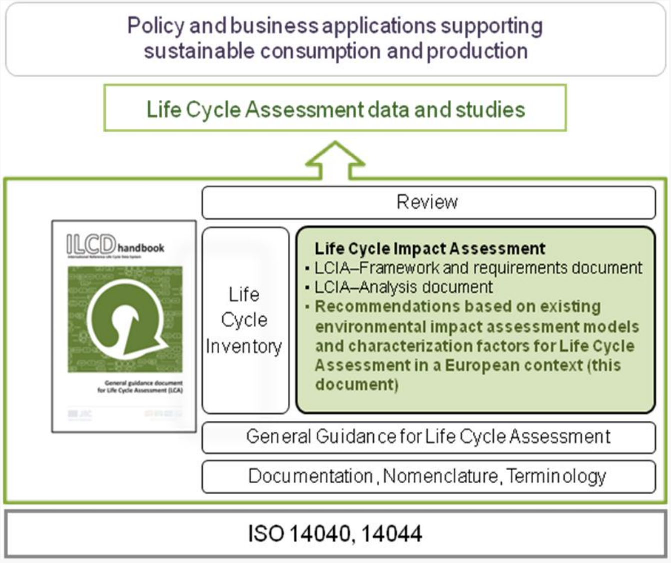
Impact categories considered in the so-called Life Cycle Impact Assessment (LCIA) include climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related), respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion. The emissions and resources derived from LCI are assigned to each of these impact categories. They are then converted into indicators using factors calculated by impact assessment models. These factors reflect pressures per unit emission or resource consumed in the context of each impact category. Emissions and resources consumed, as well as different product options, can then be cross-compared in terms of the indicators.

## About the International Reference Life Cycle Data System (ILCD) Handbook

The ILCD Handbook is a series of detailed technical documents, providing guidance for good practice in Life Cycle Assessment in business and government. The ILCD Handbook can serve as “parent” document for developing sector- and product-specific guidance documents, criteria and simplified tools. The ILCD Handbook is based on the existing international standards on LCA, ISO 14040/44, that provide the indispensable framework for LCA. This framework, however, leaves the individual practitioner with a range of choices that can change the results and conclusions of an assessment. Further guidance is therefore needed to support consistency and quality assurance. The ILCD Handbook has been set up to provide this guidance.

**Role of this Guidance Document within the ILCD Handbook**

This guidance document presents recommendations on the methods to apply for modelling of the most common impact categories, linking emissions and resources consumed to the indicators. It builds on two other LCIA related ILCD documents, the "Analysis of existing Environmental Impact Assessment methodologies for use in LCA" (EC-JRC, 2010a) and the "Framework and Requirements for LCIA models and indicators" (EC-JRC, 2010b).




The recommendations are based on existing models assessed in the overall framework of the Areas of Protection "Human Health", "Natural Environment", and "Natural Resources".

**Approach and key issues addressed in this document**

Several methodologies have been developed for LCIA and some efforts have been made towards harmonisation. Starting from the first pre-selection of existing methods and the definition of criteria, this report describes the recommended methods for each impact category at both midpoint and endpoint.

Recommendations are given for the impact categories of climate change, ozone depletion, human toxicity, particulate matter/respiratory inorganics, photochemical ozone formation, ionising radiation impacts, acidification, eutrophication, ecotoxicity, land use and resource depletion. Research needs are identified for each impact category and differentiated according to their priority.

No method development has taken place in the development of this document. The intention was to identify and promote current best practise. This document does not provide recommendations for weighting across impact categories, nor for normalisation within a given category relative to e.g. impacts in a given region.

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# ACRONYMS

| | |
|---|---|
| AG | Advisory Group of the European Platform on LCA |
| AoP | Area of Protection |
| CF | Characterisation Factors |
| DALY | Disability Adjusted Life Year |
| ELCD | European Reference Life Cycle Data system |
| EPLCA | European Platform on Life Cycle Assessment |
| GWP | Global Warming Potential |
| ICRP | International Commission on Radiological Protection |
| ILCD | International Life Cycle Data system |
| IPCC | Intergovernmental Panel on Climate Change |
| JRC | Joint Research Centre |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| MIR | Maximum Incremental Reactivity |
| NMVOC | Non-Methane Volatile Organic Compounds |
| NPP | Net Primary Production |
| PAF | Potentially Affected Fraction of species |
| PDF | Potentially Disappeared Fraction of species |
| SETAC | Society of Environmental Toxicology and Chemistry |
| UNEP | United Nations Environment Program |
| UNECE | United Nations Economic Commission for Europe |
| US EPA | United States Environment Protection Agency |
| WHO | World Health Organisation |
| WMO | World Meteorological Organisation |

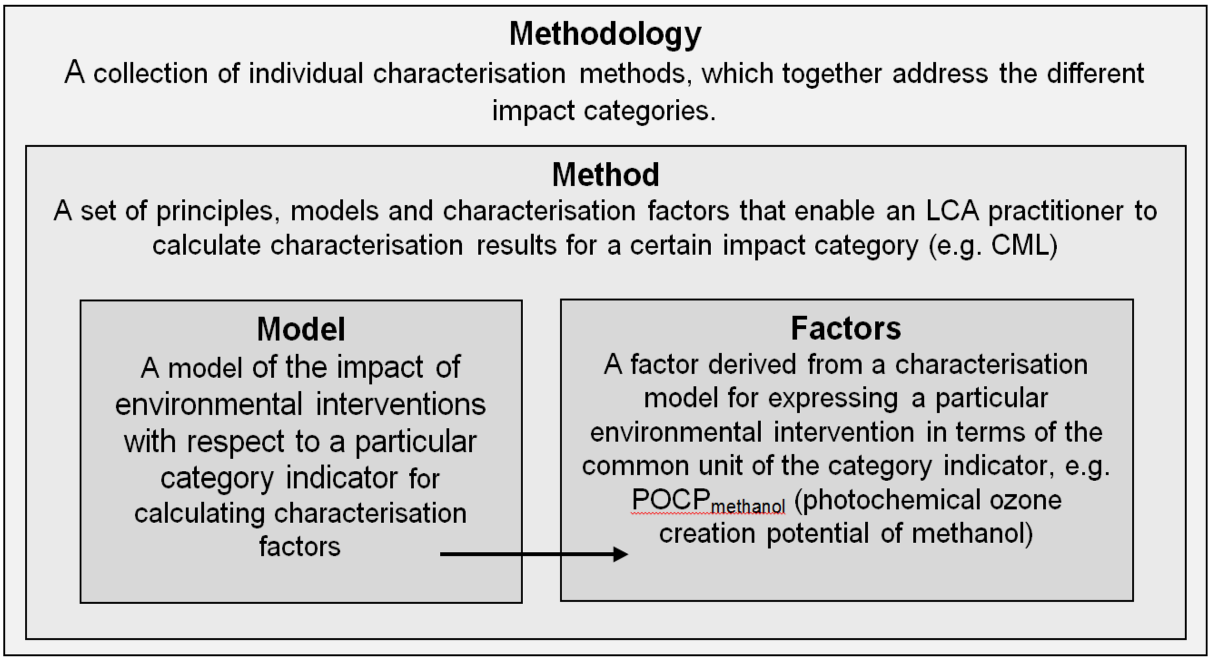
In the text

LCIA – Analysis document: ILCD - Handbook Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment (EC-JRC, 2010a)

LCIA – Framework and requirements document: ILCD – Handbook Framework and Requirements for LCIA models and indicators (EC-JRC, 2010b)

# GLOSSARY

| Definiendum | Definition |
| --- | --- |
| Area of protection (AOP) | A cluster of category endpoints of recognisable value to society, viz. human health, natural resources, natural environment and sometimes man-made environment (Guinée et al., 2002) |
| Cause-effect chain | or environmental mechanism.System of physical, chemical and biological processes for a given impact category, linking the life cycle inventory analysis result to the common unit of the category indicator (ISO 14040) by means of a characterisation model. |
| Characterisation | A step of the Impact assessment, in which the environmental interventions assigned qualitatively to a particular impact category (in classification) are quantified in terms of a common unit for that category, allowing aggregation into one figure of the indicator result (Guinée et al., 2002) |
| Characterisation factor | Factor derived from a characterisation model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the impact category indicator (ISO 14040) |
| Characterisation methodology, methods, models and factors | Throughout this document an “LCIA methodology” refers to a collection of individual characterisation “methods” or characterisation “models”, which together address the different impact categories, which are covered by the methodology. “Method” is thus the individual characterisation model while “methodology” is the collection of methods. The characterisation factor is, thus, the factor derived from characterisation model which is applied to convert an assigned life cycle inventory result to the common unit of the category indicator. |



| Definiendum | Definition |
|---|---|
| Classification | A step of Impact assessment, in which environmental interventions are assigned to predefined impact categories on a purely qualitative basis (Guinee et al 2002) |
| Elementary flow | Material or energy entering the system being studied has drawn from the environment without previous human transformation (e.g. timber, water, iron ore, coal) , or material or energy leaving the system being studied that is released into the environment without subsequent human transformation (e.g. $CO_2$ or noise emissions, wastes discarded in nature) (ISO 14040) |
| Endpoint method/model | The category endpoint is an attribute or aspect of natural environment, human health, or resources, identifying an environmental issue giving cause for concern (ISO 14040). Hence, endpoint method (or damage approach)/model is a characterisation method/model that provides indicators at the level of Areas of Protection (natural environment's ecosystems, human health, resource availability) or at a level close to the Areas of Protection level. |
| Environmental impact | A consequence of an environmental intervention in the environment system (Guinee et al 2002) |
| Environmental intervention | A human intervention in the environment, either physical, chemical or biological; in particular resource extraction, emissions (incl. noise and heat) and land use; the term is thus broader than “elementary flow” (Guinee et al 2002) |
| Environmental profile | The result of the characterisation step showing the indicator results for all the predefined impact categories, supplemented by any other relevant information (Guinee et al 2002) |
| Impact category | Class representing environmental issue of concern (ISO 14040). E.g. Climate change, Acidification, Ecotoxicity etc. |
| Impact category indicator | Quantifiable representation of an impact category (ISO 14040). Eg Kg $CO_2$-equivalents for climate change |
| Life cycle impact assessment (LCIA) | "Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle." (ISO 14040) The third phase of an LCA, concerned with understanding and evaluating the magnitude and significance of the potential environmental impacts of the product system(s) under study |
| Midpoint method | The midpoint method is a characterisation method that provides indicators for comparison of environmental interventions at a level of cause-effect chain between emissions/resource consumption and the endpoint level. |
| Sensitivity analysis | A systematic procedure for estimating the effects of choices made regarding methods and data on the outcome of the study (ISO 14044) |

# 1 Introduction

Life Cycle Thinking (LCT) is a core concept in Sustainable Consumption and Production (SCP) for business and policy. The environmental pillar of LCT is supported by Life Cycle Assessment (LCA), an internationally standardised tool (ISO14040 and ISO14044) for the integrated environmental assessment of products (goods and services). Upstream and downstream consequences of decisions must be taken into account to help avoid the shifting of burdens from one impact category to another, from one country to another, or from one stage to another in a product's life cycle from the cradle to the grave.

A Life Cycle Assessment consists of four phases (ISO 14040). In the Goal and scope definition phase, the aim of the LCA is defined and the central assumptions and system choices in the assessment are described. In the Life Cycle Inventory (LCI) phase, the emissions and resources are quantified for the chosen products. In the Life Cycle Impact Assessment (LCIA) phase, these emissions and resource data are translated into indicators that reflect environment and health pressures as well as resource scarcity. This calculation is based on factors which represent the predicted contribution to an impact per unit emission or resource consumption. These factors are generally calculated using models. In each phase, in the Interpretation phase, the outcome is interpreted in accordance with the aim defined in the goal and scope of the study.

Since the early 1990'ies numerous LCIA methodologies[1] have been developed. The use of several different LCIA methods makes it difficult to compare LCA results and interpret them. To some extent the differences represent different LCIA approaches that may be of interest in certain applications. But a default/baseline method is needed and a single method may be needed in some applications.

The ISO 14042 standard on impact assessment published in 1999, and the later update in the ISO 14044 standard in 2006, brought some standardization on basic principles/framework. This addresses the choice of models[2] in very general terms, and most of the existing LCIA methodologies can be seen as ISO compatible.

As the ISO guidelines on LCA provide a framework rather than technically detailed standardisation, the SETAC working groups, later followed by task forces under the UNEP-SETAC Life Cycle Initiative, started voluntarily work on scientific consensus and development of a recommended best practice. These have been complemented by activities of many other organisations such as JEMAI, US EPA and the European Commission. As result of these activities, recommendations on the best approaches and the underlying principles were developed; see for example Udo de Haes et al, 2002. Achievements include:

[1] See the glossary: Throughout this document an "LCIA methodology" refers to a collection of individual characterisation "models" or characterisation "methods", which together address the different impact categories, which are covered by the methodology. "Method" is thus the individual characterisation model while "methodology" is the collection of methods.
[2] See the glossary

- Consensus on the need to integrate midpoint and endpoint[3] models in a consistent framework to combine the advantages of both concepts (Bare et al., 1999, Bare et al., 2000).
- A generic set of quality criteria for assessing different methods, and the application of these criteria on the most widely used impact assessment methods (Udo de Haes et al., 2002, Margni et al., 2008).
- A growing global consensus among model developers based on best practice for e.g. toxicological effects (fate, exposure and effect). (Hauschild et al., 2008, Rosenbaum et al., 2008).

This is the setting of the International Reference Life Cycle Data System (ILCD), to develop a coherent and consistent LCIA methodology (framework, characterisation models, and characterisation factors) based on an analysis of existing characterisation models, factors and insights.

The International Reference Life Cycle Data System (ILCD) Handbook is a series of technical guidance documents for LCA that complement the International Standards to provide the basis for greater consistency and quality of life cycle data, methods and assessments. This is also the basis for the ILCD Data Network, an open network of inventory data sets provided by government and private organisations that help guarantee quality and consistency.

Reflecting the global nature of product life cycles and the necessity of having globally agreed methods and data, the ILCD is developed in close collaboration with UNEP and with participating national authorities developing LCA databases. This is facilitated by the European Commission, including interactions with representatives of its 27 Member States and Advisory Groups (AG) from business associations, software and database developers, as well as life cycle impact assessment methodology developers[4]. Recognising that most product systems include activities at global level, the recommendations aim for a global validity.

This document is a part of a series of documents developed to give recommendations on the framework and methods for LCIA:

1. ILCD Handbook: Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment [LCIA – Analysis document- EC-JRC (2010a)]
2. ILCD Handbook Framework and requirements for LCIA models and indicators [LCIA – Framework and Requirements document EC-JRC (2010b)] focused on definition of evaluation criteria for recommended LCIA methods and general recommendations for characterisation models and Areas of Protection
3. Guidance on recommended LCIA characterisation methods (models and factors)

[3] See the glossary.
[4] see http://lct.jrc.ec.europa.eu/assessment/partners for details

4. Characterisation factors of the recommended methods, accessible as spreadsheet via the website of the European Platform on LCA[5]

This report describes, the recommended methods for each impact category at both midpoint and endpoint level starting from the first pre-selection of existing methods (LCIA – Analysis document, EC-JRC, 2010b) and the definition of criteria (LCIA – Framework and Requirements document, EC-JRC, 2010b).

## 1.1 Summary of Recommended Methods

The tables below present the summary of recommended methods (models and associated characterisation factors) and their classification both at midpoint and at endpoint.

The recommended characterisation models and associated characterisation factors are classified according to their quality into three **levels: "I"** (recommended and satisfactory), **level "II"** (recommended but in need of some improvements) or **level "III**" (recommended, but to be applied with caution). A mixed classification sometimes is related to the application of the classified method to different types of substances.

Out of the methods that were listed, other methods were included in the analysis but not recommended because they were not mature for recommendation.

In the summary table, the classification "**interim**" indicates that a method was considered the best among the analysed methods for the impact category, but still immature to be recommended. This does not indicate that the impact category would not be relevant but further efforts are needed before a recommendation for use can be given. The evaluation of the methods is reported in the description of each impact category (Chapter 3).

For more clarification, the reader is referred to the section of Chapter 2 where details on the assessment procedure, based on both scientific and stakeholder's acceptance criteria are presented.

The recommendations in this document take into account models that have been available and sufficiently documented for an in depth evaluation in mid 2008. Models developed after this date, have not been taken into account.

If a study intends to claim to be in compliance with the ILCD Handbook, and uses **midpoint indicators** for the assessment, the models and factors at midpoint that have a level I, level II or level III recommendation shall be used. Any geographical differentiation, addition of factors for individual flows and addition of impact methods for not yet covered impacts or improvements on methods have to be explicitly justified and reflected in both the goal and scope definition and in the results interpretation (please also refer to the "ILCD Handbook – General guide – Detailed guidance", chapter 6.7.2 to 6.7.5 and the related "Provisions 6.7 Preparing the basis for the impact assessment.")

Analogously, if a study intends to claim to be in compliance with the ILCD Handbook, and wants to use **endpoint indicators** for the assessment, the recommended models and

[5] http://lct.jrc.ec.europa.eu/

factors at endpoint, that have a level I, level II or level III recommendation, are to be used. Any geographical differentiation, addition of factors for individual interventions and addition of impact methods for not yet covered impacts or improvements on methods have to be explicitly justified and reflected in both the goal and scope definition and in the results interpretation as stated in the “ILCD Handbook – General guide – Detailed guidance”, chapter 6.7.2 to 6.7.5 and the related “Provisions 6.7 Preparing the basis for the impact assessment.” Due to the unavailability of sufficiently mature models for most endpoint categories, recommendations currently can be provided only for a few categories. In order to meet ISO and ILCD requirements to include all relevant environmental impacts, the study needs to provide and use endpoint models and factors for all relevant environmental impacts also for those where currently no recommended ILCD method exists. This applies, unless an explicit restriction to a limited set of categories is stated in the study goal as defined in the “ILCD Handbook – General guide – Detailed guidance”, chapter 5.2.2 and the related “Provisions: 5.2 Six aspects of goal definition”.

For those impacts where no models have been recommended, the methods classified as “interim” can be considered as the best among the analysed methods but not mature for recommendation.

Please note that the use of a reduced set of impact categories shall be explicitly considered in the results interpretation and be explicitly communicated to the target audience. See the “ILCD Handbook – General guide – Detailed guidance”, Provisions: 6.10 Comparisons between systems”, provision VII.”

As stated in the ILCD Handbook, the selection of the impact categories must be consistent with the goal of the study and the intended applications of the results, and it must be comprehensive in the sense that it covers all the main environmental issues related to the system.

**Table 1 Recommended methods and their classification at midpoint**

| | **Recommendation at midpoint** | | |
|---|---|---|---|
| **Impact category** | **Recommended default LCIA method** | **Indicator** | **Classification** |
| **Climate change** | Baseline model of 100 years of the IPCC | Radiative forcing as Global Warming Potential (GWP100) | I |
| **Ozone depletion** | Steady-state ODPs 1999 as in WMO assessment | Ozone Depletion Potential (ODP) | I |
| **Human toxicity, cancer effects** | USEtox model (Rosenbaum et al, 2008) | Comparative Toxic Unit for humans ($CTU_h$) | II/III |
| **Human toxicity, non-cancer effects** | USEtox model (Rosenbaum et al, 2008) | Comparative Toxic Unit for humans ($CTU_h$) | II/III |
| **Particulate matter/Respiratory inorganics** | RiskPoll model (Rabl and Spadaro, 2004) and Greco et al 2007 | Intake fraction for fine particles (kg PM2.5-eq/kg) | I |
| **Ionising radiation, human health** | Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000) | Human exposure efficiency relative to $U^{235}$ | II |
| **Ionising radiation, ecosystems** | No methods recommended | | Interim |
| **Photochemical ozone formation** | LOTOS-EUROS (Van Zelm et al, 2008) as applied in ReCiPe | Tropospheric ozone concentration increase | II |
| **Acidification** | Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008) | Accumulated Exceedance (AE) | II |
| **Eutrophication, terrestrial** | Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008) | Accumulated Exceedance (AE) | II |
| **Eutrophication, aquatic** | EUTREND model (Struijs et al, 2009b) as implemented in ReCiPe | Fraction of nutrients reaching freshwater end compartment (P) or marine end compartment (N) | II |
| **Ecotoxicity (freshwater)** | USEtox model, (Rosenbaum et al, 2008) | Comparative Toxic Unit for ecosystems ($CTU_e$) | II/III |
| **Ecotoxicity (terrestrial and marine)** | No methods recommended | | |
| **Land use** | Model based on Soil Organic Matter (SOM) (Milà i Canals et al, 2007b) | Soil Organic Matter | III |
| **Resource depletion, water** | Model for water consumption as in Swiss Ecoscarcity (Frischknecht et al, 2008) | Water use related to local scarcity of water | III |
| **Resource depletion, mineral, fossil and renewable**[6] | CML 2002 (Guinée et al., 2002) | Scarcity | II |

[6] Depletion of renewable resources is included in the analysis but none of the analysed methods is mature for recommendation

**Table 2 Recommended models and their classification at endpoint**

| | Recommendation from midpoint to endpoint | | |
|---|---|---|---|
| **Impact category** | **Recommended default LCIA method** | **Indicator** | **Classification** |
| **Climate change** | No methods recommended | | interim |
| **Ozone depletion** | No methods recommended | | interim |
| **Human toxicity, cancer effects** | DALY calculation applied to USEtox midpoint (Adapted from Huijbregts et al., 2005a) | Disability Adjusted Life Years (DALY) | II/interim |
| **Human toxicity, non-cancer effects** | No methods recommended | | interim |
| **Particulate matter/Respiratory inorganics** | DALY calculation applied to midpoint (adapted from van Zelm et al, 2008, Pope et al, 2002) | Disability Adjusted Life Years (DALY) | I/II |
| **Ionising radiation, human health** | No methods recommended | | interim |
| **Ionising radiation, ecosystems** | No methods recommended | | |
| **Photochemical ozone formation** | Model for damage to human health as developed for ReCiPe (Van Zelm et al, 2008) | Disability Adjusted Life Years (DALY) | II |
| **Acidification** | No methods recommended | | interim |
| **Eutrophication, terrestrial** | No methods recommended | | |
| **Eutrophication, aquatic** | No methods recommended | | interim |
| **Ecotoxicity (freshwater, terrestrial and marine)** | No methods recommended | | |
| **Land use** | No methods recommended | | interim |
| **Resource depletion, water** | No methods recommended | | |
| **Resource depletion, mineral, fossil and renewable** | No methods recommended | | interim |

# 2 Recommended methods for impact categories

The recommendations in this guidance document are made based on an analysis of a wide range of existing methods used in LCIA, supplemented by a selection of environmental models that cannot currently be found integrated into LCIA methodologies, but which have interesting features to consider in the development of recommendations for LCIA.

First step of the analysis was a pre-selection of models based mainly on whether they were in use in LCIA or contained elements which could be interesting for the straightforward development of models for use in LCA. If a method is used in multiple LCIA methodologies, only the most recent and up to date version of that method was considered (please refer to the LCIA- Analysis document, EC-JRC, 2010a).

The second step was the development of general recommendations for each category and the definition of assessment criteria to be used in the evaluation and comparison of the pre-selected methods. The "LCIA- Framework and requirements" (EC-JRC, 2010b) document describes the results in term of recommendations and criteria developed.

## 2.1 Procedure for analysis and classification of methods

It is the purpose of this document to recommend global default/baseline characterisation models and characterisation factors for each impact category. In doing so, this Guidance Document draws on what is available in existing LCIA methodologies[7] supplemented by a selection of environmental models that cannot currently be found as integrated into LCIA methodologies, but nevertheless have features which may be interesting to consider in the development of recommendations for LCIA. The first activity has thus been the identification and pre-selection of characterisation models at midpoint and endpoint level (see "LCIA-Analysis" document, EC-JRC, 2010a)).

In order to support the selection of the best methods, criteria for good characterisation modelling practice have been developed in advance to be used in the evaluation and comparison of the pre-selected methods.

Next to the evaluation criteria also expert judgement was applied in the decision making process and helped select the LCIA methods that are recommended.

The development of criteria and their application in evaluation of methods from the different impact categories have been decided in a consultation process involving domain

[7] The following LCIA methodologies were scrutinized for characterisation models which would be potential candidates for recommendation: CML 2002 (Guinée et al., 2002); Eco-Indicator 99 (Goedkoop and Spriensma, 2000); EDIP (1997-2003) (Wenzel et al.,1997, Hauschild and Wenzel, 1998a, Hauschild and Potting, 2005, Potting and Hauschild, 2005); EPS2000 (Steen, 1999a,b); Impact 2002+ (Crettaz et al., 2002, Jolliet et al., 2004, Payet, 2004, Pennington et al., 2005, Pennington et al., 2006, Rochat et al., 2006, Rosenbaum, 2006, Rosenbaum et al., 2007); LIME (Itsubo et al., 2004, Hayashi et al., 2000, Hayashi et al., 2004, Hayashi et al., 2006, Itsubo et al., 2008a-d); LUCAS (Toffoletto et al., 2007); ReCiPe (De Schryver et al., 2007, Huijbregts et al., 2005a,b, Struijs et al., 2007, Van Zelm et al., 2007a-b, Wegener Sleeswijk et al., 2008); Swiss Ecoscarcity or Ecological scarcity (Brand et al., 1998, Müller-Wenk, 1994, Ahbe et al., 1990, Frischknecht, 2008,2006a); TRACI (Bare, 2002, Bare et al., 2003, Hertwich et al., 1997, Hertwich et al., 1998, Hertwich et al., 1999, Hertwich et al., 2001, Norris, 2002); MEEuP methodology (Kemna et al., 2005); EcoSense (IER 2008)

experts for the respective impact categories, the European Commission and EU Member States representatives, and international partners, as described in Annex 3. Finally, a public stakeholder consultation has been carried out (partecipants also acknowledged in Annex 3).

### 2.1.1 Application of criteria and sub criteria

The criteria consist of general criteria based on fundamental requirements for LCIA methods (both characterisation models and factors), which are the same for all impact categories. These are complemented by minor groups of specific sub-criteria, which are addressing the characteristic features of each individual impact category and are outlined in LCIA- Framework and requirements document (EC-JRC, 2010b).

**General criteria**

The general criteria focus separately on scientific qualities and on stakeholder acceptance and applicability to LCI data sets.

**Scientific criteria**

1. Completeness of scope
2. Environmental relevance
3. Scientific robustness and certainty
4. Documentation, transparency and reproducibility
5. Applicability

**Stakeholder acceptance criterion**

6. Degree of stakeholder acceptance and suitability for communication in a business and policy contexts

Each criterion is specified through a number of sub criteria.

**Specific criteria**

Prior to developing the specific criteria, the environmental mechanism of the impact category in question was described with a flow diagram with all relevant pathways and flows which might be included in a characterisation model.

Based on the methods analysis and supported by the diagram, a limited number of additional category-specific sub criteria were developed under the two criteria: ‘Environmental relevance’ and ‘Scientific robustness and certainty’ to complement the general criteria and adapt them to the specificities of the impact category, capturing the central characteristics of that category and the decisive points at which the analysed characterisation methods differ and thus supporting discrimination between the different methods.

A detailed description of criteria and sub criteria is given in the LCIA- Framework and requirements document.

The detailed assessment of the characterisation methods for each impact category is provided in separate spreadsheets[8]. The spreadsheets were used as supporting working documents during the expert judgement processes

For each criterion and sub criterion a score was assigned to the characterisation models reflecting the compliance of the model with the criterion or sub criterion requirements. The used score are provided below:

A: Full compliance

B: Compliance in all essential aspects

C: Compliance in some aspects

D: Little compliance

E: No compliance

For the overall evaluation of the characterisation model, the importance of each criterion and sub criterion needs to be assessed for the impact category in question. A differentiation between normal (N) and high (H) importance is applied. Criteria of high importance are criteria which address fundamental aspects of significance for the resulting characterisation factors.

Some of the sub criteria are so important that an exclusion threshold is defined as a required minimum performance below which the characterisation model will not be considered any further in the analysis. Whenever a characterisation model fails to pass such an exclusion threshold, the analysis of that characterisation model stops.

In order to support an overall evaluation, a score for each criterion is developed based on an evaluation of the scoring of the sub-criteria. For the science based criteria, an overall score is then developed based on the scoring of each science based criterion. The compilation of the scores is based on “expert judgement” including consideration of the importance of different criteria and sub criteria. The resulting statements on the science based criteria and on the stakeholder acceptance criterion are the bases of the final method recommendations.

The findings from the evaluation are summarized in recommendations on the characterisation method for each impact category.

## 2.2 Recommendation levels

The recommended characterisation methods (models and associated characterisation factors) are classified according to their quality into three levels: “I” (recommended and satisfactory), “II” (recommended but in need of some improvements) or “III” (recommended, but to be applied with caution). A detailed description of the levels is provided below:

[8] Available at http://lct.jrc.ec.europa.eu

Level I: Recommended and satisfactory

Definition: These models and characterisation factors are recommended for all types of life cycle based decision support. Although further research needs may have been identified, these are not preventing the models/factors being seen as satisfactory given the current state-of-the art. However, updating and improvement via established mechanisms, such as e.g. the IPCC, should be followed also for these methods and factors.

Level II: Recommended, some improvements needed

Definition: The models and characterisation factors are recommended for all types of life cycle based decision support. The uncertainty of models and the resulting characterisation factors is to be more strongly highlighted. The impact on results and interpretation has to be more carefully evaluated, especially in published comparisons. The need for dedicated further research is identified for these methods/factors to further improve them in terms of precision, differentiation, coverage of elementary flows etc.

Level III: Recommended, but to be applied with caution

Definition: These models and characterisation factors are recommended to be used but only with caution given the considerable uncertainty, incompleteness and/or other shortcomings of the models and factors. These models/factors are in need of further research and development before they can be used without reservation for decision support especially in comparative assertions. The recommendation is to calculate and present the results of the LCIA with and without methods that are level III and to discuss the differences, e.g. in the interpretation of the LCA. It is also recommended to conduct sensitivity analyses applying – if available - other methods than the level III recommended ones and to discuss differences in the results, e.g. in the interpretation of the LCA. However, the level III recommended method should remain the baseline.

Interim: immature for recommendation but the most appropriate among the existing approaches

Definition: The methods and characterisation factors defined as interim are to be used only with extreme caution, and limited to in-house applications, given the considerable uncertainty, incompleteness and/or other shortcomings of the methods and factors.

Note that for some impact categories there were no existing models and factors that met the criteria for level III. For these impact categories no method is recommended in the ILCD System, as the level of maturity and/or available documentation is considered too limited to facilitate general use.

The fact that an impact category at midpoint or endpoint has no recommended methods hence does not mean that it is not relevant to include in a study, but merely that at the moment no existing method was found sufficiently mature for recommendation.

This should not be taken as a recommendation to exclude this specific impact category, but to apply a method which has been identified by the practitioner as the current best practise for the specific application. However, in the study the uncertainties and the limitations have to be clearly stated, in particular for this impact category.

In specific situations, even if there is a recommendation to use a LCIA method, the use of a different LCIA method could be accepted, provided that two conditions are met:

1. The LCIA method different from the recommended method is more suitable for the circumstances of the specific case
2. The LCIA method is in compliance with ILCD requirements.

To 1: This can be relevant especially in case of specific geographical relevance of the chosen model (models or factors developed for a specific country/ climate etc.). It has to be justified that this will significantly reduce the uncertainty associated with the impact assessment in the particular life cycle assessment, and it has to be justifiable in accordance with the goal of the study.

To 2: In the ILCD Handbook “Review schemes for Life Cycle Assessment”, minimum review requirements for LCIA are listed. An independent external review is requested for LCIA factors, whereas an independent panel review is requested for the underlying LCIA models.

Any deviation from the recommended LCIA method has to be justified and the recommended LCIA method has to remain the baseline for comparison and it has to be reflected in the interpretation.

Not necessarily all LCIA methods that are recommended within this document are fully compliant with all ILCD requirements, especially related to the requirements for review of LCIA models and factors. However the recommendation reflects that after expert and public consultations these methods were seen as being of sufficient quality. Until the methods comply with all ILCD requirements, they may be considered a preliminary recommendation.

## 2.3 Research needs

Research needs are identified for each of the impact categories and prioritised according to their importance for the characterisation modelling for the impact category, in particular where the recommended methods are classified as level II or level III, or where the methods are classified as interim. The research needs are classified according to their priority (high-medium-low) and the associated workload is estimated. The research needs are reported in Annex 2.

In a cross-cutting activity it is analysed to which extent the impact pathways, which are modelled by the recommended characterisation models, are complementary at midpoint level and at endpoint level or whether they present overlap or insufficient coverage of the relevant environmental mechanisms. Detected inconsistencies are corrected if possible, or the selection of recommended characterisation models is modified with the aim of ensuring complementarity between the impact categories to the extent possible. The check on consistency across impact categories also helped identify future research needs in order to ensure coverage of all relevant impacts.

## 2.4 Geographic scope

Life Cycle Assessment typically has a global scope as the supply chains behind products tend to be global in nature, crossing national and geographic borders, particularly in terms of raw material and energy supplies. In many cases the location of emission sources or resource use may not be known. Hence, life cycle impact assessment models and factors must firstly be globally applicable.

This guidance is intended to support Life Cycle Impact Assessment on a global level recommending default characterisation models and associated factors for each impact category. As far as available, global models were recommended. In some cases no international consensus exists on globally representative characterisation models and factors. In the absence of sufficiently sound global models, a choice had to be made for models that represent large heterogeneous regions. These may be at continental or national scale. It is assumed that the central-tendency estimate for these smaller regions will be a sufficiently good estimate of the global default value.

These choices can be seen as reflecting a European perspective on models and factors for use in Life Cycle Assessment.

Further distinctions in relation to e.g. emissions scenarios (e.g. from a high stack, in a densely populated area) and geographic/political boundaries may be helpful if associated life cycle inventory or unit process data are available (e.g. factors for China used in the context of Chinese emissions). The additional collection and use of such specific inventory/unit process data and impact assessment factors is justified when this will significantly reduce the uncertainty associated with a particular life cycle assessment (see Section 2.3 for deviations from the recommendations/baseline).

# 3 Background information on the evaluation of existing LCIA methods

The following sub-sections present the results of the analysis of existing LCIA methods at midpoint and endpoint level for each of the impact categories conducted in accordance with the evaluation criteria as developed in the guidance document LCIA- Framework and requirements (EC-JRC, 2010b). The recommended methods are classified according to the classification system as reported in the Chapter 2. The detailed assessment of each method is documented in a separate spreadsheet[9] for each impact category. These spreadsheets were used as supporting working documents for the expert judgement during the assessment of the methods.

## 3.1 Climate change

### 3.1.1 Introduction

All LCIA methodologies have an impact category Climate Change (sometimes called Global Warming), and they all use the Global Warming Potentials (GWPs) developed by the Intergovernmental Panel on Climate Change (IPPC). However, there are some differences in the use of GWP's

- IPCC periodically publishes updates, and not all methodologies use the latest factors (but could easily be updated)
- IPCC publishes GWP's for different timeframes.

### 3.1.2 Pre-selection of methods for further evaluation

The pre-selection of characterisation models for the climate change impact category has been explained in the LCIA - Analysis document (EC-JRC, 2010a) and is summarized below.

As there is a wide consensus on the use of IPCC's GWP's for characterisation at midpoint level, only this method was selected as representative for all midpoint methods currently used in LCA. At the endpoint level, four methods that are based on different models were selected: Ecoindicator 99, EPS2000, Recipe and LIME.

**Midpoint**

The GWP's published in IPCC's Fourth Assessment Report (AR4, 2007) were taken as this indicator is used as midpoint indicator in every characterisation model. All methods can in principle be easily updated with these latest figures.

[9] http://lct.jrc.ec.europa.eu/assessment/assessment/projects#consultation_impact

IPCC has three versions of the method, indicationg three different timeframes. The impact in terms of cumulative radiative forcing of greenhouse gas (GHG) emissions is either cut off after 20, 100 or 500 years.

The 500-year perspective is considered sufficiently long to assess the majotity of the damage caused by the substances with the long atmospheric residence times, while the 100- and 20-year timeframes capture partially the impact of substances with a long lifetime. In some circles, the 100-year timeframe is used as this is the basis adopted for the Kyoto Protocol. I

It should be noted that GWP's also are used as the basis in all the endpoint models, and also here the time perspectives is an issue.

**Endpoint**

Eco-indicator 99 (Goedkoop and Spriensma, 2000) takes into account human health damage from climate change. Health effects considered include heat stress, vector borne diseases and flooding. The change in radiative forcing is determined using GWP's from IPCC's Second Assessment Report (SAR, 1995) for three pilot GHGs ($CO_2$, $N_2O$ and $CH_4$), each representing a group of GHGs with a certain lifetime. The characterisation factors are expressed in Disability Adjusted Life Years (DALY). There is no model for the damage to ecosystems. The climate model used is an unpublished version of the FUND model developed by Tol (1999).

EPS2000 (Steen, 1999a,b) takes into account human health damage, loss of species and effects on primary production. Health effects considered include thermal stress, flooding, malaria and malnutrition. The change in radiative forcing is determined using GWP's from IPCC's First Assessment Report (FAR, 1990). The characterisation factors are expressed in Years Of Lost Life (YOLL), person-years of severe morbidity, person-years of morbidity, Normalized EXtinction of species (NEX), kg of crop-productivity loss and kg of wood-productivity loss. All characterisation factors are subsequently harmonized in an additional step using monetarization.

ReCiPe (De Schryver and Goedkoop, 2009a) includes human health damage and loss of species. The health effects considered include heat stress, malaria, malnutrition, diarrhoea and flooding. The change in radiative forcing is determined using the GWP's published in IPCC's Fourth Assessment Report (AR4, 2007). The characterisation factors of human health damage are expressed in DALY, while loss of species is expressed in Potential Disappeared Fraction of species (PDF). A meta-study was used (Thomas et al., 2004) for the link to biodiversity. Two versions of ReCiPe have been considered for the human health assessment: De Schryver and Goedkoop (2009a) and De Schryver et al. (2009). The difference lies in the way the temperature factor is calculated, but in essence the approaches lead to the same result. In the first approach, the damage is calculated for $CO_2$ only, and the midpoint (using GWP's published in IPCC's Fourth Assessment Report (AR4, 2007)) is used to cover other GHGs. In the second approach, GWP's are not used, but the entire environmental mechanism is calculated in a way that is compatible with the different time perspectives used. In the first approach, there is no time cut off, but different time horizons in the equivalency factors are used. In the second approach different time horizons are used.

LIME follows some of the principles of Eco-indicator 99, as it also develops mechanisms for $CO_2$, $N_2O$ and $CH_4$ as pilot substances, and then applies GWP's to incorporate additional substances. The impacts on heat and cold stress, floods, malaria, disasters, crop, plant, energy and dengue fever as well as malnutrition are covered. These are linked to human health damage (in DALY/kg), social assets (in Yen/kg), plant production (in Dry-ton/kg) and biodiversity[10] (in EINES/kg). It uses a climate model (DICE Model, Nordhaus, 1994).

The figure below describes the environmental mechanism and the position of each LCIA methods along the cause-effect chain.

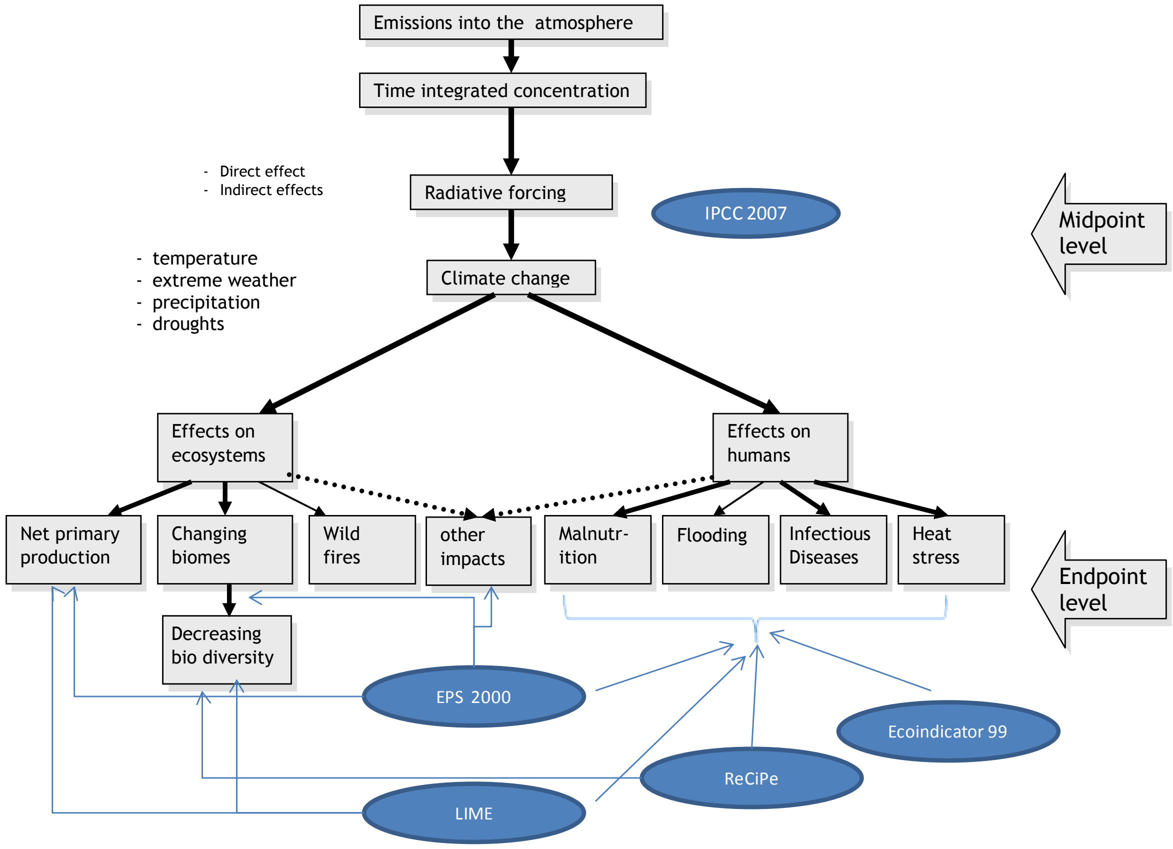



**Figure 1 Environmental mechanism for climate change and associated LCIA methods.**

## 3.1.3 Method evaluation

The five models have been rated against the criteria defined in the LCIA- Framework and Requirements document (EC-JRC, 2010b). The results are summarized in the table below[11]. Background information for the assessments can be found in a separate Excel file (Climate change.xls[12])

[10] EINES:Expected Increase in Number of Extinct Species

[11] A: full compliance; B: compliance in all essential aspects; C: compliance in some aspects; D: little compliance; E: no compliance

[12] http://lct.jrc.ec.europa.eu/

**Table 3 Summary of the evaluation results of 5 models that assess climate change in LCA context.**

| | IPCC | | EPS2000 | | ReCiPe | | Ecoindicator 99 | | LIME | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Midpoint | | Endpoint | | Endpoint | | Endpoint | | Endpoint | |
| **Completeness of scope** | A | No specific endpoints. | A | Considers human health, biodiversity and crop productivity. | A | Considers Human health and biodiversity. | C | Only human health is considered. | B | Considers human health damage, plant productivity, as well as ecosystem damage. |
| **Environmental relevance** | A | | B | Complete model, although several assumptions are made. | A | Complete model. | C | Complete human health model. | A | Complete model. |
| **Scientific robustness & Certainty** | A | IPCC combines stakeholder acceptance with best science. | D | Models contain several estimations and approximations . Uncertainty factors included. | B | No uncertainty factors included, most up to date data, scenarios included. | C | Climate model is not entirely transparent. Uncertainty factors included, scenarios included. | B | Human health well modeled, uncertainties not specified. Links to crop loss uncertain due to limited model. |
| **Documentation ,Transparency & Reproducibility** | A | IPCC provides very detailed background documentatio n. | A | Information is easily accessible. | A | Information is easily accessible. | A | Information is easily available. | E | Information in non-Japanese language only partially available. |
| **Applicability** | B | Good applicability | B | Good applicability | B | Good applicability | B | Good applicability | B | Good applicability |
| **Overall evaluation of science based criteria** | A | Broadly accepted scientific basis All methodologie s use this method at midpoint . | C | Rough model, partially outdated. | B | Up to date, well described method. | C | Link to eco-systems missing. | C | Good human health model, old climate model, lack of information. |
| **Stakeholder acceptance** | A | Generally accepted. | D | Not generally accepted. | D | Not generally accepted. | D | Not generally accepted. | E | Not generally accepted. |

## 3.1.4 Discussion on method evaluation

All the endpoint models have considerable uncertainties, as the link between cumulative radiative forcing and damages to human health and ecosystems is difficult to establish. There is an extensive amount of literature describing the link between emission scenarios, temperature increase and associated damages to human health, ecosystems and economy (e.g. crop losses). However, LCIA methods focus on the marginal effect of one kilogram of a GHG emission. The different LCIA methods rely on the following assumptions:

1. EPS converts IPCC damage estimates to estimates that can be related to a kilogram of $CO_2$-equivalent emission. It applies an average (and not marginal) approach. LIME has a similar approach, but deducts a marginal damage factor (the additional damage of an additional kilo). It also uses anold climate model. Eco-indicator 99 asked a known expert, Richard S. J. Tol, to make a specific

number of runs using the Fund model (Tol, 1999). That version of the model was never described, and as the model is constantly developing, the model is not clear or generally accepted. The original version of ReCiPe uses a large comparison study by Meinshausen (2005), who compared many international authoritative climate models, and deducted a marginal temperature curve per mass load of $CO_2$ equivalents. This study is well recognised and often referred to in other reviewed literature (De Schryver and Goedkoop, 2009a). Recently a new version of ReCiPe was developed using the IMAGE model to link emission flows to increase in $CO_2$ concentration, radiative forcing and resulting increase in temperature (De Schryver et al., 2009).

2. The models that link temperature to human health damage assume different scenarios reflecting the degree of adaption of humans to changes in the climate. Questions related to whether malnutrition will be prevented with good policy, or to whether a cure for malaria will be found, or to whether heat strokes are avoided because people purchase air conditioners, are crucial to determining the damages, as the latter are highly sensitive to the former. EPS2000 assumes little adaptation, and LIME seems not to take this into account. In Eco-indicator 99 and in ReCiPe, three versions are used that provide three adaptation scenarios, allowing the user to choose a version. Most models heavily rely on consensus documents, such as those published by the WHO (McMichael et al., 2003).

3. For damage to ecosystems, there are some important assumptions. For example, the assumption on the speed with which species can migrate, or how fast species adapt to a changed climate. The studies available disagree on the magnitude of the damages (see e.g. De Schryver and Goedkoop, 2009a).

4. The links to crop losses have the problem that temperature change can be beneficial for crop production at some latitudes, while there are damages in other latitudes or regions. There is also a dispute on how pests and diseases will be affected and on whether this is fully counterbalanced by the expected increase in crop yields, if any.

The scientifically-robust link between radiative forcing, temperature and ecosystem impacts makes ReCiPe the scientifically most robust endpoint method. There are three different versions that are based on different assumptions regarding adaptation and time perspectives. One of these versions is regarded as the default model; the other two versions can be used for sensitivity analyses. LIME also has some promising models, but due to the lack of information available in English it is difficult to interpret. EPS2000 has the benefit of using a clear model, but the model relies on some assumptions and older models.

### 3.1.5 Discussion on uncertainties and the importance of spatial differentiation

Spatial differentiation is not relevant for locating the emission origin, but is relevant for the damage assessment. Therefore, most endpoint models do the assessment on a regional-specific basis.

### 3.1.6 Recommended default method at midpoint level

At midpoint level, GWP's from the Intergovernmental Panel on Climate Change (AR4, 2007) is recommended. It is based on the most up-to-date and scientifically-robust consensus-based model available, which produces characterisation factors based on radiative forcing and residence time of the GHG emitted.

All LCIA midpoint methodologies available apply characterisation factors based on GWP's, although these are generally not updated to the latest version. Presently the up-to-date characterisation factors are from the IPCC Fourth Assessment Report published in 2007.

From a scientific/sustainability point of view, it seems best to use the 500-year time horizon, as only in this perspective all relevant impacts of all relevant emissions are better captured. On the other hand, it is clear that in almost all policy instruments, like for instance the Kyoto Protocol, the 100 year perspective is used and that this time perspective has the broadest acceptance.

Recommendation of the 100-year timeframe is proposed as default, but it is also suggested to use the shorter (20-year) and longer (500-year) timeframes as a sensitivity analysis. This check is especially relevant when assessing agricultural systems, as the $N_2O$ often emitted in these systems has a long lifetime, and thus has a significantly higher characterisation factor (factor 2) in the 500 year perspective compared to the 100 year perspective. Methane has almost a factor 4 lower characterisation factor in the 500 years perspective.

### 3.1.7 Recommended default method at endpoint level

At endpoint level, no method is considered here mature to be recommended.

As interim, the method developed by De Schryver et al. (2009) and implemented in ReCiPe could be adopted as it considers damages on both ecosystems and human health.

The method used by EPS2000 stands at the second place as interim method. Like ReCiPe, it considers damages on both man-made environment and human health, but EPS2000 is based on relatively old and simple models often relying on estimates. Eco-indicator 99 scores the same ranking, but it less up-to-date, and the models are not well documented.

### 3.1.8 Consistency between midpoint and endpoint methods

There is a benefit in having a midpoint and endpoint method for this category, as comparisons are scientifically robust at the midpoint level while the endpoint method provides natural-science based estimates at the Area of Protection level. The interim endpoint default method builds directly on the recommended midpoint default method, so there is a fine consistency.

### 3.1.9 Classification of the recommended methods

At midpoint, the recommended IPCC (2007) method for (GWP100 years) is classified as a level I method (recommended and satisfactory) for characterisation.

At endpoint, no method is recommended. If an endpoint method is required that expresses the impact in terms of DALY and species loss, the method developed by De Schryver et al. (2009) can be used, but this method is classified as an interim method because it is not sufficiently mature to be recommended.

### 3.1.10 Calculation principles

Additional midpoint factors cannot be calculated by the LCA practitioner but are also not foreseen to be needed as an essentially exhaustive list is provided by IPCC.

## 3.2 Ozone depletion

### 3.2.1 Pre-selection of methods for further evaluation

The pre-selection of characterisation models for the ozone depletion impact category has been explained in the LCIA – Analysis document and it is summarized below. All LCIA methodologies have an impact category Ozone Layer Depletion (sometimes called Stratospheric Ozone Depletion) and use the Ozone Depletion Potentials (ODPs) published by the World Meteorological Organisation (WMO) (www.wmo.ch).

As there is a wide consensus about the use of OPD's for characterisation at midpoint, only one representative was selected, in this case the EDIP method, which is based on the 1999 WMO assessment (WMO, 1999). It will be referred to as the WMO 1999 midpoint approach.

For the endpoint, the following four methods have been selected as they are based on different models

Eco-indicator 99 (Goedkoop and Spriensma, 2000)

EPS2000 (Steen, 1999a,b)

LIME (Hayashi et al., 2006)

ReCiPe (Struijs et al. 2009a and Struijs et al. 2010)

At the endpoint level, the impact pathways between the midpoints and the endpoints have been developed (Figure 2) and in table 4 is presented an overview of the environmental pathways and indicators modelled in the selected endpoint methods.

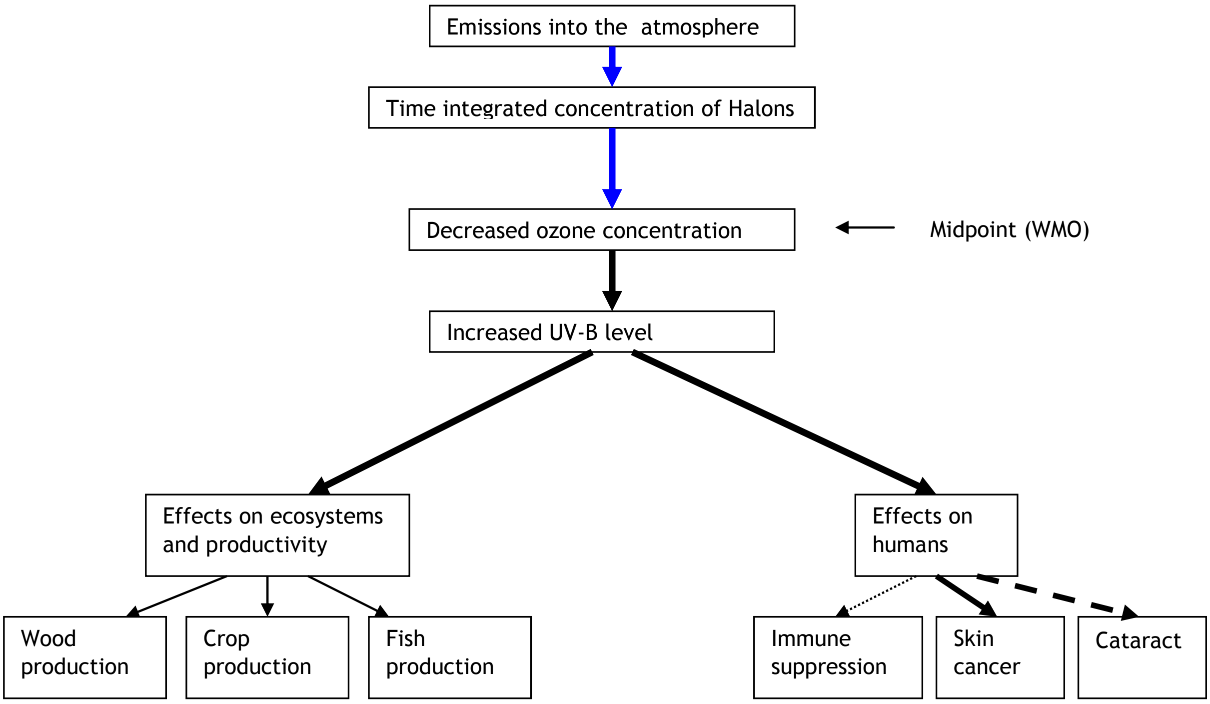



**Figure 2 Environmental impact pathways of ozone depletion**

**Table 4 Overview of the environmental pathways and indicators modelled in the selected endpoint methods.**

| Method | Human health | Crops | Plankton | Wood |
|---|---|---|---|---|
| ReCiPe | DALY | | | |
| Eco-indicator 99 | DALY | | | |
| LIME | DALY | Yen loss | Kg Loss | Kg loss + Yen loss |
| EPS2000[13] | YLL, Morbidity | | | |

## 3.2.2 Method evaluation

The five models have been rated against the criteria, identical to the climate change ones. The table below summarises the assessment[14]. Background information for the assessments is in a separate Excel file (Ozone depletion.xls [15]).

[13] When reviewing the EPS method it seems that it also has links between CFC and crops, wood and also biodiversity, but these links only include the climate impact of CFC11 and its equivalents and are therefore not considered here.

[14] A: full compliance; B: compliance in all essential aspects; C: compliance in some aspects; D: little compliance; E: no compliance

[15] http://lct.jrc.ec.europa.eu/

**Table 5 Summary of the evaluation results of 5 models that assess Ozone depletion in LCA context.**

| | WMO Midpoint | | Eco-indicator 99 | | EPS2000 | | LIME | | ReCiPe | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mid or endpoint** | Mid | | End | | End | | End | | End | |
| **Completeness of scope** | A | No specific links are made | C | Only the link to human health is modelled | B | Only human health | A | Links to human health, Net primary production and manmade resources | C | Only the link to human health is modelled |
| **Environmental relevance** | A | Midpoint method also used in all endpoint methods | B | Complete model for human health | C | Only skin cancer is included based on WMO damage estimates | A | Human health well covered, partial coverage of crop productivity effects | B | Human health well covered, no ecosystems or crop impacts |
| **Scientific robustness & Certainty** | A | Based on WMO consensus | C | Fate and damage models relatively old, and rough | D | The way the total damage is allocated using WMO is rather coarse | B | State of the art method for human health, somewhat limited models for wood productivity | A | State of the art method, (most recent of all), using novel approaches and models |
| **Documentation & Transparency & Reproducibility** | A | Detailed reports and models are available | A | Detailed reports and models are available | B | The description of the pathway is very brief | B | Backgrounds are only available in Japanese | A | Detailed reports and models are available |
| **Applicability** | B | ODP substances widely reported | B | ODP substances are widely reported | B | ODP substances are widely reported | B | ODP substances are widely reported | B | ODP substances are widely reported |
| **Overall evaluation of science based criteria** | A | WMO report is based on widely accepted science | C | Somewhat outdated | D | Rough, models, relies on some WMO estimates for future damage | B | State of the art model for human health, unique attempt to model crop losses | B | Most recent state of the art model for human health |
| **Stakeholder acceptance criteria** | A | CFC equivalents are widely used in policy | C | DALY not generally accepted, CFC equivalents are taken from alternative source | B | Relatively easy to understand model, indicators not widely accepted | D | Well accepted in Japan, limited availability on scientific backgrounds | B | DALYs are not generally accepted in EU but widely accepted in WHO and other institutes |

### 3.2.3 Discussion on method evaluation

As stated before, all LCIA methodologies have an impact category Ozone Layer Depletion and use the ODPs published by the WMO. Hence, the WMO characterisation model has high scores in almost all criteria and sub criteria, the factors are widely accepted and therefore it is the preferred choice as a default method for the calculation of midpoint characterisation factors.

For the endpoint characterisation factors all the methods have developed factors for the AoP Human Health while for crops, plankton and wood only the LIME methodology has factors. Among the others, the method proposed by Struijs (Struijs et al. 2009a and 2010) could be used as interim method, as it is based on state of the arts models, the method was published in a peer review journal, and at the moment is the most recent developed. LIME could be also considered as interim since it received high score in several of the central criteria, (the coverage of AOPs human health, natural environment and natural resources; peer reviewed; updated model) but much of the documentation is in Japanese which prevents a wide diffusion of this background data. Full translation of the methods and their background documentation is still awaited.

### 3.2.4 Discussion of uncertainties

#### 3.2.4.1 Discussion of uncertainties in the WMO equivalencies as a basis for midpoint characterisation

The uncertainties in the equivalency factors published by the WMO are widely documented and discussed in extensive stakeholder debates (WMO 1999 and 2003); this discussion is not repeated here.

#### 3.2.4.2 Uncertainty in the modelling of human health impacts

In all human health models, except EPS2000, the same principles are used. The fate of a marginal increase of emission of ODS' and the resulting worldwide increase of UVB exposure is calculated, taking into account population density, latitude and altitude etc. There are several factors that contribute to the uncertainty in such models:

> The sensitivity for skin cancer highly depends on skin colour and on individual behaviour. UV radiation is latitude dependent, and so is skin colour distribution. Overlaying the maps of predicted UV-B increase and maps of skin colour distribution is a problem, as most data reflect the original distribution of skin colour patterns over the globe, not reflecting the huge migration waves. Individual behaviour is also difficult to take into account. Sun bathing behaviour is a very important factor. Eco-indicator 99, LIME and ReCiPe all struggle with this problem. For ReCiPe a special GIS model was developed, to improve this situation. In this model the increased UV-B levels, population density, original skin colour and other factors were modelled per grid cell.

Cataract is often associated with UV-B, but there are significant problems in proving that there is indeed a link, and the data that is used to model this link is uncertain. The main reason is that it is difficult to trace back the occurrence of this disease to high or low UV exposure. Eco-indicator 99 and LIME include this link. EPS2000 does not refer to it. ReCiPe uses the link only for one of the three cultural perspectives, that it models (egalitarian) but not in the default perspective (hierarchical), because of this difficulty.

In the EPS2000 method, the model has been simplified, using an overall damage assessment report from WMO and dividing the predicted damage by the total expected emissions for the next 100 years. Due to this simplification, this method is probably the most uncertain method.

#### 3.2.4.3 Uncertainties in damage to crops

The damage pathways to crops and wood in LIME are well defined, but there are some problems due to lack of data. For wood production only data on a single species is available (Pinus Taeda), and this species only occurs at latitude of 30 to 40 degrees; still the sensitivity of this species is extrapolated over a global scale. For Plankton growth, a model is used for which data are available, especially for latitudes above 50 degrees, which is expected to be the latitude where major damages occur, so this choice can be justified to some extent.

### 3.2.5 Recommended default method at midpoint level

The WMO steady state method is in some form applied in all LCIA methodologies and is also selected as the midpoint method to be preferred. The recommendation is to use the latest WMO published ODP equivalents (currently WMO, 1999). A point of attention is that WMO publishes equivalents representing different timeframes. Different stakeholders may prefer different timeframes, but as the default it is proposed to use the infinite time perspective, as this is the most widely used version in policy. In practice, there is very little difference with the 100 year perspective as most currently used ODP substances have a lifetime shorter than 100 years. Following the WMO reasoning that after 2040 the anthropogenic impact on ozone depletion will be negligible, a shorter timeframe can also be used, but the greater policy acceptance for the 100 year perspective is taken as guidance.

### 3.2.6 Recommended default method at endpoint level

At endpoint, no methods are recommended to be used because no method is sufficiently mature to be recommended.

As interim, the model of Struijs et al. (2009a and 2010) as implemented in ReCiPe methodology uses an up to date model (AMOUR model - den Outer et al., 2008; van Dijk et al. 2008) to assess human health damages on endpoint level caused by ozone depletion. The most important limitation of the method is that there are no links to ecosystem endpoints. It is recommended to adapt this method as the best available for the endpoint level, although it has a very limited stakeholder acceptance, as it is a quite new and not easily understandable method.

The LIME method (Itsubo et al., 2008c) rely on really interesting and advanced models. It is the only method that links to crop loss, wood production and plankton loss. The ozone layer depletion model has been published in a peer reviewed scientific journal (Hayashi et al.

2006), but that article, refers to several publications in Japanese, and these publications are needed to understand the details of the method, especially for crop and plankton losses. We know that meanwhile work is ongoing, especially regarding documenting and reducing uncertainties. In some presentations researchers have shown that characterisation factors are also changing in this new work, but information in these developments is also limited to a few conference proceedings and posters. Very recently a partial draft translation has been made available. This lack of information makes it impossible to recommend this method at this stage.

The EPS2000 has a relatively simple model. It simply divides the total expected future damage predicted in a WMO report by the total expected releases over 100 years. An important benefit of this approach is that it is easy to explain and does not differ too much from a midpoint model in this respect. EPS2000 scores relatively low in the scientific criteria, but because of its relative simplicity; it scores among the best in stakeholder acceptance criteria, because of its simplicity. Due to the limited scientific quality, and limited scope (no cataract) it is not recommended.

The Eco-indicator 99 has been the starting point for the LIME and ReCiPe method. It is also the oldest, and relatively primitive, because of its age, compared to the two later methods. As with the EPS2000, the simplicity can be seen as strength if stakeholders are to understand it, but the ozone depletion problem is certainly more complicated. It is not recommended.

## 3.2.7 Consistency between midpoint and endpoint methods

The interim method developed for ReCiPe claims to have a real midpoint/endpoint structure, but on a closer look it has not. ReCiPe has a midpoint indicator (using WMO 1999 as reference), but this midpoint is divided in 6 sub-groups that have a specific damage characterisation factor each. This adds to precision, but is a little inconsistent with the overall framework.

## 3.2.8 Classification of the recommended default methods

The recommended midpoint method, the WMO Ozone model for ODPs, is classified as a Level I method (recommended and satisfactory) for characterisation at the midpoint level, as it is widely accepted, and highly environmental relevant.

At endpoint, no method is recommended.

If an endpoint method is required, the model of Struijs et al. (2009a and 2010), as implemented in ReCiPe methodology, and based on the AMOUR model (den Outer et al., 2008; van Dijk et al. 2008) could be used as interim method to assess human health damages caused by ozone depletion.

## 3.2.9 Calculation principles

Additional midpoint factors cannot be calculated by the LCA practitioner but are also not foreseen to be needed as an essentially exhaustive list is provided by WMO.

Additional endpoint factors are not foreseen to be needed as those presently available cover all relevant types of substances from midpoint to endpoint.

# 3.3 Human toxicity

## 3.3.1 Pre-selection of methods for further evaluation

The pre-selection of characterisation methods for the human toxicity impact category is provided in LCIA- Analysis document (EC-JRC, 2010a). Table 6 summarises the results.

**Table 6 Selected methods and underlying models for human toxicity effects for analysisa**

| Methodology | Underlying model | Reference |
|---|---|---|
| USEtox | USEtox 1.0: Model developed by a task force within the UNEP-SETAC Life Cycle Initiative | Rosenbaum et al. (2008) |
| ReCiPe [b] | USES-LCA version 2.0 | Huijbregts and van Zelm (2009) |
| IMPACT 2002+[c] | IMPACT2002 | Jolliet et al. (2003), Pennington et al. (2005) |
| TRACI | CalTOX 4.0 | Bare et al. (2003), McKone et al. (2001) |
| EDIP2003[d] | EDIP1997, combined with site dependent factors | Potting et al. (2005) |
| CML 2002 | USES-LCA version 2.0 | Huijbregts et al. (2000 ) |
| MEEUP | Based on emission limit values | Kemna et al. (2005) |
| **Endpoint only method** | | |
| EPS2000 | Direct empirical relationship between global emission and observed exposures or health impact for a few pollutants | Steen (1999a,b) |

[a] Though the present study focuses on Life Cycle Impact Assessment methods, it must be emphasized that other environmental tools such as risk assessment, substance flow analysis or environmental impact assessment provide complementary information and are more appropriate to assess e.g. localized health impacts associated with peak individual exposures, etc.

[b] The most recent version of the model USES-LCA 2.0 is the underlying model for the calculations of characterisation factors for human toxicity in ReCiPe. Previous versions of the model family USES-LCA and EUSES, employed in CML2002 and Eco-indicator99, were not included in the evaluation.

[c] The European version of the model IMPACT2002 is the underlying model for the calculations of characterisation factors for toxicity in IMPACT2002+. LUCAS and LIME contain respectively Canadian and Japanese versions of IMPACT2002 and were not included in the evaluation to avoid duplication.

[d] The most recent version of the EDIP method is evaluated (2003 version). A previous version, EDIP1997, was not included in the evaluation.

## 3.3.2 Environmental mechanism for human health effects

Figure 3 describes the position of LCIA methods in the environmental mechanism for human health effects:

Recipe, IMPACT 2002+, and USEtox are based on similar models, representing a full model-based description of chemical fate, exposure, effect and optionally severity. TRACI and CML 2002 are also similar, but differ in the way that the effect and severity indicators are calculated and their scope.

EPS2000 directly assesses impacts at the endpoint of a few contaminants based on human response to emissions, but without disaggregating the various human exposure pathways.

EDIP is a simplified approach that approximates some of these processes, without fully describing them.

MEEUP is directly based on emission limits that reflect policy objectives as the basis of the indicators, hence reflecting more a policy-based weighting than impact assessment.

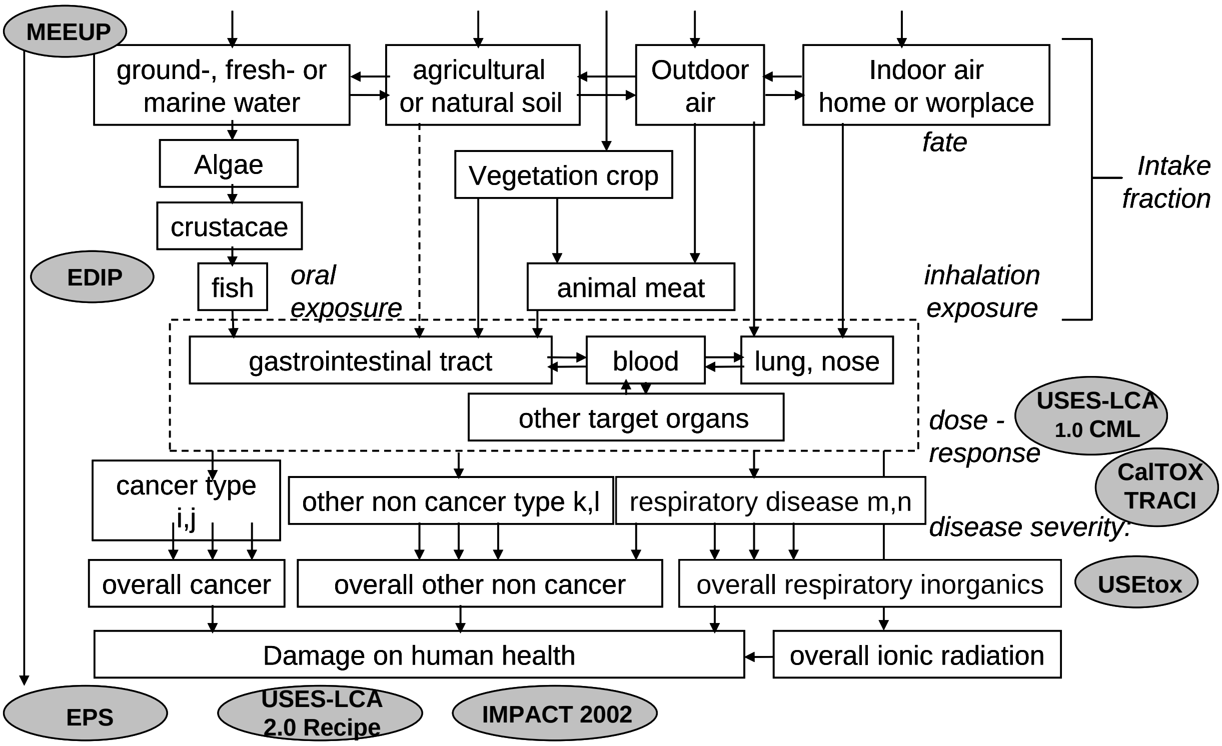



**Figure 3 Position of LCIA methods in the impact pathways of human toxicity.**

## 3.3.3 Method evaluation

The pre-selected models have been rated against the criteria defined in the LCIA-Framework and Requirements (EC-JRC, 2010b). The table below summarises the assessment[16]. Background information for the assessments is in a separate Excel file[17] (Human toxicity.xls).

[16] A: full compliance; B: compliance in all essential aspects; C: compliance in some aspects; D: little compliance; E: no compliance

[17] http://lct.jrc.ec.europa.eu/

**Table 7 Summary of the analysis of the available characterisation methods against the adapted criteria for human toxicity (in two sub- tables)**

| Criteria | | USEtox (midpoint) | | ReCiPe (midpoint and endpoint) | | IMPACT2002+ (midpoint and endpoint) | | TRACI (midpoint) |
|---|---|---|---|---|---|---|---|---|
| **Completeness of scope** | A / B | The model scope is applicable to the comparative evaluation of toxic chemicals on global and European scale. No spatial differentiation beyond continent and world compartments | B | The scope of the model for the evaluation of toxic chemicals on the European scale is applicable. No parameterization for other continents so far | A | The scope of the model is applicable to the comparative evaluation of toxic chemicals on the European scale. Parameterization is available for all continents | B / C | The scope of the model for the evaluation of toxic chemicals on the European scale is largely applicable, although the model is parameterised for the US. Some conservative assumption for human health effects |
| **Environmental relevance** | B | Environmental relevance is high for all environmental pathways, except dermal uptake. Best basis for TD50 calculations, cancer-negative chemicals and route-to route extrapolation. Not valid for direct application of pesticides on crop. Implicit equal severity. Preliminary for metals | B | Environmental relevance is high. Not valid for dermal uptake nor direct application of pesticides on crop. Best basis for estimating severity for non cancer. Some factors for indoor exposure available | B | Environmental relevance is high, best basis for direct application of pesticides on crop. Includes intermittent rain. Not valid for dermal uptake. Basic assumptions for severity. Some factors for indoor exposure available | C | Environmental relevance is good. Best method for impact pathways including dermal uptake. Use of RfD's embedding uncertainty factors is problematic. Implicit equal severity |
| **Scientific robustness & Certainty** | B | Chemical input data checked and model components extensively reviewed by a large group of model developers, model uncertainty evaluated but no parameter uncertainty available. Carry over rates are kept below 1. Metal and pesticides treatment for human toxicity require improvements. Severity factors can be taken from other method since CTU represent cases of cancer and non cancer | B | Data mostly from reviewed datatabases. Model components extensively reviewed and uncertainty estimates available, but chemical data not always reviewed. Carry over rates are kept below 1. Metal and pesticides treatment for human toxicity require improvements | B | Model components extensively reviewed and uncertainty estimates available, but chemical data not always reviewed. Carry over rates are kept below 1 in the latest developments. Metal treatment for human toxicity require improvements | B | Chemical input data have been peer reviewed at least for Toxic Release Inventory. Model components extensively reviewed and uncertainty estimates available. Carry over rates may be above 1, unless latest version of CALTOX is used. . Metal and pesticides treatment for human toxicity require improvements |
| **Documentation, Transparency & Reproducibility:** | A | The model, documentation and results are published, available on line and the model can be easily used free of charge to calculate new chemicals | A / B | The model, documentation and results will be published and the model can be used free of charge | A / B | The model, documentation is available, but details on processes are not readily available. Results are published and the model can be used free of charge | A | The model, documentation and results are published, very well documented and the excel spreadsheet relatively transparent. The model can be used free of charge |
| **Applicability:** | A | Database with > 1250 human toxicological characterisation factors (recommended /interim). Intake fractions compatible with future indoor and work environment exposure factors | A / B | Database with > 1000 human toxicity characterisation factors is available that can be easily applied and updated | A / B | Database with > 800 human toxicity characterisation factors is available that can be easily applied and updated | B | Database with > 380 human toxicity characterisation factors is available that can be easily applied and updated |
| **Science based criteria overall evaluation** | B | USEtox includes all vital model elements in a scientifically sound way, except for metals and direct impact of pesticides. It is sufficiently documented and has the largest substance coverage. Uncertainty may require further attention | B | ReCiPe addresses human toxicity and includes all vital model elements in a scientifically sound way, except for metals and direct application of pesticides. It is well documented | B | IMPACT2002+ addresses human toxicity and includes all vital model elements in a scientifically sound way, except for metals. It is well documented | B / C | TRACI and CALTOX include all vital fate model elements in a scientifically sound way, except for metals and direct application of pesticides on crops. It is well documented. Use of uncertainty factors should be avoided |
| **Stakeholders acceptance: Overall evaluation** | A / B | Principles of the model are transparent and the parsimonious nature of USEtox reinforces transparency. The model is being endorsed by an international authorative body (UNEP) | B | Principles of the model are transparent and based on the EUSES-system applied in the EU to evaluate new and existing chemicals, but the LCA version is not officially endorsed by an international authorative body | C | Principles of the model are transparent, but the model is not yet endorsed by an authorative body | B | Principles of the model are easy to understand and endorsed by the US-EPA and other state agencies |

| Criteria | | EDIP2003 (midpoint) | | CML 2002 (midpoint) | | MEEuP (midpoint) | | EPS2000 (endpoint) |
|---|---|---|---|---|---|---|---|---|
| **Completeness of scope:** | B / C | The scope of the model for the evaluation of toxic chemicals on the European scale is fully applicable but the cause-effect chain is only partial | A / B | The scope of the model for the evaluation of toxic chemicals on the European scale is fully applicable. Some parameterization for other continents so far | E | No human toxicological impact mechanisms included. Indicators derived from policy-based emission limit values | C | The EPS2000 framework has been the precursor of endpoint methods. Many pathways or mechanisms are not covered. This is because EPS2000 only models probable impacts from present, average emissions of toxic substances, and these are estimated to mostly occur in trace amounts and result in impacts that are considered insignificant |
| **Environmental relevance:** | C | Environmental relevance is good for all environmental pathways but dermal uptake. Cause-effect chain not fully described. | B | Environmental relevance is good to high. Not valid for dermal uptake nor direct application of pesticides on crop. | D / E | No specific focus on human toxicological impacts, as emission limit values are used as impact indicator | D | Some data may be used to evaluate other models. Incomplete pathways and questions of consistency across locations in the operational calculation of factors to be addressed. The monetarisation approach is of interest |
| **Scientific robustness & Certainty:** | C | Data mostly from reviewed datatabases. Model published in peer reviewed book. No uncertainty or experimental verification available | B | Data mostly from reviewed datatabases. Model components extensively reviewed and uncertainty estimates available, but chemical data not always reviewed. Metal and pesticides treatment for human toxicity require improvements | | Not further evaluated, because the thresholds within the categories 'completeness of scope' and 'environmental relevance' were not reached | C | Relative weakness in data consistency between regions, etc. Willingness to pay interesting in case of monetarization approaches |
| **Documentation, Transparency & Reproducibility** | A | The model, documentation and published in detail. Results are published and the model can be used free of charge | A | The model, documentation and results are published in detail and the model can be used free of charge | | Not further evaluated, because the thresholds were not reached | B | The approach is relatively well documented and explained |
| **Applicability** | B | Database with > 180 human toxicity characterisation factors is available that can be easily applied and updated | A / B | Database with > 850 human toxicological characterisation factors is available that can be easily applied and updated | | Not further evaluated, because the thresholds within the categories 'completeness of scope' and 'environmental relevance' were not reached | C | Impacts of emissions not specifically mentioned are modelled as zero |
| **Science based criteria overall evaluation** | C | EDIP addresses human toxicity and includes the effect part in a scientifically sound way, except for metals and direct application of pesticides. It is well documented. The fate assessment is, however, very simplified and no information is available on the uncertainties involved in the model results | C | The model addresses human toxicity and includes all vital model elements in a scientifically sound way, except for metals and direct application of pesticides. It is well documented | E | No compliance with science-based criteria for the evaluation of human toxicity impacts. Political emission targets are used in the indicator development | C | Coverage limited in number of substances and impact pathways. Empirical data may contribute to the empirical evaluation of other models. Willingness to pay data may be used for valuation purposes |
| **Stakeholders acceptance: Overall evaluation** | C | Principles of the model are transparent, but the model is not endorsed by an authorative body | B | Principles of the model are easy to understand and based on the EUSES-system applied in the EU to evaluate new and existing chemicals, but the LCA version is not officially endorsed by an international authoritative body | | Not further evaluated, because the thresholds within the science based criteria were not reached | C | Principles of the model are transparent, but the model is not endorsed by an authoritative body |

### 3.3.4 Discussion on method evaluation

As stated in the LCIA- Framework and requirements document (EC-JRC, 2010b), LCA characterisation models and factors for human toxicity effects must be based on models that account for a chemical's fate in the environment, human exposure, and differences in toxicological response. Therefore, one of the midpoint methods (MEEuP) was not further evaluated since the proposed approach didn't have a human toxicity model behind the calculations.

For the five remaining human toxicity methods at midpoint, one (USEtox) has an almost full compliance with the science-based criteria, two (IMPACT2002+ and ReCiPe) show compliance in all essential aspects, one (TRACI) has a good science-based criteria compliance, while the remaining three (EDIP2003, CML2002 and EPS2000) show compliance only in some aspects. For the evaluation of stakeholder's acceptance criteria, the USEtox model also stands out compared to the other models as the principles of the model are easy to understand and UNEP encourages its use by businesses and governments.

Several features make USEtox the preferred choice as a default method for the calculation of characterisation factors:

- straightforward multimedia models are widely used in LCIA for modelling chemical fate and human exposure. USEtox reflects the latest consensus amongst such modellers and their associated models. It also reflects the principles of the earlier OECD consensus model (Klasmeier et al., 2006) that focused on fate and long range transport of contaminants. Similar to the other multimedia model based approaches, USEtox includes a number of vital model elements of toxicological effects assessment (Hauschild et al., 2008). Nevertheless it has undergone limited testing and shows the same fundamental limitations as all simple multimedia models
- it offers the largest substance coverage with more than 1250[18] human toxicological characterisation factors and reflects more up to date knowledge and data on cancer effect factors than other approaches.
- the model has been set up to model a global default continent, and it has a nested multimedia model in which it is possible to consider global, continental and urban scale differentiation.

### 3.3.5 Discussion of uncertainties and the importance of spatial-temporal differentiation

USEtox has similar uncertainties when compared to many of the other fundamentally similar models such as USES-LCA, Impact 2002, and CALTOX.

Degradation half-lives are in most cases the parameters driving uncertainty for the fate part of the assessment (Hertwich et al, 1999). The low dose extrapolation and dose-

[18] The number covered is relative compared to the number of classes of chemicals with similar behaviour, hence similar factors; however, no guidance on this yet exists in order to have default factors per chemical group/class. Such developments would extend the application of such models to a much broader range of chemicals

response modelling are responsible for the highest uncertainties in the effect part (Crettaz et al.2002, Pennington et al.2002).

For the quantification of the uncertainty of human toxicity characterization factors, e.g. Hofstetter (1998) provided expert based estimates yielding a 95% percent confidence limit of a factor 2 to 80 assuming on a lognormal distribution. Based on comparisons among the different models, e.g. Rosenbaum et al. (2008) suggested an additional model uncertainty of a factor 10. This generally results in a factor 100 for the uncertainty of recommended characterisation factors and a factor 1000 for the factors that are characterised as “interim” in the USEtox context (similar to Level III here, i.e. recommended, but to be applied with caution)

It is expected that the accuracy and overall reliability of the factors will lie at least in this range. But an uncertainty of 2 to 3 orders of magnitude is significantly lower than the roughly 12 orders of magnitude variation between the characterisation factors of different chemicals. Similar situations may exist for other impact categories.

As with all LCA results, best-estimates must be used for decision support, reflecting the current state of scientific knowledge and often predictions to low concentrations at which actual impacts may not be known. As discussed in Rosenbaum et al. (2008), characterisation factors presented here must be used in a way that reflects the large variation of 12 orders of magnitude between characterization factors for toxicological effects for different chemicals as well as the 3 orders of magnitude uncertainty on the individual factors.

In practice, this means that for the LCA practitioner, these characterisation factors for human toxicity can be useful to identify the 10 or 20 most important chemicals pertinent for their application. The life-cycle human toxicity scores enable thus the identification of all chemicals contributing more than e.g. one thousandth to the total score. In most applications, this will allow the practitioner to identify 10 to 20 chemicals to look at in priority and perhaps more importantly to disregard 400 other substances whose impact is not significant for the considered application. In practice, this means that for the LCA practitioner these toxicity factors are very useful to identify the priority contaminants pertinent to their application. The factors for toxicological effects thus enable the identification of chemicals contributing more than e.g. one thousandth to the total indicator result. In most applications where this is important, this will allow the practitioner to identify the chemicals that contribute the most to the indicator and, perhaps more importantly, to disregard 400+ other substances whose impact is not significant for the considered application. This is important in the interpretation phase, as well as where refinement of the study may be needed.

Furthermore, spatial differentiation may influence results, especially for chemicals with short lifetimes: the population density around the point of emission in case of inhalation being the dominant route , the agricultural production intensity in case of food dominant pathways, the vicinity of the emission relative to a drinking water source, etc. No comprehensive assessment or approach currently exists to account for these spatial, as well as temporal, variations in LCA studies. These may be partially cancelled out by other factors, such as having multiple sources of emissions or may be negligible relative to other sources of uncertainty/variation for many contaminants. Nevertheless, at the time of writing, it is not possible to provide general recommendations for differentiations in LCIA for toxicological effects that will reduce uncertainty and justify the collection of additional emission-scenario specific data.

## 3.3.6 Recommended default method at midpoint level

The use of USEtox as multimedia model, combining chemical fate and exposure with toxicological data, is recommended for midpoint indicators.

It results from a consensus building effort amongst related modellers and, hence, the underlying principles reflect common and agreed recommendations from these experts. The model accounts for all important parameters in the impact pathway as identified by a systematic model comparison within the consensus process.

This type of multimedia model integrates all environmental media into one consistent model, provides default estimates for use in applications such as LCA, and is widely adopted. It is adopted e.g. for regulatory assessments in e.g. the European Union (EUSES, see EC, 2004) and for persistence screening calculations as recommended by bodies such as the OECD (Klasmeier et al., 2006). This type of model is already widely used in LCIA and was recommended by SETAC (Udo de Haes et al, 2002) as well as by the working group of the UNEP/SETAC Life Cycle Initiative (Jolliet et al. 2006).

In USEtox, a distinction is made between recommended and interim characterization factors, reflecting the level of expected reliability of the calculations in a qualitative way (Rosenbaum et al. 2008).

Some characterisation factors (e.g. for 'metals', 'dissociating substances' and 'amphiphilics' - detergents) are classified based on expert opinion as interim due to the considered higher uncertainty of the factors for these substance groups relative to others in current practice. For the remaining set of chemicals, factors are also classified as interim when route-to route extrapolation of the effects data is particularly uncertain or when the target site is linked to the considered exposure route (nasal, lung or gastrointestinal target sites).

The calculation of separate midpoint factors for cancer and non cancer is recommended, as at least this distinction of effects is generally feasible in current practice and likely significant. Equally exposure to particulate matter or respiratory inorganics and ionizing radiation are to be considered separately.

## 3.3.7 Recommended default method at endpoint level

For the endpoint characterization, it is proposed as an initial basis to apply the most recent values that are proposed by Huijbregts et al. (2005a) using Disability Adjusted Life Years (DALYs) per case, as recommended in the section 3.1 of the requirement document (LCIA - Framework and requirements document, EC-JRC, 2010b). Since present knowledge does not enable to determine the exact effect endpoint for many chemicals, averages severities are calculated separately for cancer (11.5 DALY/case) and non-cancer (2.7 DALY/case) based on individual illnesses and used by default.

For cancer effects, the additional uncertainty linked to the severity factor will be limited, as these numbers are primarily based on statistical data for years of life lost and the variation between effects is about one order of magnitude (see e.g. Crettaz et al. 2002).

For non-cancer effects, the variation can be several orders of magnitude. Therefore no method is recommended and USEtox has to be considered as interim for non-cancer effects at the endpoint level.

As highlighted by Pennington et al. 2002, extreme caution is advocated when comparing the likelihood and potential consequence estimates across chemical emissions in an LCA study, particularly between noncancer and cancer effect results.

These estimates provide preliminary or screening level, insights only due to high model uncertainty. While the framework for the calculation of LCA characterization factors allows for the consideration of nonlinear low-dose response curves, mechanistic thresholds, and multiple background exposure concentrations, the availability of required data is limited in practice. Assumption of a default linear low-dose-response relationship remains pragmatically necessary. For truly nonlinear dose-response curves with mechanistic thresholds, likelihood measures may only reflect an erosion of the margin of exposure—an impact on the capacity of the world to accommodate such emissions. Acknowledging this high model uncertainty is important when interpreting the results of an LCA study".

### 3.3.8 Consistency between midpoint and endpoint methods

Compatibility between midpoint and endpoints recommendations is ensured since the midpoint indicator defined in USEtox as Comparative Toxic Units ($CTU_{human}$) corresponds to cases of cancer and non cancer, whereas the severity factor reflects the Disability Adjusted Life Years per case. These can therefore be combined in a straightforward way.

### 3.3.9 Classification of the recommended default methods

The midpoint method is generally classified as "recommended but in need of some improvements" (Level II out of III) for both cancer and non-cancer effects due to non polar organics.

The recommended endpoint method is described as Level II for cancer effects except for polar organics and as interim for non cancer effects, since the derivation of severity factors for the latter is much more variable and uncertain than for carcinogens. For non-cancer effects, no method is recommended and USEtox as to be considered as interim.

Note that, both for midpoint and endpoint, in the mixed classification in the summary table (II/III and II/interim) the second level of classification refers to substances belonging to the classes of metals and amphiphilics and dissociating chemicals, where the characterisation factors are down scored.

The present version of the USEtox model is not applicable to account for the contribution to population exposure of the direct application of pesticides on crops, or for direct human exposures associated with e.g. the use stage.

### 3.3.10 Calculation principles

In case a midpoint characterisation factor is missing for an important elementary flow in the inventory, it can be determined using the model as documented in Rosenbaum et al. (2008).

The latest version of the USEtox model may be downloaded at www.usetox.org to calculate characterization factors for new substances.

The calculation to fill data gaps requires the availability of the needed substance properties among which particularly the toxicity and degradability data can be uncertain and difficult to find. These are normally the input parameters contributing most to the overall uncertainty of the characterisation factor.

# 3.4 Particulate matter/Respiratory inorganics

## 3.4.1 Pre-selection of methods for further evaluation

The pre-selection of characterisation models for the particulate matter/respiratory inorganics impact category has been described in LCIA - Analysis document (EC-JRC, 2010a) and is summarized in Table 8.

**Table 8 Selected methods and models for respiratory inorganics.**

| Model/Method | Underlying model |
|---|---|
| **Generic models. Do not consider secondary aerosols.** | |
| USEtox (iF) (Rosenbaum et al. 2008) | Model based on a thorough evaluation of a large set of existing human toxicological and ecotoxicological models developed for LCA under the auspices of the UNEP-SETAC Life Cycle Initiative. |
| IMPACT 2002 (iF) (Pennington et al. 2005) | Steady-state model. Can easily be adapted to any spatial characteristics. |
| Humbert (2009) (iF, uF, endpoint) | Fate and exposure based on the UPFM model (Humbert, 2009). Effect and severity based on epidemiologic studies. Humbert. (2009) evaluate intake fractions, but also uptake fractions. |
| **Simplified compilation of results.** | |
| Hofstetter (1998) (iF, endpoint) | Compilation of different results. Effects are based on epidemiologic studies. Underlying method for the LCIA methodologies Eco-indicator 99 (Goedkoop and Spriensma, 2000) and IMPACT 2002+ (Jolliet et al., 2003). |
| **Simplified spatial approaches.** | |
| Greco et al. (2007) | Only fate and exposure evaluation.<br>Two outputs are made: 1) specific iF for the different US counties, based on the S-R matrix, and 2) regressions.<br>The underlying model of Greco et al. (2007) is a Source to Receptor (S-R) matrix. The S–R matrix is a regression-based derivation of output from the Climatologic Regional Dispersion Model (CRDM) which uses assumptions similar to the Industrial Source Complex Short Term model (ISCST3).<br>The considered parts for the present assessment are the regressions that are derived from the results of the 3080 US counties. These regressions evaluate iF as a function of population (density) at different radius. |
| RiskPoll (Rabl and Spadaro 2004) | This simplified model has been calibrated with different projects to reflect main factors on influence on intake and subsequent damages. Effects are based on epidemiologic studies. |

| **Detailed spatial models underlying the results.** | |
|---|---|
| TRACI (Bare et al. 2003) | Fate and exposure based on Wolff (2000), using the CALPUFF model.<br>Effect based on epidemiologic studies (Nishioka et al., 2002). |
| van Zelm et al. (2008) | Fate and exposure based on EUTREND. Effect based on epidemiologic studies. Underlying model for the LCIA methodology ReCiPe (Goedkoop et al., 2009). |
| EcoSense (IER 2008) | Fate and exposure using a source-receptor matrix (based on EMEP), WTM dispersion model and ISC model. Local scale modelling using the ISC model. Effect based on epidemiologic studies. |

In the figure below the description of the environmental mechanism for respiratory inorganics is provided.

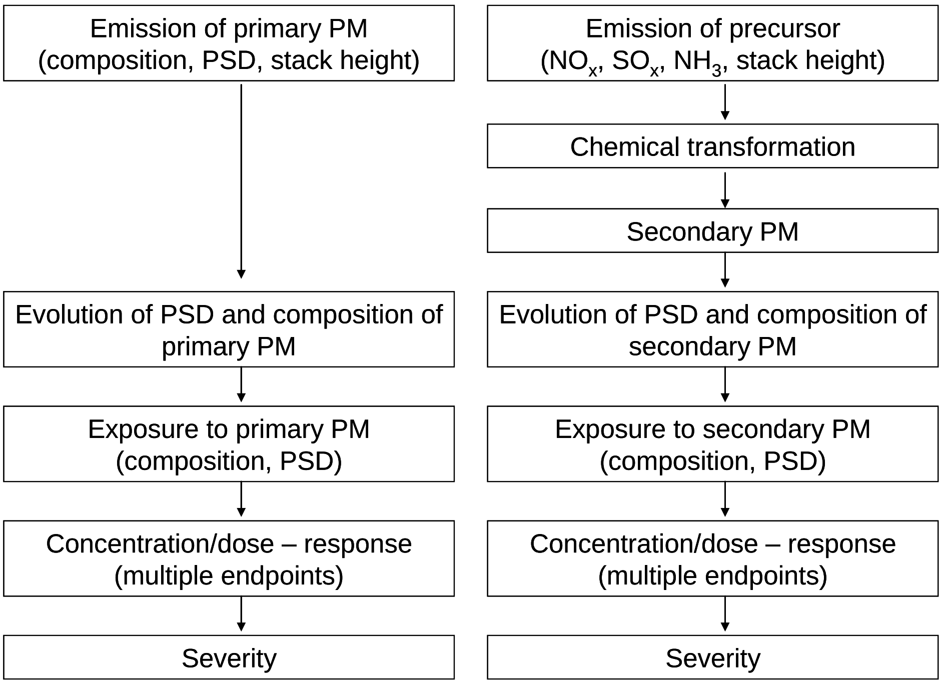



**Figure 4 Environmental mechanism for respiratory inorganics (derived from Humbert 2009)**

## 3.4.1.1 Intake fraction evaluation

The intake fractions (iF) calculated by different models are compared in table 8.3. Urban conditions represent a city of 10'000 $km^2$ having 10'000'000 inhabitants (1'000 pers/$km^2$). These parameters are the one used to represent urban conditions in the USEtox model (Rosenbaum et al., 2008). The values have been "corrected" for differences in breathing rates among the articles. The adjusted breathing rate is 13.3 $m^3$/pers·day (based on EPA, 1997). Only the adjusted intake fractions are presented in the table below.

**Table 9 Comparison of intake fractions between different models**

| Model | Urban | Rural | Average | Continental |
|---|---|---|---|---|
| Greco et al. 2007' counties | **5.2** ppm | **0.64** ppm | **1.6** ppm | **0.93** ppm |
| Greco et al. 2007' regressions | **6.5** ppm | **0.56** ppm | | **0.84** ppm |
| USEtox (low advection (500 $m^2/s$)) | **16** ppm | | | **0.79** ppm |
| USEtox (high advection (3200 $m^2/s$)) | **4.7** ppm | | | **0.79** ppm |
| RiskPoll | **6.7** ppm | | | |
| van Zelm et al. (2008) | | | **4.9** ppm | (**4.9** ppm) |
| Humbert et al. (2008) | **18** ppm | **0.18** ppm | **5** ppm | (**5** ppm) |
| *Marshall et al 2005' regressions (intra-urban only)* | ***37** ppm* | | | |
| *Heath* | ***18** ppm* | ***0.78** ppm* | | |
| *Heath (regressions)* | ***21** ppm* | ***0.89** ppm* | | ***2.2** ppm* |

Table 9 shows that the PM2.5 intake fraction varies more between low (rural median iF of 0.5ppm) and high (urban median iF of 15ppm) population densities with a factor 10 to 100 variation than between the model themselves with a factor 5 variation. Thus the ability to differentiate between low and high population densities is a key characteristic before considering the quality of the model itself.

### 3.4.1.2 Effect and severity evaluation

The treatment of effect and severity in the different models and methods evaluated is presented in the table below.

**Table 10 Treatment of effect and severity in the different models and methods evaluated (modified from Humbert 2009).**

| Model/Method | Type of endpoint considered | Effect factor |
|---|---|---|
| USEtox | Not considered. Only iF is valid at present stage. | No effect factor, only intake fraction |
| IMPACT 2002 | Chronic mortality; Respiratory admission; Chronic bronchitis incidence (adults); Bronchitis (children); Restricted activity days; Asthma attacks (adults and children) | Based on Hofstetter (1998): 43 DALY/kg $PM_{10}$ inhaled (average breathing rate of 20 $m^3$/pers·day), corresponds to 64 DALY/kg $PM_{10}$ inhaled (average breathing rate of 13.3 $m^3$/pers·day) |
| Humbert et al. (2009) | Chronic mortality; Respiratory admission; Chronic bronchitis incidence (adults); Bronchitis (children); Restricted activity days; Asthma attacks (adults and children) | 67 DALY/kg $PM_{10}$ inhaled (average breathing rate of 13.3 $m^3$/pers·day) |
| Hofstetter (1998) | Bronchodilator usage; Cough; Lower respiratory symptoms (wheeze); Chronic bronchitis; Chronic cough; Restricted activity days (RAD); Respiratory hospital admissions; Acute Mortality (AM); Chronic mortality; Expiratory Reserve Volume (ERV) for Chronic Obstructive Pulmonary Disease (COPD; ERV for asthma; ERV for croup in preschool children | 64 DALY/kg $PM_{10}$ inhaled (average breathing rate of 13.3 $m^3$/pers·day) |

| Model/Method | Type of endpoint considered | Effect factor |
|---|---|---|
| Greco et al. (2007) | No effect and severity modelling | N/A (average breathing rate of 20 $m^3$/pers·day) |
| TRACI | Premature mortality; chronic bronchitis; cardiovascular hospital admissions; restricted activity days | 25 DALY/kg $PM_{2.5}$ inhaled. 10.9 DALY/case |
| van Zelm et al. (2008) | Chronic mortality; acute mortality; acute respiratory morbidity; acute cardiovascular morbidity<br>Van Zelm et al. (2008) re-evaluated the effect and severity factors using clear input parameters. However, it does not consider effects caused by chronic bronchitis (adults) that are identified important by Hofstetter (1998) and Humbert et al. (2009). | 57.8 DALY/kg $PM_{10}$ inhaled (average breathing rate of 13 $m^3$/pers·day) |
| RiskPoll | short-term mortality; long-term mortality; respiratory hospital admissions; cerebrovascular hospital admissions; chronic bronchitis – adults; restricted activity day – adults; asthmatics (bronchodilator use) – adults; asthmatics (lower respiratory) – adults; asthmatics (coughing) – adults; chronic cough – children; asthmatics (bronchodilator use) – children; asthmatics (lower respiratory) – children; asthmatics (coughing) – children; congestive heart failure - elderly | PM10 = 32 YOLL/kg inh (long-term mortality)<br>PM2.5 = 54 YOLL/kg inh (long-term mortality)<br>(nitrates are considered PM10; sulphates are considered PM2.5) |
| EcoSense | Increased mortality risk (infants); new cases of chronic bronchitis; increased mortality risk – $YOLL_{acute}$; life expectancy reduction – $YOLL_{chronic}$; respiratory hospital admissions; cardiac hospital admissions; work loss days; net restricted activity days; minor restricted activity days; lower respiratory symptoms; LRS excluding cough; cough days; medication use/bronchodilator use. Concentration Response Function are published, and have been aggregated in "DALY due to morbidity" and "YOLL due to mortality", resulting in DALY per emissionof primary particulate matter and per precursor for nitrates and sulfates | 1E-4 DALY/kg $PM_{10}$ emitted |

In terms of severity, long-term mortality dominates most analyses of the effect factors. The effect and severity factor varies by a factor 4 (between 20 and 80 DALY depending on the size of PM considered and the model considered).

### 3.4.2 Method evaluation

The nine models have been rated against the criteria. The tables below summarises the assessment[19]. Background information for the assessments is in a separate Excel file[20] (Particulate matter.xls). Note that Greco et al. (2007) reports only the intake fraction.

[19] A: full compliance; B: compliance in all essential aspects; C: compliance in some aspects; D: little compliance; E: no compliance

[20] http://lct.jrc.ec.europa.eu/

**Table 11 Summary of the analysis of the available methods against the criteria for respiratory inorganics. (divided in two sub tables)**

| | | USEtox (iF) | | IMPACT 2002 (iF) | | Humbert et al.2009 (iF, uF, endpoint) | | Hofstetter 1998 (iF, endpoint) | | Greco et al.2007 (iF) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Completeness of scope** | C | Not complete since no factors for secondary/precursor at this stage. Useful for calibration (i.e., compare the results of other methods to the one of USEtox for PM10) and ensure consistency with other methods. | C | Not complete since no factors for secondary/precursor at this stage. | D | Not complete since only primary PM are considered. | C | The scope of the model for the evaluation of respiratory effects from inorganics on the European scale is applicable. It is not spatially adaptable. | B / E | The scope of the model for the evaluation of respiratory effects from inorganics is applicable for fate and exposure (B). Indeed, it only evaluates intake fraction. Does not evaluate the effect and severity (E). |
| **Environmental relevance** | C | Acceptable for first approximation of CF for primary PM10. No secondary PM treated. Urban emissions can be explicitly modeled. | C | Acceptable for first approximation of CF for primary PM10. No secondary PM treated. Urban emissions can be explicitly modeled. | C | Good for primary PM. Consider the influence of the PSD. Not complete since no secondary PM. Urban emissions can be explicitly modeled. | C | Good overall. Lack differentiation between urban and rural. Lack difference between low/high stack (i.e., mobile/point sources). | B / E | Good overall. Regressions very useful. No effect is considered. Can be used for fate and exposure, but not for effect and severity. Only low (i.e. mobile) sources. Lack NH3. |
| **Scientific robustness & Certainty** | C | Chemical input data and model components extensively reviewed by a large group of model developers, but no uncertainty estimates available. No secondary PM provided. Some limitations (dose-response function only mass based and not surface or number, influence of PSD not considered). | C | Some limitations (dose-response function only mass based and not surface or number, influence of PSD or composition not considered). | B | Good basis for future research. | C | Science based but with some limitations (dose-response function only mass based and not surface or number, influence of PSD not considered). Does not reflect the latest scientific knowledge. | B / E | The model is science based, but only until intake fraction. Does not go further. Some limitations (influence of PSD or composition not considered). Treatment of secondary PM simplified. |
| **Documentation, Transparency & Reproducibility** | A | Extensively documented. Easy to reproduce results and modify input parameters. | B | Easy to reproduce results and modify input parameters. But only partly documented. | D | At the time of the evaluation not published | B | Acceptable. Published as a book so not as easy to get access to. | B | Good documentation. Factors published. Background data and models referenced. Not easy to reproduce results and modify input parameters. |
| **Applicability** | B | Good for primary PM10. No secondary/precursor PM. | B | Good for primary PM10. No secondary/precursor PM. | B | Very good applicability. But only for primary PM. | A | Very good applicability | A / E | Good applicability but only for fate and exposure. Lack factors for NH3. (E) for lacking effect/severity. |
| **Science based criteria** | C | Acceptable for first approximation of CF for primary PM10 (lack of latest knowledge regarding surface or number might be better than mass and influence of PSD). No secondary PM treated. Can have an urban box. | C | Acceptable for first approximation of CF for primary PM10 (lack of latest knowledge regarding surface or number might be better than mass and influence of PSD). No secondary PM treated. Can have urban box. | C | Good basis for future research. Unpublished yet. | C | Good science. Lack of latest knowledge regarding surface or number might be better than mass based and influence of PSD, as well as fate and damage modeling. CF specific to urban emissions not considered. No difference between low/high stacks (mobile/point sources). | B | Good science behind. Lack of latest knowledge regarding that the surface or number might be better than mass and influence of PSD. Regressions easy to adapt to specific spatial conditions. Allow to have CF for urban emissions. Risk to underestimate iF caused by emissions in densities higher than 1000 pers/km2. For mobile sources only. Lack values for NH3. |
| **Stakeholders' acceptance** | B | Principles of the model are easy to understand and the model is endorsed by an international authoritative body (UNEP) | C | Method already extensively used. But only primary PM is present. | D | Not published at the time of the preliminary analysis of methods | B | Good. | B / E | Good for fate and exposure(B). Effect and severity missing (E) |

| | | RiskPoll (iF, endpoint & CBA) | | TRACI (iF, endpoint) | | van Zelm et al. 2008 (iF, endpoint) | | Ecosense (iF, endpoint & CBA) |
|---|---|---|---|---|---|---|---|---|
| **Completeness of scope** | B | Complete assessment of impacts and damage costs due to primary and secondary PM, including model for creation of secondary PM due to $SO_2$ and NOx emissions. Both local and regional impacts can be modeled. | C | The scope of the model for the evaluation of respiratory effects from inorganics is applicable if European and US conditions considered comparable. But not spatially adaptable. | C | The scope of the model for the evaluation of respiratory effects from inorganics on the European scale is applicable. But not easily spatially adaptable. | A | The scope of the model for the evaluation of respiratory effects from inorganics on the European scale is applicable. The user has to provide longitude and latitude |
| **Environmental relevance** | B | Complete assessment of impacts and damage costs due to primary and secondary PM, including model for creation of secondary PM due to $SO_2$ and NOx emissions. Both local and regional impacts can be modeled. | C | Good overall. But valid for US. Lack difference between urban and rural emissions. Lack easy adaptability to specific population density. | C | Good overall. Lack value for PM2.5. Lack explicit difference between urban and rural, though underlying approach is spatially adaptable. Has low/high (mobile/point) difference. | B | Good overall. But lack easiness of spatial adaptability. Lack explicit difference between urban and rural. Has low/high (mobile/point) difference. |
| **Scientific robustness & Certainty** | B | Model is based on detailed and thorough review of epidemiological evidence. Recently updated for the NEEDS project of ExternE. Some limitations (influence of PSD or composition not considered). | B | The model is science based. But with some limitations (dose-response function only mass based and not surface or number, influence of PSD or composition not considered). Secondary PM treatment not simplified, as in Greco et al. (2007). | B | The approach is science based. But with some limitations (dose-response function only mass based and not surface or number, influence of PSD or composition not considered). | B | The model is science based. But with some limitations (dose-response function only mass based and not surface or number, influence of PSD or composition not considered). |
| **Documentation & Transparency & Reproducibility** | B | Detailed documentation available in "Methodology Update 2005", at www.externe.info. Easy to reproduce results with the simplified version. The model can be used to re-run different cases with different inputs. | B | Documentation referenced. Not easy to reproduce results and modify input parameters. | B | Good documentation. Factors published. Background data and models referenced. Not easy to reproduce results and modify input parameters, though underlying approach is spatially adaptable. | B | Good documentation Easy to reproduce results with the simplified version. But not easy to modify input parameters. |
| **Applicability** | B | Applicable on all continents | A | Very good applicability | A | Very good applicability | A | Good applicability |
| **Overall evaluation of science based criteria** | B | Model is based on detailed and thorough review of epidemiological evidence, recently updated for the NEEDS project of ExternE. Lack of latest knowledge regarding that the surface or number might be better than mass and influence of PSD. CF specific to urban emission considered. | B | Good science based. But valid for US and not easily adaptable for regionalization. Lack of latest knowledge regarding surface or number that might be better than mass and influence of PSD. CF specific to urban emissions not considered, though underlying approach is spatially adaptable. CF for mobile and point sources (proxy for low and high stack). | B | Good science. Lack of latest knowledge regarding surface or number that might be better than mass based and influence of PSD. CF specific to urban emissions not considered, though underlying approach is spatially adaptable. Lack value for PM2.5. Has different values for different stack height (proxy for mobile and point sources). | B | Good science based. Valid for EU and not easily adaptable for regionalization. Lack of latest knowledge regarding surface or number that might be better than mass and influence of PSD. CF specific to urban emission considered. |
| **Stakeholders acceptance criteria** | C | Principles of the model easy to understand, and full documentation is readily available. | B | Good. There is an authoritative body behind (US EPA). | B | Good. Not spread out yet. | B | Good acceptance. There is an authoritative body behind (EU). |

### 3.4.3 Discussion on method evaluation

The intake fraction calculated for primary particle matter by the different models ranges from 0.5 ppm to 40 ppm depending for example on the population density or the height of emission points. It is essential to select a model that covers both primary and secondary particulates and can be adapted to various population densities and heights of emission points. Both RiskPoll and Greco et al. (2007) enable, in a simplified approach, to calculate the intake fraction, adjusting the population density to be consistent with other human health impacts (e.g. human toxicity, ionizing radiation, etc.). Any user can customize these two models to calculate factors for specific situations without excess time investment.

Greco et al.(2007) represents an interesting alternative to RiskPoll: a) it covers both primary and secondary aerosols (apart from $NH_3$); b) population densities can be adapted to match any landscape parameters (because of regressions). Weaknesses are: 1) does not evaluate secondary PM from $NH_3$, 2) only addresses mobile (i.e., low stack) sources, and 3) cannot adapt to different wind speeds. The secondary PM from $NH_3$ as well as the stack height would need to be extrapolated from other studies[21].

RiskPoll (Rabl and Spadaro, 2004) makes a complete assessment of impacts and damage costs due to primary and secondary PM, including model for creation of secondary PM due to $SO_2$ and $NO_x$ emissions. It also parameterizes the dominant factors of influence for generic landscape characteristic. It can be adapted to match various landscape parameters, though not as easily as Greco et al. (2007). Calculations for new substances are not straightforward and intake fractions have to be calculated separately since they are not readily available in the present software. The advantage over Greco et al. (2007) is that RiskPoll differentiates between low and high stacks.

*a) Other methods for sensitivity study or for further research*

Results of van Zelm et al.(2008) and TRACI can be used for sensitivity analysis. Average and country specific values for different height of release, from EcoSense EU27, can be used for hotspot and sensitivity analysis. Actually, EcoSense makes a complete assessment of impacts and damage costs due to primary and secondary PM, including model for creation of secondary PM due to NH3, SO2 and NOx emissions for two different emission scenarios (i.e. 2010 and 2020)

EcoSense: Being a regularly updated model of seemingly high scientific quality developed for policy support in the European energy sector, EcoSense could be an interesting candidate for future recommendations within the impact categories for respiratory inorganics but also for photochemical ozone formation, acidification and eutrophication. Since it does not provide characterisation factors, it cannot be considered for recommendations at this point, but investigation of the possibilities to adapt EcoSense to characterisation modelling at both midpoint level and endpoint level.

Furthermore, it has good data for Europe (EC, 2005). However it is less well adapted for global calculations, and lacks ease of adaptation to match any landscape parameters. Part of

[21] Note that if Greco et al. (2007) is used, regressions parameters have to be multiplied by 13.3/20 to account for the fact that the regressions were derived for an average breathing rate of 20 $m^3$/pers·day, whereas the average breathing rate of the US population (EPA 1997) is 13.3 $m^3$/pers·day.

it is possible with the online version that also provides overall correlations. This however needs further research for application within the LCA framework since simplified data are only available for overall costs without intermediary results such as intake fraction. The environmental relevance of Ecosense is good but lack explicit difference between urban and rural, though underlying approach is spatially adaptable even not easily. Has low/high (mobile/point) difference.

TRACI and van Zelm et al. (2008) have the advantage to differentiate between low/high (i.e., mobile/point) sources, but both are not easily adaptable to other landscape parameters, though the underlying models can be modified. Van Zelm et al. (2008) don't have values for $PM_{2.5}$. EcoSense makes the assessment of impacts and damage costs due to primary and secondary PM, including model for creation of secondary PM due to $NH_3$, $SO_2$ and $NO_x$ emissions for emission scenario 2010 and 2020. EcoSense provides values for release height >100 m and average of all sources.

b) *Models not selected* as the recommended model but useful for consistency or further research:

a) USEtox (lack of value for secondary particles but useful to calibrate the selected model and ensure consistency with other impacts on human health, USEtox is better for human toxicity impact than for respiratory inorganics because several mechanisms influencing the fate of PM are not considered (e.g. coagulation). Apart from USEtox, all the other method input date were not peer reviewed

b) Hofstetter (1998) (van Zelm et al. (2008) is a better update),

c) IMPACT 2002 (no value for secondary particles),

d) Humbert et al. (2009). Good method to differentiate between particle size and only method that considers surface or number instead of mass as the proxy for health effects. It has an excellent adaptation to specific spatial conditions. CF specific to urban emission considered. However, it is only available for primary particles.

#### 3.4.3.1 Discussion of uncertainties and the importance of spatial differentiation

Spatial differentiation between emissions in low and high population density is a key factor for the fate and exposure for primary and secondary particulate matter (Humbert, 2009). On the effect side, it has been suggested that Reactive Oxidant Stress is a major determinant in the health effects (e.g., Donaldson et al., 2003). The exact mode of action is however still undefined, especially whether impacts are due to a physical effect of PM or to other organic or inorganic substances adsorbed to particulate (making in that case surface a better proxy than mass to evaluate the adverse health effects). In addition, the use of epidemiological data implies that PM attributed impacts can be due to other pollutants or physical factors whose concentration could be correlated to PM. Care must especially be taken to avoid possible double-counting between impacts of PM-attributed impacts and impact of other correlated variables in case of common endpoint.

The uncertainty of the intake fraction is evaluated to approximately a $95^{th}$ percentile confidence limit of a factor 3 assuming a log-normal distribution (e.g., Marshall et al. 2005).

The uncertainty of the effect (i.e., slope) factor is judged to approximately a factor 2, and the uncertainty of the severity factor to approximately another factor 2 (between approximately 6 and 12 DALY/case of long term mortality). By uncertainty is meant scientific knowledge of the phenomena, and not the variability in function of the population density. Overall, the characterisation factor therefore has an uncertainty of a factor 6 ($5^{th}$ and $95^{th}$ percentile).

### 3.4.4 Recommended default method at midpoint (fate and exposure level)

Following the discussion above, it is recommended to use RiskPoll (Rabl and Spadaro, 2004) as a basis for calculating intake fractions and to use Greco et al. (2007) and the other models described in the discussion on method evaluation to check and possibly adjust the order of magnitude of the intake fraction. According to WHO, it is recommended to consider in a first step the fraction below 2.5 μm as a harmful fraction that reaches the target site. Furthermore, if surface or number is considered a better proxy of impacts than mass, $PM_{2.5}$ is a good approximation.

### 3.4.5 Recommended default method at endpoint (effect and severity level)

It is recommended to recalculate the effect and severity factors, starting from the work of van Zelm et al. (2008) that provides a clear framework, but using the most recent version of Pope et al. (2002) for chronic long term mortality and including effects from chronic bronchitis as identified significant by Hofstetter (1998) and Humbert (2009).

### 3.4.6 Consistency between midpoint and endpoint methods

Since the endpoint model is an effect and severity calculation applied to the exposure estimate provided by the midpoint characterisation, there is good consistency between midpoint and endpoint model.

### 3.4.7 Classification of the recommended default methods

At midpoint, intake fraction calculations based on RiskPoll (Rabl and Spadaro, 2004) and Greco et al. (2007) are classified as Level I (recommended and satisfactory) since the human health effects of PM has been extensively studied.

At endpoint, for the effect and severity factor, these effects are well demonstrated for primary particles (Level I) but more uncertain for secondary particles (Level II out of III, i.e. “recommended with some improvements needed”). The user must however be conscious that the estimated effect of PM may be an indicator of the overall effect of the air pollution rather than based on a proven cause-effect relationship for PM.

### 3.4.8 Calculation principles

The number of flows contributing to this impact category is rather modest and largely covered by existing factors. However, the location and the associated population density in the deposition area is crucial to the impact at midpoint level (intake fraction), and a study may require that characterisation factors be calculated to represent the population density conditions in the actual area affected by important emissions from the product system. This requires running the recommended midpoint model with the relevant population density and possible emission height information. The endpoint factors (effect and severity) are substance/agent specific and not influenced by local conditions.

# 3.5 Ionizing radiation

## 3.5.1 Pre-selection of methods for further evaluation

For damage to **human health** related to the routine releases of radioactive material to the environment (see Figure 5 for the impact pathway), the method described in Frischknecht et al. 2000 has been considered, since to our knowledge this is the only method that meets the general requirements for a quantitative approach. The fate and exposure model has been based on the ExternE work carried out by Dreicer et al., 1995, who described the routine 14 atmospheric and liquid discharges in the French nuclear fuel cycle. Data from UNSCEAR (1993) were used for 3 additional radionuclides.

Frischknecht et al. 2000 list the DALYs for the same types of cancers which are used for human carcinogens, with 0.05 fatal and 0.12 non-fatal cases per Man-Sv, as reported by Ron and Muirhead (1998). Radiation induced cancer cases are assumed to occur at the same age pattern as for other cancer causes. The number of severe hereditary effects is assumed to be 0.01 case per Man-Sv [ICRP[22], 1999], resulting in 61 DALYs per case without age weighting.

For damage to **ecosystem** (see the impact pathway at Figure 6**)**, the model developed by Garnier-Laplace et al. (2008 and 2009) has been analysed, that uses " the Dose Rates associated with a 50% Effect defined as the percent change in the (average) level of the observed endpoint during a chronic external gamma irradiation exposure experiment, named $EDR_{50}$ expressed in µGy/h" (Garnier-Laplace et al., 2006). The ecotoxicological effect factor is calculated by converting the dose rates into the corresponding medium concentration (i.e. water and sediment for freshwaters) for nine commonly adopted reference organisms covering different phyla. The final effect factor is calculated as 0.5 divided by the geometric mean of the $HC_{50r,o}$ for the nine reference organisms and associated with the 95% confidence interval. To model the endpoint indicator a PDF calculation is foreseen to be applied to the midpoint indicator score (Based on Posthuma and de Zwart, 2006 as for ecotoxicity).

The pre-selected models are reported in the table below.

[22] ICRP is the International Commission on Radiological Protection

**Table 12 Selected methods and underlying models**

| **Human toxicity** | **Underlying model** | **Reference** |
|---|---|---|
| Human health damages due to ionizing radiation | Dreicer et al. 1995<br>UNSCEAR, 1993 | Frischknecht et al., 2000 also used in Ecoindicator 99, IMPACT 2002, ReCiPe and Swiss Ecofactor<br>. |
| **Ecotoxicity** | | |
| Screening Level Ecological Risk Assessment for radioactive releases | AMI – Payet et al., 2004<br>EDEN, v.1.5 | Garnier-Laplace, 2008, 2009 also based on Garnier-Laplace, 2006 |

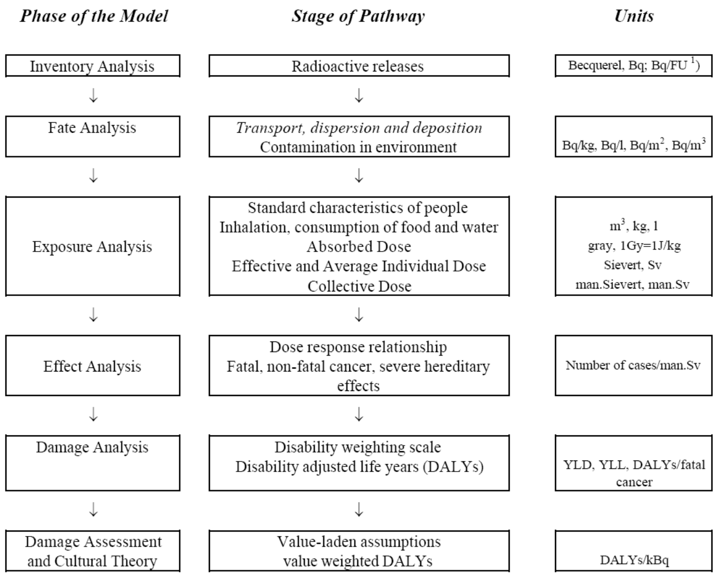



**Figure 5 Overview of impact pathway stages of radioactive releases for human health (adapted from Frischknecht et al. 2000).**

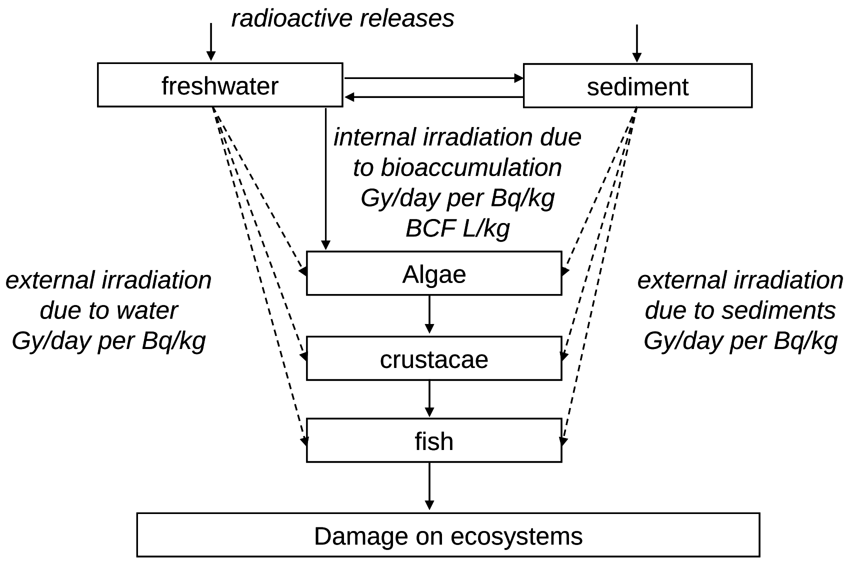



**Figure 6 Overview of impact pathway on ecosystem for radioactive releases to freshwater. Plain lines refer to physical transfers of radioactive substances, whereas dotted lines correspond to exposures to radioactive radiation.**

## 3.5.2 Method evaluation

Since currently only a single method is presently considered relevant for each of the ionizing radiation subcategories, no detailed criteria-based comparison were planned as with the other impact categories (See LCIA- Framework and requirements document, EC-JRC, 2010b). Hence, no specific criteria have been developed for this impact category. Instead the evaluation is focused on the level of quality reached by the available methods within each main criterion. Table 13 summarizes both model performances[23] for human toxicity and ecotoxicity. The assessments are documented also in a separate Excel file[24] (Ionising radiation.xls).

**Table 13 Summary table on the analysis of the characterisation methods for ionizing radiation.**

| **Criteria** | **Frischknecht et al. 2000** | | **Garnier-Laplace et al. 2008 and 2009** | |
|---|---|---|---|---|
| | | **human health** | | **ecosystem health** |
| **Completeness of scope** | | The model scope is applicable to the comparative evaluation of impact of radioactive substances on human health. It is valid on global and European scale and compatible with human toxicity category, also leading to DALYs at endpoint. The method is based on site-specific fate and exposure models for French Nuclear facilities and data has been generalised for a site-independent assessment. No spatially differentiated factors are presently available. There is no independent midpoint with this category, but intermediary data on fate and exposure and on number of cases. | B | For ecotoxicity of radioactive substances, the model is fully applicable to the comparative evaluation of radionuclides on global and European scale. Its underlying framework is consistent with that used for ecotoxicity |
| **Environmental relevance** | B | Environmental relevance is high. The framework enables to provide separate intermediary results on fate and exposure, on dose-response and related number of cases and on DALY per case in a consistent way with the human toxicity framework. No urban area since releases mostly occur outside of large agglomerations | B | Environmental relevance is high for freshwater ecotoxicity, but ecotoxic impacts in marine and terrestrial compartments are not considered. The model applied to convert radiative doses to corresponding concentration represents the state-of-the-art and accounts for organism specific absorption rates relative to their preferred life medium (sediment, water). The model does not cover the endpoint, but here the method applied for ecotoxicity can be adapted since chemical and ionizing radiation are directly comparable in this respect. |
| **Scientific robustness & Certainty** | B | The scientific quality of the model used is good and uncertainty has been documented at each assessment step. The endpoint approach based on DALY is sound and consistent with other human health impact categories. Dose-response is directly based on human subject exposed in Nagasaki and Hiroshima and is therefore more reliable than for human toxicity. | B | All factors are based on at least three Effect Dose 50% at 3 different trophic levels, therefore qualifying for the ecotoxicity requirement for recommended factors (rather than interim). |
| **Documentatio, transparency & Reproducibility** | A | The model, documentation and results are published in peer reviewed journals and very well documented with detailed data and sources used for each radionuclide and model part, ensuring further reproducibility | C | The underlying models and principles have been published in peer reviewed journals. However documentation of the characterization factors applicable in LCA is only available as grey literature |

[23] A: full compliance; B: compliance in all essential aspects; C: compliance in some aspects; D: little compliance; E: no compliance

[24] http://lct.jrc.ec.europa.eu/

| Criteria | Frischknecht et al. 2000 | | Garnier-Laplace et al. 2008 and 2009 | |
|---|---|---|---|---|
| | | human health | | ecosystem health |
| **Applicability** | B | Frischknecht et al (2000) calculate the characterization factors per emission (Bq) for 21 radionuclides to outdoor air, 13 to water and 15 to ocean covering 31 nuclides as a whole, which are supposed to be the most important in nuclear power plant operations. Factors can be easily applied. Update requires specific knowledge | B | Characterization factor for the 13 most frequent releases from nuclear power plants to water. Factors can be easily applied. Update requires specific knowledge |
| **Science based criteria** | B | The proposed framework includes all vital model elements in a scientifically sound way. There is a need to update some of the input data and/or models | B | The model addresses the freshwater part of the environment problem, includes all vital model elements in a scientifically sound way. Documentation needs to be improved. |
| **Stakeholders acceptance** | B/C | Principles of the model are transparent The model has been widely used but not endorsed by an international authoritative body | **C** | Principles of the model are transparent and compatible with the USEtox framework, but the LCA version has not been peer reviewed yet and is not officially endorsed by an international authoritative body |

## 3.5.3 Discussion on method evaluation: uncertainties and limitations

For human health impacts, the uncertainty in the fate analysis is approximately a factor 2 to 4 (Dreicer et al., 1995), but for globally dispersed radionuclides (i.e., Tritium (H-3), Carbon-14, Krypton-85, and Iodine-129), for which the uncertainty is probably greater than an order of magnitude. An important source of uncertainty is related to the very long half-lives of these radioactive materials. The global exposure of Tritium, Carbon-14, Krypton-85, and Iodine-129 has been calculated for a time horizon of 100.000 and 100 years. The uncertainties for the global exposure are considerable for these substances and a coefficient of variation of 10 to 50 has to be assumed (a coefficient of variation of 10 means that the confidence intervals varies between the median divided by 10 and the median multiplied by 10). The coefficient of variation typically amounts to a factor 3 for cancer endpoint and to a factor 5 for hereditary diseases. The uncertainty on the DALY per case of hereditary is estimated to a factor 1.5.

Uncertainty for the ecosystem impacts has been characterized using bootstrap methods and leading to 95% confidence intervals on the $HC_{50}$ for each radionuclide.

It is important to note that the present framework involves significant simplifications that need to be further refined long-term. The different biochemical reactions in the body tissues are not fully defined and the multiple radiochemicals toxicity might lead to non additive synergies. Low-dose ionizing radiation might induce trans-generational instability that differs significantly from one species to another. Delayed genomic instability in human, animal and vegetal cells would be difficult to quantitatively model in detail.

### 3.5.4 Recommended default method for human health impact of ionizing radiation

For the midpoint and endpoint characterization, the method proposed by Frischknecht et al., 2000 is recommended. It includes all vital model elements in a scientifically sound way and the method is well documented. Intermediary results on fate and exposure and on number of cases are available and should be kept separate. Anyway, at endpoint no method is recommended, due to the high uncertainty on the DALYs per case of severe hereditary effects. Frischknecht et al., 2000 at endpoint could be only used as interim.

### 3.5.5 Recommended default method for the ecosystem impacts of ionizing radiation

At midpoint and at endpoint, no method is recommended for ecosystem impacts of ionising radiation.

As interim, for the midpoint characterization, the approach developed by Garnier-Laplace et al.2008 and 2009 could be used. The model addresses the freshwater part of the environment problem, includes all vital model elements in a scientifically sound way. The midpoint method for impacts of ionizing radiation is classified as not recommended since at the moment there has been no peer review on the characterisation. The method can be upgraded to level III, once characterization factors have been published in a peer reviewed publication and properly documented based on an ERA- type approach recently published (Garnier Laplace et al, 2009)

The model does not cover the endpoint. The method of Posthuma and De Zwart, 2006 could be applied as for ecotoxicity (since chemical and ionizing radiation are both based on Hazardous Concentration affecting 50% of species ($HC_{50}$) at their 50% effect ($EC_{50}$) and are directly comparable in this regard), but, due to the existing limitation of the methods, no recommandation of using this endpoint is done.

### 3.5.6 Consistency between midpoint and endpoint methods

If also interim methods are considered, consistency is good between midpoint and endpoint both for human health impacts and ecosystem impacts.

### 3.5.7 Classification of the recommended default methods

For human health, at midpoint (e.g. incidences of cancer or other diseases) the method of Frischknecht et al., 2000 is classified as being recommended for human toxicity impacts of ionizing radiation at level II out of III (recommended but in need of some improvements).

At endpoint no method is recommended, due to the high uncertainty on the DALYs per case of severe hereditary effects. The method of Frischknecht et al., 2000 can be used as interim

No method is recommended for ecosystem impacts at midpoint and at endpoint.

At midpoint, as interim, the method developed by Garnier-Laplace et al. 2008 and 2009 could be used.

### 3.5.8 Calculation principles

Most important radionuclides are covered by existing factors; the need for calculation of additional factors is limited.

## 3.6 Photochemical ozone formation

### 3.6.1 Pre-selection of methods for further evaluation

The impact category appears under a number of different names in the various LCIA methodologies: (tropospheric) ozone formation, photochemical ozone formation or creation, photo oxidant formation, photo smog, or summer smog. There are minor differences in terms of substances included and atmospheric and meteorological conditions assumed in the modelling, but in essence they all address the impacts from ozone and other reactive oxygen compounds formed as secondary contaminants in the troposphere by the oxidation of the primary contaminants Volatile Organic Compounds (VOC) or carbon monoxide in the presence of nitrogen oxides, $NO_x$ under the influence of light. In the "LCIA-Analysis document" the pre-selection of characterisation methods for the ozone formation impact category is described. The pre-selected methods are briefly introduced below:

**Midpoint**

- CML2002 and EDIP97: Photochemical Ozone Creation Potential (POCP) based on UK AEA model using a simplified description of the atmospheric transport (Lagrangian type model). CML2002 applies the latest version from Derwent et al, 1998, EDIP97 adopts a distinction between areas with high and low background concentration of $NO_x$ and applies a Swedish modification (Andersson-Sköld et al, 1994) for estimating the ozone formation in low $NO_x$ regions – expressed as $C_2H_4$ equivalents. Both represented by CML2002.
- EDIP2003: Two sub categories, both site-dependent at the level of country in Europe based on RAINS model (Hauschild et al, 2006), which applies the Eulerian EMEP model (Heyes et al, 1996). Impact on humans modelled as number of people exposed in excess of WHO guidance value for chronic effects times duration (WHO, 1989) – expressed as pers·ppm·hours. Impacts on vegetation modelled as area of ecosystem exposed above guiding threshold for chronic effects times duration (WHO, 1987) – expressed as $m^2$·ppm·hours. It has factors for Non-Methane Volatile Organic Compounds (NMVOC), $CH_4$, CO and $NO_x$. Substance-specific characterisation factors are possible through correction with relative POCP-factor.
- LIME: Models ozone formation from 8 archetypes of VOCs in $C_2H_4$ equivalents at midpoint using a Japanese modification of the Photochemical Box Model from US EPA (Schere & Demerjian, 1984, modified 1992, as quoted in the Japanese LIME documentation) to produce Ozone Conversion Equivalency Factors (OCEF) which are geographically differentiated for seven Japanese regions (Itsubo et al., 2008d).

- MEEuP: No environmental science-based characterisation model – the emitted masses of individual NMVOCs are simply added (Kemna et al., 2005). Not further evaluated
- ReCiPe: Models marginal increase in ozone formation due to emissions of NMVOC or $NO_x$ applying the LOTOS-EUROS spatially differentiated model averaging over 14000 grid cells to calculate European factors. Substance-specific CF possible through correction by the substance's POCP factor relative to the POCP-factor for an average NMVOC (van Zelm et al, 2008).
- TRACI: Maximum Incremental Reactivity (MIR) model from Carter, 2000 for characterisation factors, average factors for US based on weighting according to population density patterns, characterisation factor for $NO_x$ based on national influence relative to NMVOCs (Norris, 2003).

**Endpoint**

- EcoSense: Fate and exposure modelling spatially differentiated at the level of country in EU15 using a simplified description of the atmospheric transport (Lagrangian type model). Linear effect model for human health damage based on epidemiological data and for crop damage based on laboratory data for loss of crops (Krewitt et al, 2001). The model has been updated into EcoSenseWeb 1.3 (Preiss & Klotz, 2008).
- EPS2000: Fate model based on a pre-1992 version of UK AEA's POCP model, linear effect model based on epidemiological data for human health impacts and on empirical or lab data for loss of crops (Steen, 1999b).
- LIME: Damage to human health (expressed as DALY) is modelled based on epidemiological data from ExternE taking regional differences in population density into account, damage to crop and wood production (in economic figures) and damage to primary production (loss of NPP) are modelled based on empirical data from Japan.
- ReCiPe: Models human health damage by applying constant damage factor for acute human health effects (expressed as DALY) based on European statistics. Chronic effects and non-linearity due to existence of thresholds are disregarded due to lack of evidence. Damage to vegetation is not considered.

For the evaluation the following methods are left out: EI99 (ReCiPe is a follow up), IMPACT 2002+ (same as EI99), LUCAS (same as TRACI but applied in Canada) and Swiss Ecoscarcity (in accordance with Swiss regulation, no distinction between NMVOCs, i.e. weight-based summation as in MEEuP).

Figure 7 shows the cause-effect chain for photochemical ozone formation from airborne emissions of VOCs, carbon monoxide or nitrogen oxides with the most important pathways highlighted (bold arrows). The analysed LCIA methods are positioned along the cause-effect chain.

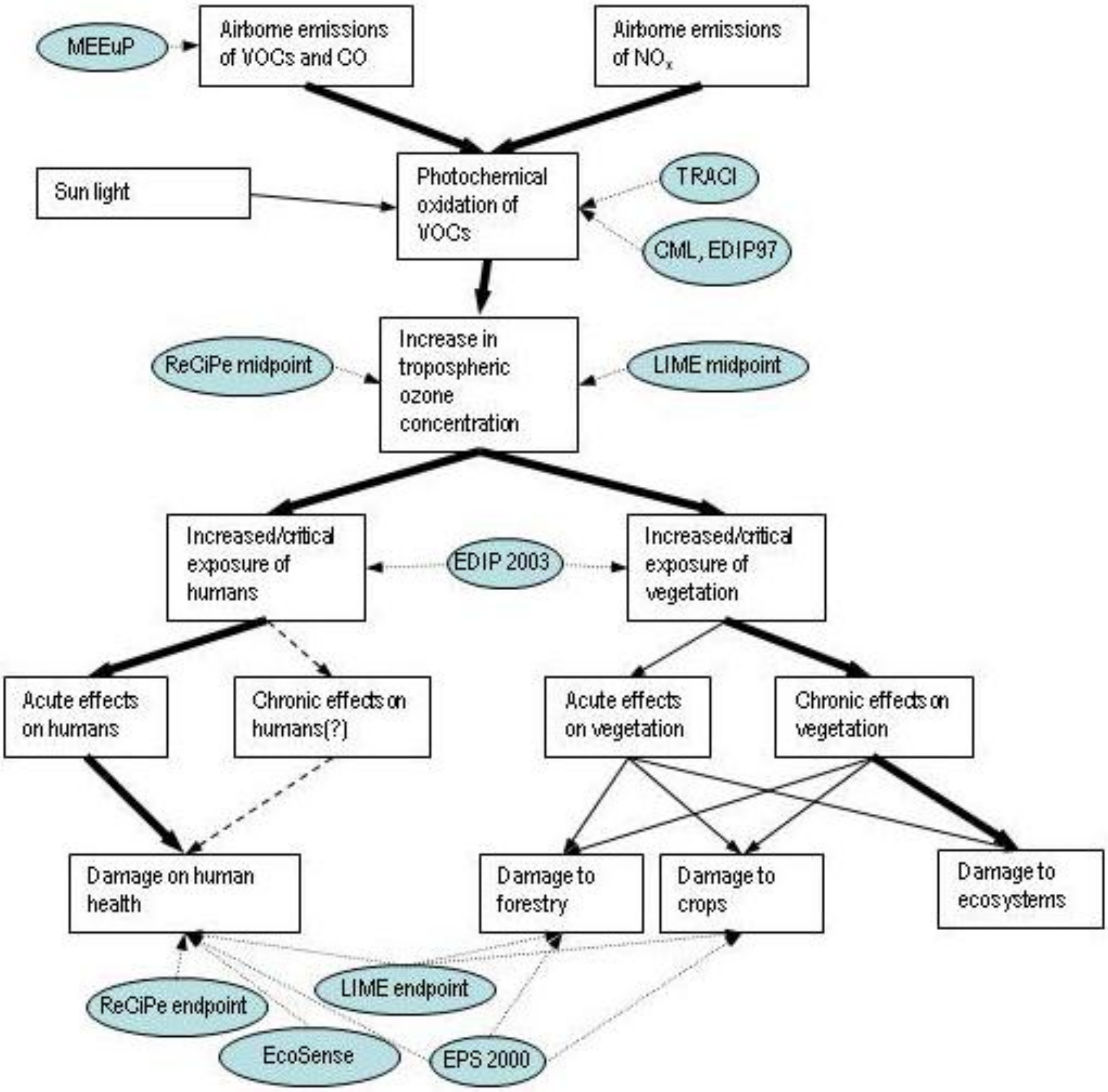



**Figure 7 Flow diagram for photochemical ozone formation and position of analysed LCIA methods along the cause-effect chain.**

## 3.6.2 Method evaluation

The pre-selected models have been rated against the criteria defined in the LCIA-Framework and Requirements (EC-JRC, 2010b). The results are summarized in the Table 14 and Table 15[25]. Background information for the assessments is in a separate Excel file[26] (Photochemical ozone.xls)

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[25] A: full compliance; B: compliance in all essential aspects; C: compliance in some aspects; D: little compliance; E: no compliance

[26] http://lct.jrc.ec.europa.eu/

**Table 14 Summary of the evaluation results of the midpoint characterisation methods against the criteria for photochemical ozone formation**

| . Criteria | | CML 2002 (Derwent et al., 1998) | | EDIP2003 | | LIME midpoint | | MEEuP | | ReCiPe midpoint van Zelm et al., 2008 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Completeness of scope** | B / C | The scope of the model is fully applicable for the evaluation of photochemical ozone formation on the European scale - estimated from realistic worst case for North Western Europe | B | The scope of the model is fully applicable for the evaluation of photochemical ozone formation parameterised to European conditions | B | The scope of the model is fully applicable for the evaluation of photochemical ozone, parameterised to Japanese conditions | C | No characterisation model, NMVOC emissions are simply summed on a weight basis | A / B | The scope of the model is fully applicable for the evaluation of photochemical ozone formation, parameterised to European conditions |
| **Environmental relevance** | B / C | Environmental relevance is high and both AOPs are addressed. | A / B | Environmental relevance is high, and both AOPs are addressed. Spatial differentiation is supported within Europe | B | Environmental relevance is high and both AOPs are addressed. Regional spatial differentiation within Japan supported. Does not cover NOx | | Not further evaluated, because a threshold within the category 'environmental relevance' was not reached | C | Environmental relevance is high, but damage to natural environment not represented. Spatial differentiation can easily be developed for Europe |
| **Scientific robustness & Certainty** | B / C | Underlying fate model heavily reviewed and continuously updated, no detailed treatment of uncertainty in resulting CFs | B | Underlying fate model and adaptation to LCIA use reviewed, uncertainty from spatial variability quantified and several temporal scenarios investigated | D | Underlying fate model hardly state-of-the-art, no treatment of uncertainty in resulting CFs | | Not further evaluated, because a threshold within the category 'environmental relevance' was not reached | B / C | Midpoint model reviewed and bench marked against other models from the field, no treatment of uncertainty in resulting CFs |
| **Documentation & Transparency & Reproducibility** | C | The method and CFs documented and accessible for reproducible application in LCA. Characterization model and input data not easily accessible. | B / C | The method and CFs documented and accessible for reproducible application in LCA. Characterization model and input data not easily accessible. | B / C | The method is documented and accessible, the CFs only available in Japanese, Characterization model and input data not easily accessible. | | Not further evaluated, because a threshold within the category 'environmental relevance' was not reached | B | The method and CFs documented and accessible for reproducible application in LCA. Characterization model and input data not easily accessible. |
| **Applicability** | A | 127 characterisation factors are available and can easily be applied - update depends on developers of POCP model | A | Characterisation factors for NMVOCs, $CH_4$, CO and NOx are available and can easily be applied - update depends on developers of RAINS model | B | Characterisation factors for 8 archetype VOCs are available and can easily be applied and updated | | Not further evaluated, because a threshold within the category 'environmental relevance' was not reached | A / B | Characterisation factors for NMVOC and NOx are available and can easily be applied - update depends on developers of LOTOS-EUROS model |
| **Science based criteria** | B / C | Addressing the European scale based on realistic worst case for North Western Europe. Well reviewed but no treatment of uncertainty in CFs. Method and CFs documented and accessible for 127 substances | B | Addresses the European conditions and supports spatial differentiation within Europe. Underlying fate model and adaptation to LCIA use reviewed. Uncertainty from spatial variability quantified and temporal scenarios investigated. Method and CFs documented and accessible for NMVOCs, $CH_4$, CO and NOx | B / C | Addresses Japanese conditions and supports regional spatial differentiation within Japan. Underlying fate model rather old. No treatment of uncertainty in resulting CFs. | | Not further evaluated, because a threshold within the category 'environmental relevance' was not reached | B | Parameterised to European conditions, only addresses human health impacts. Spatial differentiation can easily be developed for Europe. Midpoint model reviewed and bench marked against other models from the field, no treatment of uncertainty in resulting CFs. Method and CFs documented and accessible for NMVOC and NOx. |
| **Stakeholders acceptance:** | B / C | Based on models and data used in the evaluation of photo oxidants for the EC, but difficult to understand without expert knowledge | B / C | Moderate stakeholder acceptance, Danish government behind the method. Expert knowledge is required to understand the model | B / C | Moderate stakeholder acceptance, Japanese govern behind the method. Expert knowledge is required to understand the model | A | Good stakeholders acceptance, but not further evaluated, threshold not reached | B / C | Moderate stakeholder acceptance, Dutch government behind the method. Expert knowledge is required to understand the model |

**Table 15 Summary of the evaluation results of the midpoint and endpoint characterisation methods against the criteria for photochemical ozone formation.**

| Criteria | TRACI (mid) Norris, 2003 | | EcoSense (end) Krewitt et al., 2001 | | EPS2000 (end) | | LIME (end) | | ReCiPe (end) van Zelm et al., 2008 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Completeness of scope** | B | The scope of the model is fully applicable for the evaluation of photochemical ozone formation, parameterised to US conditions | A / B | The scope of the model for the evaluation of photochemical ozone formation on the European scale is applicable. | B | The scope of the model is fully applicable for the evaluation of photochemical ozone formation parameterised to European conditions (for POCP) | B | The scope of the model is fully applicable for the evaluation of photochemical ozone, parameterised to Japanese conditions | B | The scope of the model is fully applicable for the evaluation of photochemical ozone formation, parameterised to European conditions, but addresses only human health impacts |
| **Environmental relevance** | B / C | Environmental relevance is high although characterisation is weighted towards human health impacts | B | High environmental relevance for HH and partially for Natural environment (represented by crops) | B | Environmental relevance is high, but damage to natural environment not represented, damage models very simple based on empirical data | B | High environmental relevance for both AOPs. Damage model for HH simple and based on European data, damage model for vegetation and crops not available for review. It does not cover NOx | B | Environmental relevance is high, but damage to natural environment not covered |
| **Scientific robustness & Certainty** | C | Midpoint model extensively reviewed, further components derived from reviewed information, no treatment of uncertainty in resulting CFs. | B | Good science based and reviewed. Valid for EU. No treatment of uncertainty in resulting CFs | C / D | Fate model reviewed but not updated version, effect model based on rough empirically based estimates. Consistent uncertainty considerations, but not of all aspects. | B / C | Model components reviewed but old and hardly represent state of the art globally. No uncertainty considerations. | B / C | Midpoint model reviewed and benchmarked against other models of the field. Effect model developed based on empirical data, chronic effects and threshold for effects not considered due to lack of evidence |
| **Documentation & Transparency & Reproducibility** | C | The method principles and the CFs are documented and accessible. Characterization model and input data not easily accessible. | B | Good documentation Easy to reproduce results with the simplified version. But not easy to modify input parameters. | B | The method principles and the CFs are documented and accessible for reproducible application in LCA. Characterization model and input data not easily accessible. | B / C | The method is documented and accessible, the CFs only available in Japanese, reproducibility not clear. Characterization model and input data not easily accessible. | B | The method and CFs documented and accessible for reproducible application in LCA. Characterization model and input data not easily accessible. |
| **Applicability** | A | App. 580 characterisation factors are available and can easily be applied - update depends on developers of MIR model | A / B | Characterisation factors for NMVOC and NOx are available and can easily be applied - update depends on developers of EcoSense model | A / B | 65 characterisation factors are available and can easily be applied - update of fate model depends on developers of POCP model, update of damage model easy based on new empirical data | B | Characterisation factors for 8 archetype VOCs are available and can easily be applied and updated | A / B | Characterisation factors for NMVOC and NOx are available and can easily be applied - update depends on developers of LOTOS-EUROS model |

| Criteria | TRACI (mid) Norris, 2003 | | EcoSense (end) Krewitt et al., 2001 | | EPS2000 (end) | | LIME (end) | | ReCiPe (end) van Zelm et al., 2008 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Science based criteria overall evaluation** | B / C | Parameterised to US conditions, weighted towards human health impacts (?). Fate model extensively reviewed, further components derived from reviewed information, no treatment of uncertainty in resulting CFs. Method principles and CFs documented and accessible for app. 580 substances. | B | Parameterised to European situation addressing human health and partially for vegetation damage (represented by crops). Model is strongly reviewed. No treatment of uncertainty in resulting CFs | B / C | The fate model addresses the European scale based on realistic worst case for North Western Europe (POCP, old version). Damage to natural environment partly represented (through crops), damage models very simple based on empirical data. Consistent uncertainty considerations, but not of all aspects. Method principles and CFs documented and accessible for 65 substances. | B / C | Parameterised to Japanese conditions, addressing human health impacts (based on European effect data), vegetation and crops (Japanese effect data). Model components reviewed but old and hardly represent state of the art globally. No uncertainty considerations. The method and CFs documented, CFs available for 8 archetype VOCs, but only in Japanese for the moment. Does not cover NOx | B | Parameterised to European conditions, addresses only human health impacts. Midpoint model reviewed and benchmarked against other models of the field. Effect model developed based on empirical data, chronic effects and threshold for effects not considered due to lack of evidence. |
| **Stakeholders acceptance** | B | Moderate stakeholder acceptance, USEPA behind the method. Expert knowledge is required to understand the model | B | Good acceptance. There is an authoritative body behind (EU). | B / C | Low stakeholder acceptance, no authoritative body behind the method. Pure scientific work, understood with expert knowledge | B / C | Moderate stakeholder acceptance, Japanese government behind the method. Expert knowledge is required to understand the model | B / C | Moderate stakeholder acceptance, Dutch government behind the method. Expert knowledge is required to understand the model |

### 3.6.3 Discussion on uncertainties and the importance of spatial differentiation

Spatial differentiation has been found more important than differentiation between substances for vegetation impacts and in particular for human health impacts, where, for example, Hauschild et al, 2006 find variations up to several orders of magnitude between countries within Europe (primarily due to variations in population densities on the geographical scale which is relevant for photochemical ozone). It is thus important that the recommended model is able to support spatial differentiation.

### 3.6.4 Recommended default method at midpoint level

The LOTOS-EUROS model as applied in the ReCiPe method for photochemical ozone formation (van Zelm et al, 2008), consist of a detailed fate and exposure model for human health impacts and is developed in a form which makes it readily adaptable for calculation of a set of consistent CFs for each continent if integrating continent-specific atmospheric fate models. A global default factor can be found as a weighted average of the continent factors or perhaps calculated using a global average atmospheric fate model. Furthermore, the present version of the model can provide spatially differentiated factors, but only for Europe. This method is recommended for characterisation at midpoint level of photochemical ozone formation impacts on human health.

ReCiPe currently calculates the indicator value by summing impacts from grid cells in which there is a resident human population. This gives the indicator a bias towards human health impacts and makes it inappropriate to represent impacts on the AOP Natural environment. The recommendation is therefore to calculate the area- and time integrated ozone concentration increases by the LOTOS-EUROS model, aggregating over all of Europe without giving priority to inhabited regions, before applying these as characterisation factors at midpoint level for photochemical ozone formation. Factors should be provided for NMVOC, $CH_4$, CO and $NO_x$, at present factors for CO and $CH_4$ are missing (more long-lived than the typical NMVOC and hence dispersed over a larger region).

EDIP 2003 is based on the RAINS model and meets the science based criteria. Respects non-linearity of photochemical ozone formation and addresses both human health and vegetation impacts. It provides spatially differentiated CFs as well as overall site-generic factors for Europe. Adaptation to other continents is not straightforward.

### 3.6.5 Recommended default method at endpoint level

The method developed in ReCiPe is a recommended for human health impacts at endpoint. It meets the science based criteria well, is peer reviewed and benchmarked against other models, provides factors for $NO_x$ as well as for NMVOCs, and its environmental relevance is high for a European setting. It has a good link to the recommended midpoint and applies of the same framework which makes it adaptable to other continents and to the global situation if the relevant effect data can be incorporated. The recommendation of the model in its present form depends on the justification of the assumption that only acute effects of ozone exposure are important, and that there is no threshold for exposure below which effects can be disregarded. Factors should be provided for NMVOC, $CH_4$, CO and $NO_x$.

For impacts on vegetation at endpoint level, a model might rather easily be built on EDIP2003 midpoint model, which already models the time and area-integrated exposure above a critical level for vegetation.

The characterisation factors both at midpoint and endpoint level should be extended with the possibility for substance differentiation applying additional factors based on the substance POCP or MIR value. Derwent and co-workers find the two systems to generally show a fine agreement over a wide range of reactivities (Derwent et al., 1998) with a tendency for the POCP to give an increased resolution of substances with low POCP values due to its focus on long-range transport. Since the MIR values are available for around 600 individual VOCs compared to less than 140 for POCP, this favours the use of MIR to distinguish the individual NMVOCs if wanted. The differentiation thus obtained is most important for distinction between pure hydrocarbons on one side, and halogenated VOCs on the other.

EcoSense obtained the highest scores in many criteria, but it applies a rather simplified atmospheric transport model the relevance of which has been put into question for the complex photochemical formation of ozone. An updated version of the EcoSense model (Ecosense web 1.3) applies a more realistic modelling for ozone formation and should be considered for potential future recommendation. It considers both human health and ecosystem quality (only considering damage on crops). Spatial and temporal explicit evaluation was already done for Europe, South America and Asia (Preiss and Klotz, 2008). Within the EcoSenseWorld model, the population data are based on SEDAC global gridded population, background emission and meteorological data grid could be adjustable to any region of the world in order to apply the WTM model.

### 3.6.6 Consistency between midpoint and endpoint methods

For the recommended models for human health impacts there is a fine consistency between midpoint and endpoint as they have been developed applying the same model in a consistent framework.

### 3.6.7 Classification of the recommended default methods

At midpoint, the recommended default method is the LOTOS-EUROS model as applied in the ReCiPe method (Van Zelm et al, 2008), is classified as Level II out of III (Recommended, some improvements needed).

At endpoint, the recommended method is the method developed by Van Zelm et al., 2008 as implemented in ReCiPe. It is classified as Level II out of III (Recommended, some improvements needed).

### 3.6.8 Calculation principles

The models provide unspecific factors for NMVOC and NOx respectively, but the characterisation factors both at midpoint and endpoint level should be extended with the possibility for substance differentiation applying additional factors based on the substance POCP or MIR value. The two systems generally show a fine agreement, and since the MIR values are available for around 600 individual VOCs compared to less than 140 for POCP, this favours the use of MIR to distinguish the individual NMVOCs if wanted. Calculation of additional substance factors outside this selection is not possible for the LCA user, but the difference between individual substances is generally modest, so the importance is limited.

# 3.7 Acidification

## 3.7.1 Pre-selection of methods for further evaluation

Current LCIA characterization models focus on terrestrial acidification as it tends to precede aquatic acidification when inland water is acidified after the depletion of the acid neutralization capacity of its watershed. The impact indicators of existing methods cover the majority of impact mechanisms and relevant elementary flows for the Area of Protection (AOP) Ecosystem Quality.

Only few methods, such as EDIP97 and the CML method also cover waterborne emissions, but the methods are not sufficiently developed; besides, aquatic acidification may be considered as a separate impact category.

Characterization factors for acidification are traditionally calculated at midpoint level, as it is the case for the majority of the LCIA methods considered in this analysis (Potting et al. 1998a,b; Norris 2003; Kemna et al. 2005; Seppälä et al. 2006). Others are damage oriented LCIA methods and relate emissions of acidifying substances to impacts on the endpoint biodiversity (Goedkoop et al. 2000; van Zelm et al. 2007). The analysed midpoint and endpoint approaches follow the same cause-effect chain up to the modelled changes in soil parameters, but they differ in the effect factor.

In the LCIA- Analysis document (EC-JRC, 2010a) pre-selection of characterisation models for the acidification impact category is reported. Here, these methods are briefly presented:

**Midpoint**

- TRACI acidification potentials are based on the model developed by (Norris, 2003). It provides generic and spatially differentiated characterization factors for the US. A fate model, ASTRAP is used to link the emission to the deposition on land area. TRACI considers acidification potentials due to the acidic deposition on the entire land and inland water area whether soil and ecosystems are sensitive or not. The dose-response curve implicitly equals 1.
- EDIP 2003 provides European Country-dependent Characterisation Factors adopting the Unprotected Area (UA) method (Potting et al. 1998a), which is based on a category indicator measuring changes in area of unprotected ecosystems due to emission reductions at country level within Europe. UA also considers a fate transport model linking the emission to the deposition to land and inland water

area using the European RAINS model (Amann et al. 1999). The indicator measures the increase in area of ecosystem that becomes unprotected by exposure over its critical load. The dose-response curve implicitly equals 1.

- MEEUP (Kemna et al. 2005). Its framework relates to European Community legislation and strategies and the Gothenburg protocol. It considers acidification potential in term of $H^+$ releases without addressing chemical fate of chemicals in air and in soil, i.e. all emissions and subsequent depositions generate an acidification potential. 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 and major lakes\rivers is determined using the EMEP model combined with a European critical load database. The acidification potential is expressed in accumulated Exceedance. The dose-response curve implicitly equals 1. A more recent publication (Posch et al. 2008) updated the factors of the AE method using the newest 2006 version of the EMEP Eulerian atmospheric dispersion model (Tarrason et al. 2006), which provides also depositions onto different land cover categories, and the newest critical load data base (Hettelingh et al. 2007) consisting of about 1.2 million different ecosystem such as forests, surface waters, and semi-natural vegetation.
- CML 2002 uses the method of Hazard index (HI) (Huijbregts et al. 2001) and also provides European spatially-specific characterization factors (CF) for acidifying and eutrophying air pollutants. The CFs express the marginal change in the hazard index of all ecosystems in Europe, comparing the actual load to the critical load weighted over ecosystems and region. Atmospheric transport and deposition is determined using the European RAINS model. The HI method assumes a dose-response slope inversely proportional to the critical load itself.
- ReCiPe is a midpoint-endpoint method. The midpoint indicator adopts the Base saturation method developed by Zelm and colleagues (2007a), which calculates the atmospheric fate with the EUTREND model (Van Jaarsveld et al. 1997). It only considers terrestrial ecosystems. It uses the simulation model for acidification’s regional trends, SMART 2, (Kros 2002) to characterize soil sensitivity at midpoint level as a change in soil base saturation. The change in base saturation per unit deposition is presently only available for Europe. Dose-response is determined in endpoint modelling.
- LIME (Hayashi et al. 2004) is a midpoint-endpoint method. The midpoint indicator expresses $SO_2$ equivalency of Atmospheric Deposition Factor (ADF), which indicates an increase of $H^+$ deposition per unit area to an additional emission acidifying chemical. The fate (deposition) of the emissions is calculated with an atmospheric transport model or with empirical data depending on the chemical. It only considers terrestrial ecosystems. Dose-response is determined in endpoint modelling.

**Endpoint**

- ReCiPe adopts the approach of van Zelm and colleagues (2007a), which further model the cause-effect chain up to damages on biodiversity with a physiologically based dose-response model. Based on Monte-Carlo simulations for 240 plant species, it expresses the change in potentially not occurring fraction of plant species per change in base saturation [dimensionless].
- Eco-indicator 99 (Goedkoop and Spriensma. 2000) uses a simplified fate assumption to determine the fraction of an acidifying emission that is deposited on Europe (equal for all the chemicals). The effect factor is determined applying the Dutch Nature Planner model that focuses on the percentage of threatened species in The Netherlands caused by acidifying emissions. The indicator expresses the change in Potentially Disappeared Fraction of species (PDF)* $m^2$ * yr per marginal change in deposition.
- The damage factor of LIME (Hayashi et al. 2004) indicates the total Net primary production (NPP) damage in all of Japan due to the additional emission of causative substances. Net primary production (NPP) of existing vegetation was adopted as an impact indicator of terrestrial ecosystems. The aluminium toxicity was adopted as the major factor influencing the effect on terrestrial ecosystems due to acidification.

Payet (2006) proposed in relationship with the European funded NOMIRACLE project (and IMPACT 2002+ developments) a dose-effect relationship to assess a change in pH concentration in a non-buffered water body in terms of fraction of affected, or disappeared species. As this method is not readily operational it has not been further considered in this evaluation. However, despite the fact that it has still not been validated with field measurements and needs to be complemented by a fate model, it could set an interesting basis for further developments in assessing the effect of acidifying chemicals on aquatic ecosystems.

Figure 8 shows the cause-effect chain for airborne acidifying emissions with the most important pathways highlighted (bold arrows). The analysed LCIA methods are reported according to their position in the cause-effect chain. The MEEUP method is not included in the figure as it doesn't follow the cause effect chain, but merely represents a potency related to an elementary flow.

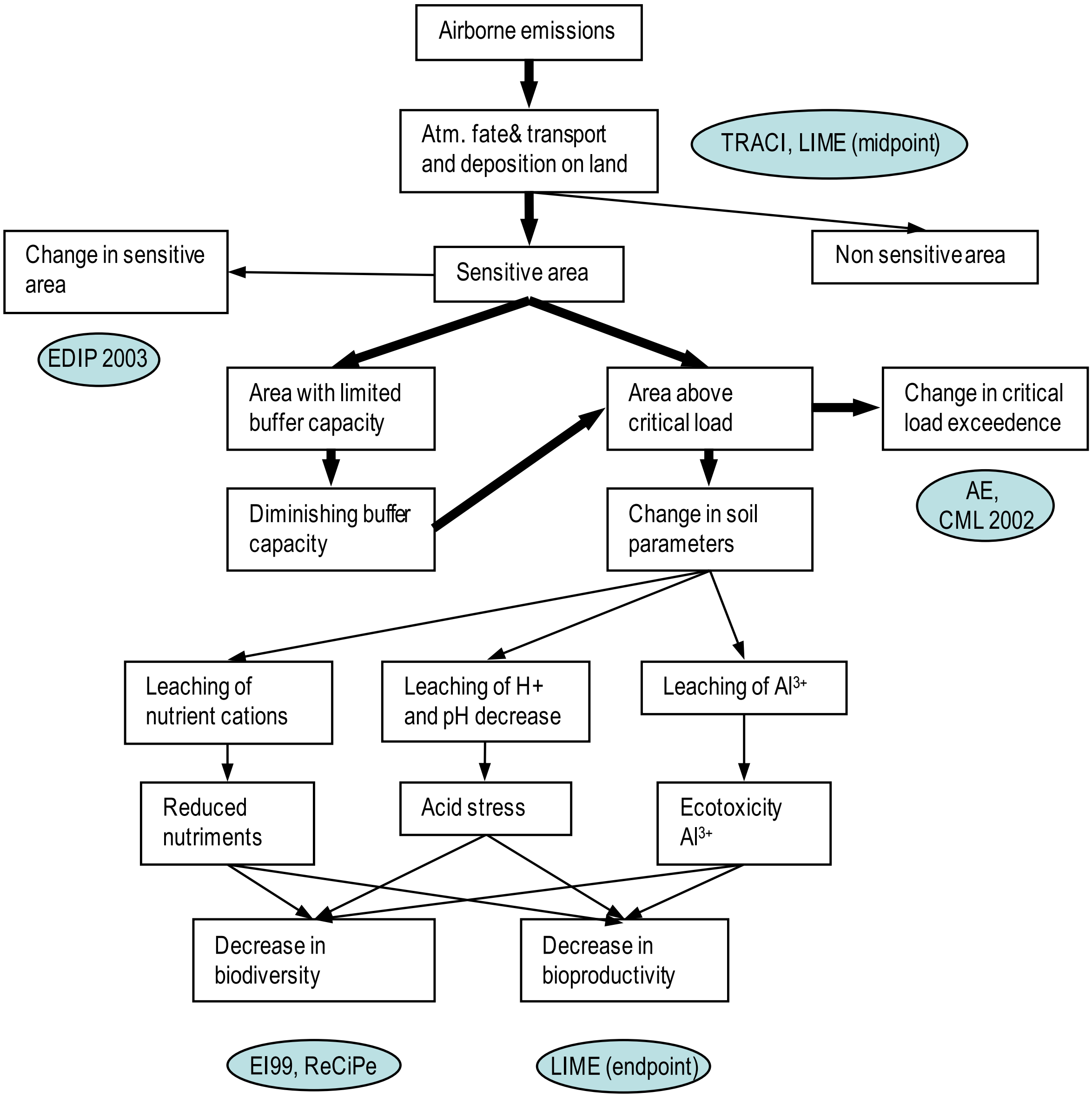


**Figure 8 Flow diagram for acidification. The LCIA methods are positioned along the cause-effect chain.**

## 3.7.2 Method evaluation

The 10 models have been rated against the criteria reported in the "LCIA- Framework and requirements document" (EC-JRC, 2010b). The results are summarized in the table below[27]. Discussions of specific issues in the evaluation of the models against the criteria are presented in the background documentation[28] (Acidification.xls), where a table with the detailed evaluation including the whole sets of sub-criteria is given.

[27] A: full compliance; B: compliance in all essential aspects; C: compliance in some aspects; D: little compliance; E: no compliance

[28] http://lct.jrc.ec.europa.eu/

**Table 16 Summary table documenting the analysis of the midpoint characterisation methods against the adapted criteria for acidification. (split into two tables)**

| | TRACI (Norris, 2003) | | EDIP 2003 (Potting et al.,1998) | | MEEUP (Methodology report) | | Accumulated Exceedence (Seppälä et al., 2006) | |
|---|---|---|---|---|---|---|---|---|
| **Completeness of scope** | B / C | The scope of the model for the evaluation of acidifying chemicals is largely applicable, although the model is parameterized for US and addressed terrestrial acidification only. CFs are rather at the safe side in soil fate | D | The scope of the model for the evaluation of acidifying chemicals is not compatible with LCA the method discounts effects of acidifying deposition occurring in area above the critical load | C | The scope of the model for the evaluation of acidifying chemicals is not applicable, as lacking of an atmospheric fate model. CF are therefore rather at the safe side in line with a regulatory context | B | The scope of the model for the evaluation of acidifying chemicals on the European scale is fully applicable |
| **Environmental relevance** | C | Limited environmental relevance. The method fully considers atmospheric fate, but not the soil sensitivity to acidifying deposition | D | Limited environmental relevance. Consider a full atmospheric fate, the marginal change in biodiversity, but discount deposition in area above critical load | E | Lack of environmental relevance is obvious, do not consider atmospheric fate and soil sensitivity, thus it doesn't enable any regional differentiation | A | High environmental relevance for biodiversity. Full atmospheric and soil assessment considered. Sensitive to emission scenario and current critical load |
| **Scientific robustness & Certainty** | B | Not further evaluated, because the thresholds within the category 'environmental relevance' were not reached | | Not further evaluated, because the thresholds within the categories 'completeness of scope' and 'environmental relevance' were not reached | | Not further evaluated, because the thresholds within the category 'environmental relevance' were not reached | B | Model components extensively reviewed and uncertainty estimates available in term of spatial variation and emission scenarios |
| **Documentation & Transparency & Reproducibility** | D | Not further evaluated, because the thresholds within the category 'environmental relevance' were not reached | C | Not further evaluated, because the thresholds within the categories 'completeness of scope' and 'environmental relevance' were not reached | | Not further evaluated, because the thresholds within the category 'environmental relevance' were not reached | B | The method and the CFs are well documented and accessible. Characterization model and input data not easily accessible. Can potentially be adapted to generate CFs for different continents if complemented with a global atmospheric model and expert judgment on sensitive areas |
| **Applicability** | | Not further evaluated, because the thresholds within the category 'environmental relevance' were not reached | | Not further evaluated, because the thresholds of 'completeness of scope' and 'environmental relevance' were not reached | | Not further evaluated, because the thresholds within the category 'environmental relevance' were not reached | A | Readily applicable. Most important acidifying chemical are covered. |
| **Science based criteria** | E | The method lacks of sufficient environmental relevance. It fully considers atmospheric fate, but not the soil sensitivity to acidifying deposition. It needs to be at least complemented by average soil fate factors distinguishing for sensitive and non-sensitive areas | E | The method is not in line with the scope of LCA and lack of sufficient environmental relevance as the increase in deposition in sensitive area is discounted, i.e. change in area above critical load is not relevant enough in the LCA context | E | The method is not in line with the scope of LCA and lack of environmental relevance is obvious as it does not consider atmospheric fate and soil sensitivity, thus it doesn't enable any regional differentiation | A / B | The method meets the science based criteria. It Includes atmospheric and Soil fate factors distinguishing between load to sensitive area and insensitive area for biodiversity. It could be applicable worldwide at continental level if complemented by a global atmospheric fate model and expert estimate on soil sensitive area. |
| **Stakeholders acceptance criteria** | | Not further evaluated, because the thresholds within the science based criteria were not reached | | Not further evaluated, because the thresholds within the science based criteria were not reached | | Not further evaluated, because the thresholds within the science based criteria were not reached | B | AE-type calculations are used for policy purposes in Europe by the European Commission and the UNECE LRTAP Convention, but models and data are difficult to understand without expert knowledge |

| | CML 2002 (Huijbregts et al.2001) | | ReCiPe midpoint (van Zelm et al., 2007a) | | LIME midpoint (Hayashi et al. 2004) | |
|---|---|---|---|---|---|---|
| **Completeness of scope** | B | The scope of the model for the evaluation of acidifying chemicals on the European scale is fully applicable | B / C | The scope of the model for the evaluation of acidifying chemicals on the European scale is fully applicable, but factors are based on acidification of forests soil only | B | The scope of the model for the evaluation of acidifying chemicals is largely applicable, although the model is parameterized for Japan. |
| **Environmental relevance** | B | High environmental relevance for biodiversity: Full atmospheric and soil assessment considered. Sensitive to emission scenario and current critical load. Relevance of the dose-response being curve being dependent of the buffer capacity itself has to be verified | B | High environmental relevance for biodiversity: Full atmospheric and soil fate considered for forests Extrapolated to other ecosystems only in a second step. Sensitive to emission scenario and current critical load. It further includes an effect factor | D | Limited environmental relevance. The CF fully considers atmospheric fate, but not the soil sensitivity |
| **Scientific robustness & Certainty** | B / C | Model components extensively reviewed and uncertainty estimates available in term of spatial variation and emission scenarios. Not full up-to-date data and models | B / C | Model components extensively reviewed; uncertainty estimates not provided, but discussed in term of temporal emission scenarios | | Not further evaluated, because the thresholds within the category 'environmental relevance' were not reached |
| **Documentation & Transparency & Reproducibility** | B | The method and the CFs are well documented and accessible. Characterization model and input data not easily accessible. Can potentially be adapted to generate CFs for different continents if complemented with a global atmospheric model. Feasibility of the dose-response curve should be verified for other continents | B / C | The method and the CFs are well documented and accessible. Characterization model and input data not easily accessible. Can potentially be adapted to generate CFs for different continents if complemented with a global atmospheric model and expert judgment on sensitive areas | | Not further evaluated, because the thresholds within the category 'environmental relevance' were not reached |
| **Applicability** | A | Readily applicable. Most important acidifying chemical are covered. | A | Readily applicable. Most important acidifying chemical are covered. | | Not further evaluated, because the thresholds within the category 'environmental relevance' were not reached |
| **Overall evaluation of science based criteria** | B | The method meets the science based criteria. Conclusions for Accumulated Exceedence method apply. Relevance and feasibility of the dose-response curve should be verified for other continents (data requirement higher). To be seen if/how expert judgment can be incorporated. It needs to be complemented by a global atmospheric fate model. | B | The method meets the science based criteria. Base saturation factor is likely to provide an interesting alternative to the critical load based methods. Extension of the concept to other ecosystems than forests is required. The possibility to determine proxies of the changes in base saturation and in dose-response for various continents need also to be further explored. It needs to be complemented by a global atmospheric fate model. | E | The method generally meets the science based criteria, but the selected midpoint indicator lack of sufficient environmental relevance. In fact the cause-effect chain is only modelled up to the deposition of acid eq. Potentials and do not account for a sensitive and non sensitive area. |
| **Overall evaluation of stakeholders acceptance criteria** | C | Based on models and data used in the evaluation of acidifying impacts for the EC (apart the final category indicator), but difficult to understand without expert knowledge | C / D | Moderate stakeholder acceptance, Dutch government behind the method. Expert knowledge is required to understand the model | C | Not further evaluated, because the thresholds within the science based criteria were not reached |

**Table 17 Summary table documenting the analysis of the endpoint characterisation methods against the adapted criteria for acidification.**

| | ReCiPe Endpoint (van Zelm et al., 2007a) | | Ecoindicator 99 (Goedkoop and Spriesma, 2000) | | LIME endpoint (Hayashi et al. 2004) | |
|---|---|---|---|---|---|---|
| **Completeness of scope** | B / C | The scope of the model for the evaluation of acidifying chemicals on the European scale is applicable, but factors are based on acidification of European forests only | C | The scope of the model for the evaluation of acidifying chemicals on the European scale is applicable, but factors are based on acidification of Dutch forests only | B / C | The scope of the model for the evaluation of acidifying chemicals is largely applicable, although the model is parameterized for Japan, factors are based on acidification of forests only |
| **Environmental relevance** | B | High environmental relevance for ecosystem quality: Full atmospheric and soil fate considered for forests and extrapolated to other ecosystems. Sensitive to emission scenario and current critical load. It further includes an effect factor | C | Limited environmental relevance. Does not enable discriminating between the atmospheric fates of chemicals. Soil fate considered for forests and extrapolated to other ecosystems. It further includes an effect factor | B | High environmental relevance for ecosystem quality: Full atmospheric and soil assessment for forests considered and extrapolated to other ecosystems. Sensitive to emission scenario and sensitive area |
| **Scientific robustness & Certainty** | B / C | Model components extensively reviewed and uncertainty estimates available in term of spatial variation and emission scenario | C | The method itself has not been peer reviewed, but the underlying models components are. However, poor scientific quality for the fate model. Expert judgment on uncertainty estimates | C | Model components extensively reviewed, but the dose-response model is poorly representative as the plant growth rate is based on 1 species. Uncertainty is not discussed |
| **Documentation & Transparency & Reproducibility** | B | The method and the CFs are well documented and accessible. Characterization model and input data not easily accessible. Can potentially be adapted to generate CFs for different continents if complemented with a global atmospheric model and expert judgment on sensitive areas | C | The method and the CFs are well documented and accessible. Characterization model and input data not easily accessible. Data requirement higher. | B / C | The method and the CFs are well documented and accessible. Characterization model and input data are not easily accessible. Need to be complemented by a global fate model, effect model should be verified for other continents |
| **Applicability** | A | Readily applicable. Most important acidifying chemical are covered. | A | Readily applicable. Most important acidifying chemical are covered. | A | Readily applicable. Most important acidifying chemical are covered. |
| **Overall evaluation of science based criteria** | B / C | The method meets the science based criteria in some aspects. Base saturation factor and dose-response slopes are likely to provide an interesting basis for the next generation of acidification methods. Additional studies are, however, required to verify the approach chosen by Van Zelm et al, and extension of the concept to other ecosystems than forests is required. The possibility to determine proxy of the changes in base saturation and in dose-response for various continents need to be further explored. It needs to be complemented by a global atmospheric fate model. | C | The method meets the science based criteria in some aspects. Poor scientific quality for the fate model and rather old soil fate and effect models are used. It is therefore difficult to generate effect data for other continents than Europe. | B / C | The method meets the science based criteria in some aspects. The effect factor is poorly representative as based on 1 plant species. The model is parameterized for Japan. To generate CFs for other region, it needs to be complemented by a global fate model and effect model should be verified for other continents. |
| **Overall evaluation of stakeholders acceptance criteria** | C / D | Moderate stakeholder acceptance, Dutch government behind the method. Expert knowledge is required to understand the model | C | Low stakeholder acceptance, no authoritative body behind the method. Pure scientific work, understood with expert knowledge | B / C | Moderate stakeholder acceptance, Japanese government behind the method. Expert knowledge is required to understand the model |

### 3.7.3 Discussion on method evaluation

As stated in the LCIA - Framework and requirements document (EC-JRC, 2010b), some specific criteria of ‘Environmental relevance’ and ‘scientific robustness’, have been specified for acidification and represent the basis for the evaluation. The main criteria focus on: the presence of an atmospheric fate and transport model; a fate sensitivity factor discriminating between sensitive (including areas with limited buffer capacity) and insensitive areas; acidification potential considered at midpoint; updating emission data and temporal changes evaluation for future emission. For endpoint methods, also the presence of a dose-response model for biodiversity/bioproductivity is considered relevant.

### 3.7.4 Discussion of uncertainties and the importance of spatial differentiation

The uncertainties in different methods are mainly expressed in term of spatial and temporal variability or by expert judgment estimates (Eco-indicator 99). The intrinsic uncertainty of the fate and effect models is not reported for any of the recommended models.

Temporal variability is usually taken into account through present and future emission scenarios. Characterization factors for acidification increase up to a factor of 13 from 20 years to a 500 years’ time horizon and influence the difference between chemicals up to a factor 4 as shown by Van Zelm and colleagues (2007a).

In general spatial variability in atmospheric fate can model differences in deposition of acidifying chemicals on a few tens or hundreds kilometres scale (typically 100 x100 km scale). Soil fate modelling can be even more detailed up to a few square kilometres. This source of uncertainty could result in differences in CFs up to two or three orders of magnitude among individual European countries with different integrated sensitivity (Potting et al. 1998a; Posch et al. 2008). This difference is very important compared to the variability of the CFs among the chemicals, which is typically ranging within one order of magnitude. In case the emissions take place only in specific locations or countries, it makes therefore little sense to distinguish between individual substances such as $SO_2$ and $NO_x$ and disregarding the spatial variability.

### 3.7.5 Recommended default method at midpoint level

Following midpoint methods evaluation, the method of AE (Accumulated Exceedence) (Seppälä et al. 2006) was chosen.

TRACI, EDIP 2003, MEEuP and LIME (at midpoint) were not recommended because they didn’t reach some evaluation thresholds.

The scope of the TRACI model for the evaluation of acidifying chemicals is largely applicable. At the moment, the model is parameterized only for US and addresses terrestrial acidification only. The method was not chosen because it presents a limited environmental relevance: it fully considers atmospheric fate, but not the soil sensitivity to acidifying deposition. Environmental relevance can be improved by complementing the model with an estimation of soil fate factors distinguishing between sensitive and non-sensitive areas.

Finally, the ASTRAP model for atmospheric fate, which is used in the TRACI model, is considered outdated.

The scope of the EDIP 2003 model for the evaluation of acidifying chemicals is not compatible with LCA. The method discounts effects of acidifying deposition occurring in areas above the critical load. As for TRACI, the atmosphere deposition model (RAINS) is dated before 2000.

MEEuP is completely lacking environmental relevance because it disregards atmospheric fate and soil sensitivity. Furthermore it doesn't enable any regional differentiation.

LIME (at midpoint) generally meets the science based criteria, but the selected midpoint indicator lacks of sufficient environmental relevance. In fact the cause-effect chain is only modelled up to the deposition of acid equivalents potentials and does not account for sensitive and non sensitive areas.

CML2002 reaches a good evaluation with the exception of being less up-to-date and showing less stakeholder importance than others.

RECIPE (at midpoint) sets an interesting basis for the next generation of acidification methods based on Base saturation factor (an alternative to the critical load based methods). Nevertheless, an extension of the concept to other ecosystems than forests is required and the feasibility to generate a set of consistent CFs for each continent still has to be further explored (e.g. the possibility to determine proxies for the effect factor for various continents).

AE (Accumulated Exceedence) is to be preferred as default method for midpoint evaluation of acidification. The updated factors provided by Posch and colleagues (2008) should be used. The method meets the science based criteria, and it shows a good stakeholder acceptance as AE-type calculations are used for policy purposes and by the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP). It includes atmospheric and soil fate factors sensitive to emission scenario and distinguishes between load to non-sensitive and sensitive areas. This is probably the most readily adaptable method that can be used in further research to generate Global default Characterisation Factors (CFs) or a set of consistent CFs for each continent if complemented by a set of regional/continental models which are consistent with each other (that could eventually be integrated in one global model, although not required) and expert estimate on soil sensitive area.

Similar conclusions apply for CML and ReCiPe (midpoint) methods, but they both suffer from a weaker stakeholder importance. In addition CML is based on less up-to-date data and models, and for ReCiPe the feasibility to generate a set of consistent CFs for each continent still has to be further explored (e.g. the possibility to determine proxies for the effect factor for various continents).

### 3.7.6 Recommended default method at endpoint level

At endpoint level, no method is recommended to be use because no methods are sufficiently mature to be recommended.

As interim, among other the method developed by van Zelm and colleagues (2007a), as used in Recipe, can be used but only for internal applications.

All the methods need to be complemented by a global fate model and effect models should be verified for other continents.

LIME (at endpoint) presents model components extensively reviewed, and shows a high environmental relevance for ecosystem quality. Full atmospheric and soil assessment for forests is considered and extrapolated to other ecosystems. Sensitive to emission scenario and sensitive area are present but the dose-response model is poorly representative as the plant growth rate is based on 1 species.

Ecoindicator 99 meets the science based criteria in some aspects but it has a poor scientific quality for the fate model and rather outdated soil fate and effect models are used.

However, among the evaluated endpoint methods, the one developed by van Zelm and colleagues (2007a) (as described in ReCiPe methodology) sets the most interesting basis for the next generation of acidification methods. Therefore this method is qualified as interim, due to the fact that the dose-response model and the integration with the recommended midpoint model need to be further evaluated and the feasibility to adapt the effect factor for different ecosystems needs to be further explored (currently based on European forest only). Furthermore, it doesn't consider terrestrial acidification in other ecosystem apart from forest and acidification on aquatic ecosystem

### 3.7.7 Consistency between midpoint and endpoint methods

The recommended midpoint method for acidification provides an indicator based on the exceedance of an acidifying deposition over the critical load. This indicator is not fully consistent with the interim endpoint indicator as (1) it is based on a different characterization model linking emission to the change in soil parameters and (2) it is selected on a 'side track' of the cause-effect chain to the damages. Therefore the dose-response model and indicator of the interim method by van Zelm et al. is currently independent of the AE indicator and its integration with this latter still need to be further evaluated.

### 3.7.8 Classification of the recommended default methods

At midpoint, the Accumulated Exceedence model (Seppälä et al. 2006 and Posh et al. 2008) is classified as “recommended with some improvements needed” (Level II out of III).

At endpoint level, no method is recommended to be used.

If an endpoint method is required, the method proposed by van Zelm et al. (2007a) can be use, but this method is classified as an interim method, because the method is not mature enough to be recommended.

### 3.7.9 Calculation principles

Additional midpoint characterisation factors cannot be calculated by the LCA practitioner but require access to and expertise in the underlying model. The number of substances contributing to acidification is quite limited and hence the need for additional factors is not foreseen to be an issue.

# 3.8 Eutrophication

## 3.8.1 Pre-selection of methods for further evaluation

Characterization factors for eutrophication are traditionally calculated at midpoint level, as it is the case for the majority of the LCIA methods considered in this analysis (Guinée et al., 2002, Potting et al. 2005; Norris 2003; Seppälä et al. 2006). Others are damage oriented LCIA methods and relate emissions of eutrophying substances to impacts on the endpoint biodiversity (Steen, 1999a,b; Goedkoop and Spriensma, 2000; Payet, 2006; Goedkoop et al. 2009, Itsubo et al., 2008a).

To the extent the methods consider impacts from biological material (BOD or COD), the characterisation factor is typically calculated from the characterisation factor for N or P based on the amount of biological material (expressed as BOD or COD) which would on average be produced by natural (primary) production of biological material per input of N or P in aquatic systems.

Several of the analysed characterisation models have separate treatment of terrestrial and aquatic systems, and most of them only address one of the two.

In LCIA- Analysis document (EC-JRC, 2010a) the pre-selection of characterisation models for the terrestrial and aquatic eutrophication is shown separately for the two sub categories terrestrial and aquatic eutrophication.

### 3.8.1.1 Terrestrial eutrophication

**Midpoint**

- Accumulated Exceedance (AE): Provides European country-dependent characterisation factors for Acidification and Terrestrial Eutrophication. The atmospheric transport and deposition model to land area is determined using the EMEP model combined with a European critical load database. The eutrophication potential is expressed in accumulated exceedance. The dose-response curve implicitly equals 1 (Seppälä et al., 2006).
- CML2002: Enrichment of terrestrial ecosystems with the macronutrients N and P. Characterisation model based on the stoichiometry given by the Redfield ratio between N and P (derived from the average composition of algae). Also provides characterisation factors for organic material emissions to water presented as BOD or COD. Expressed as $PO_4^{3-}$-equivalents (Guinée et al., 2002). EDIP97 applies similar approach expressing results in $NO_3^-$-equivalents (Hauschild and Wenzel, 1998b), but the two models are so similar that only CML2002 is analysed here.
- EDIP2003: Increase in area of terrestrial ecosystem exposed above critical load for N, site-dependent at country-level in Europe – expressed as $m^2$ unprotected ecosystem, calculated using the RAINS model (Hauschild and Potting, 2005).

**Endpoint**

- Eco-indicator 99: Uses a simplified fate assumption to determine the fraction of an acidifying or eutrophying emission that is deposited on Europe (equal for all the chemicals). The effect factor is determined applying the Dutch Nature Planner model that focuses on the percentage of threatened species in The Netherlands caused by acidifying and eutrophying emissions. The indicator expresses the change in PDF $m^2$ yr per marginal change in deposition (Goedkoop and Spriensma, 2000)
- EPS2000: Covers both terrestrial and aquatic eutrophication. Assumes equal distribution between deposition on natural areas, agricultural areas and water. Damage factor for terrestrial ecosystems is based on estimate of eutrophication's share in number of endangered species in Sweden which is assumed to be valid globally (Steen, 1999 a,b).

IMPACT 2002+, LIME and ReCiPe do not include terrestrial eutrophication impacts.

#### 3.8.1.2 Aquatic eutrophication

**Midpoint**

- CML2002: Enrichment of aquatic ecosystems with the macronutrients N and P. No fate model. Characterisation model based on the stoichiometry given by the Redfield ratio between N and P (derived from the average composition of algae). Also provides characterisation factors for organic material emissions to water presented as BOD or COD. Indicator results expressed as $PO_4^{3-}$-equivalents (Guinée et al., 2002). EDIP97 applies similar approach expressing results in $NO_3^-$-equivalents (Hauschild and Wenzel, 1998b), but the two models are so similar that only CML2002 is analysed here.
- EDIP2003: Combination of EDIP97 characterisation factors ($NO_3^-$equivalents) with exposure factors expressing the degree to which the emitted nutrient reaches the aquatic end compartment after removal processes active in the fate model. For waterborne emissions the exposure factors are calculated using the CARMEN model, for airborne emissions of $NO_x$ and $NH_3$, the exposure factor is calculated using RAINS. (Hauschild and Potting, 2005, Potting and Hauschild, 2005).
- LIME midpoint: Increase in nutrients and COD and resulting oxygen depletion and impacts on benthic communities modelled in four Japanese closed marine water bodies as consequence of emissions of N and P- compounds and organic material to water (no consideration of impacts in freshwater). (Itsubo et al., 2008a)
- ReCiPe midpoint: Approach similar to EDIP2003 but using EUTREND for atmospheric emissions and distinguishes freshwater systems (only P-emissions considered) and marine systems (only N considered) (Struijs et al., 2009b)
- TRACI: Characterisation factor product of nutrient factor, determined by the substance's content of N or P, and a transport factor, which reflects the probability that the emission arrives in an aquatic environment to which it is the limiting nutrient. Nutrient factors are identical to CML2002 characterisation factors

(including factors for COD and BOD). Transport factors are spatially differentiated at the level of US states and developed for both atmospheric and waterborne transport. Indicator results expressed as $PO_4^{3-}$-equivalents (Norris, 2003).

**Endpoint**

- EPS2000: Covers both terrestrial and aquatic eutrophication and includes factor for BOD and COD emissions to water. Very simple fate model for waterborne emissions assuming a fixed global distribution of N and P between N- and P-limited systems and disregarding removal processes. For emissions of NOx a fixed fraction is assumed to be deposited on water. Damage factor for waterborne emissions is extrapolated from Scandinavian situation to the world. Damage factor for airborne NOx emissions is based on the estimated contribution in the Baltic Sea region, which is assumed to be globally representative (Steen, 1999a,b).
- IMPACT2002+ endpoint: Uses CML2002 characterisation factors at midpoint and considers damage to freshwater systems using a damage model developed to represent the relationship between P-exposure and species diversity in terms of fraction of affected, or disappeared species. This method is not readily operational and it has still not been validated with field measurements and needs to be complemented by a fate model. Nevertheless, it could set an interesting basis for further developments in assessing the effect of eutrophication on aquatic ecosystems (Payet, 2006).
- LIME: Increase in nutrients and COD and resulting oxygen depletion and impacts on benthic communities modelled in four Japanese closed marine water bodies (no consideration of impacts in freshwater). Damage calculated for airborne N-emissions and waterborne emissions of N and COD and expressed as loss of benthos biomass and loss of fishery catches (Itsubo et al., 2008a).
- ReCiPe endpoint: Predicted P concentration increases in freshwater systems at midpoint are linked to ecosystem damage (potentially disappeared fraction of species) using database correlating P concentrations and macro fauna species diversity in Dutch ecosystems to predict damage in terms of potentially disappeared fraction of species (Struijs et al., 2009b)

For the evaluation the following methods are left out: LUCAS (same as TRACI but applied in Canada), IMPACT2002+ midpoint (taken directly from CML2002, but distinguishes between N- and P limited watersheds), MEEUP (identical to CML2002 but adds factors for BOD, DOC, TOC and suspended solids derived from the CML2002 factor for COD by scaling it in accordance with EU legislation, e.g. EU Directive on urban wastewater treatment) and Swiss Ecoscarcity (in accordance with Swiss regulation, targets set for compounds or total N and P, no characterisation modelling). Eco-indicator 99 does not cover aquatic eutrophication.

Figure 9 shows the cause-effect chain for eutrophication of the aquatic and terrestrial environment from air- and waterborne emissions of nutrients (N and P) and biological material (COD or BOD) with the most important pathways highlighted (bold arrows). The analysed LCIA methods are reported according to their position along the cause-effect chain.

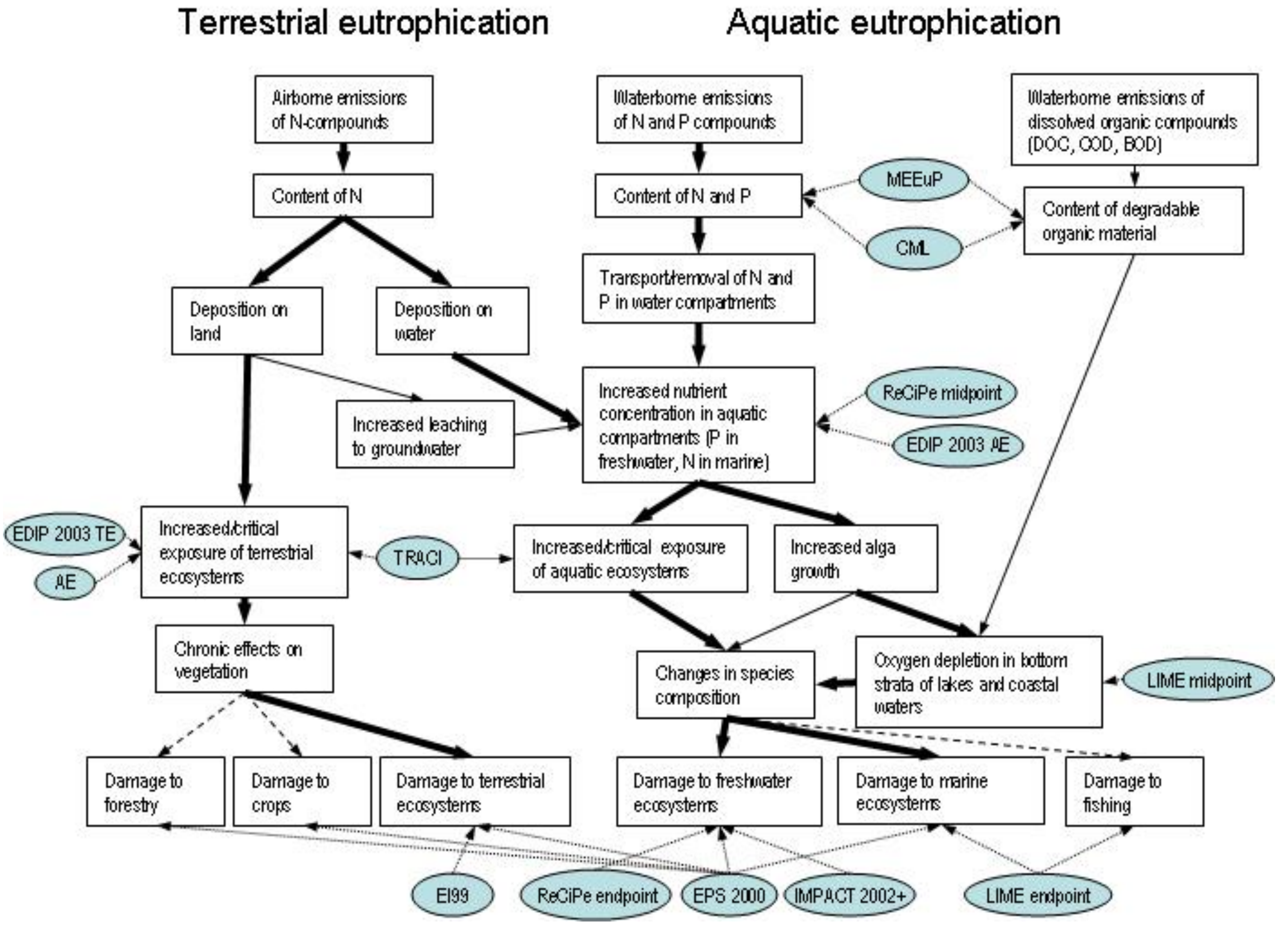


**Figure 9 Flow diagram of the cause-effect chain for eutrophication Method evaluation**

## 3.8.2 Method evaluation

The methods have been rated against the criteria developed in guidance document LCIA - Framework and requirements document (EC-JRC, 2010b). The results are summarized in the table below[29]. Discussions of specific issues in the evaluation of the models against the criteria are presented in the background documentation[30] (Eutrophication.xls), where a table with the detailed evaluation including the whole sets of sub-criteria is given.

[29] A: full compliance; B: compliance in all essential aspects; C: compliance in some aspects; D: little compliance; E: no compliance

[30] http://lct.jrc.ec.europa.eu/

**Table 18 Summary of the evaluation results of the midpoint characterisation methods against the criteria for aquatic eutrophication. ( at mid and endpoint)**

| Criteria | CML 2002 | | EDIP2003 aquatic | | LIME midpoint | | ReCiPe midpoint | | TRACI Norris, 2003 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Completeness of scope** | B-C | The scope of the model for the evaluation of eutrophying substances is applicable for aquatic as well as terrestrial ecosystems. Global validity, no temporal differentiation | A-B | The scope of the model for the evaluation of eutrophying substances is applicable for aquatic ecosystems on the European scale. No consideration of terrestrial ecosystems. Spatial differentiation at the level of countries, no temporal differentiation | C | The scope of the model for the evaluation of eutrophying substances is limited to aquatic ecosystems and only addresses issues related to oxygen depletion. No consideration of terrestrial ecosystems. The model represents Japanese coastal waters, freshwater systems ignored | B | The scope of the model for the evaluation of eutrophying substances is limited to aquatic ecosystems where it addresses all relevant issues. The model represents European freshwaters and marine coastal waters. Spatial differentiation according to archetype emission situations, no temporal differentiation | B-C | The scope of the model for the evaluation of eutrophying substances is applicable for aquatic ecosystems, but not for terrestrial ecosystems. The model is parameterized for US and spatially differentiated at the level of US states, no temporal differentiation |
| **Environmental relevance** | D-E | Environmental relevance is low, most important fate processes determining availability and exposure of sensitive environments are missing | A-B | Environmental relevance high, removal processes in aquatic system modelled, but no distinction between freshwater and marine systems. | B-C | Environmental relevance is high although removal processes for nutrients are missing | A-B | Environmental relevance high, removal processes modelled, distinction between N- and P-limited systems. | A-B | Environmental relevance is high although removal processes for nutrients are missing |
| **Scientific robustness & Certainty** | D-E | Midpoint model of limited environmental relevance due to missing fate considerations, no treatment of uncertainty | B | Underlying fate model and adaptation to LCIA use reviewed, uncertainty from spatial variability quantified and several emission situations covered | C | Model components based on existing Japanese models and partially reviewed (?). No uncertainty considerations. | B | Model components based on existing European models and reviewed quantification of spatially determined uncertainty range and characterisation of different emission situations | B-C | Midpoint model reviewed, further components derived from reviewed information, some treatment of uncertainty in resulting CFs. |
| **Documentation & Transparency & Reproducibility** | A | The method principles and the CFs are documented and accessible for use in a reproducible way. Characterization model and input data easily accessible and applicable. | B | The method and CFs documented and accessible for use in a reproducible way. Characterization model and input data not easily accessible. | B-C | The method is documented and accessible, the CFs only available in Japanese, reproducibility not clear. Characterization model and input data not easily accessible. | B | The method is documented and accessible with all CFs for use in a reproducible way. Characterization model and input data not easily accessible. | C | The method principles and the CFs are documented and accessible for use in a reproducible way. Characterization model and input data not easily accessible. |
| **Applicability** | A | Characterisation factors for most relevant compounds available and easy to supplement | A | Characterisation factors for most relevant compounds available and easy to supplement - update depends on developers of underlying model | A | Characterisation factors for most relevant compounds available and easy to supplement - update depends on developers of underlying model | A | Characterisation factors for most relevant compounds available and easy to supplement - update depends on developers of underlying model | A | Characterisation factors for most relevant compounds available and easy to supplement - update depends on developers of ASTRAP model |

| Criteria | CML 2002 | | EDIP2003 aquatic | | LIME midpoint | | ReCiPe midpoint | | TRACI Norris, 2003 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Science based criteria overall evaluation** | B-C | Global validity and very limited uncertainty due to nearly total absence of fate modelling, which also means limited environmental relevance. Method principles and CFs documented and accessible for all main contributing substances. | B | Based on models for European conditions, addresses all aspects of aquatic eutrophication for both airborne and waterborne emissions. Spatial differentiation supported for European countries. Spatially determined uncertainty discussed, found to be low. Site-generic and site-dependent CFs documented and accessible for all relevant substances. | B | Parameterised to Japanese conditions, addressing oxygen depletion in coastal waters in Japan (a bit narrow scope) Model components reviewed (?). No uncertainty considerations. Method principles and CFs documented and accessible for all main contributing substances. | B | Based on models for European conditions, addresses all aspect of aquatic eutrophication for both airborne and waterborne emissions. Spatial differentiation found of low importance but can be developed for European countries. No treatment of uncertainty in resulting CFs, but factors developed for different emission sources. Method and CFs documented and accessible for N-total, P-total, NOx and NH3. | B | Parameterised to US conditions. Fate model well reviewed, but NH3 not covered. Further components derived from reviewed information, some treatment of spatially determined uncertainty in resulting CFs. Method principles and CFs documented and accessible for all main contributing substances. |
| **Stakeholders acceptance: Overall evaluation** | B-C | Limited stakeholder acceptance. Model easily understandable | B | Moderate stakeholder acceptance, official Danish LCIA methodology. Model reasonably understandable | C | Moderate stakeholder acceptance, method accepted by Japanese government(?). Expert knowledge is required to understand the model | B-C | Moderate stakeholder acceptance, method accepted by Dutch government. Model reasonably understandable | B-C | Moderate stakeholder acceptance, method accepted by US EPA. Model reasonably understandable |

## At endpoint

| Criteria | EPS2000 Steen, 1999 | | IMPACT 2002+ endpoint | | LIME endpoint | | ReCiPe endpoint | |
|---|---|---|---|---|---|---|---|---|
| **Completeness of scope** | A-B | The scope of the model for the evaluation of eutrophying substances is applicable for aquatic as well as terrestrial ecosystems. Lacks an atmospheric fate model. No spatial or temporal differentiation, global validity | B-C | The scope of the model for the evaluation of eutrophying substances is applicable for aquatic freshwater ecosystems, but not for terrestrial ecosystems. The damage model is based on European database. Spatial differentiation at the level of countries in Europe, no temporal differentiation | C | The scope of the model for the evaluation of eutrophying substances is limited to aquatic ecosystems and only addresses issues related to oxygen depletion. No consideration of terrestrial ecosystems. The model represents Japanese coastal waters, freshwater systems ignored | B | The scope of the model for the evaluation of eutrophying substances is limited to aquatic ecosystems where it addresses all relevant issues. Spatial differentiation according to archetype emission situations, no temporal differentiation. Effect model based on Dutch data for freshwaters and marine coastal waters |
| **Environmental relevance** | C | Environmental relevance is limited, no real fate model, but global average situation estimated for both fate and effect based on Swedish/Scandinavian data | D-E | Environmental relevance is high on effect side but low on fate side for freshwater systems, marine systems not considered. | B | Environmental relevance is high although removal processes for nutrients are missing | A-B | Environmental relevance high, important removal processes in water modelled, distinction between exposure of N- and P-limited systems for damage modelling, only damage model for the latter. |
| **Scientific robustness & Certainty** | B-C | Very simple fate model which has not been reviewed, effect model based on rough empirically based estimates. Consistent uncertainty considerations, but not of all aspects. | C-D | Endpoint model internally peer reviewed in project, no treatment of uncertainty | B-C | Some model components have been reviewed but for other the situation is not clear. The model addresses the main aspects of oxygen depletion in estuaries and coastal waters. No uncertainty considerations. | B | Model components based on existing European models and reviewed. Quantification of spatially determined uncertainty range and characterisation of different emission situations |

| Criteria | EPS2000 Steen, 1999 | | IMPACT 2002+ endpoint | | LIME endpoint | | ReCiPe endpoint | |
|---|---|---|---|---|---|---|---|---|
| **Documentation & Transparency & Reproducibility** | B | The method principles and the CFs are documented and accessible for use in a reproducible way. Characterization model and input data not easily accessible. | B | The method principles and the CFs are documented and accessible for use in a reproducible way. Characterization model and input data easily accessible and applicable. | B-C | The method is documented and accessible, the CFs only available in Japanese, reproducibility not clear. Characterization model and input data not easily accessible. | B | The method is documented and accessible with all CFs for use in a reproducible way. Characterization model and input data not easily accessible. |
| **Applicability** | B | Not all relevant substances have characterisation factors | A | Characterisation factors for most relevant compounds available and easy to supplement | A | Characterisation factors for most relevant compounds available and easy to supplement - update depends on developers of underlying model | A-B | All relevant substances included |
| **Science based criteria overall evaluation** | B-C | Very simple fate modelling, no removal mechanisms considered. Damage to natural environment very simple based on empirical data. Consistent uncertainty considerations, but not of all aspects. Method principles and CFs documented and accessible for a limited selection of contributing substances. | B-C | Very simple fate modelling, no removal mechanisms considered. Damage to natural environment considers impacts from P compounds on freshwater ecosystems only. No uncertainty considerations. Method principles and CFs documented and accessible for all main contributing substances (P compounds). | B | Parameterised to Japanese conditions, addressing damage to benthic communities of coastal waters in Japan (a bit narrow scope) Model components reviewed (?). No uncertainty considerations. Method principles and CFs documented and accessible for all main contributing substances. | B | Based on models for European conditions, addresses all aspect of aquatic eutrophication for both airborne and waterborne emissions. Spatial differentiation found of low importance but can be developed for European countries. No treatment of uncertainty in resulting CFs, but factors developed for different emission sources. Method and CFs documented and accessible for N-total, P-total, NOx and NH3. |
| **Stakeholders acceptance: Overall evaluation** | D | Low stakeholder acceptance, model easily understandable | C | Limited stakeholder acceptance. Model easily understandable | B-C | Moderate stakeholder acceptance, method accepted by Japanese government (?). Expert knowledge is required to understand the model | C | Moderate stakeholder acceptance, method accepted by Dutch government. Model reasonably understandable |

**Table 19 Summary of the evaluation results of the endpoint characterisation methods against the criteria for terrestrial eutrophication.**

| Criteria | Accumulated Exceedence (Seppälä et al., 2006) | | CML 2002 | | EDIP2003 terrestrial | | EPS2000 Steen, 1999 | | Eco-indicator 99 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Completeness of scope** | A - B | The scope of the model for the evaluation of eutrophying substances is applicable for terrestrial ecosystems on the European scale. No consideration of aquatic ecosystems | B - C | The scope of the model for the evaluation of eutrophying substances is applicable for aquatic as well as terrestrial ecosystems. Global validity, no temporal differentiation | B - C | The scope of the model for the evaluation of eutrophying substances is applicable for terrestrial ecosystems on the European scale. No consideration of aquatic ecosystems. Spatial differentiation at the level of countries, temporal differentiation included | A - B | The scope of the model for the evaluation of eutrophying substances is applicable for aquatic as well as terrestrial ecosystems. Lacks an atmospheric fate model. No spatial or temporal differentiation, global validity | B - C | The scope of the model for the evaluation of eutrophying on the European scale is applicable, but factors are based on combined eutrophication/acidification of Dutch forests only. Lacks an atmospheric fate model |
| **Environmental relevance** | A - B | High environmental relevance for natural environment. Full atmospheric and soil assessment considered. Sensitive to emission scenario and current critical load | D - E | Environmental relevance is low, most important fate processes determining availability and exposure of sensitive environments are missing | B - C | High environmental relevance for natural environment. Full atmospheric and soil assessment considered. Sensitive to emission scenario and current critical load | C | Environmental relevance is limited, no real fate model, ,but global average situation estimated for both fate and effect based on Swedish/Scandinavian data | B | Limited environmental relevance. Does not enable discriminating between the atmospheric fates of chemicals. Soil fate considered for forests and extrapolated to other ecosystems. It further includes an effect factor |
| **Scientific robustness & Certainty** | B | Model components extensively reviewed and uncertainty estimates available in term of spatial variation and emission scenarios | D - E | Midpoint model of limited environmental relevance due to missing fate considerations, no treatment of uncertainty | B | Underlying fate model and adaptation to LCIA use reviewed, uncertainty from spatial variability quantified and several temporal scenarios investigated | B - C | Very simple fate model which has not been reviewed, effect model based on rough empirically based estimates. Consistent uncertainty considerations, but not of all aspects. | C | The method itself has not been peer reviewed, but the underlying model components have. However, poor scientific quality for the fate model. Expert judgment on uncertainty estimates |
| **Documentation & Transparency & Reproducibility** | B - C | The method and the CFs are well documented and accessible. Characterization model and input data not easily accessible. Can potentially be adapted to generate CFs for different continents if complemented with a global atmospheric model and expert judgment on sensitive areas | A | The method principles and the CFs are documented and accessible for use in a reproducible way. Characterization model and input data easily accessible and applicable. | B - C | The method and CFs documented and accessible for use in a reproducible way. Characterization model and input data not easily accessible. | B | The method principles and the CFs are documented and accessible for use in a reproducible way. Characterization model and input data not easily accessible. | B - C | The method and the CFs are well documented and accessible for use in a reproducible way. Characterization model and input data not easily accessible. |
| **Applicability** | A | Characterisation factors for most relevant compounds available and easy to supplement - update depends on developers of underlying model | A | Characterisation factors for most relevant compounds available and easy to supplement | A | Characterisation factors for most relevant compounds available and easy to supplement - update depends on developers of underlying model | B | Not all relevant substances have characterisation factors | A | Readily applicable. Most important eutrophying substances are covered. |

| Criteria | Accumulated Exceedence (Seppälä et al., 2006) | | CML 2002 | | EDIP2003 terrestrial | | EPS2000 Steen, 1999 | | Eco-indicator 99 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Science based criteria overall evaluation** | A | The method meets the science based criteria. It Includes atmospheric and soil fate factors distinguishing between load to sensitive area and insensitive area for biodiversity. It could be applicable worldwide at continental level if complemented by a global atmospheric fate model and expert estimate on soil sensitive area. | B - C | Global validity and very limited uncertainty due to nearly total absence of fate modelling, which also means limited environmental relevance. Method principles and CFs documented and accessible for all main contributing substances. | B | Based on models for European conditions, addresses terrestrial eutrophication for airborne emissions. Spatial differentiation supported for European countries. Quantification of spatially determined uncertainty in resulting site-generic CFs. Site-generic and site-dependent CFs documented and accessible for all relevant substances. | B - C | Very simple fate modelling, no removal mechanisms considered. Damage to natural environment very simple based on empirical data. Consistent uncertainty considerations, but not of all aspects. Method principles and CFs documented and accessible for a limited selection of contributing substances. | B - C | The method meets the science based criteria in some aspects. Poor scientific quality for the fate model and rather old soil fate and effect models are used. It is therefore difficult to generate effect data for other continents than Europe. |
| **Stakeholders acceptance: Overall evaluation** | B | High stakeholder acceptance, but models and data are difficult to understand without expert knowledge | B - C | Limited stakeholder acceptance. Model easily understandable | B - C | Moderate stakeholder acceptance, official Danish LCIA methodology. Expert knowledge is required to understand the model | D | Low stakeholder acceptance, model easily understandable | C - D | Low stakeholder acceptance, no authoritative body behind the method. Pure scientific work, understood with expert knowledge |

### 3.8.3 Discussion on method evaluation

Specific criteria of 'Environmental relevance' and 'scientific robustness' have been specified for aquatic and terrestrial eutrophication in the LCIA - Framework and requirements document (EC-JRC, 2010b).

The main criteria focus on: the presence of a fate and transport model; advection out of a region not considered a final loss; influential fate processes considered (for aquatic systems: denitrification, precipitation and sedimentation of P; for terrestrial systems: oxidation, deposition); for damages on ecosystems, a fate sensitivity factor discriminating between sensitive and insensitive recipients is considered; magnitude of exceedance for exposure above critical level is considered; potency or dose-response is included; distinction of individual N- and P-compounds; latest knowledge for the cause-effect chain with the critical links are covered (Atmospheric fate and transport model, exposure model, potency or dose-response model); coverage of the impacts in the modelling from midpoint to endpoint is complete.

It has to be noted that for LIME, some information is missing or partially incomplete in the documentation available for this guideline due to difficulties in accessing the parts of the background information that was not provided in English.

### 3.8.4 Discussion of uncertainties and the importance of spatial differentiation

The uncertainties are mainly expressed in term of spatial and temporal variability or by expert judgment estimates (Eco-indicator 99). The intrinsic uncertainty of the fate and effect models is not reported for any of the recommended models.

Temporal variability is taken into account for some of the terrestrial eutrophication models through present and future emission scenarios.

Spatial differentiation in atmospheric fate can model differences in deposition of eutrophying substances on a few tens or hundreds kilometres scale (typically 100 x100 km scale). Soil fate modelling can be even more detailed up to a few square kilometres. This source of uncertainty could be up to two or three orders of magnitude between individual European countries (Potting et al. 1998 b; Posch et al. 2008) and is very important compared to the variability between chemicals, which is typically ranging within one order of magnitude. It therefore makes little sense to assess terrestrial eutrophication, distinguishing between individual substances like $NO_x$ and $NH_3$ and disregarding the spatial variability.

For aquatic eutrophication, the spatially determined variation between countries in Europe (Potting and Hauschild, 2005, Goedkoop et al., 2009) or states within USA (Norris, 2003) is found to be less than one order of magnitude making this level of spatial differentiation less important for aquatic eutrophication. Here, however, the distinction of aquatic receiving environments according to their limiting nutrient makes a crucial difference, and a distinction between freshwater systems (generally P-limited) and marine water systems (generally N-limited) is seen as very important.

It is questioned above whether organic material emissions should be counted as contributing to eutrophication. If they are classified as eutrophying, their factors should be derived from the factors for N or P assuming a standard primary production of BOD per added nutrient.

## 3.8.5 Recommended default method at midpoint level

### 3.8.5.1 Terrestrial eutrophication

AE (Accumulated Exceedence) is to be preferred as recommended model for midpoint evaluation of terrestrial eutrophication. The method meets the science based criteria, and it shows a good stakeholder acceptance as AE-type calculations are used for policy purposes in Europe by the European Commission and by the United Nations Economic Commission for Europe's Long-range Transboundary Air Pollution Convention (UNECE LRTAP). It includes atmospheric and soil fate factors sensitive to emission scenario and distinguish between load to non-sensitive and sensitive areas. This is probably the most readily adaptable method that can be used to generate a set of consistent CFs for each continent (or for a generic one) if complemented by a set of regional/continental models which are consistent with each other (that could eventually be integrated in one global model) and expert estimate on soil sensitive area. Recommendation of the AE approach will also ensure consistency between the treatment of terrestrial eutrophication and terrestrial acidification for which impact category it is also recommended at midpoint level.

CML2002 and EDIP97 apply a similar approach, so only CML2002 was considered here. The weak points of CML2002 are that it does not include any spatial and temporal differentiation; it considers a worst case scenario, and there is no treatment of uncertainty. Environmental relevance is low, most important fate processes determining availability and exposure of sensitive environments are missing;

EDIP2003 is based on models for European conditions, and it addresses terrestrial eutrophication for airborne emissions. Spatial differentiation is supported at the level of European countries. It provides site-generic CFs with a quantification of their spatially determined uncertainty. It quantifies the area exposed to critical level but disregards exposure above thresholds. Compared to AE it has a moderate stakeholder acceptance.

### 3.8.5.2 Aquatic eutrophication

Most of the characterisation models for aquatic eutrophication have a rather weak modelling of the fate and ignore some of the important removal processes for both N and P. The best modelling of aquatic fate at midpoint level is performed using the CARMEN model (Klepper et al., 1995), as applied in two methodologies, ReCiPe and EDIP2003.The model is likewise restricted to a European validity.

ReCiPe uses a more recent model for atmospheric fate and adopts a more consistent framework presenting the characterisation factors as nutrient concentration increases distinguishing aquatic receiving compartments according to the limiting nutrient. Therefore the approach used in ReCiPe is preferred as recommended default method at midpoint level for aquatic eutrophication.

CML, TRACI and EDIP2003 methods have the strength of addressing both terrestrial and aquatic eutrophication. CML lacks a fate model, while TRACI and EDIP both suffer from a weaker performance in some of the central science based criteria concerning the quality of the underlying models and for EDIP concerning the distinction of receiving water bodies according to limiting nutrient.

LIME has a very restricted focus on oxygen depletion in marine environment which makes it unsuitable in a global, let alone a European context.

## 3.8.6 Recommended default method at endpoint level

### 3.8.6.1 Terrestrial eutrophication

At endpoint, no methods are recommended to be used for terrestrial eutrophication.

None of the evaluated endpoint models (Eco-indicator 99 and EPS2000) reach the sufficient scientific quality and consensus when linking midpoint to damage indicators, therefore no formal recommendation has been done as at that stage.

EPS2000 has a very simple fate model (not reviewed) and effect model. Environmental relevance is limited and a global average situation is estimated from Swedish data. It does provide consistent uncertainty considerations, but not for all aspects.

Eco-indicator 99 addresses only terrestrial eutrophication and does so together with acidification. It has a very simple fate model (not reviewed) and effect model. It represents only Dutch conditions. Uncertainty considerations are limited.

### 3.8.6.2 Aquatic eutrophication

At endpoint, no methods are recommended to be used for aquatic eutrophication.

As interim, the damage model to freshwater ecosystems (from P exposure) based on empirical data for a large selection of Dutch ecosystems, as implemented in ReCiPe, can be used. This approach is seen as the most relevant and scientifically sound for damage modelling in freshwater eutrophication.

LIME is, among the evaluated endpoint models, the only one that addresses marine eutrophication in a scientifically sound way, but its focus on oxygen depletion effects on benthic communities that is too restricted to support a recommendation and the model is not straightforward to be extended beyond the present Japanese setting. Therefore no formal recommendation has been done for marine eutrophication.

EPS2000 also addresses aquatic eutrophication at endpoint level but it has no real fate model and its effect model is based on questionable and undocumented extrapolation from Swedish/Scandinavian damage data to estimate global damage data. It therefore performs too weakly in the science-based criteria to support a recommendation.

## 3.8.7 Consistency between midpoint and endpoint methods

For the models for freshwater eutrophication there is a fine consistency between midpoint and the interim method for endpoint as they have been developed applying the same model in a consistent framework. No endpoint model is recommended for terrestrial and aquatic (both freshwater and marine) eutrophication.

### 3.8.8 Classification of the recommended default methods

Terrestrial eutrophication

As midpoint charachterisation method for terrestrial eutrophication it is recommended the use of the Accumulated Exceedence (Seppälä et al. 2006 and Posh et al. 2008), classified as being “recommended with some improvements needed” (Level II out of III).

No endpoint method is recommended for terrestrial eutrophication.

Aquatic eutrophication

The midpoint method recommended for aquatic eutrophication (both freshwater and marine) is the method developed by Struijs et al., 2009b that uses the EUTREND model for atmospheric emissions and distinguishes freshwater systems (only P-emissions considered) and marine systems (only N considered). It is classified as being “recommended with some improvements needed” (Level II out of III)

No endpoint method is recommended for aquatic eutrophication.

If an endpoint method is required, the method for aquatic eutrophication as developed in ReCiPe can be used as interim for damage in freshwater systems, being the most appropriate among the existing approaches but still with considerable shortcomings and uncertainties.

No endpoint method can be used as interim for marine eutrophication.

### 3.8.9 Calculation principles

Additional midpoint characterisation factors cannot be calculated by the LCA practitioner but require access to and expertise in the underlying model. The number of substances contributing to eutrophication is quite limited and hence the need for additional factors is not foreseen to be an issue.

# 3.9 Ecotoxicity

## 3.9.1 Pre-selection of methods for further evaluation

The pre-selection of characterisation models for the ecotoxicity impact category is presented in LCIA- Analysis document (EC-JRC, 2010a) and is summarized in the table below.

**Table 20 Selected midpoint methods and underlying models for ecotoxicity.**

| Midpoint method | Underlying model | Reference |
|---|---|---|
| USEtox | Model developed under auspices of UNEP/SETAC Life Cycle Initiative | Rosenbaum et al. (2008) |
| ReCiPe[a] | USES-LCA version 2.0 | Huijbregts and Van Zelm (2009) |
| IMPACT 2002+[b] | IMPACT2002 | Jolliet et al. (2003) |
| TRACI | CalTOX 4.0 | Bare et al. (2003) |
| EDIP2003[c] | EDIP1997, combined with site dependent factors | Tørsløv et al. (2005) |
| Swiss Ecoscarcity | Based on a combination of actual emissions and emission limit values | Frischknecht et al. (2008) |
| MEEuP | Based on emission limit values | Kemna et al. (2005) |
| **Endpoint method** | | |
| EPS2000 | Based on empirical information of red list species supposed to be threatened by chemicals and total emission loads | Steen (1999a, b) |
| ReCiPe[a] | USES-LCA version 2.0 | Huijbregts and Van Zelm (2009) |
| IMPACT 2002+[b] | IMPACT2002 | Jolliet et al. (2003) |

[a] The most recent version of the model USES-LCA is the underlying model for the calculations of characterisation factors for ecotoxicity in ReCiPe. Previous versions of the model family USES-LCA and EUSES, employed in CML2002 and Eco-indicator99, were not included in the evaluation.

[b] The European version of the model IMPACT2002 is the underlying model for the calculations of characterisation factors for ecotoxicity in IMPACT2002+. LUCAS and LIME contain respectively Canadian and Japanese versions of IMPACT2002 and were not included in the evaluation.

[c] The most recent version of the EDIP method is evaluated (2003 version). A previous version, EDIP1997, was not included in the evaluation.

The methods that were analysed can be divided into three groups according to their fate modelling: 1. Full multimedia fate modelling (USEtox, ReCiPe, IMPACT2002+, Caltox (TRACI), 2. Partial fate modelling - Environmental key properties (EDIP) and 3. no fate modelling (Swiss Ecoscarcity and MEEuP). Methods within Group 1 and 2 model impacts at the same level in the impact pathway predicting Potentially Affected Fraction of species (PAF) in some form, while methods in group 3 are not showed in the figure: they do not really target PAF's at all as they are not based on fate assessment.

Figure 10 illustrates the environmental mechanism of ecotoxicological impacts and corresponds to the framework of fate and ecotoxicological effect assessment.

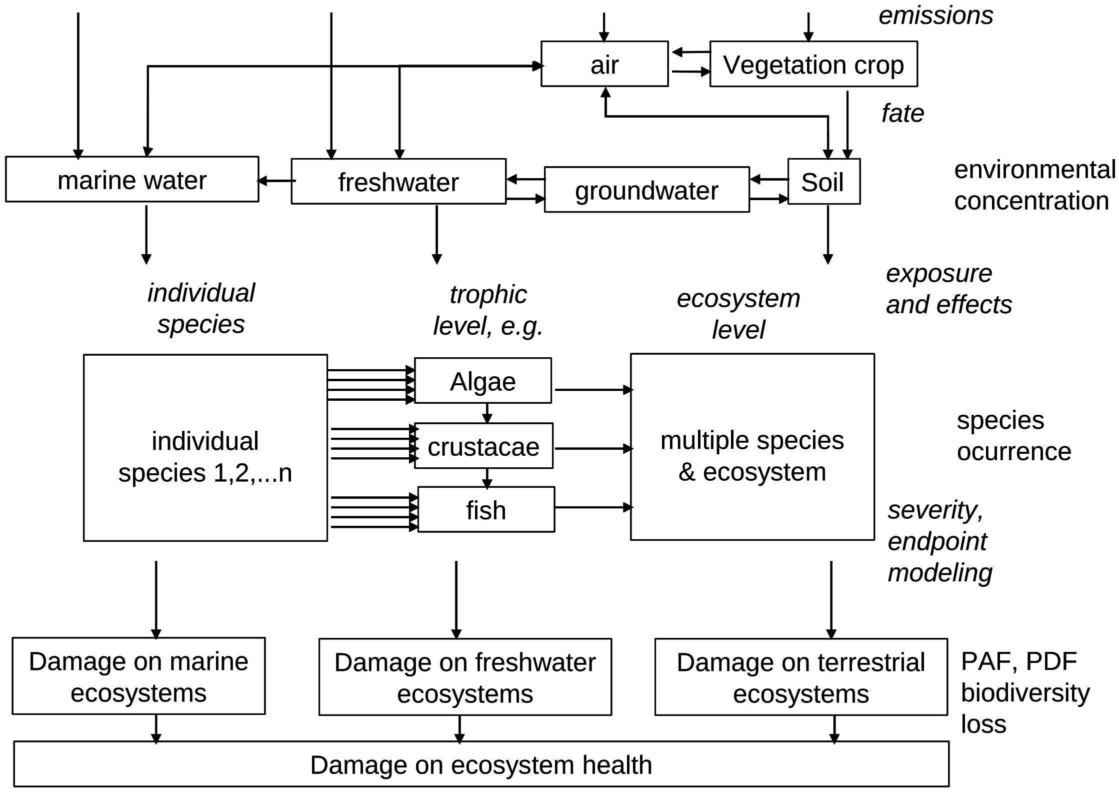


**Figure 10 Flow diagram for ecotoxicity**

## 3.9.2 Method evaluation

The methods have been rated against the criteria developed in guidance document LCIA - Framework and requirements document (EC-JRC, 2010b). The results are summarized in the table below[31]. Table 21 summarizes the evaluation of the five most prominent midpoint models for ecotoxicological impact assessment in LCIA, while Table 22 gives the summary of the evaluation of the two remaining midpoint models and the three endpoint models considered. Discussions of specific issues in the evaluation of the models against the criteria are presented in the background documentation[32] (Ecotoxicity.xls), where a table with the detailed evaluation including the whole sets of sub-criteria is given.

[31] A: full compliance; B: compliance in all essential aspects; C: compliance in some aspects; D: little compliance; E: no compliance
[32] http://lct.jrc.ec.europa.eu/

**Table 21 Summary table documenting the analysis of five midpoint characterisation methods against the adapted criteria for ecotoxicity.**

| | USEtox (midpoint) | | ReCiPe (midpoint) | | IMPACT2002+ (midpoint) | | TRACI (midpoint) | | EDIP2003 (midpoint) | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Completeness of scope** | A | The scope of the model for the generic evaluation of chemicals is fully applicable | A/B | The scope of the model for the generic evaluation of chemicals is fully applicable, except that the model is parameterised for European circumstances | A/B | The scope of the model for the generic evaluation of chemicals is fully applicable, except that the model is parameterised for European circumstances | A/B | The scope of the model for the generic evaluation of chemicals is fully applicable, except that the model is parameterised for US circumstances | A/B | The scope of the model for the generic evaluation of chemicals is fully applicable, but not adaptable to a spatial and temporal explicit evaluation |
| **Environmental relevance** | B/C | Environmental relevance is high for freshwater ecotoxicity, except for the exclusion of marine and terrestrial ecotoxicity | B | Environmental relevance is high, although ecotoxicity data are based on acute EC50 and terrestrial ecotoxicity is based on aquatic data | A/B | Environmental relevance is high. Terrestrial ecotoxicity is, however, based on aquatic data | B | Environmental relevance is high. Ecotoxicity effect factors are, however, based on NOEC instead of $EC_{50}$ data | B/C | Environmental relevance is high, but marine compartment and fate processes, such as advective transport of chemicals, are excluded |
| **Scientific robustness & Certainty** | B | Chemical input data and model components extensively reviewed by a large group of model developers, but no uncertainty estimates available | B | Model components extensively reviewed and uncertainty estimates available, but chemical data not always reviewed | B | Model components extensively reviewed and uncertainty estimates available, but chemical data not always reviewed | B | Model components extensively reviewed and uncertainty estimates available, but chemical data not always reviewed | C/D | Effect assessment is scientifically robust, but intermedia transport is not comprehensively included nor verification of model results and uncertainty estimates |
| **Documentation & Transparency & Reproducibility** | A | The model, documentation and results are published and the model can be used free of charge | A | The model, documentation and results are published and the model can be used free of charge | A | The model, documentation and results are published and the model can be used free of charge | A | The model, documentation and results are published and the model can be used free of charge | A | The model, documentation and results are published and the model can be used free of charge |
| **Applicability** | B/C | Database with > 2000 ecotoxicological CF for freshwater ecotoxicity is available, can be easily applied and updated. Data for marine and terrestrial ecotoxicity is lacking | A | Database with > 2000 ecotoxicological characterisation factors is available that can be easily applied and updated | A/B | Database with > 400 ecotoxicological characterisation factors is available that can be easily applied and updated | B | Database with > 100 ecotoxicological characterisation factors is available that can be easily applied and updated | B | Database with > 100 ecotoxicological characterisation factors is available that can be easily applied and updated |
| **Overall evaluation of science based criteria** | B | The model addresses the freshwater environment, includes all vital model elements in a scientifically sound way, except for metals, and is sufficiently documented | B | The model addresses the freshwater, marine and terrestrial environments, includes all vital model elements in a scientifically sound way, except for metals, and is well documented | B | The model addresses the freshwater, marine and terrestrial environments, includes all vital model elements in a scientifically sound way, except for metals, and is well documented | B | The model addresses the freshwater and terrestrial environments, includes all vital fate model elements in a scientifically sound way, except for metals, and is well documented. The ecotoxicological effect assessment can be further improved by using EC50 data | C | The model addresses the freshwater and terrestrial environments, includes the effect part in a scientifically sound way, except for metals, and is well documented. The fate assessment is, however, very simplified and no information is available on the uncertainties involved in the model results |
| **Overall evaluation of stakeholders acceptance** | A/B | Principles of the model are easy to understand and the UNEP encourages its use by businesses and governments. | B | Principles of the model are easy to understand and based on the EUSES-system applied in the EU to evaluate new and existing chemicals, but the LCA version is not officially endorsed by an international authoritative body | B/C | Principles of the model are easy to understand, but the model is not endorsed by an authoritative body | B | Principles of the model are easy to understand and endorsed by the USEPA | C | Principles of the model are easy to understand, but the model is not endorsed by an authoritative body |

**Table 22 Summary table documenting the analysis of the two remaining midpoint models and three endpoint models for ecotoxicity.**

| | Swiss Ecoscarcity (midpoint) | | MEEuP (midpoint) | | EPS2000 (endpoint) | | ReCiPe (endpoint) | | IMPACT2002+ (endpoint) | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Completeness of scope** | E | No ecotoxicological impact mechanisms included. Indicators derived from policy-based emission limit values | E | No ecotoxicological impact mechanisms included. Indicators derived from policy-based emission limit values | A | The scope of the model for the generic evaluation of chemicals is fully applicable | A / B | The scope of the model for the generic evaluation of chemicals is fully applicable, except that the model is parameterised for European circumstances | A / B | The scope of the model for the generic evaluation of chemicals is fully applicable, except that the model is parameterised for European circumstances |
| **Environmental relevance** | E | No specific focus on ecotoxicological impacts, as actual emissions and emission limit values are used as impact indicator | E | No specific focus on ecotoxicological impacts, as emission limit values are used as impact indicator | E | No modelling of chemical-specific ecotoxicological impacts along the environmental cause-effect chain | C | Environmental relevance for endpoint assessment of effects on ecosystem biodiversity is rather low | C | Environmental relevance for endpoint assessment of effects on ecosystem biodiversity is rather low |
| **Scientific robustness & Certainty** | | Not further evaluated due to lack of environmental relevance | | Not further evaluated due to lack of environmental relevance | | Not further evaluated due to lack of environmental relevance | D | Hardly any validation data available for the endpoint effect factors | E | No validation data available for the endpoint effect factors |
| **Documentation & Transparency & Reproducibility** | | Not further evaluated due to lack of environmental relevance | | Not further evaluated due to lack of environmental relevance | | Not further evaluated due to lack of environmental relevance | A | The model, documentation and results are published and the model can be used free of charge | A | The model, documentation and results are published and the model can be used free of charge |
| **Applicability** | | Not further evaluated due to lack of environmental relevance | | Not further evaluated due to lack of environmental relevance | | Not further evaluated due to lack of environmental relevance | A | Database with > 2000 ecotoxicological characterisation factors is available that can be easily applied and updated | A / B | Database with > 400 ecotoxicological characterisation factors is available that can be easily applied and updated |
| **Overall evaluation of science based criteria** | E | No compliance with science-based criteria for the evaluation of ecotoxicological impacts. Political emission targets are used in the indicator development | E | No compliance with science-based criteria for the evaluation of ecotoxicological impacts. Political emission targets are used in the indicator development | E | No compliance with science-based criteria for the evaluation of ecotoxicological impacts. Cause-effect chain of individual chemicals not included | D | There is little compliance for the endpoint effect part of the method, as the overall concept of the endpoint effect factors is hardly validated | D | There is little compliance for the endpoint effect part of the method, as the overall concept of the endpoint effect factors is hardly validated |
| **Overall evaluation of stakeholders acceptance** | | Not further evaluated, because the thresholds within the science based criteria were not reached | | Not further evaluated, because the thresholds within the science based criteria were not reached | | Not further evaluated, because the thresholds within the science based criteria were not reached | C | Principles of the model are relatively easy to understand, but the endpoint part of the model is not endorsed by an authoritative body. | C | Principles of the model are relatively easy to understand, but the endpoint part of the model is not endorsed by an authoritative body |

### 3.9.3 Discussion on method evaluation

As stated in the LCIA- Framework and requirements document (EC-JRC, 2010b), LCA characterisation models and factors for ecotoxicity effects must be based on models that account for a chemical's fate in the environment, species exposure, and differences in toxicological response (likelihood of effects and severity).

Therefore, two of the midpoint methods (Swiss Ecoscarcity and MEEuP) were not further evaluated since the proposed approaches haven't an ecotoxicity model behind the calculations. Amongst the five remaining ecotoxicity methods, four of them (USEtox, IMPACT, ReCiPe, TRACI) show compliance with criteria in all essential aspects for the science-based criteria, while EDIP has a compliance only in some aspects due to a rather simplistic fate assessment. For the evaluation of stakeholders' acceptance criteria, the USEtox model stands out compared to the other models, as the principles of the model are easy to understand and the UNEP encourages its use by businesses and governments.

For all the three evaluated endpoint methods (EPS2000, ReCiPe, IMPACT2002+), there is little or no compliance with the scientific and stakeholder acceptance criteria, as the overall concept of the endpoint effect factors is hardly validated and the endpoint part of the methods is not endorsed by an authoritative body.

Posthuma and De Zwart (2006) indicated for responses of fish species assemblages that the observed loss of species due to mixture toxicity matches the predicted risks based on EC50-data, at least in a relative sense (slope 1:1), and with a maximum observed fraction of lost species equal to the EC50-based ecotoxicity predictor variable. Nevertheless, so far the methods are immature to be used even at interim.

Also for terrestrial and marine ecotoxicity none of the methods is recommended.

### 3.9.4 Discussion on uncertainties and the importance of spatial differentiation

Uncertainty in the fate factors of organic chemicals is mainly caused by uncertainty in the degradation rates (Rosenbaum et al., 2008), and for e.g. metals the lack of addressing true metal bioavailability in the fate calculations (see e.g. Chapman et al., 2003 and Chapman, 2008 for a critical review on this aspect). In the effect factor calculations, uncertainty is mainly due to the lack of toxicity data for species of various trophic levels (Van Zelm et al., 2007b).

As discussed in Rosenbaum et al. (2008), the characterisation factors for ecotoxicity must be used in a way that reflects the large variation of 12 orders of magnitude between chemical impacts per unit emission as well as the 2 orders of magnitude uncertainty on the individual characterisation factors. In practice, this means that for the LCA practitioner, these characterisation factors for ecotoxicity can be useful to identify the 10 or 20 most important chemicals pertinent for their application. The life-cycle ecotoxicity scores enable thus the identification of all chemicals contributing more than e.g. one thousandth to the total score. In most applications, this will allow the practitioner to identify 10 to 20 chemicals to look at in priority and perhaps more importantly to disregard 400 other substances whose impact is not significant for the considered application. The same types of conclusions are also found in screening risk assessments (e.g. Harbers et al., 2006).

Research towards the importance of including spatial differentiation in the calculation of characterisation factors for ecotoxicity has been hardly addressed within LCA, although e.g. Tørsløv et al. (2005) indicate that excluding spatial variability is probably less influential compared to the importance of parameter uncertainty, for instance, in degradation rates and toxicity data, in the calculation of characterisation factors for ecotoxicity.

## 3.9.5 Recommended default method at midpoint level

USEtox is preferred as the recommended default method for the midpoint evaluation of freshwater ecotoxicity impacts. This is equally consistent with the model recommended for toxicity impacts for humans. It results from a consensus building effort amongst related modellers and, hence, the underlying principles reflect common and agreed recommendations from these experts. The model accounts for all important parameters in the impact pathway as identified by a systematic model comparison within the consensus process. The model addresses the freshwater part of the environment problem and includes the vital model elements in a scientifically up-to-date way. USEtox has also been set up to model a global default continent.

In USEtox, a distinction is made between interim and recommended characterization factors, reflecting the level of expected reliability of the calculations in a qualitative way (Rosenbaum et al. 2008). Ecotoxicological characterisation factors for ‘metals’, ‘dissociating substances’ and ‘amphiphilics’ (e.g. detergents) are all classified as interim in USEtox. The providers argue that this is due to the relatively high uncertainty of addressing fate and effects for all chemicals within these substance groups at this time. For the remaining set of chemicals, recommended aquatic ecotoxicological characterisation factors are based on effect data of at least three different species covering at least three different trophic levels (or taxa)

No available method is recommended to address marine and terrestrial ecotoxicity. It should be noted that the use of indicators for freshwater ecosystems is not a proxy for marine and terrestrial ones and, in many cases, only accounts for part of the long-term fate and ecosystem exposure of emissions. Actually, chemicals that doesn’t remain long in freshwater and have a high persistence may imply terrestrial or marine effects not yet addressed by USEtox.

## 3.9.6 Recommended default method at endpoint level

The USEtox midpoint model is recommended for the midpoint calculations for freshwater ecotoxicity. No model

No method is recommended for the endpoint assessment of ecotoxicity, as no method is mature enough.

Both at midpoint and at endpoint, no method is recommended for marine and terrestrial ecotoxicity.

### 3.9.7 Classification of the recommended default methods

At midpoint, USEtox is a satisfactory method for freshwater aquatic ecotoxicity, recommended for non polar organics but needing minor improvements (Level II). At the moment, it is not considered to apply very well to metals, dissociating substances and amphiphilics (e.g. detergents). These substances are classified as Level III.

The endpoint characterisation ecotoxicity models for all chemicals are classified as immature to be recommended due to the preliminary nature of the results available and the assumptions made between the midpoint indicator and impacts on ecosystems. Substantial research still needs to be carried out on this issue before general conversion rules can be developed to address toxicity effects on biodiversity.

### 3.9.8 Calculation principles

In case a midpoint characterisation factor is missing for an important elementary flow in the inventory, it can be determined using the model as documented in Rosenbaum et al. (2008). The latest version of the USEtox model may be downloaded at www.usetox.org to calculate characterization factors for new substances.

The calculation requires the availability of the needed substance properties among which particularly the toxicity and biodegradability data can be uncertain and difficult to find. These are normally the input parameters contributing most to the overall uncertainty of the characterisation factor.

## 3.10 Land use

### 3.10.1 Pre-selection of methods for further evaluation

Extensive research has been done on the impact category *land use* (e.g. Müller-Wenk, 1998a; Köllner, 2001; van der Voet, 2001; Weidema and Lindeijer, 2001). In 2007, a framework for land use impact assessment in LCA was published by Milà i Canals *et al.* (2007a), which not only gives a description of land use impacts, but also suggests possible indicators at both midpoint and endpoint levels, and includes guidelines on how to address the reference land system.

The midpoint characterisation factor for land use, in the earliest stage of the cause-effect chain, is mostly taken as the amount and quality deficit of land occupied or transformed. Some midpoint methods use indicators like soil structure, soil pH or soil organic carbon. The endpoint characterisation factor mostly refers to the amount of species lost due to land use or to the change in Net Primary Production (NPP) of the land used.

The pre-selection of characterisation models for the land-use impact category has been explained in another ILCD document: “Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment” and is summarized in the table below.

**Table 23 Selected midpoint methods and underlying models for land use.**

| **Midpoint method** | **Underlying model** | **Reference** |
|---|---|---|
| ReCiPe | Not based on a specific model | De Schryver and Goedkoop (2009b) |
| Milà i Canals | Based on Soil Organic Matter (SOM) | Mila i Canals *et al.* (2007b) |
| Baitz | Based on seven quality indicators | Baitz (2002) further developed by Bos and Wittstock (2008) |
| **Endpoint method** | | |
| EPS2000 | Based on species diversity loss and production of wood | Järvinen and Miettinen (1987) |
| Eco-Indicator 99 (EI99) | Based on species diversity loss | Köllner (2000) in Goedkoop and Spriensma (2000) |
| ReCiPe | Based on species diversity loss | De Schryver and Goedkoop (2009b) |
| LIME | Based on species diversity loss and production of wood loss? | Itsubo *et al.* (2008b) |
| Swiss Ecoscarcity | Based on species diversity loss | Köllner (2001), Köllner and Scholz (2008) |

Additional recent developments exist but have not yet resulted in available characterisation factors and, therefore, have not been further evaluated. These include:

- Michelsen (2007): The main value seems to lie in assessing biodiversity from an ecosystem rather than species diversity point of view. The study is focused on forestry, but a similar approach could be developed for other land–use types
- A new project group under the UNEP/SETAC Life Cycle Initiative on land use.[33]

The methods considered at the midpoint level are:

- **ReCiPe**

  This method is a follow-up of the CML2002 method by Guiné *et al*. (2002). The surface area occupied or transformed is taken into account, without any further characterisation. In that sense, ReCiPe is not a characterisation model but rather a selection of LCI parameters, like the method of Baitz (2002).

- **Milà i Canals (2007b)**

  This method considers Soil Organic Matter (SOM) as a soil quality indicator. SOM is qualified as a keystone soil quality indicator, especially for assessing the impacts on fertile land use (agriculture and forestry systems). It influences properties like buffer capacity, soil structure and fertility. However, it must be noted that in LCIA it should be combined with biodiversity indicators. In highly acidified or waterlogged soils the SOM may not correlate directly with soil quality. The LCA practitioner is expected to know

[33] See http://fr1.estis.net/builder/includes/page.asp?site=lcinit&page_id=337831BE-0C0A-4DC9-AEE5-9DECD1F082D8

the location, the timeframe, and the SOM values before and after the land occupation, the SOM value of the reference land system, the relaxation rate, and associated SOM values. Based on this, the LCA practitioner is expected to calculate the characterisation factors for the foreground system. Characterisation factors for certain land use flows in the background system are provided in Milà i Canals *et al.* (2007c).

- **Baitz (2002)**

The method proposed by Baitz (2002) and further developed by Bos and Wittstock (2008) is based on an inventory of seven indicators that can be used to describe the impacts related to land occupation and transformation. For each indicator, a description and a classification is given for its dependence on a set of fundamental quality parameters, such as the main types of soil, the slope of the landscape, the carbon content and the maturity of the landscape. The LCA practitioner is expected to investigate which conditions apply for a certain area (assuming this is known) and assess in which class the landscape falls under. When no site-specific information is available, data are taken from a background database as country-specific averages. The following indicators are to be used:

(1) Erosion stability,

(2) Filter, buffer and transformation function for water,

(3) Groundwater availability and protection (against leaching into the groundwater - partially dependent on water permeability)

(4) Net Primary Production (NPP),

(5) Water permeability and absorption capacity,

(6) Emission filtering absorption and protection, and

(7) Ecosystem stability and biodiversity[34].

Until now, the different indicators cannot be combined or weighted at the midpoint level. All indicators are calculated as elementary flows that in a next step should be used as indicators to characterize impact categories which are yet to be defined. The method is relatively unknown, partly because most information is available in German and just recently released in English.

At the endpoint level, the following methods have been evaluated:

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[34] To illustrate how the method works, the indicator for the ecosystem stability and biodiversity (one of the seven indicators) is described. The practitioner is expected to determine a value for the following parameters:

1. Maturity (MG)
2. Naturalness (NK)
3. Species richness (AR)
4. Diversity of land structures (SV)
6. Level of anthropogenic interference (AB)

To help users, there are default values, and often these default values depend on the country in which the land is used or other relatively easily-identifiable factors. Once values have been chosen, the resulting factor is calculated with the formula MG + NK + (AR+SV)/2 + AB. The result is an Ecosystem stability and biodiversity factor with a value between 1.5 and 22.

- **EPS2000**

This method considers the use of land and its effects on the production of wood. For land use, only regional effects are considered. The characterisation factors for land use are expressed in Normalized EXtinction of species (NEX), while the factors for wood productivity are expressed in kg of dry wood. Both units are added together using Willingness to Pay as the basis for conversion.

- **Eco-indicator 99**

This method considers land transformation and occupation in Central Europe. Both local and regional effects are taken into account. Unlike other methods discussed here, possible double counting with other impact categories is avoided by adapting other impact categories. The reason for doing this is that these land-use models are based on "observed" effects and not on modelled effects, as is the case for eutrophication and ecotoxicity. It is therefore difficult to link the disappearance of species to either direct land-use impacts, or to the impacts from the use of herbicides / manure. For example, in the eco-indicator 99, direct effects from manure on land are considered to be taken into account by land use and excluded from the impact category eutrophication.

The characterisation factors are expressed in potentially disappeared fraction of species: PDF*occupation time for occupation, and PDF*restoration time for transformation.

- **ReCiPe**

This method considers land transformation and occupation in Northwest Europe. Both local and regional effects are taken into account. Three levels of land-use intensity are considered. The characterisation factors are expressed in potentially disappeared fraction of species (PDF) for occupation, and PDF*restoration time for transformation. The underlying mathematical calculations are based on the work of Köllner (2001), although some different assumptions are applied. The model is not reviewed and does not include uncertainty data.

- **LIME**

This method considers the effects of land use in Japan, based on biodiversity changes and effects on primary production. Primary production effects are calculated for Japan according to the adopted land-use classification system and applying the Chikugo Model (Uchijima and Seino 1985). The biodiversity loss is based on extinction probability of vascular plants on the red-species list of Japan. The model considers the life expectancy of the target species by calculating the amount of species throughout Japan.

- **Swiss Ecoscarcity**

This method is based on the work of Köllner (2001) to analyse the effects of land use. It considers land occupation, based on plant species loss in the Swiss plateau. Both local and regional effects are taken into account. The original characterisation factors are expressed in ecosystem damage potentials (EDP), which are based on a nonlinear effect-damage function. The publication of Köllner in 2008 is based on his

PhD thesis produced in 2001 and on the underlying mathematical framework. In both publications several types of characterisation factors are produced. However, the factors used by Swiss Ecoscarcity are the total damages (local + regional), while the publication in 2008 only presents the local damage factors. As the work of 2001 is used today by the Swiss Ecoscarcity method, this is used here.

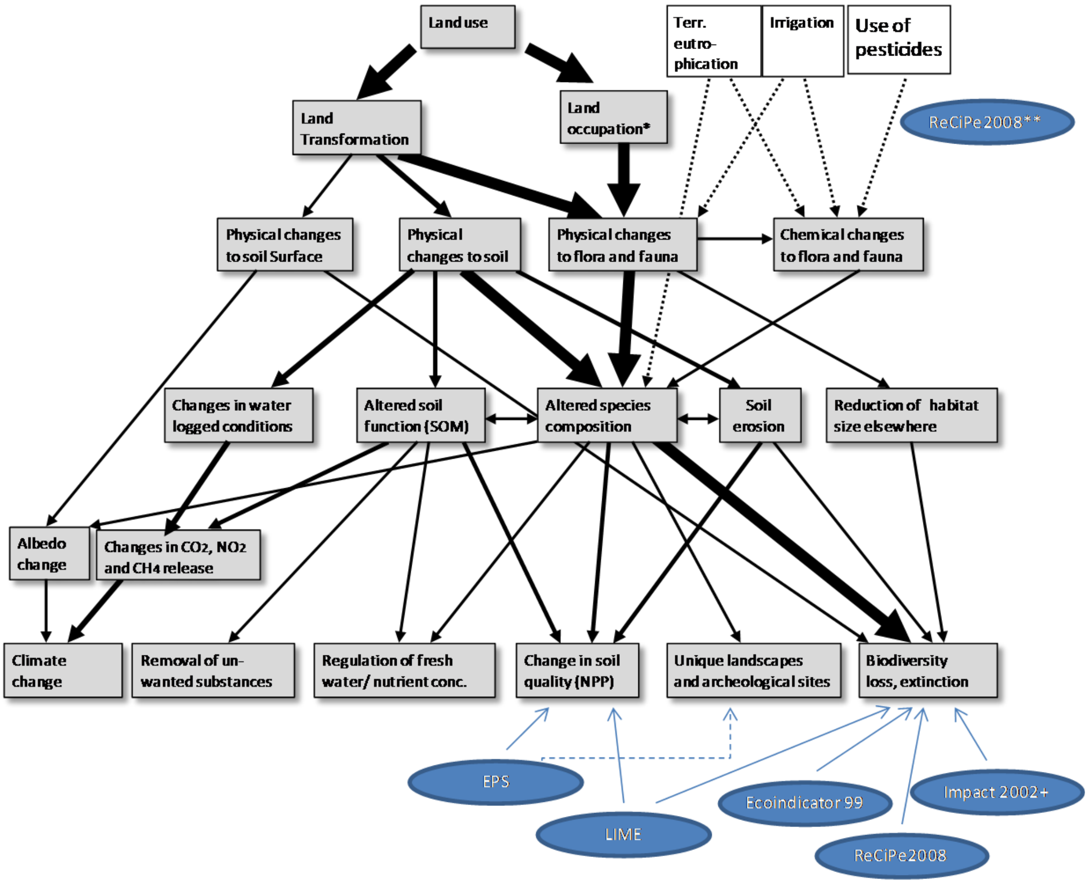


**Figure 11 Flow diagram of the cause-effect chain of land use (adapted from Weidema and Lindeijer (2001))**35.

## 3.10.2 Method evaluation

The methods have been rated against the criteria developed in the LCIA - Framework and Requirements document (EC-JRC, 2010b). Table 24 summarizes the results of the evaluation of the three most prominent midpoint models for land-use impact assessment in LCIA while Table 25 summarizes the evaluation of the five analysed endpoint models. Discussions of specific issues in the evaluation of the models against the criteria[36] are presented in the background documentation[37] (Land use.xls), where a table with the detailed evaluation, including the whole set of sub-criteria, is given.

[35] In the figure: NPP=Net Primary Production; SOM= Soil Organic Matter; * Land occupation does not entail land transformation but is responsible for maintaining an altered state; ** Amount of area transformed or occupied.

[36] A: full compliance; B: compliance in all essential aspects; C: compliance in some aspects; D: little compliance; E: no compliance

[37] http://lct.jrc.ec.europa.eu/

**Table 24 Summary of the evaluation results of three midpoint models that assess land use in an LCA context.**

| | ReCiPe Midpoint | | Baitz (2002), further developed by Bos and Wittstock (2008) | | Milà i Canals *et al.* (2007b) | |
|---|---|---|---|---|---|---|
| **Completeness of scope** | E | No impact mechanism included. | B | Seven different indicators describing soil quality. Most data must be collected by the practitioner. When no site-specific data are available, country-average data are used. | C | Limited impact indicator, based on soil organic matter (SOM). Case-specific characterisation factors (CF) should be developed by the user. Site-specific data are needed. CFs available for elementary flows based on the land-use classification system CORINE+. |
| **Environmental relevance** | E | Characterisation model does not distinguish different species composition between land use types. | C | Characterisation model includes seven different land use effects. Only local effects are considered. | C | The charactersation model includes one indicator. Only local effects are considered.. |
| **Scientific robustness & Certainty** | 0 | Not further evaluated due to lack of environmental characterisation model. | B | The main scientific value is in the comprehensive selection of indicators, and the pragmatic guidance to users for calculating characterisation factors. | A | Characterisation model is reviewed and is recent (2007). |
| **Documentation,Transparency & Reproducibility** | 0 | Not further evaluated. | D | A general bakground database is available. Documentation is available in both German and English, although the latter is not publicly available yet. | A | The model documentation and characterisation factors are published and available free of charge. |
| **Applicability** | 0 | Not further evaluated. | E | Characterisation factors should be determined by the user. The method provides guidance. Already implemented and tested in some databases. | E | Default factors are available for background processes. Case-specific characterisation factors should be produced by the practitioner. Considerable information is needed. |
| **Overall evaluation of science-based criteria** | E | No compliance with science-based criteria for the evaluation of land use impacts. | D | Seven quality indicators describing different soil-quality aspects; there is no way to aggregate these at midpoint level. Characterisation factors are not available; normalisation is not available. | C | Only one indicator describing soil quality. Case-specific characterisation factors should be produced by the practitioner. Model is reviewed and good for agro- and forestry-systems. |
| **Overall evaluation of stakeholders' acceptance** | E | No compliance with science-based criteria for the evaluation of land use impacts. | D | Complex method that produces different indicators. Not endorsed by an authoritative body. | C | Principles of the model are relatively easy to understand, but not endorsed by an authoritative body. Exclusion of biodiversity is a limitation for several relevant stakeholders. |

**Table 25 Summary of the evaluation results of five endpoint models that assess land use in an LCA context.**

| | ReCiPe | | Eco-Indicator 99 | | EPS2000 | | LIME | | Swiss Ecoscarcitiy | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Completeness of scope** | C | Valid for Northwest Europe. Indicator based on biodiversity. Possible double-counting not considered. | C | Valid for mid-Europe. Indicator based on biodiversity. Double-counting with pesticides and fertilisers considered. | D | Indicator based on biodiversity (red list species) and wood productivity. Biodiversity only based on Swedish data. Possible double-counting not considered. | D | Valid for Japan. Indicator based on biodiversity and NPP. | C | Valid for mid-Europe. Indicator based on biodiversity and adopts the CORINE classification. |
| **Environmental relevance: Overall evaluation** | C | Characterisation model reflects loss of species based on species-area relationship. Considers land use intensiveness. Exclusion of effects on primary production. | D | Characterisation model reflects loss of species based on species-area relationship. Exclusion of effects on primary production. | D | No characterisation model used. Inclusion of biodiversity and primary production effects based on empirical data. | C | Characterisation models include effects on primary production and biodiversity loss. | D | Characterisation model reflects biodiversity loss. Transformation not available in Ecoscarcity implementation. |
| **Scientific robustness & Certainty: Overall evaluation:** | C | Only input data reviewed. No uncertainty figures available. Most recent data used. | C | Only input data reviewed. Uncertainty figures available. Relatively old data employed. | C | Only input data reviewed. Uncertainty figures available. Relatively old data employed. | E | Indicators cannot be confirmed due to lack of documentation. No model uncertainties considered. | B | Characterisation model is reviewed. Uncertainty figures available. |
| **Documentation,Transparency & Reproducibility: Overall evaluation** | A | The model documentation and results are published and available free of charge. | A | The model documentation and results are published and available free of charge | A | The model documentation and results are published and available free of charge. | E | English documentation does not exist. | A | The model documentation and results are published and available free of charge. |
| **Applicability: Overall evaluation** | B | Characterisation factors are available, can be easily applied and updated | B | Characterisation factors are available and can be easily applied and updated. | B | Characterisation factors are available and can be easily applied and updated. | D | Characterisation factors are not available in English . | B | Characterisation factors are available and can be easily applied and updated. |
| **Overall evaluation of science based criteria** | C | Based on most recent data and knowledge, considers land-use intensiveness, but does not take into account double-counting effects | D | Based on old data, does not consider land-use intensity, but takes into account effects of double-counting and uncertainty data. | D | No characterisation model used, considers NPP and biodiversity effects. Based on old data, uncertainty data included. | D | The characterisation model produced only applies to Japan. Lacks English documentation. | C | Based on recent data and knowledge, considers several land-use types (only for occupation). It does not take into account double-counting effects. The model is reviewed. |
| **Overall evaluation of stakeholders acceptance** | C | The principles of the model are relatively easy to understand, but the model is not endorsed by an authoritative body. | C | The principles of the model are relatively easy to understand, but the model is not endorsed by an authoritative body. | C | The principles of the model are relatively easy to understand, but the model is not endorsed by an authoritative body. | C | The principles of the model are relatively easy to understand, but the model is not endorsed by an authoritative body. | C | The principles of the model are relatively easy to understand, but the model is not endorsed by an authoritative body. |

### 3.10.3 Discussion on method evaluation

In general, land-use methods do not score highly against most criteria, as developments are still ongoing. The ReCiPe Midpoint method is only a simple addition of the land area used (in square metres), without any characterisation (and, hence, differentiation) of the different land-use types and associated environmental impact. Mila I Canals et al. (2007b) go one step further and include a characterisation model based on changes in soil organic matter (SOM) . Baitz (2002) midpoint method requires rather extensive set of LCI parameters, despite the availability of default values, and excludes a characterisation model.

All endpoint models use "observed" damages to biodiversity, depending on the way the land is managed or used, while LIME and EPS2000 also use "observed" productivity indicators. The use of "observed" data is an important difference from other impact categories where a clear cause-effect mechanism is used. In land-use models, researchers try to reason back from the observed damages. This means the quality differentiation is strongly correlated with the quality, the interpretation and the scope of the "observed" data.

### 3.10.4 Recommended default method at the midpoint level

At the midpoint level, two interesting approaches have been identified. The method of Baitz (2002), which is further developed (Bos and Wittstock, 2008), has a low score on applicability, as only parameters that can be used as inventory items are provided and no characterisation factors given - the user has to determine these. The method produces five to seven indicators describing soil quality as a whole. However, weighting is necessary in order to aggregate these at the endpoint level, which is difficult, as there is no normalisation data available and all units differ. The method by Milà i Canals et al. (2007b) produce only one indicator describing soil quality as a whole. However, it does not cover biodiversity impacts. In this method, the user is expected to determine the characterisation factors of relevance for the foreground system. Milà i Canals et al. (2007c) give characterisation factors for some land use flows in the background system.

The midpoint method implemented in ReCiPe (De Schryver and Goedkoop, 2009b) simply adds up all land occupation and transformation. It is simple and robust, but misses environmental relevance.

Based on the above information, the method by Milà i Canals (2007b) is chosen as the most appropriate among the existing approaches, even though its scope is currently limited.

### 3.10.5 Recommended default method at the endpoint level

At the endpoint level, all methods evaluated are too immature to be recommended. However, the ReCiPe method may be used as an interim solutionThe ReCiPe method considers land occupation and transformation, but only for 12 different land-use types, specifically chosen to be the most stable according to the model used and most relevant for LCA. The model distinguishes three types of arable land-use intensity. It is based on the most recent British data and inventory data by Köllner (2001) as additional information.

The Swiss Ecoscarcity model, also based on the work of Köllner (2001), is not recommended as it does not consider land-transformation impacts. Nevertheless, the more recent work of Köllner (2008) contains elements and data which can be used for further research. All land-use methods available at the moment work with data that represent only a limited region of Europe with specific vegetation types. As a result, these cannot be easily transferred to other ecosystems and continents.

### 3.10.6 Consistency between midpoint and endpoint methods

As the recommended method at the midpoint level and the interim method at the endpoint level operate with different environmental impact pathways, there is poor consistency between them. This is identified as a research need for this impact category (see Annex 2).

### 3.10.7 Classification of the recommended default methods

At midpoint, the method by Milà i Canals et al. 2007 is classified as recommended, but to be applied with caution (Level III).

At endpoint level, no method is recommended to be used. However, if an endpoint method is required, the ReCiPe method can be used as an interim, as it is not mature enough for recommendation.

### 3.10.8 Calculation principles

The recommended midpoint method has a number of default characterisation factors for several land-use elementary flows that are based on the land classification system CORINE +. Additional characterisation factors may be calculated provided data on SOC exists for further land use types in other regionsThe interim endpoint method provides characterisation factors for a range of land-use types and conversions. The user can choose different time horizons for land transformations. A separate section in the report is devoted to the linkage between the LCI parameters and the characterisation factors.

## 3.11 Resource depletion

### 3.11.1 Pre-selection of methods for further evaluation

Several authors address the effects of resource use and propose ways to integrate resource depletion into the LCA framework, e.g. Müller-Wenk (1998b), Meadows et al. (2004), Steen (2006), and Stewart and Weidema (2005).

The pre-selection of characterisation models for the resource-depletion impact category has been explained in another ILCD document ("Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment") and is summarized in Table 26. Not all models initially proposed in that document cover exactly the same impacts arising from the use of resources. As a result, it is difficult to analyse all different models on resource depletion as one single group.

Following the impact pathway, resource depletion impacts are suggested to be divided into four categories reflecting the lack of consensus on what the issue is for this impact category (see also discussion on the AoP Natural Resources in another ILCD document: "Framework and requirements",EC-JRC, 2010b).

Category 1 methods are at the first step of the impact pathway. They use an inherent property of the material as a basis for the characterisation. The environmental relevance is low in terms of expressing resource depletion, but the characterisation factors are relatively robust and certain. As described in the AoP Natural Resources, those methods that do not include the concept of resource scarcity are not considered. Therefore, these methods were considered incompatible with the AoP Natural Resources (irrespective of the quality of the method).

Category 2 methods address the scarcity of the resource. They have a higher environmental relevance, and potentially also a higher uncertainty.

Category 3 methods focus on water and are treated as a separate category due to the regional dependence of this resource issue, which the characterisation model needs to consider.

Category 4 describes the endpoint methods. These aim to cover the entire environmental mechanism.

The different models are grouped in the analysis on the basis of the resources they take into account and on the level in which they are located in the cause-effect chain of resource depletion.

Figure 12 gives an overview of the classification of the different methods analysed in this section, according to the impacts they cover and their position in the cause-effect chain. A recommendation will be considered for each of the four categories analysed.

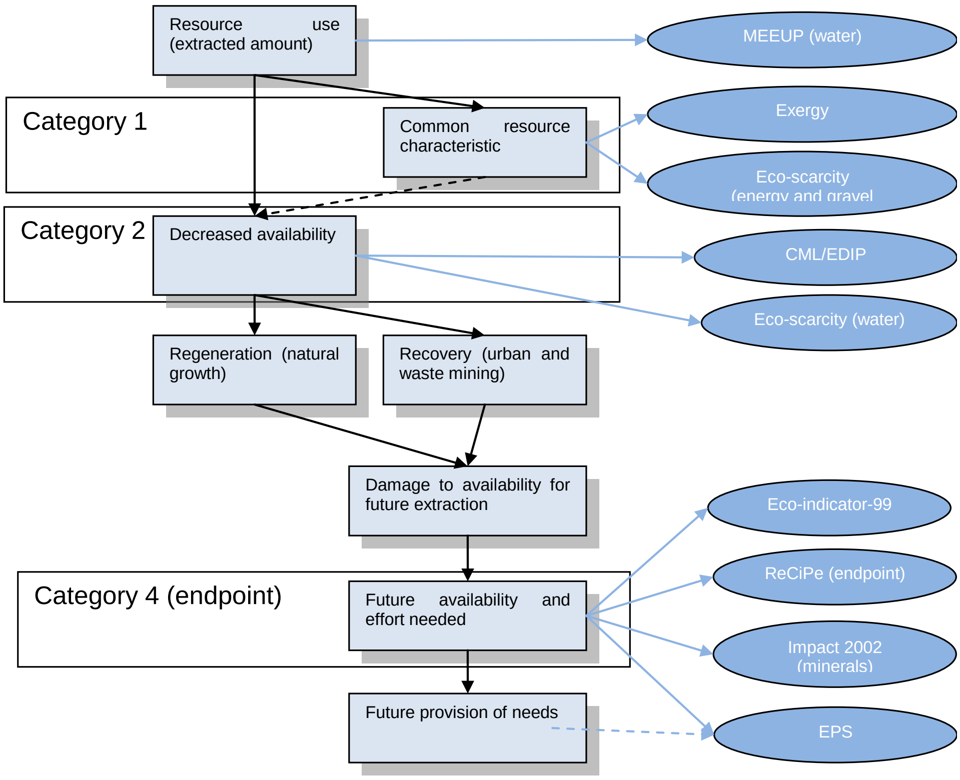


**Figure 12 Overview of methods classification for resource depletion**

**Table 26 Selected methods and underlying models for resource depletion. (see description of each method below)**

| Midpoint method | Underlying model | Reference |
|---|---|---|
| Swiss Ecoscarcity (energy and gravel) | | Frischknecht *et al.* (2008) |
| Exergy | CEENE: Cumulative exergy extraction from the natural environment | Dewulf *et al.* (2007) |
| CML2002 | Guinée and Heijungs, 1995 | Guinée *et al.* (2002) |
| EDIP1997 (2004 update) | EDIP 1997 (Nedermark) | Hauschild (1998, updated in 2004) |
| MEEUP (water) | | Kemna *et al*. (2005) |
| Swiss Ecoscarcity (water) | | Frischknecht *et al.* (2006b) |
| **Endpoint method** | | |
| Eco-indicator 99 (EI99) | Müller-Wenk (1998b) | Müller-Wenk (1998b) and Goedkoop (1999) |
| EPS2000 | | Steen (1999) |
| IMPACT 2002+ | Fossil fuels: IMPACT2002+; Minerals as in EI99 | Jolliet (2003) |
| ReCiPe | | Goedkoop and De Schryver (2008), De Schryver and Goedkoop (2009c) |

## 3.11.2 Pre-selection of midpoint methods

The following models were pre-selected.

- **Exergy**

This method is based on Dewulf et al. (2007). Exergy[38] values have been determined for a list of resources covering fossil fuels, minerals, nuclear energy, land resources, renewable resources (e.g. wind power and hydropower), atmospheric resources and water resources. The method addresses several shortcomings of earlier exergy methods, like double counting in bio-based fuels and confusing exergy loss in ores with exergy loss in the minerals that actually contain the metals being exploited.

- **Swiss Ecoscarcity 2007 (energy)**

The Ecoscarcity method covers a number of resource depletion categories. We selected the “energy” resource impact categories, to remain within the scope of this assessment. Fossil depletion is characterised by using the net calorific value of the fuels as the basis of the characterisation. This is a common practice in many other methods (e.g. IMPACT2002+ at midpoint, and ReCiPe at midpoint). The renewable energy is characterised by the amount produced. For example, for solar input, it is not the use of solar energy that falls on the PV panels, but the actual electric power that can be effectively used. Fossil and renewable energy can be combined using the

[38] Exergy of a resource expresses the maximum amount of useful work the resource can provide. Energy is never destroyed (first law of thermodynamics), but the energy contained in, for example, lukewarm water can provide much less work than the same amount of energy in overheated steam.

distance-to-target approach, where the difference between the actual use and the desired target use, set by the Swiss government form the basis of the weights adopted. For non-renewable resources, the energy content (net calorific value, in MJ) is multiplied by a factor of 3.3, while the renewable energy resources are multiplied with a factor 1.1. As a consequence, this impact category concerns not only one but two midpoints. For non-renewable resources, MJ (higher heating value) per kg is used as a characterisation factor. For renewable resources, a correction factor is sometimes used for the ratio between primary energy input and produced energy. Wood is only considered to be renewable if there is an appropriate forest-management regime.

- **CML 2002**

This method includes non-renewable resources (fossil fuels and minerals). In Guinée et al. (2002) only the ultimate stock reserves are included, which refers to the quantity of resources that is ultimately available, estimated by multiplying the average natural concentration of the resources in the earth's crust by the mass of the crust (Guinée, 1995). In Oers et al. (2002), additional characterisation factors have been listed on the basis of USGS economic reserve and reserve base figures in addition to the ultimate reserve. The characterisation factors are named 'abiotic depletion potentials' (ADP) and expressed in kg of antimony equivalent, which is the adopted reference element. The abiotic depletion potential is calculated for elements and, in the case of economic reserves and reserve base, several mineral compounds.

- **EDIP 1997**

This method was updated in 2004 and includes non-renewable resources (fossil fuels and minerals). The amount of the resource extracted is divided by the 2004 global production of the resource and weighted according to the quantity of the resources in economically-exploitable reserves. Effectively, this means that the global annual production drops out, so that the characterisation model is based on the economic reserves only. The characterisation factors are expressed in person-reserve, meaning the quantity of the resource available to an average world citizen.

- **MEEUP**

The part of this method that concerns only water as a resource has been selected. It includes the use of both process and cooling water. The characterisation factor expresses the amount of water used (litres). MEEUP also addresses other resource categories, but these are directly taken from other methods, e.g. CML 2002.

- **Swiss Ecoscarcity (water)**

This method concerns only water. Its characterisation factors distinguish six levels of water scarcity in a given region. As such, it is the first method that differentiates the regional severity of water availability.

### 3.11.3 Pre-selection of endpoint methods

The following endpoint methods were pre-selected:

- **Eco-indicator 99**

This method includes non-renewable resources (fossil fuels and minerals). The characterisation factor is expressed as Surplus Energy. This expresses the additional energy requirements due to mining resources with a decreased grade at some point in the future. This point is arbitrarily chosen as the time mankind has mined 5 times the historical extraction up to 1990. Current technology is assumed. The method calculates the depletion of elements, not ores.

- **EPS2000**

This method includes non-renewable resources (fossil fuels and minerals) and renewable resources (water, fish, meat and wood). The amount of resource depleted is directly normalized and weighted using monetization. Characterisation factors are expressed in Willingness to Pay, indicating the costs of extracting and purifying the element. The characterisation is based on future technologies and abundance of metal ores in the Earth's crust. It is based on depletion of element concentrations, and expressed in amount of element in ore concentrations.

- **IMPACT 2002+**

This method includes non-renewable resources (fossil fuels and minerals). The mineral depletion is modelled as in Eco-Indicator 99. The characterisation factor of fossil fuels is expressed as total primary energy, including feedstock energy for energy carriers (higher heating value). The surplus energy and the actual fossil fuel energy contents are added using a weighting factor of 1; there is no clear justification.

- **ReCiPe**

This method includes non-renewable resources (fossil fuels and minerals). For minerals, the marginal increase of costs due to the extraction of an amount of ore is the basis of the model. Furthermore, mineral depletion is based on depletion of ores, instead of elements. This is an advantage because most minerals come from different ores, and each ore usually produces several minerals. Some minerals are almost exclusively co-products and with the ReCiPe method these can now be modelled in greater detail. For fossil fuels, the marginal increase of oil production costs (due to the need to mine non-conventional oils) is used. Characterisation factors are expressed as Surplus Costs. These are the costs incurred due to the fact that, after the extraction of the "best" (highest grade) resources, future mining becomes more expensive. In this cost calculation, a depreciation rate of 3% is chosen. Current technology is assumed to determine the costs.

### 3.11.4 Method evaluation

Tables 27 and 28 summarize the evaluation[39] of the six most prominent midpoint models for resource depletion in LCIA, and give the summary of the evaluation of the four endpoint models considered. The detailed scores are reported in a separate excel file [40](Resource depletion.xls).

[39] A: full compliance; B: compliance in all essential aspects; C: compliance in some aspects; D: little compliance; E: no compliance

[40] http://lct.jrc.ec.europa.eu/

**Table 27 Summary of the analysis of six midpoint characterisation methods against the adapted criteria for resources.**

| | Exergy | | Swiss Ecoscarcity energy | | CML2002 | | EDIP2003 | | MEEuP | | Swiss Ecoscarcity water | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Category 1** | | **Category 1** | | **Category 2** | | **Category 2** | | **Category 3** | | **Category 3** | |
| **Completeness of scope** | A | The model is very complete. It covers minerals, fossil fuels and flow resources (including, solar, wind, hydropower and water). | C | The model is relatively complete for energy resources, with an interesting but Swiss specific correction factor for renewability. | C | The model is relatively complete for mineral and fossil-fuel depletion. | C | The model is relatively complete for mineral and fossil fuel-depletion. An attempt for water use and wood extraction is made. | E | The model includes adding up water amounts, but does not differentiate according to regional differences in water scarcity. | C | The model is relatively complete for water depletion, in a regionally-specified way. |
| **Environmental relevance** | C | Very complete implementation of the exergy concept. However, this method does not reflect scarcity. | C | The renewability factor is a new concept, but needs elaboration to become useful. | B | Characterisation factors for economic reserves, reserve base , and ultimate reserves are available. Antimony is the reference resource adopted. | C | Based on 1990 extraction rates and economically-exploitable reserves. Does not capture importance of a resource well, since extraction rates are not included. Water impact is not applicable, only one CF for all types of wood. | D | Simplistic environmental model for assessing the impact of water. | B | The model assesses water depletion on a regional basis. Recovery rates are included. |
| **Scientific robustness & Certainty** | B | The paper is reviewed by external experts. Uncertainties are described but not quantified. | E | There is only a very rudimentary scientific model. | B | The paper is reviewed by external experts. Uncertainties are described but not quantified. | C | The paper is reviewed by external experts. High uncertainties arise in the economically-based reserves calculations, but these are not quantified. | E | There is no scientific model. | C | The paper is not reviewed yet, proposed by the UNEP-SETAC Life Cycle Initiative but suggested in SETAC UNEP results. Uncertainties are discussed but not quantified. |
| **Documentation, Transparency & Reproducibility** | A | The model and results are very well documented. | B | The model documentation and results are so far only available in German. | A | Documentation is available online. The website has descriptions and factors. | A | The model documentation and results are easy available. | A | The documentation is easily available. | B | The model documentation and results are so far only available in German. |
| **Applicability** | A | Characterisation factors are available and can be easily applied. | A | Characterisation factors are available and can be easily applied. | A | Characterisation factors are available and can be easily applied. | A | Characterisation factors are available and can be easily applied. | A | Characterisation factors are available and can be easily applied. | B | Characterisation factors are available and can be applied when country is specified. |
| **Science-based criteria** | B | The model is very complete. However, there are different views on whether exergy is a relevant indicator. | C | Mixture of science and Distance-to-Target. | B | Robust method for mineral resources. characterisation factors for available for economic reserve, reserve base, and ultimate reserves. | B | Robust method for non-renewable resource depletion, which is based on economically-exploitable reserves. | D | Too simplistic for consideration as a science based method. | B | Promising approach for water use. |
| **Stakeholders acceptance** | C | It is not clear whether policy-makers are interested in using exergy as a resource indicator. | D | This method is mainly interesting for Swiss policymaking. | B | The principles of the method are relatively easy to understand, but the model is not endorsed by an authoritative body. | B | The principles of the method are relatively easy to understand, but the model is not endorsed by an authoritative body. | E | Simple method, not endorsed by an authoritative body. | B | The principles of the method are relatively easy to understand, but the model is not endorsed by an authoritative body. |

**Table 28 Summary of the analysis of four endpoint characterisation methods against the adapted criteria for resources.**

| | EPS2000 | | ReCiPe | | Eco-Indicator 99 (EI99) | | IMPACT2002+ | |
|---|---|---|---|---|---|---|---|---|
| Category | Category 4 | | Category 4 | | Category 4 | | Category 4 | |
| **Completeness of scope** | A | The model includes minerals, energy resources, wood and fish extraction. | B | The model is relatively complete for minerals and fossil. Additional substance flows can be added. | B | The model is relatively complete for minerals and fossil. More substance flows can always be added. | B | The model is relatively complete for minerals and fossil |
| **Environmental relevance** | B | Models potential situation in distance future, when average rock is used as an ultimate resource. | C | The model focuses on deposit depletion and, from this, mineral depletion. It has a short time-horizon. | D | This model adopts surplus energy for future extraction efforts as an indicator. | D | This model adopts surplus energy for future extraction efforts as an indicator. |
| **Scientific robustness & Certainty** | C | Assuming the very long time perspective is chosen, the method is relatively consistent, but uncertainties are high. | B | Relatively novel approach that develops theory on a basis of data from 500 mines, and takes into account the important co-products from deposits. Uncertainties due to economic-based weighting exist. | C | For a medium-term perspective, the method is reasonably consistent although quite dependent on one reference. | D | Similar to eco-indicator 99, but without considering different scenarios. |
| **Documentation, Transparency & Reproducibility** | A | The model documentation and results are easily available. | A | The model documentation and results are easily available | A | The model documentation and results are easily available. | A | The model documentation and results are easily available. |
| **Applicability** | B | Characterisation factors are available and can be easily applied. | B | Characterisation factors are available and can be easily applied. | B | Characterisation factors are available and can be easily applied. | B | Characterisation factors are available and can be easily applied. |
| **Science based criteria** | C | Method based on very long time scenarios, with many assumptions | B | Relatively complete scientific model described in all details, based on large dataset of mining data | C | Relatively simple model, based on estimated slope factors. Combination with fossil fuels somewhat problematic | C | Relatively simple model, based on estimated slope factors. Combination with fossil fuels somewhat problematic |
| **Stakeholders acceptance** | C | The principles of the method are understandable but not well accepted or endorsed by an authoritative body. | C | The principles of the method are complex. The model is recent and thus not accepted yet. Not endorsed by an authoritative body. | C | The principles of the method are understandable, but not well accepted or endorsed by an authoritative body. | C | Relatively simple method, but not well accepted or endorsed by an authoritative body. |

## 3.11.5 Discussion on method evaluation

As discussed above, there is some unclarity as to what exactly the Impact Category Resource Depletion should reflect (see also the discussion on the Area of Protection in the ILCD: "Framework and requirements document" (EC-JRC, 2010b). This has highlighted the need to distinguish four categories of methods:

1. methods based on a property of a resource, irrespective of the level of depletion. It is proposed that, regardless of the quality of such methods, they should not be considered to express "resource depletion" because these do not express scarcity (which is the intended aspect of resource use that has to be captured) ;
2. methods based on the "use to availability ratio" or "use to availability - current rate of extraction ratio". These are midpoint methods that express the scarcity of a resource;
3. methods for water. These are treated separately, as scarcity of water is very dependent on location; there is no global market for water, and thus no global scarcity as that e.g. for oil; and
4. endpoint methods. These attempt to quantify (some of) the consequences of the depletion of resources for society.

The lack of a clear definition of the AoP Natural Resources results in a similar vagueness in the scope of this impact category. Consequently, different methods present different ranges of scope. For example, some methods take into account biotic resources, especially the so-called "fund" resources (e.g. wood and fish), whereas others consider biotic resources covered by the land-use impact category.

## 3.11.6 Recommended default method for category 1

Exergy, as a midpoint indicator, is considered to be the most mature method in category 1. The exergy method is based on an inherent property of a resource. For bio-based products, the exergy in the solar radiation absorbed is used.

This impact pathway does not describe the depletion processes, but the consumption of exergy. This value does not depend on the scarcity of the resource (i.e. even if the last tonne of the resource is depleted, the exergy value remains the same). The method does not address the question of whether or not exergy losses from solar energy are as important as exergy losses in the stock of minerals in the earth. These different types of exergy consumption are added without further weighting. If this assumption is accepted, and if there is agreement on the fact that exergy losses represent the midpoint of interest, the exergy method is well developed, easy to apply and overcomes several limitations of alternative methods.

The most important question is whether any method in this category has sufficient environmental relevance to be recommended, as the factor does not take into account the future scarcity of a resource, while it somehow considers the aspect of dispersion which is also an indicator of availability. As justified under the description of the AoP Natural Resources (see ILCD Framework and requirements document), the method to be recommended must have an element that reflects the scarcity of the resource. Given that category 1 methods do not fulfil this criterion, no method within this category is recommended.

## 3.11.7 Recommended default method for category 2

The CML method uses the Abiotic Depletion Potential (ADP), given in kg of antimony equivalents, to be multiplied with the amount of a given resource extracted. For ADP, the annual production of the resource (the extraction rate) is divided by the reserves squared, and the result divided by the same ratio for the reference resource, antimony. The value for reserves is squared to take into account the fact that a simple ratio of annual production over reserve may, in the case of higher production rates corresponding to larger reserves and vice versa, fail to reflect the impact that e.g. 1 kg of resource extraction has on overall scarcity. By including the annual production rate, CML also captures the current importance of a given resource.

The CML method is recommended in the ILCD framework since it captures scarcity by including extraction as well as reserves of a given resource. Characterization factors are given for metals, fossil fuels and, in the case of reserve base and economic reserves, mineral compounds (van Oers et al. 2002). In addition, the method covers most of the substances/materials identified as critical by the European Commission's Ad-hoc Working Group on defining critical raw materials (European Commission 2010).

Data on reserves and production are taken from the US Geological Survey (http://minerals.usgs.gov/minerals/pubs/mcs/).

Oers et al. (2002) give characterization factors for economic reserves, reserve base, and ultimate reserves. The characterization factors given for the *reserve base* are recommended, as this reflects a longer time horizon and the possibility of improvement in mining technology, making feasible the exploitation of previously sub-economic deposits. The reserve base includes deposits which meet certain minimal chemical and physical requirements to potentially become economically exploitable within planning horizons (Oers et al. 2002).

## 3.11.8 Recommended default method for category 3 for water

The Swiss Ecoscarcity (water) method is preferred for a midpoint evaluation which considers the impact of water depletion. The method has a very rudimentary environmental model because it relates water use to local scarcity of water. Thi enables differentiation between situations where water extraction causes different levels of impact.

## 3.11.9 Recommended default method for category 4

At the endpoint level, all methods evaluated are too immature to be recommended. However, the ReCiPe method may be used as an interim solution.

This model's indicator is based on the marginal increase of extraction costs, due to the extraction of a certain amount of a resource. This indicator allows a combination of fossil and mineral depletion. The environmental mechanism is built upon a large dataset covering 500 mines, and it primarily determines the effect on deposits. A deposit usually contains many different minerals, and many minerals are almost exclusively mined as co-products of other metals. Consequently, the model does more justice to the real world than methods that only address the depletion of single minerals. The extraction of single metals is calculated using a system of price allocation. This is one of the uncertain factors as metal prices fluctuate significantly.

For fossil resources, the gradual change from conventional (liquid) oil to unconventional oils is taken as the factor that drives up extraction costs. The damage pathway is only developed for oil. Other fossil fuels are added by using the energy content of the fuel as a basis. The model has only recently become available and, thus, it is too early to evaluate its acceptance.

The EPS2000 method incurs in high uncertainties due to its focus on a very long time frame. However, in addition to mineral and fossil depletion, it considers water, wood and fish depletion. These items should be considered in further research and development.

### 3.11.10 Consistency between midpoint and endpoint methods

The recommended midpoint method is not compatible with the interim endpoint method. This is because midpoint indicators reflect an early stage of the cause-effect chain and, in this case, the information becomes too aggregated to be used in a further modelling step.

Eco-indicator99 and IMPACT2002+ do not have a midpoint for minerals, but Impact 2002 does have a (category 1) midpoint for fossil fuels. ReCiPe has the same midpoint for fossil fuels, and a midpoint for minerals that is close (along the environmental mechanism) to the endpoint. EPS2000 has a category 1 indicator for the midpoints.

For water, no endpoint model has been evaluated.

### 3.11.11 Classification of the recommended default methods

For category 1, the exergy method is the best in its category, but it is not seen appropriate for recommendation, as it does not address the scarcity of the resource.

For category 2, the CML 2002 method is classified as recommended method with some improvement needed (Level II), preferably with a sensitivity analysis on ultimate versus economic reserves.

For category 3 (water), the Swiss Ecoscarcity method is classified as a Level III, recommended, but to be applied with caution.

For category 4, the ReCiPe method is classified as an interim, immature for recommendation, but the most appropriate among the existing approaches.

No method is recommended for renewable resources.

### 3.11.12 Calculation principles

The recommended midpoint method has a very complete coverage of the commonly-used metals, but additional indicators may need to be calculated for rare earth metals. Sufficient guidance is given in the methodology documentation. Users have to collect data on annual production.

Adding characterisation factors to the endpoint models for metals and minerals is considerably difficult. This is important because only the most important metals are covered. In ReCiPe, factors for Phosphate, Indium, Lithium and other minor metals are missing. The reason for this is that these metals were not in the original mining dataset used. When a different dataset is used, it may be difficult to get characterisation factors that are comparable with the existing set.

# 3.12 Other impacts

## 3.12.1 State of the field

Besides the core set of impact categories that are always or often included in LCIA, there is a number of impact categories that are only occasionally or never addressed. This is so for various reasons:

- for some impact categories (e.g., noise, accidents), no appropriate inventory data are available in most case studies or LCI-databases
- for some impact categories (e.g., noise, impacts of Genetically Modified Organisms (GMO)) and for some specific material (such as nanomaterial) no characterisation factors are available
- for some impact categories (e.g., erosion, impacts of GMO), there is no consensus on the characterisation model or even on the main principles for characterisation.

For many of these “other impact categories”, two or three of these reasons apply. As such, they cannot yet be recommended as a mandatory impact category for the European Platform on LCA. But on the other hand, some of these impact categories may be extremely important. For instance, it has been suggested that disturbance by noise is responsible for a substantial part of the DALY-score for human health (e.g., Hofstetter & Müller-Wenk, 2005), and that erosion, desiccation and other physical disturbances can play a decisive role in ecosystem degradation (Cotler & Ortega-Larrocea, 2006). Below is given a short description of some of these “other impact categories”, followed by some recommendations for future research.

What exactly counts as one of the “other impact categories” is not immediately clear. In the context of the present project, an *a priori* restriction has been made to noise, accidents, desiccation, erosion, and salination.

## 3.12.2 Framework

### 3.12.2.1 Introduction

The common LCA-framework in terms of inventory-characterisation model-impact assessment appears to be difficult to apply for many of these other impact categories. Whereas emissions (in kg) of the same pollutant from different unit processes can be meaningfully aggregated and subsequently fed into a characterisation model, noise (in dB) from different unit processes cannot simply be added. The same applies to impact from GMO and erosion; here we even don't know the appropriate metric for reporting inventory aspects (elementary flows). For a few impact categories, this may be easier. Accidents, at least conceived in terms of number of casualties, can be calculated for a unit process, aggregated over the life cycle, and converted into some generic impact number, perhaps DALY. Below, we will briefly discuss the most important "other impact categories" as to methods proposed and research prospects.

### 3.12.2.2 Noise

Noise, or noise nuisance, refers to the environmental impacts of sound. In principle, these impacts could cover at least human health and ecosystem health, but the environmental mechanisms are complex, non-linear and highly dependent upon local circumstances. Moreover, noise is similar to odour in that a given level of exposure is experienced differently by different individuals. Hence, whether or not sound waves will lead to 'nuisance' depends partly on the actual situation and partly on the person interviewed. On the other hand, even when noise is not experienced as nuisance, or when it does not lead to hearing loss, it may still impair human health, e.g. by inducing cardiovascular diseases (Babisch, 2006)

Most LCIA methodologies do not have an impact category 'noise'. This runs counter to the observed fact that most people deem noise to be a major environmental problem, but is probably due to the unavailability of an appropriate and practically feasible impact assessment method for noise.

Two lines of approach, which have recently been elaborated, are by Müller-Wenk (2004) and Meijer et al. (2006).

The paper by Müller-Wenk describes a method for a quantitative assessment in LCA of noise impacts on human health originating from road vehicle noise. An adaptation to rail noise is planned. The method starts out from the following data: transport distance in km, quantity transported, category of vehicle, time (day/night) and country of transport. The magnitude of health impairment due to noise is determined separately for each vehicle class (cars, trucks, etc) and is calculated per vehicle-kilometre driven during the day or at night time on the Swiss road network. This health impairment is expressed in cases of sleep disturbance or communication disturbance, and furthermore aggregated in DALY (Disability Adjusted Life Years) units representing the number, duration and severity of the health cases. The method is modelling the full cause-effect chain from the noise emissions of a single vehicle up to the health damage. As in some other modern concepts of environmental damage assessment, the analysis is subdivided into the four modules of fate analysis, exposure analysis, effect analysis and damage analysis. The fate analysis yielding the noise level increment due to an additional road transport over a given distance is conducted for transports with known or with unknown routing, the latter case being more important in LCA practice. The current number of persons subject to specific background levels of noise is determined on the basis of the road traffic noise model, LUK, developed by the Swiss canton of Zürich. The number of additional cases of health impairment due to incremental noise is calculated with data out of the Swiss Noise Study 90 (cf. Müller-Wenk, 2002). An assessment of the severity of sleep disturbance and communication disturbance, in comparison to other types of health impairment, was performed by a panel consisting of physicians experienced in the field of severity weighting of disabilities.

Meijer et al. 2006 build on Müller-Wenk, 2004 and elaborate this for indoor exposure to noise by outdoor road transport. They have developed a methodology to calculate damages to human health of occupants due to indoor exposure to noise emitted by neighbourhood car traffic. The goal of the study was to assess the influence of the location of the dwelling on the health of the occupants, compared to the damage to human health associated with the rest of the life cycle of that dwelling. Fate, exposure and human health effects were addressed in the calculation procedure. Fate factors for noise were based on noise levels generated by traffic. Effect factors for noise were based on linear relationships between noise level changes and health effects, while taking into account threshold values for noise levels for negative impacts. Damage factors were calculated on the basis of disability adjusted life years (DALYs). A default noise reduction due to the dwelling itself is included in the calculations. The indoor exposure models used to calculate health damages are based on the work of Müller-Wenk for noise. In the fate calculations, noise levels are calculated for a scenario rather than on a per-vehicle base because of the non-linear relationship between traffic density and noise level, and because there are threshold values for the noise levels above or under which a change in noise level has no effect on the human health. For the calculation of the effect factors for traffic noise, data from epidemiological researches – as obtained by Müller-Wenk – was used. In these works, a linear dose-response relationship between average noise levels and negative impacts was adopted.

Both approaches focus on road transport. As this is only one part of the life-cycle, application for LCA in general will lead to biased results (e.g., air transport will be much better than road transport). Of course, road transport is a major source of noise disturbance, and the approaches can in principle be extended to include other sources of noise. Another criticism is that the DALY-conversion has been made by a panel that concentrated on noise issues, so that a too strong emphasis on noise is reflected in high DALY-values. On some of these issues, improvements have been made the last few years. For instance, there is an EU directive (2002/49/EC) in which noise maps of exposure are to be made by the member states, progress has been made in understanding the cause-effect mechanisms (see, e.g., Babisch, 2006) and the DALY-weighting has improved (Mathers et al., 2003)

Although the need is stressed for developing a method to incorporate noise (from transportation or otherwise) into LCA in a generally applicable way, and we think that the last few years the state of knowledge has improved, no recommended approach is available for LCA in general at this moment.

### 3.12.2.3 Accidents

The term “accidents” has many meanings. The accidental spill of chemicals does not require a separate impact category, but may be taken into account along with the regular emissions of chemicals, likewise, for nuclear facilities. Here, this impact category is taken to refer to casualties resulting from accidents. The area of protection is human health, no casualties that cause effects on ecosystems (such as car collisions with wildlife) are considered. Most LCIA-methodologies do not include an impact category ‘casualties’. Schmidt et al. (2004) describe a very useful method for including the working environment in LCA, which encompasses casualties. This casualty analysis is based on a database developed by EDIP in which the working environment impacts per kilo of produced goods are listed for a number of economic activities. Hofstetter & Norris (2003) discuss injuries (casualties) related to working environment accidents and these are part of the analysis of "indoor & occupational exposure". Also here, we might take out of their full method for the working environment a method for assessing casualties. However, all approaches mentioned focus on the occupational part, which is only one part of the life-cycle wide casualties. As such, no approach can be recommended at the present stage of development.

#### 3.12.2.4 Desiccation

Desiccation refers to local impacts due to water use, mainly in agricultural areas. Water use as a resource has been discussed in the document on resource depletion. The impacts on landscape, vegetation, soil productivity, etc. have, as far as we know, not been addressed in the context of LCA. However, desiccation is an extremely important issue with impacts on all three areas of protection. Hence, an LCA that provides answers to a question on, say, cotton versus wool, without addressing desiccation is of a very restricted value. Desiccation obviously has much to do with land use, and it could be assessed under that name. However, none of the methods for land use in LCIA take into account the water use, but focus on issues like vegetation before and after.

#### 3.12.2.5 Erosion

For erosion three approaches have been found in literature: Cowell & Clift (2000), Muys & Garcia Quijjano (2002) and Mattsson et al. (2000). According to Cowell & Clift (2000) the loss of soil mass is an indicator for depletion of resources (soil as a resource). As a characterisation model the soil static reserve life is proposed (SSRL = R/E). The soil static reserve life is a function of global reserves of agricultural soil (R, i.e. total topsoil in the world in tonnes) and current annual global net loss of topsoil mass by erosion (E in tonnes/year). The necessary inventory data to calculate the impact score is the loss of soil mass (in tonnes), either measured or estimated (e.g. using erosion models like USLE; see http://topsoil.nserl.purdue.edu/usle/; http://www.fao.org//docrep/t1765e/t1765e0e.htm). At this moment no operational factors are available. To derive such factors information is necessary on the reserve of the topsoil, i.e. area and depth of topsoil suitable for agriculture. Furthermore also worldwide erosion data should be available. Finally because soil is not globally available (i.e. not shipped all over the world like ores and fossil fuels) a differentiation of the factors for different regions is recommendable, using regional reserves and regional erosion rates. Moreover, it is not quite clear what the inventory items are to which erosion applies. So, even when the LCIA part is solved, additional work might be needed to connect it to the LCI databases.

The method of Muys & Garcia Quijano (2002) describes the land use impact by 17 quantitative indicators divided over 4 impact sub- categories: soil, water, vegetation structure and biodiversity. The indicator soil erosion is a sub-indicator in the sub-impact category soil. In this method it is proposed to transform the loss of soil mass into a loss of soil depth (in m) using the bulk density of the soil. Finally, the loss of soil depth over a period of 100 years is compared to the total rootable soil depth up to 1m. A complete loss of the soil within a period of less than 100 years leads to the maximum impact score. (Erosion risk factor = E (kg/ha/yr) × 100 yr/ Total Rootable Soil Depth (1m)). The necessary inventory data to calculate the impact score is the loss of soil mass (in tonnes), either measured or estimated (e.g. using erosion models like USLE).

At this moment no operational factors are available. To derive such set information, more or less the same information is necessary as described for the method of Cowell & Clift, (2000). The method of Mattson et al. (2000) describes the land use impact by 9 indicators for 3 impact sub categories soil fertility (7), biodiversity (1) and landscape (1). Most indicators are described qualitative. The indicator soil erosion is a sub-indicator in the impact sub category soil fertility. In this method it is proposed to use the loss of soil mass (kg) as an indicator for erosion impact without using characterisation factors.

None of the methods discussed above is elaborated in an operational set of characterisation factors. As such, no approach can be recommended at the present stage of development.As part of future research, it is recommended to determine the problem of erosion and the associated interventions properly first. Erosion basically is a natural phenomenon that will occur any way. Human activities may, due to their nature and intensity, enhance erosion. In a systems analysis as LCA, soil is considered to be environment by most practitioners as also done in toxicity models. When soil is part of the environment system, soil loss cannot be the intervention, as it doesn't cross the economy-environment boundary.[41] Similar to global warming, the impact category should actually be something as "enhanced erosion or enhanced soil loss". Then, the proper interventions still need to be determined. Man can enhance erosion by removing terraces, cutting hedgerows on steep slopes, by deep ploughing and other agricultural practices. Interventions could thus be soil disturbance by ploughing or cutting hedgerows. What one needs to know is thus extent of natural loss of soil as a reference and the marginally increased loss of soil (kg/ha/yr) due to all kinds of soil disturbance interventions (ploughing, cutting hedgerows etc.). All these different interventions should be linked to characterisation factors indicating the marginally increased soil loss due to that specific intervention, fully comparable to global warming, for example. Perhaps, a generic characterisation factor per agricultural activity type could be developed. To what extent this would be possible in practice, remains to be investigated but some work has already been done that can be used as starting point of development (see Guinée et al., 2006). Like desiccation, erosion could be taken into account as an aspect of land use. This, however, requires a large restructuring of the way land use is now being assessed in most LCIA methods.

## 3.12.2.6 Salination

Salination may refer to an effect with two different causes: the deposition of ions, and the removal of water. Current LCIA methods do not adequately characterize the effects of common ions associated with salinity impacts. Salination (or salinisation) of water resources and of agricultural plots is of strategic concern in countries as South Africa and Australia, and the need for life-cycle assessments to be able to incorporate salinity effects is apparent. There is sufficiently clear cause-effect relationships between the sources (deposition of ions and removal of water) and impacts of salinity, and impacts are claimed to be sufficiently different in nature from existing categories to warrant a separate salinity impact category. For

[41] That is, it contradicts the basic approach of LCA, where interventions by the economic system lead to a deficit or excess in the environment, which on its turn leads to impacts such as resource depletion or toxicity. Considering a physical activity, such as ploughing, clearing and levelling, as the intervention, requires a radical departure from the present elementary flow based LCA.

the second pathway, removing water, a clear overlap with desiccation is present. To what extent these two issues can and should be separated is not yet clear.The references include only specific methods as developed for soil salinisation in Australia (Feitz & Lundie, 2002) and water and soil salinisation in South Africa (Leske & Buckley, 2003, 2004 a, b). Salination may, like desiccation and erosion, be included in a revised land use methodology. This is, however, a research recommendation, not a recommended practice for now.

### 3.12.3Cause-effect chains

For some of these “other impact categories”, a cause-effect chain can be drafted. For noise, for instance, we have a clear idea of a facility (the unit process) which generates a sound (the elementary flow), which propagates into the environment (fate), and leads to impacts on man or ecosystems (effect). However, even here we already meet some problems. One of the approaches discussed includes in the LCA of a house the impacts due to road traffic noise on the street where the house is located. In the life cycle inventory of the house, we would probably account for the sound emissions of mining, construction, and disposal, but it is unclear if the sound emissions of a road transport which is part of a different product life cycle should be included in the impacts of the life cycle of a house.For some other impact categories, the situation is already more confusing at the outset. For erosion, for instance, it is already not exactly clear what the elementary flow is. If that is unclear, we cannot connect it to a unit process, and not connect it to an impact pathway.It appears that more research is needed to bring more structure into the cause-effect chains of the other impact categories prior to proposing characterisation factors.

### 3.12.4Method selection

No models have been selected for further analysis.

### 3.12.5Method evaluation

As no models were analyzed, no evaluation can be made besides the overall remark that it is premature to include the other impact categories in general purpose LCAs.

### 3.12.6Conclusion

The other impact categories (here restricted to noise, accidents, desiccation, erosion, and salination) are definitely important categories, and they deserve attention in future LCA developments. In particular for specific LCAs (e.g., comparing different transport means, comparing different agricultural practices) differences in impacts on noise, erosion, desiccation, etc. may be critical. There is, however, no generally applicable model for these impact categories. Development of the cause-effect framework and models to address the associated midpoint or endpoint categories need to be developed. Moreover, it is important to develop other missing categories as well; examples include the impact of genetic pollution, landscape and aesthetic issues, and impacts of electromagnetic fields and light. Research needs are described in Annex 2.

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# 5 Annex 1 - Consistency across midpoint and endpoint indicators

During the analysis of the different methods for addressing a variety of impact categories by a number of authors, it is inevitable that inconsistencies are introduced, such as:

- The same criterion can be adhered to more strictly for one impact category than for another one. For instance, the criterion "Ability for third parties to freely generate additional, consistent factors and to further develop models" will perhaps be more important for toxicity than for climate change.
- Authors know their own work better, and they also know it when it has not yet been fully published. For instance, some of the methods within ReCiPe or IMPACT2002+ are known to some authors and not to others.
- The cause-effect chains of the different impact categories sometimes show inconsistencies. For instance, models for human toxicity do not take into account that people will change their diet to prevent exposure to contaminants, while endpoint models for ozone depletion are explicitly based on reduction scenarios.

Sometimes, such inconsistencies are justifiable. The need to generate extra characterisation factors for toxicity models is large, while it is small for climate change. But sometimes, it is not. Differences in background knowledge of the different authors have been levelled through the internal and external review process. A central task has therefore been to identify inconsistencies in the description and assessment of methods and impact categories, and where needed to remove such inconsistencies. Some questions that came up during this consistency analysis were the following:

- Do midpoint and endpoint methods have intrinsic differences in their assessment? For instance, do all midpoint methods show less environmental relevance, and more scientific robustness, than endpoint methods? In the analysis we have decided that the really interesting comparison is across impact categories at midpoint and across impact categories at endpoint. Giving all midpoint methods an E (lowest score) on relevance and all endpoint methods an E (lowest score) on robustness would then not be discriminating within the two subsets. Therefore, it was decided that midpoint methods can still give a good score on environmental relevance, and endpoint methods on scientific robustness.
- The newer methods, like EDIP 2003 and ReCiPe, have an advantage over the older ones, like Eco-indicator 99 and EPS2000, in that they build on the experiences and models of the older ones. They stand on the shoulders of giants, so to say. But that has a price: often not all of their elements have been published in the open literature, and the experience with and acceptance of these methods is limited because they are still very new. Since there is a rapid development towards better and more complete methods in LCIA today, we have decided in the interest of the durability of the recommendations to give priority to the newer methods in this issue, provided that we assess the underlying science as being good based on our own reviews.

Fundamental discussions about the types of mechanisms that should ideally be included in a model for a certain impact category have not played a role in the assessment, but have been placed in the chapters on the Areas of Protection.

Apart from the analysis, also the recommendations on characterisation methods have been checked to ensure consistency across impact categories at midpoint and endpoint level. It is analysed whether the impact pathways, which are modelled by the recommended characterisation models, are complementary at midpoint level and at endpoint level or whether they present overlap or insufficient coverage of the relevant environmental mechanisms. Detected inconsistencies are corrected if possible, or the recommendations are modified with the aim of ensuring complementarity between the impact categories to the extent possible.

## 5.1 Handling of cultural perspectives and time perspective

Some of the recommended characterisation methods have been developed in three versions in accordance with different mindsets or perspectives inspired from cultural theory and reflecting the uncertainty of the data/method (Thomson, 1990, and introduced in LCA by Hofstetter, 1998). The theory of cultural perspectives is used to manage the relatively wide range of choices that have to be made in endpoint models. Each choice has an impact on the characterisation factors. The Cultural theory is a social science based and widely used method to group this wide range of choices into three consistent, but hypothetical stakeholder perspectives, the Egalitarian, the Individualist and the Hierarchist perspective. Each perspective can be linked to one of three fundamentally different perceptions of the world. For example there are different views on the time perspective to be used. The question whether future generations are equally important as present generations does not have a wrong or right answer, but it depends on the worldview of the stakeholder who has to decide whether an assessment is acceptable or not. Another choice is the required level of scientific proof in order to accept that there is a problem. Another example is to what extent we can assume that predicted damages can be partially avoided by proper management or by technology development. The Egalitarian perspective assumes that future generations are very important, it is pessimistic about the role of management and technology, and assumes the precautionary principle regarding the inclusions of the effects. On the other end of the scale, the Individualist perspectives combines the short time perspective with an optimistic view on what market forces and innovation can prevent, while it has a low confidence in management solutions: it assumes that only proven effects are relevant. The Hierarchist perspective is consensus driven. It assumes that a long time perspective is relevant, and bases itself on scientific consensus in many choices. The recommended LCIA framework does not operate with different perspectives, and where the recommended method does, the hierarchical perspective is recommended, while the other perspectives are used in a sensitivity assessment. In terms of time perspective, the recommendation is to choose a time perspective which includes the full impact, i.e. in principle an infinite time perspective (corresponding to the hierarchical or egalitarian time perspective for those methods which are developed with different perspectives). In the concrete case of climate change the recommended time horizon is 100 years due to a lower uncertainty. Factors with a 500 years' time perspective are provided but factors for a much shorter time horizon are also provided for sensitivity analysis.

# 6 Annex 2 - Research needs

The research recommendations accompanying the model recommendations are presented for each impact category and differentiated according to their priority, and the estimated amount of work required is estimated.

In addition to the research needs outlined below, there is a general need to identify where spatial and temporal variations from global defaults are statistically justifiable to warrant distinction in practice. Furthermore, where trully global models are not available there is a need to further investigate the importance of this discrepancy and, if necessary, default more global models.

For all impact categories, there is equally a general need for a practical framework and methods to identify and quantify the main sources of parameter (stochastic) and model (systematic) uncertainty. These can then be used to further define where developments are essential. These methods must be compatible with approaches used in the inventory phase of LCA.

## 6.1 Climate change

For the midpoint method, based on IPCC there are no further research recommendations for e.g. the LCIA community, only suggesting to follow the updates provided (on average every 4 years). For endpoint methods the following research issues are identified:

**High priority**

- Improve the link between the emission of $CO_2$ equivalent emissions and the expected temperature increase. A relatively low effort task could be to review climate models, similar to the study of Meinshausen (2005) used in ReCiPe (De Schryver and Goedkoop, 2009a), that allow for establishing this link and for further interpreting the causes if these models have a significant difference in results.
- Improve and update the link between temperature increase and ecosystem damage, which are still being debated in the scientific literature. A relatively low effort task would be a further literature study on models that predict ecosystem damages. A clear point of attention is in a number of assumptions on if species can migrate, and if so how fast, and on which scientific basis we can indeed make a link between temperature increase and habitat alteration (Thomas et al., 2004)
- Extend the environmental mechanisms in the LCIA method, to cover other pathways than via temperature increases, such as humidity increases and rainfall.
- Improve and further develop the link between climate change and change in biomass and food productivity, which is still being debated. Within this field the scientific work performed is limited.
- Improve and extend the range of linkages between temperature increase and expected human health damages (like emerging and re-emerging diseases) such as done in WHO assessments (McMichael, 2003). An important issue is to clearly distinguish different adaptation scenarios, possible policy measures and potential

technological breakthroughs, as these all have significant effect. Also here a further review of existing studies would be a first priority, and will need a relatively low effort.

- Develop a procedure to deal with the different sets of assumptions on adaptation and other responses, similarly to, but better than the perspectives used in ReCiPe, based on cultural theory (Thompson et al., 1990)
- Consider heating related stress not only for human health but also for impact to ecosystem

The main recommendation for the long term research is to develop links to ongoing climate change impact research centres, and request to provide up to date data that reflects the effect of releasing a kilo of $CO_2$ equivalents, instead of assessing entire energy scenarios.

# 6.2 Ozone depletion

**High priority**

- Develop a better understanding of whether it is desirable to base the fate model on the sharply declining emission scenarios.
- Develop a better understanding of the way the damage to ecosystems (vegetation, marine plankton in Arctic and Antarctic regions) can be incorporated. A first step would be to further study (and translate) the LIME method, and to further investigate other publications that link stratospheric ozone layer thickness to damages on ecosystems and crops. (e.g. Ravishankara et al.2009)

# 6.3 Human toxicological effects

The following research recommendations are relevant for the further development of human toxicological effect methods (models and factors):

**High priority**

- Analysis of uncertainty and the provision of practical guidance for straightforward use in LCIA/LCA based e.g. on clusters of similar chemicals
- Development of straightforward methods to fill data gaps based e.g. on similarity of physical/chemical parameters
- Analysis of spatial and temporal distinctions necessary to reduce uncertainty based e.g. on clusters of similar chemicals and emission scenarios
- Development of compatible factors to accommodate indoor air emissions including in the work environment (*large amount of work*)
- Development of compatible factors to better model e.g. metals and their speciation in fate, exposure and effects *(large amount of work)*
- Development of compatible factors for pesticides and other agricultural improving chemicals focusing on exposure associated with crop residues *(medium amount of work)*

**Medium priority**

- Identification of when spatial and possibly temporal differentiation is important.
- Improvement of human exposure models (high amount of work, long-term research)

**Low priority**

- Inclusion of dermal route of exposure. With the possible exception of e.g. cosmetics and some nanoparticles, this is however likely to be of limited importance for the intake fraction according to Hertwich et al.(2001) *(low amount of work)*.
- Improvement of endpoint modelling for non-cancer effects (*medium amount of work, long-term research*)

# 6.4 Particulate matter/Respiratory Inorganic

**High priority**

- Spatial differentiation of fate and exposure needs to be improved to capture emissions in other types of environment (oceans, etc.) (medium workload).
- Differentiate effect factors between PM depending on the source and size distribution (diesel, gasoline, coal, etc.) (high workload)
- Include $NH_4$+ as secondary aerosol coming from $NH_3$ emissions. For agricultural practice, $NH_3$ emissions and health effects coming from NH4+ secondary aerosols can be very relevant. On the short term, the possibility to have an Interim factor for $NH_3$ extrapolated from van Zelm et al. (2008) will be explored.
- Modelling of effect factors needs to consider surface and number instead of solely mass as a proxy for adverse health effects (medium workload).
- Evaluate whether ‘chronic bronchitis (adults)’ is an important endpoint and what is the severity factor associated to ‘chronic bronchitis (adults)’.

**Medium priority**

- Modelling of fate and exposure needs to consider the evolution of Particle Size Distribution (medium workload).
- Modelling of CF for sizes smaller than 2.5 μm (medium workload).
- Investigate the possibility to use the EcoSense model to cover respiratory inorganic impact in LCA in a consistent way with other criteria pollutants (medium workload)

# 6.5 Ionizing radiation

**High priority**

- Ensure a better compatibility of the fate and exposure model developed for the ionising radiation impact category with USEtox for both human and ecotoxicity, for similar population densities and ecosystem characteristics *(low workload)*
- Cover Radon for indoor emission in a compatible way to outdoor exposure (medium workload)

- Extend the number of radionuclides covered for both human health and ecosystems (high workload)

**Medium priority**

- Update of the 1990 DALY to latest WHO 2002 statistics, ensuring a full consistency with the treatment of cancers used for the human toxicity category (with average of 11.5 DALY per case of cancer against 17 DALY/case as reported by Frischknecht et al., 2000). *(low workload)*
- Include the marine and terrestrial environment for the ecosystem damage assessment (high workload)
- Consider the radioactive waste disposal in underground facilities (disregarded in Frishknecht et al, 2000 due to lack of data availability) (high workload)

**Low priority**

- Further develop the endpoint modelling for ecosystems, in conjunction with ecosystem impacts, including long-term genomic research to study genomic instabilities and indirect effect of radiation (high workload)

**Methods/ research needs highlighted during the public consultation**

- A different approach to handling the calculation of characterisation factors was suggested and needs to be further assessed. Using latest UNSCEAR reports for the assessment of human exposure towards ionising radiation (as specified by Preiss and Klotz 2008).
- Using latest (ICRP, 2007) recommendations regarding risk factors for impact assessment.
- Note that no exposure factor (i.e., collective dose) is provided for C-14 releases into freshwater, while those into soil and surface ocean are stated to be about the same as those into air (UNSCEAR, 2000 paragraphs 233-236). This could be due to a lack of the global C model that does not distinguish a freshwater compartment and can therefore not assess corresponding releases. But there is no reason to believe that releases into freshwater are irrelevant if releases into soil and surface oceans should lead to the same exposure.
- The severity factors as given in Frischknecht et al. (2000) could be used in combination with the exposure factor and the effect factor from Preiss & Klotz (2008), even though the DALYs are dated.

# 6.6 Photochemical ozone formation

**High priority**

- As a research recommendation, ReCiPe might be expanded at endpoint to include vegetation impacts by combining the LOTOS-EUROS model with information of vegetation distribution and sensitivities in Europe (*high amount of work).*

- Investigate the current updates of the EcoSense model and their ability to provide both geographically differentiated and site-generic characterisation factors addressing both human health impacts and crop impacts from photochemical ozone formation
- A damage model for vegetation might also be based on EDIP2003 midpoint results, which would require linkage of the present time and area integrated exposure above a threshold for vegetation effects to damage on the AOP Natural environment *(low amount of work)*
- The decision to only include acute mortality effects of ozone in modelling should be further consolidated. In essence it means that the human health issue of photochemical ozone is a local smog issue in heavily populated/industrialised areas since it is unlikely that regional ozone concentrations should reach a level where acute effects may be observed. This distinguishes the human health impacts from the vegetation impacts which are indeed of a regional character *(low amount of work)*
- The assumption of linear dose-response curve for human health effects without any threshold as applied in the LOTOS-EUROS should be further consolidated. Moreover, the application of SOMO35 , i.e. including threshold as implemented in EcoSense, should also be further consolidated (*low amount of work*)
- Midpoint characterisation factors for CO and $CH_4$ should be calculated with the LOTOS-EUROS and EcoSense model *(low amount of work)*
- The importance of human health damages from photochemical ozone formation compared to damage from particulate matter/respiratory inorganics should be investigated. Preliminary results based on calculations of normalisation references for the two impact categories suggest several orders of magnitude lower damage from photochemical ozone, which would argue that photochemical ozone formation is primarily of concern due to its damage to vegetation *(low amount of work)*

**Medium priority**

- The recommended models should be adapted to other continents by modifying their fate, exposure and effect models or replacing them with similar models already developed for these continents. *(high amount of work)*

# 6.7 Acidification

**High priority:**

- Provide/derive CF factors explicitly for $SO_3$ and NO and $NO_2$ (*low to medium amount of work)*
- Determine a set of consistent global default or continental/regional CFs at midpoint level using the Seppälä et al. (2006) method by (*medium amount of work*):
    - Calculating a set of consistent regional/continental emission-deposition fate factors, which could ideally be calculated from a global atmospheric fate and transport model
    - Mapping (changes) in sensitive area at the global scale, expert judgment could also be applied

  - Calculating a set of characterization factors for each region/continent, by connecting global emission-deposition matrices with the global sensitive area information

- Quantify uncertainties: model uncertainties and variability (*low amount of work*):
  - between individual emission countries
  - between different regions/continents in respect to a global generic factor
  - as a function of emission time and changes in current emission level.

**Medium priority**

- Determine a clear link between the midpoint Accumulated Exceedance calculations and the endpoint assessment, by building a scientific consensus on the dose-response model proposed by van Zelm and colleagues (2007) (*high amount of work*) and particularly:
  - Seeking for independent confirmation whether base saturation is a suitable starting point instead currently used rapidly changing variables (pH, Al concentrations, etc.)
  - Modelling the changes of key soil parameters (base saturation or pH) on a global scale for different soil types
  - Expanding the effect model approach, based on the dose-response curve of European forest, to various ecosystem types
  - Calculating a set of regional/continental characterization factors by connecting atmospheric soil and fate calculations with a regionalized effect model
- Investigate the need to address the waterborne emissions of acidifying substances within the proposed framework and calculate CFs (*high amount of work*)
- Ocean acidification via $CO_2$ immission from atmospheric point of view is getting prominent in the climate change community + what comes in via the rivers (*high amount of work*)
- Investigate the aspect of neglecting deposition in areas below the critical load in an LCA perspective (h*igh amount of work*)
- Investigate effect of acidification damage on climate change for endpoint characterisation (*high amount of work*)
- Develop characterisation factors for relevant strong and weak acids, particularly HCl and acetic and formic acid *(low to medium amount of work)*

# 6.8 Eutrophication

**High priority**

- Development of a model for LCIA purposes that is capable of evaluating terrestrial, freshwater and marine fate and effects in an integrated and consistent way and applicable to a regional as well as a global scale, building on elements in the analysed approaches *(high amount of work)*

- Investigate damage approach proposed by Payet, 2006 for freshwater systems and compare to approach applied in ReCiPe to develop a damage model for freshwater systems based on a broader European data base *(high amount of work)*
- Compare fate models from TRACI, LIME and ReCiPe midpoint models to determine differences and derive simplifications and generalisations which may be applied in a global midpoint characterisation model for aquatic eutrophication *(medium amount of work)*
- Develop damage model for marine eutrophication linking increase in nutrient concentrations at midpoint level to damage to biodiversity in marine ecosystems at regional and global levels (*high amount of work)*

**Medium priority**

- Quantify uncertainties: model uncertainties and variability (*low amount of work*)
    - between individual emission countries
    - between different regions/continents in respect to a global generic factor
    - as a function of emission time and changes in current emission level

## 6.9 Ecotoxicological effects

**High priority**

- Provide framework and methods for assessing uncertainty (see also human toxicological effects).
- Further develop approach for addressing data gaps (see also human toxicological effects).
- Guidance for when temporal and spatial distinctions are necessary (see also human toxicological effects)
- Inclusion of bioavailability, where not implicitly included in toxicity data, considering also changes in future availability due to long-term geochemical and geological processes in the soil (see e.g. Ligthart et al 2010)
- Consider biomagnification and its relative importance
- Take into account indirect ecological effects of chemicals via food web changes
- Inclusion of the internal critical body burden concept in LCIA for ecotoxicity to support better inter-substance interpolation
- Further evaluation of model calculations with field data on changes in species diversity and development of endpoint methods

**Medium priority**

- Further develop terrestrial fate and ecotoxicity effect models and marine ecotoxicity effect models that can have an application in LCIA (high effort and long term research)

- Inclusion of fate and effects of metabolites, assuming not considered in the toxicological effects data
- Factors for metal, in particular Zinc (Ligthart et al, 2010)

# 6.10 Land use

For land use *midpoint* characterisation the following research issues are identified:

**High priority**

- Immature methods (Milà i Canals, Baitz) should be extensively tested *(high amount of work)*
- Characterisation factors should be developed, based on existing models *(high amount of work)*

An important input to this research can come from a newly established working group on land use[42]

For land use *endpoint* characterisation the following research issues are identified:

**High priority**

- Include regionalized characterisation factors (worldwide), based on more input data and other reference land use types. Special attention should be paid to developing countries *(high amount of work)*
- Continue the work on soil quality impacts, transformed to the correct unit *(high amount of work)*
- Include effects on climate change, transformed to the correct unit. (*high amount of work)*
- Immature methods (Recipe) should be extensively tested *(low amount of work)*

**Medium priority**

- Implement uncertainty data and distribution *(low amount of work)*
- Include impacts on primary production, transformed to the correct unit *(high amount of work)*
- Include more relevant land use types *(high amount of work)*
- Implement elements and available data from the work of Köllner 2008 should be considered and used in further developments of land use models *(low amount of work)*

**Low priority**

- Implement clear description on uncertainty in the data *(low amount of work)*
- Let the work be reviewed *(low amount of work)*

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[42] http://fr1.estis.net/builder/includes/page.asp?site=lcinit&page_id=337831BE-0C0A-4DC9-AEE5-9DECD1F082D8

## 6.11 Resource depletion

**High priority**

- More clarity on the AoP resources, on for example which impacts it covers needs to be developed *(high amount of work)*
- Discussions with stakeholders and experts are needed on what is actually important and what does society want to protect (including the short-term vs. long-term resource depletion) *(high amount of work)*
- Development of a model to assess biotic resource and species depletion at the midpoint and endpoint level *(high amount of work)*
- Investigate and model the effects of resource depletion (water depletion, biotic resources) in developing countries. The model on water depletion, considered in Swiss Ecoscarcity 2007, is a good starting point *(high amount of work)*

**Medium priority**

- Have a critical review of the ReCiPe approach and develop a programme to further improve the main weaknesses. This would involve contributions from geologists, and economists *(high amount of work)*
- Assessment of water consumption/ freshwatere usage and the related impacts *(high amount of work)*
- Investigate if the use to stock ratio can be developed with other references than ultimate reserves. This reference may not be the most environmental relevant. In this sense we call for a combination of strength of EDIP and CML at midpoint level *(high amount of work)*
- For the exergy method, investigation is needed on the acceptability of major conceptual choices used. For example, the assumption that all exergy losses are equally relevant *(low amount of work)*

**Methods/ research needs highlighted during the public consultation**

- For water depletion, Mila I Canals et al.2009 and Pfister et al.2009 were suggested to be considered.
- It should also be investigated how the environmental damage cost for water abstraction has been derived. This could be an alternate way for endpoint for freshwater usage.

## 6.12 Other impacts

The other impact categories (noise, accidents, desiccation, erosion, and salination) are definitely important categories, and they deserve attention in future LCA developments. In particular for specific LCA studies (e.g., comparing different transport means, comparing different agricultural practices) differences in impacts on noise, erosion, desiccation, etc. may be critical. There is, however, no generally applicable model for these impact categories.

Development of the cause-effect framework and models to address the associated midpoint or endpoint categories need to be developed.

The table below gives a first opinion on the research priority and an estimate of the research effort for the five different impact categories that have been analysed.

In addition, the research efforts for desiccation and salination, and probably also erosion, should be combined effort, probably merged under the impact category of land use impacts. Finally, an open mind towards additional missing impact categories is needed. Especially for activities going on in developing countries, the OECD-based impacts might be insufficient.

**Table 29 Research needs for impacts covered under "other impacts"**

| Impact | Priority | amount of work |
|---|---|---|
| Noise | high | medium |
| Accidents | low | low |
| Desiccation | high | high |
| Erosion | high | high |
| Salination | high | high |

**Methods/ research needs highlighted during the public consultation**

- Methods that accounts for dissecation, like Pfister et al.2009
- Heat stress has only been addressed toward human health (in climate change), while it is clearly affecting ecosystems (e.g. in cooling water releases), (Verones et al. 2010).

## 6.13 Ecological footprint

**High priority**

- How should a score based on the footprint method be interpreted in an LCA context
- How to deal with double counting on demand for land for carbon sequestration, timber production and biodiversity
- How to combine with other impact categories

**Low priority**

- Include more land use types
- Extrapolate the effects of carbon dioxide to other emissions

# 7 Annex 3 – Development of this document

**Based on and considering the following documents**

The background document has been drafted taking into account amongst others the following existing sources:

- Harmonised ISO standards
  - ISO 14040: 2006 Environmental management - Life cycle assessment – Principles and framework
  - ISO 14044: 2006 Environmental management - Life cycle assessment - Requirements and guidelines
- Guidance documents in the field of Life Cycle Impact Assessment (LCIA)

This ILCD Handbook builds on two previous impact assessment documents:

ILCD - Handbook Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment (EC-JRC 2010a)

ILCD – Handbook Framework and Requirements for LCIA models and indicators (EC-JRC, 2010b)

The methods, analyses and recommendations in this guidance document build on existing methods and achievements made in the scientific communities, including the voluntary achievements of task forces of the Society of Environmental Toxicology and Chemistry (SETAC) and more recently in the joint Life Cycle Initiative facilitated by the United Nations Environment Program (UNEP) with SETAC. We equally acknowledge the US Environmental Protection Agency (EPA) for providing workshop documentation and other documents related to the scope and framework of LCIA.

A wealth of information and publications on the LCIA framework, methodologies and methods has been taken into account as referenced in the document.

**Drafting**

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**Invited stakeholder consultations**

An earlier draft version of this document has been distributed to more than 60 organisations and groups, covering EU Member States, European Commission (EC) Services, National Life Cycle Database Initiatives outside the European Union, business associations as members of the Business Advisory Group, Life Cycle Assessment software and database developers and Life Cycle Impact Assessment method developers as members of the respective Advisory Groups, as well as other relevant institutions.

**Disclaimer:** Involvement in the development or consultation process does not imply an agreement with or endorsement of this document.

**Public consultation**

A public consultation was carried out on the advance draft guidance document from October 18, 2010 to November 26, 2010. This included a public consultation workshop, which took place on 27th October 2010, in Brussels.

**Overview of involved or consulted organisations and individuals**

The following organisations and individuals have been consulted or provided comments, inputs and feedback during the invited or public consultations in the development of this document:

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**Internal EU steering committee**

- European Commission services (EC),
- European Environment Agency (EEA),
- European Committee for Standardization (CEN),
- IPP representatives of the 27 EU Member States

**National LCA database projects and international organisations:**

- United Nations Environment Programme, DTIE Department (UNEP-DTIE)
- World Business Council for Sustainable Development (WBCSD)
- Brazilian Institute for Informatics in Science and Technology (IBICT)
- University of Brasilia (UnB)
- China National Institute for Standardization (CNIS)
- Sichuan University, Chengdu, China
- Japan Environmental Management Association for Industry (JEMAI)
- Research Center for Life Cycle Assessment (AIST), Japan
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- European Aluminium Association
- European Automobile Manufacturers' Association (ACEA)
- European Cement Association (CEMBUREAU)
- European Confederation of Iron and Steel Industries (EUROFER)
- European Copper Institute
- European Confederation of woodworking industries (CEI-Bois)

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- European Federation of Corrugated Board Manufacturers (FEFCO)
- Industrial Minerals Association Europe (IMA Europe)
- Lead Development Association International (LDAI), global
- Sustainable Landfill Foundation (SLF), Europe
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Abstract

Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) are the scientific approaches behind moder environmental policies and business decision support related to Sustainable Production and Consumption (SCP). The International Reference Life Cycle Data System (ILCD) Handbook provides governments and businesses with a basis for assuring quality and consistency of life cycle data, methods and assessments. This guidance document provides recommendations on models and characterisation factors that should be used in Life Cycle Impact Assessement (LCIA) to analyse the emissions into air, water and soil, as well as the natural resources consumed in terms of their contributions to different impacts on human health, natural environment, and availability of resources. It supports the calculation of indicators for different impacts such as climate change, ozone depletion, photochemical ozone formation, respiratory inorganics, ionising radiation, acidification, eutrophication, human toxicity, ecotoxicity, land use and resource depletion for use in a common integrated framework, such as LCA. The principle target audience for this document is the Life Cycle Impact Assessment (LCIA) expert but also the experienced LCA practitioner and decision makers that are interested in the Impact Assessment models and indicators used in LCA.

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