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ReCiPe 2008

A life cycle impact assessment method

which comprises harmonised category indicators

at the midpoint and the endpoint level

First edition

Report I: Characterisation

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PREFACE

The first Life Cycle Assessment (LCA) dates from the 1990s, when the first product studies were made. An LCA is based on a systematic examination of the environmental impacts of products/activities, with the aim of revealing the environmental dimension of sustainability. Factors such as child labour, costs (product) and safety are usually not considered. An LCA study provides information and support in finding possible answers to environmental problems related to product life cycles.

The publication in 1992 of the CML LCA-guide (Centrum Milieukunde Leiden) marked a breakthrough in the scientific foundation of LCA methodology. From that moment onwards, the Netherlands has played an important role in the field of LCA methodology. A further Dutch innovation was the development of Eco-indicator 95 and its later version, Eco-indicator 99, by PRé Consultants. The CML-guide and the Eco-indicator guide are currently widely accepted methodologies. However, they are based on different points of departure:

1. The CML uses the approach that has been proposed as the baseline method for characterisation (Handbook on LCA) – the midpoint approach.
2. The Eco-indicator 99 focuses on the interpretation of results and uses the endpoint approach.

In 2000, a special session that focussed on understanding the strengths and weaknesses of the midpoint and endpoint methods was organised in Brighton, immediately following the SETAC conferences. At the end of this session, the 50 LCA experts who had participated jointly concluded that it would be desirable to have a common framework in which both midpoint and endpoint indicators can be used. This consensus became the basis of the ReCiPe method. Here, we acknowledge Dik van der Meent from RIVM, who seized the initiative and brought together experts from RIVM, Radboud University Nijmegen, CML and PRé to embark on a project aimed at harmonising the CML midpoint and the PRé endpoint approach into a single, consistent methodology. It soon became evident to all associated with the project that such a task goes much further than harmonising existing methods. In fact, almost all existing midpoint and endpoint characterisation models had to be entirely re-designed. Only a few midpoints and one endpoint model (ionising radiation) survived the rebuilding of methods.

This report describes the implementation of a method that is harmonised with respect to modelling principles and choices, but which offers results at both the midpoint and endpoint levels. From a methodological point of view, this is a major improvement as it enables the LCA-approach to be both flexible and more uniform.

The present report 'ReCiPe' presents the latest state of affairs of LCIA in the Netherlands. This report can be used as a recipe to calculate life cycle impact category indicators, and it will also be useful to those individuals who want to obtain in-depth knowledge of LCIA and the underlying rationale. ReCiPe 2008 builds on the Eco-indicator 99 and the CML Handbook on LCA (2002). The work reported herein was carried out between 2001 and 2008. This report represents the final stage of a process that started in 1990, with a commission from the Ministry of Housing, Spatial Planning and the Environment (VROM). A second, related report on weighting will also be presented within the near future.

Henk Strietman

Chair of the advisory committee.
Ministry of Housing, Spatial Planning and Environment (VROM)

SUMMARY

Life cycle assessment (LCA) is a methodological tool used to quantitatively analyse the life cycle of products/activities within the context of environmental impact. The application of this tool underwent major changes during the 1990s. It was initially developed to compare clearly defined end product alternatives, such as various forms of milk packaging or baby diapers. However, it has been rapidly incorporated into higher strategic levels, including decision- and policy-making at the firm/corporate levels. Life cycle assessment is currently used for assessing a wide range of products and activities, from ecolabeling to product design as well as energy systems, food production and transportation alternatives; it now clearly extends beyond only an assessment of end products. The current debate to which LCA is being subjected is closely linked to the involvement of stakeholders and the systematic use of quality assurance aspects, including peer review and uncertainty analyses. At an international level, the process of standardisation has yielded an ISO-standard (the 14040-series) and the establishment of working groups within the scientific community (SETAC) and within UNEP. At the same time, developments at the national level and within individual universities research centres and consultancy firms have led to a further development of procedures and methods for carrying out an LCA.

These developments clearly demonstrate that there is no single ‘gold standard’ method that is applicable in all situations. It has been stated that LCA is goal- and scope-dependent, and this most certainly also applies to LCA methodologies. However, at the same time, the autonomous developments in LCA have sometimes led to discrepancies between methods that cannot be explained by necessity alone, and for which historical factors play an important role.

One such example is the development of midpoint-oriented and endpoint-oriented methods for life cycle impact assessment (LCIA). A number of methods used for LCIA convert the emissions of hazardous substances and extractions of natural resources into impact category indicators at the midpoint level (such as acidification, climate change and ecotoxicity), while others employ impact category indicators at the endpoint level (such as damage to human health and damage to ecosystem quality). The existence of methods addressing midpoints and others addressing endpoints can be justified and is legitimate given that the choice of method is intricately linked to the product/activity under assessment. A series of interviews of users of LCA in the Netherlands confirms this, but there are differences between the underlying models that are – at the very least – confusing and which also may be unnecessary. One example is the assumption that the wind speed and temperature entered as environmental properties in the fate model are different. It is therefore desirable that methods for LCIA should be harmonised at the level of detail, while allowing a certain degree in freedom in terms of the main principles; in the current case, this would be their orientation towards midpoint or endpoint indicators.

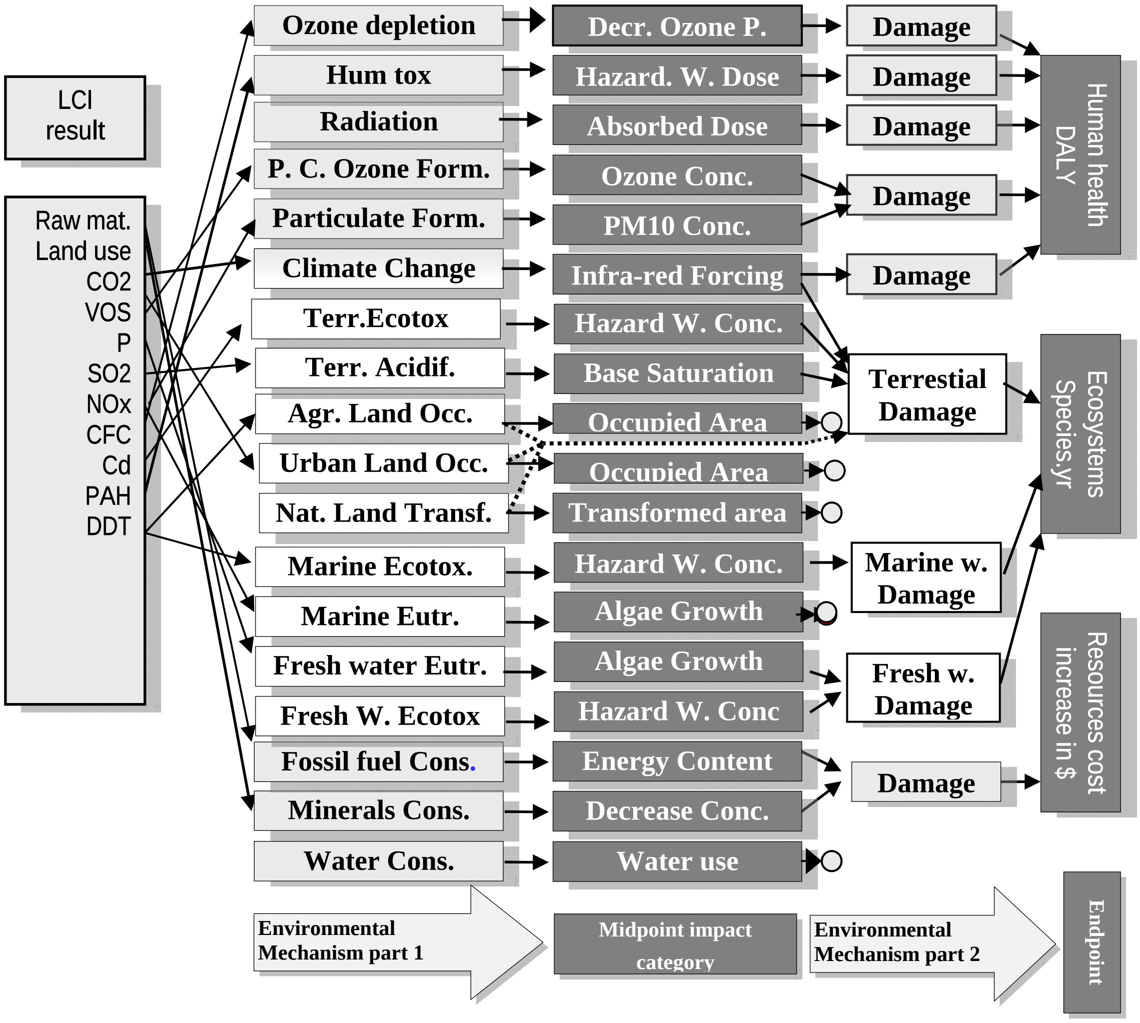
This report describes the implementation of an LCIA method that is harmonised in terms of modelling principles and choices, but which offers results at both the midpoint and endpoint level. Phase 1 of the project concentrated on an analysis of the differences and similarities between two main approaches to a LCIA. In particular, the focus was on the first part of a LCIA when impact categories and category indicators are chosen and characterisation models are selected or developed to convert LCI results into category indicator results. These two main approaches were:

1. the method proposed as the baseline method for characterisation in the *Handbook on LCA* (Guinée et al., 2002); we will refer to this as the midpoint approach;
2. the method advanced in the *Eco-indicator 99* (Goedkoop & Spriensma, 1999); this will be referred to as the endpoint approach.

Phase 1 consisted not only of an analysis, but also resulted in a proposed synthesis of these two approaches. Here, we describe the synthesis in the form of concrete methods for the characterisation of life cycle inventory results in terms of impact category indicators at the midpoint and endpoint levels, respectively. Extensive cooperation with the RIVM and with the University of Nijmegen ensured access to knowledge and models over a wide range of environmental issues, from acidification to climate change.

The method for LCIA described in this report has been given the name ReCiPe 2008, as it – like many other reports on LCIA – provides a recipe to calculate life cycle impact category indicators. The acronym also represents the initials of the institutes that were the main contributors to this project and the major collaborators in its design: RIVM and Radboud University, CML, and PRé.

The figure below sketches the relations between the LCI parameter (left), midpoint indicator (middle) and endpoint indicator (right). Weighting and normalisation are not analysed in this project.



For some of these conversion and aggregation steps, uncertainties have been incorporated in the form of different perspectives:

individualist (I)

hierarchist (H);

egalitarian (E).

The principles of the models and prodcedures are described in this report. For operational application, a spreadsheet with the characterisation factors is available on the ReCiPe website. These factors apply, as much as possible, to the substances and compartments of elementary flows as defined by the ecoinvent consortium.

CONTENTS

1 INTRODUCTION

Reinout Heijungs[1], *Mark Goedkoop, Mark Huijbregts, An De Schryver, Jaap Struijs*

1.1 MAIN IDEA

Life cycle assessment (LCA) is a methodological tool used to quantitatively analyse the life cycle of products/activities within the context of environmental impact. The application of this tool underwent major changes during the 1990s. It was initially developed to compare clearly defined end product alternatives, such as various forms of milk packaging or baby diapers. However, it has been rapidly incorporated into higher strategic levels, including decision- and policy-making at the firm/corporate levels. Life cycle assessment is currently used for assessing a wide range of products and activities, from ecolabeling to product design as well as energy systems, food production and transportation alternatives; it now clearly extends beyond only an assessment of end products. The current debate to which LCA is being subjected is closely linked to the involvement of stakeholders and the systematic use of quality assurance aspects, including peer review and uncertainty analyses. At an international level, the process of standardisation has yielded an ISO-standard (the 14040-series) and the establishment of working groups within the scientific community (SETAC) and within UNEP. At the same time, developments at the national level and within individual universities research centres and consultancy firms have led to a further development of procedures and methods for carrying out an LCA.

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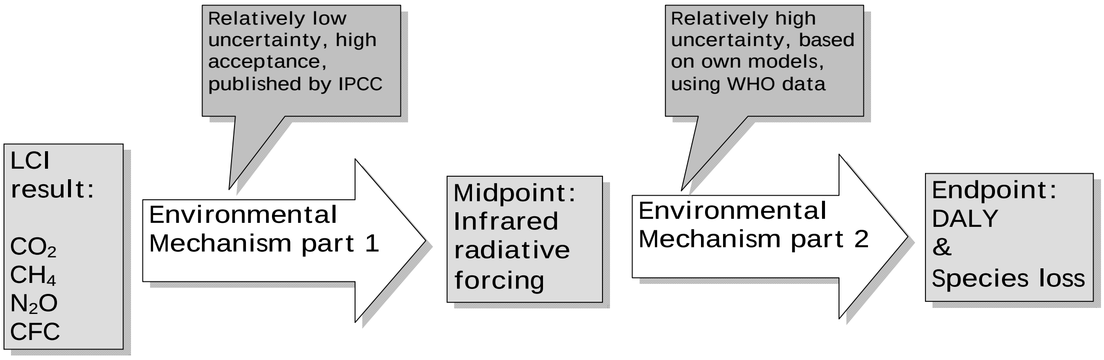

Figure 1.1: Example of a harmonised midpoint-endpoint model for climate change, linking to human health and ecosystem damage.

Figure 1.1 shows a simplified representation of the midpoint and endpoint approach to climate change. The impact category indicator at the midpoint level is infrared radiative forcing, expressed in CO_2-equivalents, while the impact category indicator at the endpoint level is twofold: damage to human health and damage to ecosystem diversity (not shown in this figure). The aim of the project reported here is to have both indicators positioned along the same environmental mechanism.

ReCiPe 2008 comprises two sets of impact categories with associated sets of characterisation factors. Eighteen impact categories are addressed at the midpoint level:

1. climate change (CC)
2. ozone depletion (OD)
3. terrestrial acidification (TA)
4. freshwater eutrophication (FE)
5. marine eutrophication (ME)
6. human toxicity (HT)
7. photochemical oxidant formation (POF)
8. particulate matter formation (PMF)
9. terrestrial ecotoxicity (TET)
10. freshwater ecotoxicity (FET)
11. marine ecotoxicity (MET)
12. ionising radiation (IR)
13. agricultural land occupation (ALO)
14. urban land occupation (ULO)
15. natural land transformation (NLT)
16. water depletion (WD)
17. mineral resource depletion (MRD)
18. fossil fuel depletion (FD)

At the endpoint level, most of these midpoint impact categories are further converted and aggregated into the following three endpoint categories:

1. damage to human health (HH)
2. damage to ecosystem diversity (ED)
3. damage to resource availability (RA)

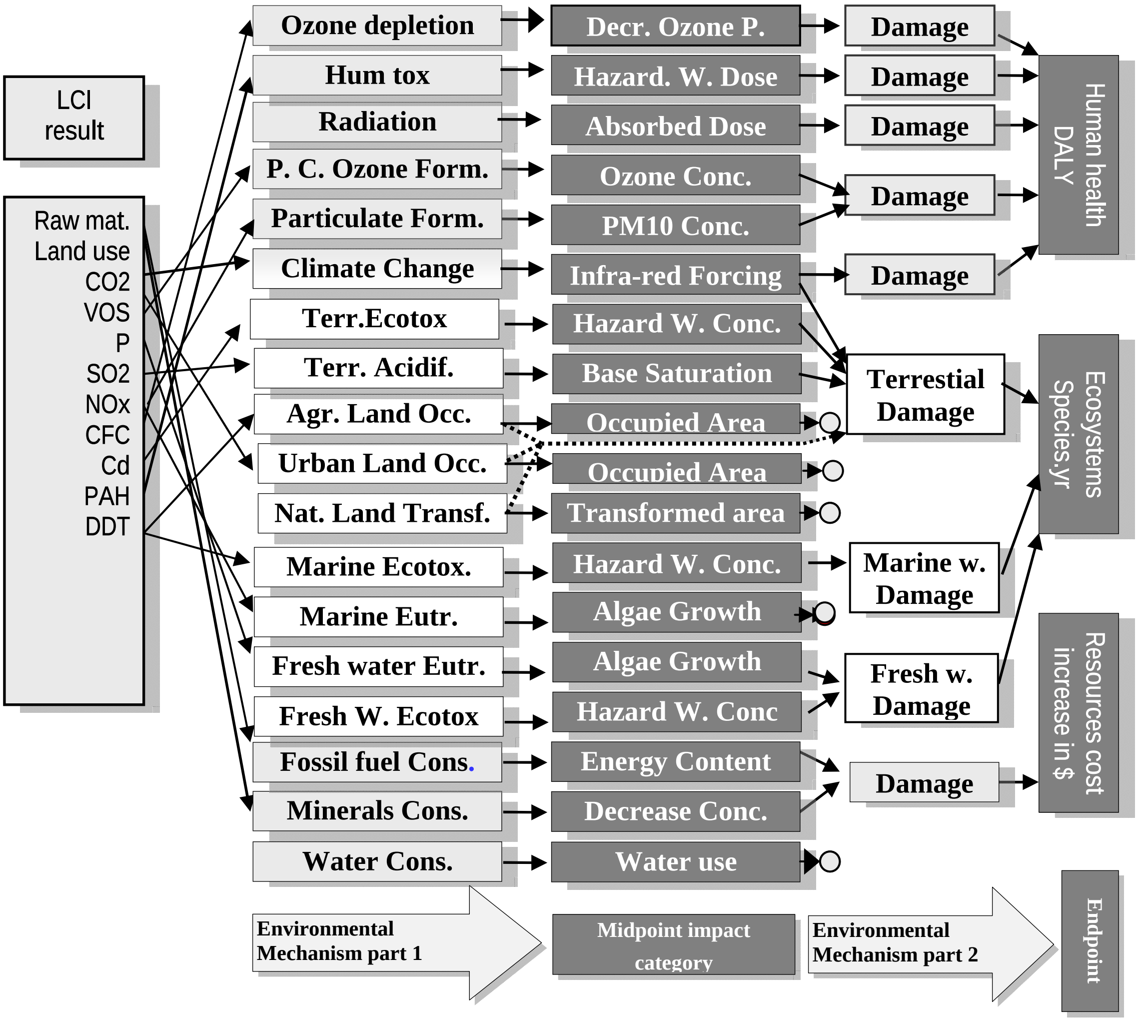

Figure 1.2: Relationship between LCI parameters (left), midpoint indicator (middle) and endpoint indicator (right) in ReCiPe 2008.

Similar to the Eco-indicator 99 method we developed three versions using the cultural perspectives theory of Thompson 1990. According to this theory consistent sets of subjective choices on time horizon, assumed manageability etc. can be grouped around three perspectives, identified by the names: individualist (I), hierarchist (H) and egalitarian (E).

1.2 STRUCTURE OF THE REPORT

The next chapter describes the outline and main principles of the new method. Then subsequent chapters are devoted to the following environmental issues:

- climate change
- ozone depletion
- acidification
- eutrophication
- toxicity
- human health damage due to PM_{10} and Ozone
- ionising radiation
- land-use
- water depletion
- mineral resource depletion
- fossil fuel depletion

These issues are not impact categories, but they have been linked to a number of midpoint and endpoint impact categories.

The report closes with appendices. A number of these provide general information, but most provide additional details on the information presented in the various chapters. For operational application, a spreadsheet with the characterisation factors is available on the ReCiPe website [www.lcia-recipe.info/]. These factors apply, as much as possible, to the substances and compartments of elementary flows as defined by the Ecoinvent consortium.

2 OVERALL ARCHITECTURE

Reinout Heijungs[2]*, Mark Huijbregts and Mark Goedkoop*

2.1 CHOICE OF AREAS OF PROTECTION

A decision was made in the scoping document (Heijungs et al., 2003) to develop the method for three areas of protection – human health, ecosystems and resources, respectively – and to have an endpoint indicator for each area. The area of protection for the man-made environment was excluded.

2.2 CHOICE OF ENVIRONMENTAL MECHANISMS TO BE INCLUDED

A clear requirement of the ISO14044 standard, and one repeatedly appearing in published reports, is that the characterisation factors be based on environmental mechanisms that link (man-made) interventions to a set of areas of protection. The end of the environmental mechanism is called the endpoint. A point positioned half way along the environmental mechanism can be chosen as an indicator – often referred to as the midpoint.

As a seemingly endless number of environmental mechanisms can link interventions to the areas of protection chosen, a selection of the most relevant environmental mechanisms is essential. Determining which of the mechanisms is the most relevant depends on the scope of a study and the region within which the interventions occur.

A number of environmental mechanisms have a global scope, while others have a regional one. This difference means that a particular environmental mechanism can have very important impacts in one region, but not in another. Our first choice has been to identify, develop and use environmental mechanisms that have a global validity wherever possible.

Environmental mechanisms such as acidification, eutrophication, photochemical ozone formation, toxicity, land-use and water-use all depend on regional conditions and regionally different parameters. Although we have often used European-scale models for these mechanisms, we have attempted to generalise the models as much as possible to be relevant for all developed countries in temperate regions. This means the ReCiPe method has a limited validity for all regions that cannot be defined as well-developed temperate regions. This is especially relevant for the Fate (and, if applicable, the Exposure) model. Four examples of regional conditions that can affect the validity of ReCiPe are:

- hygienic conditions (access to clean water) and food patterns; these can be quite different in less-developed regions, with significant impacts on the parameters of the Exposure model.
- differences in weather conditions in tropical area; these can influence the parameters of the Fate model.
- background concentrations, which can differ significantly between regions on a worldwide scale. In large areas of the world, acidification and eutrophication are probably a non-issue.
- population density differences, which can have very significant effects.

As these distortions mainly apply to the Fate and Exposure models, the problem is equally valid for the midpoints and endpoints, as the environmental mechanism between the midpoint and endpoint can be considered to be independent of the region, with the exception of land-use, for which the environmental mechanism at the endpoint level is very region-dependent. If an endpoint model for water-use would have been developed, this would also be very regionally dependent.

The focus on well-developed temperate regions also implies that a number of potentially very important environmental mechanisms are not included, such as land-use-related issues (erosion, salination, depletion of soil).

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2.3 CHOICE OF IMPACT CATEGORIES AND CATEGORY INDICATORS ALONG ENVIRONMENTAL MECHANISMS

2.3.1 GENERAL PRINCIPLES

The overall principle underlying our choice of impact categories is based on a compromise between a number of different principles.

- Impact categories are supposed to reflect issues of direct environmental relevance. This implies, for example, that waste is not an impact category but that the effects of waste processing should be part of the method in terms of its effects on climate change, toxicity, land-use, etc.
- Impact categories at the midpoint are defined at the place where mechanisms common to a variety of substances come into play. For example, acidification involves a whole series of steps, starting with the release of acidifying substances and ending with impacts on ecosystems. Somewhere along this pathway, there is a point at which the acidifying substances have an effect on the soil's base cation saturation (BCS). Other acidifying substances have different pathways before that point is reached, but they all have an identical pathway beyond that point. The modelling of impacts beyond this point will increase the policy relevance of the indicator (making it less abstract) – but at the expense of introducing a common uncertainty. Therefore, the BCS provides a suitable indicator for the acidification midpoint impact category.
- Impact categories are names, but category indicators are measurable places in an impact pathway. The calculation of the magnitudes of these category indicators – i.e. the category indicator results – requires characterisation factors, which in turn require characterisation models. Thus, category indicators should be chosen such that a characterisation model that addresses this category indicator exists or can be developed.

In the next section, the choice of impact categories and category indicators at the midpoint level is presented.

Impact categories at the endpoint level should correspond to areas of protection that form the basis of decisions in policy and sustainable development. For the environmental domain, these areas of protection are human health, ecosystem quality, resource availability, and, occasionally, man-made environment. This latter area is excluded from ReCiPe due to a general lack of both consensus and approaches. The resulting choice for the impact categories and category indicators at the endpoint level will be presented in another section.

A general criterion used to define impact categories and indicators is that impact categories at the midpoint should have a stand-alone value in a midpoint-oriented LCIA method, but that they should also be usable as an intermediate step in an endpoint-oriented method. One implication of this approach is that a PEC/PNEC[3]-based toxicity midpoint cannot be used in conjunction with a potentially disappearing fraction (PDF)-based[4] ecosystem quality endpoint because, in this particular case, part of the information needed to calculate the endpoint would have been lost at the midpoint level. Consequently, either the midpoint or the endpoint should be redefined, or both.

This criterion is needed to guarantee that the endpoint indicators can be calculated using the results of the midpoint calculations.

2.3.2 IMPACT CATEGORIES AND CATEGORY INDICATORS AT THE MIDPOINT LEVEL

The choice made with respect to categories and indicators at the midpoint level is presented in Table 2.1.

[3] PEC means Predicted Environmental Concentration, PNEC Predicted No-Effect Concentration
[4] PDF: Potentially Disappeared Fraction (of species)

Table 2.1: Overview of the midpoint categories and indicators.

Impact category		Indicator	
Name	**abbr.**	**name**	**unit***
climate change	CC	infra-red radiative forcing	W×yr/m^2
ozone depletion	OD	stratospheric ozone concentration	ppt†×yr
terrestrial acidification	TA	base saturation	yr×m^2
freshwater eutrophication	FE	phosphorus concentration	yr×kg/m^3
marine eutrophication	ME	nitrogen concentration	yr×kg/m^3
human toxicity	HT	hazard-weighted dose	–
photochemical oxidant formation	POF	Photochemical ozone concentration	kg
particulate matter formation	PMF	PM_{10} intake	kg
terrestrial ecotoxicity	TET	hazard-weighted concentration	m^2×yr
freshwater ecotoxicity	FET	hazard-weighted concentration	m^2×yr
marine ecotoxicity	MET	hazard-weighted concentration	m^2×yr
ionising radiation	IR	absorbed dose	man×Sv
agricultural land occupation	ALO	occupation	m^2×yr
urban land occupation	ULO	occupation	m^2×yr
natural land transformation	NLT	transformation	m^2
water depletion	WD	amount of water	m^3
mineral resource depletion	MRD	grade decrease	kg^{-1}
fossil resource depletion	FD	upper heating value	MJ

** The unit of the indicator here is the unit of the physical or chemical phenomenon modelled. In ReCiPe 2008, these results are expressed relative to a reference intervention in a concrete LCA study.*
† The unit ppt refers to units of equivalent chlorine.

The actual modelling of interventions into midpoint indicators is performed by the use of characterisation factors; see Table 2.2 for an overview.

Table 2.2: Overview of the midpoint categories and characterisation factors.

Impact category		Characterisation factor	
Abbreviation	**Unit***	**Name**	**Abbreviation**
CC	kg (CO_2 to air)	global warming potential	GWP
OD	kg (CFC-11[5] to air)	ozone depletion potential	ODP
TA	kg (SO_2 to air)	terrestrial acidification potential	TAP
FE	kg (P to freshwater)	freshwater eutrophication potential	FEP
ME	kg (N to freshwater)	marine eutrophication potential	MEP
HT	kg (14DCB to urban air)	human toxicity potential	HTP
POF	kg (NMVOC[6] to air)	photochemical oxidant formation potential	POFP
PMF	kg (PM_{10} to air)	particulate matter formation potential	PMFP
TET	kg (14DCB to industrial soil)	terrestrial ecotoxicity potential	TETP
FET	kg (14DCB to freshwater)	freshwater ecotoxicity potential	FETP
MET	kg (14-DCB[7] to marine water)	marine ecotoxicity potential	METP
IR	kg (U^{235} to air)	ionising radiation potential	IRP
ALO	m^2×yr (agricultural land)	agricultural land occupation potential	ALOP
ULO	m^2×yr (urban land)	urban land occupation potential	ULOP
NLT	m^2 (natural land)	natural land transformation potential	NLTP
WD	m^3 (water)	water depletion potential	WDP
MRD	kg (Fe)	mineral depletion potential	MDP
FD	kg (oil†)	fossil depletion potential	FDP

** The unit of the impact category here is the unit of the indicator result, thus expressed relative to a reference intervention in a concrete LCA study.*
† The precise reference extraction is "oil, crude, feedstock, 42 MJ per kg, in ground".

In comparing Table 2.1 and Table 2.2, the reader will observe that there is a discrepancy in the units. According to Table 2.1, the indicator for climate change has the unit W×yr/m^2. For the characterisation factor, one would thus expect to find the unit (W×yr/m^2)/kg – at least when the emission of greenhouse gases is expressed in kilo-

5 CFC-11: Chlorofluorocarbon
6 NMVOC: Non Methane Volatile Organic Carbon compound
7 14-DCB: 1,4 dichlorobenzene

grammes. In the definition of global warming potentials (GWPs), however, a reference substance has been introduced, CO_2 to air, so that the characterisation factor is a dimensionless number that expresses the strength of a kilogramme of a greenhouse gas relative to that of a kilogramme CO_2 to air. Thus, although the indicator addressed is infra-red radiative forcing, the midpoint calculation does not calculate a score in $W \times yr/m^2$, but only a kilogramme CO_2 to air-equivalent. In this process, the absolute yardstick is therefore lost, which has important repercussions when linking the midpoints to endpoints.

The exact details of these categories, indicators and characterisation factors are elaborated upon in subsequent chapters. A number of these are discussed together. For example, the impact categories freshwater eutrophication and marine eutrophication are discussed together in one chapter on eutrophication.

2.3.3 IMPACT CATEGORIES AND CATEGORY INDICATORS AT THE ENDPOINT LEVEL

At the endpoint level, things are a bit easier: there are fewer impact categories, and there are fewer differences with existing methods for LCIA. Table 2.3 provides an overview.

Table 2.3: Overview of the endpoint categories, indicators and characterisation factors.

Impact category		**Indicator**	
Name	**abbr.**	**name**	**unit**
damage to human health	HH	disability-adjusted loss of life years	yr
damage to ecosystem diversity	ED	Loss of species during a year	yr
damage to resource availability	RA	increased cost	$

Note the correspondence between the three endpoint impact categories and three of the four areas of protection; for example, the impact category damage to human health corresponds to the area of protection human health. For the area of protection man-made environment, there is no impact category, because no appropriate indicators and characterisation factors are available.

In the following sections, we describe the areas of protection (AoPs) in more detail.

2.3.4 HUMAN HEALTH

Life cycle assessments commonly assess damage to human health using the concept of ‘disability-adjusted life years’ (DALY). Hofstetter (1998) introduced the DALY-concept in LCA, which he based on the work carried out by Murray and Lopez (1996) for the World Health Organisation. The DALY of a disease is derived from human health statistics on life years both lost and disabled. Values for disability-adjusted life years have been reported for a wide range of diseases, including various cancer types, vector-borne diseases and non-communicable diseases (Frischknecht et al. 2000; Goedkoop and Spriensma, 1999; Murray and Lopez, 1996).

When equal weightings are applied to the importance of 1 year of life lost for all ages and any discount for future damages is disregarded, DALY is the sum of years of life lost (YLL) and years of life disabled (YLD):

$$DALY = YLL + YLD \tag{2.1}$$

In turn, the YLD is equal to

$$YLD = w \times D \tag{2.2}$$

where *w* is a severity factor between 0 (complete health) and 1 (dead), and *D* is the duration of the disease.

Although the concept of DALYs has proven to be a useful metric in the assessment of human health damage in LCA (Hofstetter 1998), the actual calculation depends on a number of subjective assumptions. First, DALYs refer to a specified region and time frame, such as the world in 1990 (Murray and Lopez, 1996). Thus, applying world average DALY estimates in the calculation of characterisation factors implies acceptance of the assumption that damage to human health due to life cycle emissions can be represented by world averages. For LCA case studies focusing on region-specific human health impacts, however, such DALY estimates should be used with care: taking another region in the world as a starting point for the DALY calculation may cause a change in the results. For example, in established market economies in 1990, DALYs were up to twofold lower for cancer diseases and up to fivefold lower for non-cancer diseases – when compared with average world DALYs (Murray and Lopez, 1996). These differences can be explained by the more advanced medical health care available in the established market economies than that indicated by the world average. For the same reason, differences in medical health care in 1990 compared with that potentially available in the (distant) future may result in differences in DALYs. This may be particularly important for emissions occurring now but having their impact in the future, such as emissions of carcinogenic substances. Secondly, in most LCIA methodologies, DALYs are calculated without applying age-specific weighting and without discounting future health damages. These two starting points, however, are a matter of debate (Hellweg et al., 2005; Hofstetter and Hammitt, 2002). For example, using non-uniform age weights and a future discount rate of 0.03, as proposed by Murray and Lopez (1996), DALY estimates typically decrease by a factor of 2. Third, the use of YLDs includes a subjective assessment of the weighting of health disabilities (Krewitt et al. 2002) – which is why some of the LCIA methodologies explicitly exclude YLD from the damage assessment. For cancer diseases, DALYs and years of life lost differ by up to a factor of 1.2, indicating that the inclusion of years of life disabled does not have a large influence on DALY outcomes (Crettaz et al., 2002; Huijbregts et al., 2005). The situation is different for a number of non-cancer diseases, such as musculoskeletal, neuropsychiatric and sense-organ diseases and vector-borne diseases. For these disease types, the years of life disabled make a major (dominant) contribution to the DALY estimates (Murray and Lopez, 1996). As health-preference measurements tend to be rather stable across groups of individuals and regions of the world (Hofstetter and Hammitt, 2002), it is expected, however, that the influence of subjective assessments on years of life disabled estimates on the DALY outcomes will be small.

In ReCiPe, we apply the DALY concept, including years of life lost and years of life disabled, without age weighting and discounting, as a default setting for quantifying the damage contributing to the human health area of protection within LCA.

2.3.5 ECOSYSTEMS

Ecosystems are heterogeneous and very complex to monitor. A number of treaties, decrees and nonbinding agreements (UNCED, UNEP, Council of Europe) have been drawn up that list those attributes considered to be important to mankind on a whole, such as biodiversity, aesthetic and cultural values, ecological functions and services, ecological resources and information functions (in genes).

One approach to describing ecosystem quality is in terms of energy, matter and information flows. When such flows are used to characterise ecosystem quality, it can be said that a high ecosystem quality is the condition that allows flows to occur without noticeable disruption by anthropogenic activities. In contrast, a low ecosystem quality is the condition in which these flows are disrupted by anthropogenic activities. Consequently, it is the level of the disruption that is the most important parameter when ecosystem quality is being measured.

To complicate things yet further, these flows can exist on many different levels. While the information flow can be described at the level of ecosystems, species and genes, the material and energy flow can be described in terms of free biomass production, as proposed by Lindeijer et al. (1998).

It is quite evident that all of these attributes cannot be modelled on all of these levels and dimensions. In the ReCiPe 2008 model, we concentrate on the information flow – at the species level. This means accepting the assumption that the diversity of species adequately represents the quality of ecosystems.

Anthropogenic factors can affect all species groups in the practical sense. It is impossible to monitor them all. We therefore had to choose those species groups that can be used as an appropriate representative of the total ecosystem quality. It is also important to choose between:

- the complete and irreversible extinction of species;
- the reversible or irreversible disappearance of a species or stress on a species in a certain region during a certain time.

Although the first type of damage listed above is probably the most fundamental type of damage that can occur to ecosystems, it is extremely difficult to model in the LCA context, since it requires information on the location of the most threatened representatives of a species in relation to the location of an impact. In fact, we can assume that complete extinction usually occurs as a result of many different factors. This assumption implies that no single product life cycle can cause any one extinction to occur, but that all of the product life cycles together can be responsible for the full extinction.

Based on this reasoning, we have modelled the loss of species during a certain time in a certain area as the basis for the endpoint indicator. In the Eco-indicator 99 method, ecosystem quality was expressed as the potentially disappeared fraction of species (PDF) integrated over area and time. As long as only terrestrial ecosystem damage is determined, the ‘area’ can be expressed as surface area in square metres.

In ReCiPe, we also developed a characterisation factor for aquatic eutrophication (both for freshwater and marine water), and the unit of this indicator is (PDF ×) $m^3 \times yr$, which involves an integration over volume instead of area. There seem to be two alternatives for combining terrestrial and aquatic damage:

- Convert the volume into a surface, using the average depth of freshwater and marine water bodies as a basis.
- Weight the damages on the basis of the total number of species on land and in water bodies as a basis. For this option, we chose to consider the loss of each species to be equally important. This means that a change in the PDF in a species-rich compartment is more important than that in a compartment with a

lower species richness, as the same PDF in a rich compartments implies the disappearance of a larger number of species.

The latter choice assumes that all species are equally important. If surface were to be used as a basis, the impacts of freshwater biodiversity would be very much underweighted. Freshwater bodies occupy only 0.8% of the surface of the earth; consequently, a complete extinction of all those species occupying freshwater bodies (estimated to be at least 1.75 million) would hardly be visible as damage (Dudgeon 2005). However, conversion on the basis of available volume would also give a strange result, as only 0.01% of all water is freshwater.

The endpoint characterisation factor for ecosystem damage can thus be calculated by taking the sum of the PDF, multiplied with the species density

$$CF_{ED} = PDF_{terr} * SD_{terr} + PDF_{fw} * SD_{fw} + PDF_{mw} * SD_{mw} \qquad (2.3)$$

with

- CF_{ED} = the endpoint characterisation factor for ecosystem damage
- PDF_{terr} = the characterisation factor in PDF.m^2.yr, and SD_{terr} the species density factor for terrestrial systems, in species/m^2
- PDF_{fw} = the characterisation factor in PDF.m^3.yr, and SD_{fw} the species density for freshwater systems in Species/m^3.
- PDF_{mw} = the characterisation factor in PDF.m^3.yr, and SD_{mw} the species density for marine water systems in Species/m^3.

Determining the species density is not so trivial; we need to sole three problems: how many species are there, how is the distribution of species over land, fresh and marine water, and what surface and volume do we use.

The first element is the determination of species totals. The number of registered species is only a fraction of the estimated total number of species. As the LCIA models used here only register the disappearance of registered species we will only refer to registered species.

Table 2.4: Total species estimate, from the GEO 2000 by UNEP (Source: WCMC/IUCN 1998).

	known number of species	estimated total number of species
Insects	950,000	8,000,000
Fungi	70,000	1,000,000
Arachnids	75,000	750,000
Nematodes	15,000	500,000
Viruses	5,000	500,000
Bacteria	4,000	400,000
Plants	250,000	300,000
Protozoans	40,000	200,000
Algae	40,000	200,000
Molluscs	70,000	200,000
Crustaceans	40,000	150,000
Vertebrates	45,000	50,000
World total (all groups)	1,604,000	12,250,000

The second element is the distribution of species over terrestrial, freshwater and marine waters. Dudgeon et al. (2005) reported that there are approximately 1.75 million species in freshwater bodies, although only about 100,000 species have currently been described (6% of all species according to Dudgeon et al. 2005). The UN Atlas of the Oceans estimates there are some 250,000 aquatic species, of which more than half live in coastal zones. This is a significantly lower figure than the number of terrestrial species, which is estimated at 1,500,000. This difference is ascribed to the much lower variation in living conditions in the oceans. The high number of terrestrial species can also be ascribed to the very high number of arthropods (insects, spiders, etc.,), for which there is no equivalent in oceans. There is an apparent lack of consensus regarding the numbers, mainly due to the relatively large share of species that probably exist but which have not been described. We base our analysis, therefore, on the following data:

- total number of described terrestrial species: 1,500,000
- total number of described freshwater species: 100,000
- total number of described freshwater species: 250,000

The third element is the estimate of the terrestrial area and the volume of fresh and marine waters.

For terrestrial areas, we excluded agricultural areas deserts and ice regions. The overview (percentage) of the main types of land presented in Table 2.5 was taken from the FAO Global Arable–Ecological Zones database (see also http://www.fao.org/ag/agl/agll/gaez/index.htm). We combined these data with the total land surface on Earth (148.3 E6 km^2 according to Charles R. Coble et al. 1987), obtaining a damage area of 108.4 E6 km^2.

Table 2.5: Total species estimate, from the GEO 2000 by UNEP (Source: WCMC/IUCN 1998).

Terrestrial areas	Percentage of world total	Included (yes/no)	Calculated area in million km^2
grasslands	13.6%	yes	20.2
woodlands	14.5%	yes	21.5
forests	21.2%	yes	31.4
mosaics including croplands	8.5%	yes	12.6
croplands	8.3%	yes	12.3
irrigated croplands	3.0%	yes	4.4
wetlands	0.7%	yes	1.0
desert and barren land	20.9%	no	
water (coastal fringes)	3.3%	yes	4.9
ice, cold desert	5.9%	no	
urban	0.2%	no	
total			108.4

For freshwater, we only use the volume of water in rivers and streams (13,000 km^3) and lakes (250,000 km^3). We do not include soil moisture (65,000 km^3) and groundwater (9,500,000 km^3) as groundwater will generally contain few species. Soil moisture will contain many species, but the damage is captured in the terrestrial damage models.
For marine water, the total volume is enormous (1,370,000,000 km^3), but by far the most registered species will be in the upper 200-m layer, the so-called photic zone. This is also the zone where the productivity for the entire oceans is generated, except for those species dependent on the deep volcanic vents. The total volume of this layer is 72,300,000 km^3

Based on these data, we find the following species densities

- terrestrial species density: 1.38 E-8 [1/m^2]
- freshwater species density: 7.89 E-10 [1/m^3]
- marine species density: 1.82 E-13 [1/m^3]

2.3.6 RESOURCES

The risk that mankind will run out of resources for future generations is often quoted as an important issue. Some groups consider resource depletion as the only issue to be monitored.

To understand resource needs, we need to distinguish between a material and the function it can provide, or as Müller-Wenk 1998 states, the essential property of the material that is used to serve a certain purpose. Table 2.6 provides an overview of the functions and essential properties that some types of resources can provide.

Table 2.6. Function and properties of resources.

Resource	Subcategory	Type	Essential property lost?	Recycling possible	Function	Time shortages can occur	Alternatives
minerals	metals	stock	no	yes	construction	centuries	many, also wood, etc.
	uranium	stock	yes	no[8]	electricity	centuries	no (fission?)
fossil fuel		stock	yes	no	all energy	decades	within the group
wind, water, solar energy		flow	yes	no	electricity	indefinite	within the group
energy crops	(see also agriculture)	flow	yes	no	all energy	see agriculture	other energy
water		fund/flow	no	yes	agriculture, humans, ecosystems	present	no
land (surface)	for urban use	fund/flow	sometimes	sometimes	living, transport, working	present	intensify use
	for agricultural use	fund/flow	sometimes	sometimes	feeding, energy crops	present	intensify use
	for natural areas	fund/flow	sometimes	sometimes	recreation, "sustainability"[9]	present	no
	water surface	fund/flow	sometimes	sometimes	recreation, transport	present	intensify use
silvicultural extraction	hunting, fishing, herb collection	fund/flow	yes	no	feeding, medicines, energy (in Third World)	present	agriculture
	wood for construction	flow	yes	sometimes	housing, furniture	present	metals, bulk resources
bulk resources		fund	sometimes	sometimes	infra-structure, housing	centuries or longer	within group

Table 2.6 shows that there are many different types of resources as well as quite a wide range of possibilities for substituting or recycling the resource. It also demonstrates that there is quite a range in the time frame within which the resource shortage can become problematic.

We can also inverse the table and use the basic needs of future societies as a starting point to determine if there will be sufficient resources in the future. However, such an analysis is quite complex and hampered by a set of fundamental but interrelated problems:

- How does technology and, in particular, the requirements for materials change over time. 'The stone age did not end due to a lack of stones'
- Most resources can be replaced by an alternative. The reason for using a certain resource is often found in the market prices. Gold – and not copper – is the best material for conducting electricity. However, copper has been used for this purpose because of the ratio of resistance to price. More recently, there has been an observable shift from copper to aluminium for applications requiring the conduction of electricity, and if super-conducting cables become a commercial reality, the use of copper for conducting electricity will decline. Substitution does not only occur within a resource group. For example, bio-plastics can replace steel. In actual fact, there are very few resources that cannot be replaced by others. These are: water and space, especially natural areas.
- The 'size' of the fund very much depends on the willingness to pay for the use of low-grade or low-quality resources and of the efficiency improvements that are still possible for the mining of these low-grade stocks.

In many cases, resource depletion and shifts in material demand will have an impact on market prices. This often means that prices will go up, which could also negatively affect the ability to maintain and expand the man-made environment.

The working group on impact assessment in the SETAC-UNEP Life Cycle Initiative classifies resources into three categories: biotic, abiotic (flow, fund and stock) and land. This group further distinguishes various approaches for assessing abiotic (stock) resources:

[8] A breeder reactor can in principle generate plutonium, forming a large stock of U^{238} as alternative fuel, at the same or higher rate than the depletion of the scarce U^{235}.

[9] Sustainability refers to a wide range of functions, such as climate regulation, metabolism, gene pool preservation, among others.

- Addition of the total mass (ores) or energy content of the resources. This approach is not recommended.
- Aggregation based on deposit (D) and current consumption (U), with three alternative expressions (1/D, U/D or 1/D×U/D). In this approach, the size of the deposit remains quite uncertain. Of the three alternative formulas, the third is also the approach used in the CML 2000 method.
- Aggregation based on environmental interventions caused by future hypothetical processes, such as the method proposed Müller-Wenk 1998, based on the surplus energy for future mining of low-grade resources. The latter method has also been applied (with some modifications) in the Eco-indicator 99 model. These types of methods need to assume future scenarios, which makes the characterisation factors rather uncertain.
- Exergy, as proposed by Finnveden (1997). However, it is questionable whether exergy actually addresses the environmental problem, as the chemical entropy in the ores, rather than in the metal content of the ore, dominates the equations. Dewulf (2007) improved this concept significantly, but the problem of scarcity is still not addressed by the concept of exergy. The exergy value is a physical property of a resource that reflects the effort to produce the resource irrespective of its scarcity. Therefore, even if a resource becomes depleted rapidly, the exergy value will not change. As such, the indicator does not truly express the scarcity.

The experts directly working on ReCiPe do not recommend any of these above-mentioned approaches.

We have chosen to base the ReCiPe model on the geological distribution of mineral and fossil resources and assess how the use of these resources causes marginal changes in the efforts to extract future resources. Unlike the model of Müller Wenk used in Eco-indicator 99, we do not assess the increased energy requirement in a distant future; rather, we base our model on the marginal increase in costs due to the extraction of a resource. To this end, we develop a function that reflects the marginal increase of the extraction cost due to the effects that result from continuing extraction. In terms of minerals, the effect of extraction is that the average grade of the ore declines, while for fossil resources, the effect is that not only conventional fossil fuels but also less conventional fuels need to be exploited, as the conventional fossil fuels cannot cope with the increasing demand.

The marginal cost increase (MCI) is the factor that represents the increase of the cost of a commodity *r* ($/kg), due to an extraction or yield (kg) of the resource *r*. The unit of the marginal cost increase is dollars per kilogramme squared ($/kg^2)

$$MCI_r = \frac{\Delta Cost_r}{\Delta Yield_r}$$

The price increase itself has relatively little meaning, as a one cent price increase for a kilogramme of oil has a much higher impact on societies than the same price increase for mercury. Therefore, the price increase, expressed as dollars per kilogram ($/kg), must be multiplied with a factor that expresses the amount consumed. This step converts the extraction of a resource into increased costs to society in general. In principle, each extraction will cause a price increase that will last indefinitely and, consequently, the damage to humanity can be interpreted as indefinite damage. This is not valid in economic terms as inflation will reduce the net present value of the costs to society to a measurable number. For example, if we assume an inflation rate of 3% per year, the net present value of spending a dollar per year during an indefinite period is $33.33. If, for some reason, we want to limit the time perspective to 100 years, the net present value of spending a dollar during that 100 years is $31.80, while if the time perspective is limited to 20 years, the net present value is $15.75.

The net present value of spending one dollar a year over a time *T*, taking into account a discount rate *d*, can thus be written as:

$$NPV_T = \sum_T \frac{1}{(1-d)^T} \tag{2.4}$$

where NPV is the net present value (year).

The total cost to society due to an extraction can thus be calculated by multiplying the marginal cost increase per kilogramme with the annual consumed amount times the net present value of a dollar, taking into account the discount rate.

The generic formula for the endpoint resources is:

$$D = \frac{\Delta Cost_r}{\Delta Yield_r} \times P_r \times \sum_T \frac{1}{(1-d)^t} \tag{2.5}$$

The damage D is expressed in dollars; $\Delta Cost_r$ is the cost increase for resource r ($/kg); ΔY_r is the extracted yield of resource r that caused the price increase (kg). P_r is the global production amount of the resource per year (kg/yr), d is the discount rate and T is the time interval that is taken into account.

As a default, the discount rate is chosen to be 3%, and T is assumed to be indefinite. The last term is a summation over time, and thus the unit is years. Consequently, the unit of the damage is dollars per kilogramme extracted. Other discount rates or integration times can be used when it is believed these will help in explaining the result to stakeholders or when the results are used in a monetarisation approach. Such changes would only affect the absolute value of the damage – not the differences between resources.

The fund and flow resources are not included in the impact category, except for the use of water, as the latter is potentially a very important problem. However, we have been unable to link the use of water to a marginal increase in the cost of making water available, and this there is only a midpoint, not an endpoint.

2.3.7 MAN-MADE ENVIRONMENT

The last AoP is also the most disputed and the least clear one: man-made environment. Corrosive pollutants affect buildings, roads, cars and other structures. Climate change may flood cities or agricultural areas, and may also cause hurricanes to destroy our built environment. Plagues of insects may eat our crops. And increased UV-levels may deteriorate many man-made facilities. This AoP has not been incorporated into ReCiPe 2008.

2.3.8 AREAS OF PROTECTION AND ENDPOINT CATEGORIES

In this section two related concepts were discussed: areas of protection and endpoint categories. Though related and superficially identical, they are not the same.

- An AoP is a class of endpoints which have some recognizable value for society. Prime examples are human health, natural environment, natural resources, and man-made environment.
- An endpoint itself is a variable of direct societal concern. As such, they can act as a quantifiable representation of a (part of a) AoP.

In ReCiPe, the AoP human health has been represented by the endpoint category damage to human health, which combines mortality and morbidity. The AoP natural environment has been represented by loss of spiecies, and the AoP natural resources by the increased sot for future extractions. Table 2.7 summarizes this relationship.

Table 2.7: The connection between the areas of protection (AoPs) and the endpoint indicators in ReCiPe 2008.

Area or protection	**Endpoint category**	**Unit of endpoint indicator**
human health	damage to human health (HH)	yr
ecosystems	damage to ecosystem diversity (ED)	yr
resources	damage to resource availability (RA)	$
man-made environment	NA	NA

2.3.9 CONNECTIONS BETWEEN THE MIDPOINT AND ENDPOINT LEVEL

The principal aim of ReCiPe 2008 was the alignment of two families of methods for LCIA: the midpoint-oriented CML 2002 method and the endpoint-oriented Eco-indicator 99 method. Of special interest in this introductory chapter is therefore the actual alignment achieved. Table 2.8 displays the connection between midpoints and endpoints in terms of the midpoint categories that are modelled until the endpoints.

Table 2.8: Overview of the connection between midpoint and endpoint categories.

Midpoint impact category		**Endpoint impact category***		
Name	**abbr.**	**HH**	**ED**	**RA**
climate change	CC	+	+	
ozone depletion	OD	+	–	
terrestrial acidification	TA		+	
freshwater eutrophication	FE		+	
marine eutrophication	ME		–	
human toxicity	HT	+		
photochemical oxidant formation	POF	+	–	
particulate matter formation	PMF	+		
terrestrial ecotoxicity	TET		+	
freshwater ecotoxicity	FET		+	
marine ecotoxicity	MET		+	
ionising radiation	IR	+		
agricultural land occupation	ALO		+	–
urban land occupation	ULO		+	–
natural land transformation	NLT		+	–
water depletion	WD			–
mineral resource depletion	MRD			+
fossil fuel depletion	FD			+

** Legend: + means that a quantitative connection has been established for this link in ReCiPe 2008; – means that although this is an important link, no quantitative connection could be established.*

The primary goal of this project is to link the inventory data to one or a number of midpoints. In a second step, each midpoint is linked to one endpoint. This goal has been achieved for almost all impact categories; see Table 2.8 (and Figure 1.2). We have also attempted to establish a connection for land-use. However, due to use of observational data in which we were unable to the intermediate steps, we have not achieved this goal. For eutrophication (freshwater and marine) and water depletion, no endpoint modelling was possible within the framework of our project.

In terms of the characterisation factors for endpoint categories, we must emphasize that two sets of characterisation factors are actually needed: one to convert a midpoint indicator result into an endpoint indicator result, and one to convert an intervention (emission, extraction, landuse) directly into an endpoint indicator result. The two data sets are clearly related. Symbolically: when intervention i and midpoint indicator m are coupled with characterisation factor Q_{mi}, and midpoint indicator m is coupled with endpoint indicator e with characterisation factor Q_{em}, their combined characterisation factor Q_{ei} is determined as

$$Q_{ei} = \sum_{m} Q_{em} Q_{mi} \qquad (2.6)$$

In principle, ReCiPe 2008 reports all three sets of characterisation factors (see following section). It is standard practice in LCA to assign names and abbreviations to sets of characterisation factors. Well-known examples are the global warming potential (GWP) for climate change and the human toxicity potential (HTP) for human toxic effects. These are examples of typical midpoint categories, as is characterisation factor Q_{mi}, with i = climate change, or i = human toxicity. Characterisation factors also exist for endpoint methods such as Eco-indicator 99 or EPS, characterisation factors, but they usually do not have a name or abbreviation. One could envisage that names also be given to the two sets of endpoint-oriented characterisation factors, Q_{ei} and Q_{em}. Indeed, we will refer to the three lists of Q_{ei} as the human health factor (HHF; for i = damage to human health), the ecosystem quality factor (EQF; for i = damage to ecosystem quality) and the resource availability factor (RAF; for i = damage to resource availability). Table 2.8 shows the connections between the midpoint indicators and the endpoint indicators. Each plus sign in the three rightmost columns corresponds to the presence of a characterisation factor. The numbers Q_{em} are thus a limited set of approximately 20 fixed numbers; see Table 2.9. These will not be used in most LCA studies; instead, such studies will use the midpoint characterisation factors Q_{mi}, the endpoint characterisation factors Q_{ei}, or perhaps both. Figure 1.2 provides a global graphical representation of the connections between the midpoint and endpoint indicators.

2.3.10 THE CHARACTERISATION FACTORS

ReCiPe 2008 yields a large amount of numbers, arranged in a number of long tables. These tables have not been placed in this report, as they would take hundreds of pages, and most users would prefer a digital readable form. Therefore, the characterisation factors have been tabulated in an MS-Excel spreadsheet which is placed on the website of ReCiPe 2008, hosted at the Dutch RIVM [www.lcia-recipe.info].

One central result of the project are the quantitative links between the midpoint and the endpoint categories; see also Table 2.8. In several linkages a distinction has been made into different perspectives. These perspectives are marked as I (individualist) H (hierarchist) and E (egalitarian. The backgrounds of this differentiation are explained in Section 0

Table 2.9: The quantitative connection between midpoint and endpoint categories (the factors Q_{em}*) for three perspectives: individualist (I), hierarchist (H), and egalitarian (E).*

Midpoint impact category		**Endpoint impact category***		
abbr.	**Unit**	**HH (yr)**	**ED (yr)**	**RC ($/yr)**
CC	kg (CO_2 to air)[10]	$1.19\times10^{-06\dagger}$ (I) 1.40×10^{-06} (H) 3.51×10^{-06} (E)	$8.73x10^{-6}$ (I+H) $18.8x10^{-6}$ (E)	0
OD	kg (CFC-11 to air)	See below	0	0
TA	kg (SO_2 to air)	0	$1.52x10^{-9}$ (I) $5.8\ x10^{-9}$ (H) $14.2x10^{-9}$ (E)	0
FE	kg (P to freshwater)	0	$4.44x10^{-8}$	0
ME	kg (N to freshwater)	0	0	0
HT	kg (14DCB to urban air)	7.0×10^{-7} (I, H, E)	0	0
POF	kg (NMVOC to urban air)	3.9×10^{-8}	0	0
PMF	kg (PM_{10} to air)	2.6×10^{-4}	0	0
TET	kg (1,4-DCB to ind, soil)	0	$1.3x10^{-7}$ (I, H, E)	0
FET	kg (1,4-DCB to freshwater)	0	2.6×10^{-10} (I, H, E)	0
MET	kg (1,4-DCB to marine water)	0	4.2×10^{-14} (I, H, E)	0
IR	kg (U235 to air)	1.64E-08	0	0
ALO	$m^2\times$yr (agricultural land)	0	–	0
ULO	$m^2\times$yr (urban land)	0	–	0
NLT	m^2 (natural land)	0	–	0
WD	m^3 (water)	0	0	NA
MD	kg (Fe)	0	0	0.0715
FD	kg (oil)	0	0	7.28 (I) 16.07 (H+E)

** Empty cells correspond to missing links (see also 0), and are effectively implemented as zeros in practical calculations.*
† One should read this as follows: to convert a midpoint indicator for CC (in kg) into a (contribution to an) endpoint indicator for HH (in yr), multiply by 1.19×10^{-06} *yr/kg.*

For Ozonelayer depletion, we have not calculated a single mid to endpoint characterisation factor, but in stead we have a different factor for different subgroups of ozone depleting substances.

ODS group	**egalitarian/ hierarchist**	**individualist**
CFCs	$1.76\cdot10^{-3}$	$4.13\cdot10^{-4}$
CCL_4	$3.30\cdot10^{-3}$	$8.25\cdot10^{-4}$
CH_3CCl_3	$4.41\cdot10^{-3}$	$1.09\cdot10^{-3}$
Halons	$2.64\cdot10^{-3}$	$6.26\cdot10^{-4}$
HCFCs	$3.65\cdot10^{-3}$	$8.82\cdot10^{-4}$
CH_3Br	$4.72\cdot10^{-3}$	$1.12\cdot10^{-3}$

2.3.11 MISSING MIDPOINT AND ENDPOINT CATEGORIES

ReCiPe 2008 has been designed primarily as an attempt to align the CML 2002 midpoint and the Eco-indicator 99 systems. As such, no attempts have been made to accommodate or elaborate impact categories that are missing in either of these methodologies. At the midpoint level, important missing aspects are:

- erosion
- salination
- noise

[10] An intermediate step was inserted that link the release of one kg CO2 to a (temporary) temperature increase. This factor is 1.064E-13 (°C.year.kg-1) and is used for both the human HH and ED. There is no differentiation in perspectives

- light

At the endpoint level, we have already mentioned:

- damage to the man-made environment.

The authors acknowledge the importance of including (an aligning) these and other impact categories in future studies.

2.3.12 MISSING AND INCOMPLETE LINKS BETWEEN MIDPOINT AND ENDPOINT CATEGORIES

As indicated in Table 2.8, not all links between midpoint and endpoint categories have been established in ReCiPe 2008. A main drawback to our methodology is the absence of an endpoint model for marine eutrophication. Other identified issues are the links between the impacts of ozone depletion, photochemical oxidant formation, ionising radiation on ecosystem diversity and water depletion.

However, a number of links have been established in an incomplete manner. For example, when modelling the human health effects of climate change, choices have to be made on the mechanisms that are to be included. The chapters in this report on the impact categories discuss these weak points in more detail.

2.4 DEALING WITH UNCERTAINTIES AND ASSUMPTIONS: SCENARIOS

It is obvious that the characterisation models are a source of uncertainty: the relationships modelled reflect our incomplete and uncertain knowledge of the environmental mechanisms that are involved in climate change, acidification, etc. In ReCiPe 2008, like in Eco-indicator 99, it has been decided to group different sources of uncertainty and different choices into a limited number of perspectives or scenarios, according to the "Cultural Theory" by Thompson 1990.

Three perspectives are discerned:

individualist (I)
hierarchist (H);
egalitarian (E).

These perspectives do not claim to represent archetypes of human behaviour, but they are merely used to group similar types of assumptions and choices. For instance:

- Perspective I is based on the short-term interest, impact types that are undisputed, technological optimism as regards human adaptation.
- Perspective H is based on the most common policy principles with regards to time-frame and other issues.
- Perspective E is the most precautionary perspective, taking into account the longest time-frame, impact types that are not yet fully established but for which some indication is available, etc.

Table 2.10 and Table 2.11 shows the details of the environmental mechanism specific choices and assumptions that differ across the three perspectives, for environmental mechanism one and two of the models.

Table 2.10: Overview of choices for the three perspectives for environmental mechanism 1(see Figure 1.1), leading to each midpoint impact category.

To midpoint impact category:	**Perspectives** **I**	**H**	**E**
climate change	20-yr time horizon	100 yr	500 yr
ozone depletion	–	–	–
terrestrial acidification	20-yr time horizon	100 yr	500 yr
freshwater eutrophication	–	–	–
marine eutrophication	–	–	–
human toxicity	100-yr time horizon organics: all exposure routes metals: drinking water and air only only carcinogenic chemicals with TD_{50} classified as 1, 2A, 2B by IARC	infinite all exposure routes for all chemicals all carcinogenic chemicals with re-ported TD_{50}	infinite all exposure routes for all chemicals all carcinogenic chemicals with re-ported TD_{50}
photochemical oxidant formation	–	–	–
particulate matter formation	–	–	–
terrestrial ecotoxicity	100-yr time horizon	infinite	infinite
freshwater ecotoxicity	100-yr time horizon	infinite	infinite
marine ecotoxicity	100-yr time horizon sea + ocean for organics and non-essential metals. for essential metals the sea compartment is in-cluded only, excluding the oceanic compart-ments	infinite sea + ocean for all chemicals	infinite sea + ocean for all chemicals
ionising radiation	100-yr time horizon	100,000 yr	100,000 yr
agricultural land occupation	–	–	–
urban land occupation	–	–	–
natural land transformation	–	–	–
water depletion	–	–	–
mineral resource depletion	–	–	–
fossil fuel depletion	–	–	–

Table 2.11: Overview of choices for the three perspectives for environmental mechanism 2(see Figure 1.1), between midpoint and endpoint level.

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From midpoint impact category:	**Perspective** I	**H**	**E**
climate change	full adaptation: no cardiovascular risks no malnutrition low-range RR for natural disasters	mean adaptation: mean relative risk for all mechanisms no Diarrhoea: if GDP >6000 $/yr	no adaptation: high cardiovascular risks high risk for disasters high risk for malnutrition
climate change	dispersal of species assumed	dispersal	no dispersal
ozone depletion	–	–	–
terrestrial acidification	20-yr time horizon	100 yr	500 yr
freshwater eutrophication	NA	NA	NA
human toxicity			
photochemical oxidant formation	–	–	–
particulate matter formation	–	–	–
terrestrial ecotoxicity			
freshwater ecotoxicity			
marine ecotoxicity			
ionising radiation	–	–	–
land occupation	Positive effects of land expansion are considered	Fragmentation problem considered	No positive effects of land expansion considered
land transformation	Maximum restoration time is 100 yr	Mean restoration times	Maximum restoration times
water depletion	NA	NA	NA
mineral resource depletion	–	–	–
fossil fuel depletion	time horizon – 2030	For coal: time horizon – 2030 For all other fossils: 2030-2080	For coal: time horizon – 2030 For all other fossils: 2030-2080

2.5 IMPACT CATEGORIES AND ENVIRONMENTAL ISSUES

Throughout this report, we use a term like impact category in a technical way, either to midpoint categories that are modelled with midpoint indicators, or to endpoint categories that are modelled with endpoint indicators. This, however, is not always the most appropriate way of discussing the models, assumptions and results of ReCiPe 2008. For instance, there is a model for toxic impacts which describes the pathways (the fate) of chemicals, their intake by humans, and the effects on humans and ecosystems. Midpoint categories involved are human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity, while endpoint categories are damage to human health and damage to ecosystem diversity. It would not be convenient to devote separate chapters to the midpoint and/or endpoint categories in this case, but to have a chapter on toxicity instead, which address the various midpoints and endpoints involved.

The next chapters are written from that perspective. They address environmental issues, such as toxicity and eutrophication, without paying regard to the exact midpoint and endpoint categories in their structure. As such, the structure of the following chapters is shown in Table 2.12.

Table 2.12: Overview of the relation between environmental issues (chapters), midpoints and endpoints.

Chapter	Environmental issue	Midpoints covered	Endpoints covered
3	climate change	CC	HH, ED
4	ozone depletion	OD	HH
5	acidification	TA	ED
6	eutrophication	FE, ME	–
7	toxicity	HT, TET, FET, MET	HH, ED
8	human health damage due to PM_{10} and ozone	POF, PMF	HH
9	ionising radiation	IR	HH
10	land use	ALO, ULO, NLT	ED
11	water depletion	WD	–
12	mineral resource depletion	MRD	RA
13	fossil fuel depletion	FD	RA

2.6 CHARACTERISATION IN PRACTICE: A RECIPE

This report presents a structure for LCIA and information on models to address specific environmental issues. For some of these issues, characterisation factors are included in this report, but for other issues, such factors would amount to thousands of numbers. These have been made available in digital form; see [www.lcia-recipe.info]. The use of these characterisation factors in an LCA study proceeds according to the procedures described below.

2.6.1 CHARACTERIZATION AT THE MIDPOINT LEVEL

For characterization at the midpoint level, the formula is

$$I_m = \sum_i Q_{mi} m_i \tag{2.7}$$

where m_i is the magnitude of intervention i (e.g., the mass of CO_2 released to air), Q_{mi} the characterisation factor that connects intervention i with midpoint impact category m, and I_m the indicator result for midpoint impact category m. A template of a table for reporting the results of the calculation is given in Table 2.13.

Table 2.13: Template for reporting characterization at the midpoint level.

Midpoint category	Value	Unit
CC	*to be inserted by LCA practitioner*	kg (CO_2 to air)
OD	*to be inserted by LCA practitioner*	kg (CFC-11 to air)
TA	*to be inserted by LCA practitioner*	kg (SO_2 to air)
FE	*to be inserted by LCA practitioner*	kg (P to freshwater)
ME	*to be inserted by LCA practitioner*	kg (N to freshwater)
HT	*to be inserted by LCA practitioner*	kg (14DCB to urban air)
POF	*to be inserted by LCA practitioner*	kg (NMVOC to urban air)
PMF	*to be inserted by LCA practitioner*	kg (PM10 to air)
TET	*to be inserted by LCA practitioner*	kg (14DCB to soil)
FET	*to be inserted by LCA practitioner*	kg (14DCB to freshwater)
MET	*to be inserted by LCA practitioner*	kg (14DCB to marine water)
IR	*to be inserted by LCA practitioner*	kg (U235 to air)
ALO	*to be inserted by LCA practitioner*	$m^2 \times yr$ (agricultural land)
ULO	*to be inserted by LCA practitioner*	$m^2 \times yr$ (urban land)
NLT	*to be inserted by LCA practitioner*	m^2 (natural land)
WD	*to be inserted by LCA practitioner*	m^3 (water)
MD	*to be inserted by LCA practitioner*	kg (Fe)
FD	*to be inserted by LCA practitioner*	kg (oil)

2.6.2 CHARACTERIZATION AT THE ENDPOINT LEVEL

There are two ways to proceed for characterisation at the endpoint level. The first approach starts from the intervention, without any calculation of the intermediate midpoints. The formula is

$$I_e = \sum_i Q_{ei} m_i \tag{2.8}$$

where m_i is the magnitude of intervention *i* (e.g., the mass of CO_2 released to air), Q_{ei} is the characterisation factor that connects intervention *i* with endpoint impact category *e* and I_e is the indicator result for endpoint impact category *e*.

The second approach starts from the intermediate midpoints. The formula is

$$I_e = \sum_m Q_{em} I_m \quad (2.9)$$

where I_m is the indicator result for midpoint impact category *m*, Q_{em} is the characterisation factor that connects midpoint impact category *m* with endpoint impact category *e* and I_e is the indicator result for endpoint impact category *e*.

A template of a table for reporting the results of the calculation is given in Table 2.14.

Table 2.14: Template for reporting characterisation at the endpoint level.

Endpoint category	Value	Unit
HH	*to be inserted by LCA practitioner*	yr
ED	*to be inserted by LCA practitioner*	yr
RA	*to be inserted by LCA practitioner*	$

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3 CLIMATE CHANGE

An De Schryver en Mark Goedkoop[11]

3.1 INTRODUCTION

Climate change causes a number of environmental mechanisms that affect both the endpoint human health and ecosystem health. Climate change models are in general developed to assess the future environmental impact of different policy scenarios. For ReCiPe 2008, we are interested in the marginal effect of adding a relatively small amount of CO_2 or other greenhouse gasses, and not the impact of all emissions. Only very few researchers have made models for the marginal effect. The best known is the Fund model (Tol, 2002), which is also used in the Eco-indicator 99 (Goedkoop and Spriensma, 1999). For ReCiPe 2008, we tried to use a later version of the Fund model, but although the model is public available, the documentation is too limited to understand what the assumptions are and how to change assumptions and interpret the results.
With no models readily available, we use a simplified approach based on already available literature. The benefit of this approach is that we can rely on well-established and widely accepted studies. The disadvantage was that we had to accept many assumptions made in these studies.

The environmental mechanisms used for this impact category have a somewhat different structure, from the fate, effect and damage steps applied elsewhere. We apply the following steps:

Step 1: radiative forcing. A significant difference with other damage models is the development of the damage model for the endpoints for CO_2 only. The other substances in the category are taken into account using the IPCC equivalence factors. These equivalence factors take into account the radiative forcing of the substances and the residence time. In other words, the equivalence factors express a combined fate and (partial: up to the midpoint) effect step. We use the IPCC equivalence factors for direct effects from the 2007 report. These equivalency factors are used as the midpoint characterisation factors.

Step 2: temperature effect. The residence time and the radiative forcing of CO_2, as well as several other factors, link the emission of CO_2 to a temperature increase. Almost all studies we found correlate an emission scenario (emissions per year) with a temperature change. For our project we need the link between an emission, expressed as mass load and a (temporary) temperature increase. We found this relation in the work of Meinshausen (2005), who analysed the effect of mitigation measures in a wide range of climate models.

Step 3a: damage to human health. This is modelled using the work 'Climate change and Human health – risks and responses' Published by WHO, WMO and UNEP (McMichael et al., 2003) and 'Comparative Quantification of Health Risks: Global and regional Burden of Diseases Attributable to Selected Major Risk Factors' published by WHO (Ezzati, 2004). These reports describe how the health risk increases as a function of temperature increase for five different health effects in different world regions. This increase is combined with the current global burden of disease published by WHO in 1996 (Murray) to calculate the DALY's.

Step 3b: damage to ecosystem diversity. This is modelled using the work of Thomas, C.D 'Extinction risk from climate change' published in 2004. This study predicts the extinction of species on a global scale from three scenarios. It uses the area species relationship we also use in land-use, and it is a compilation of several regional studies.

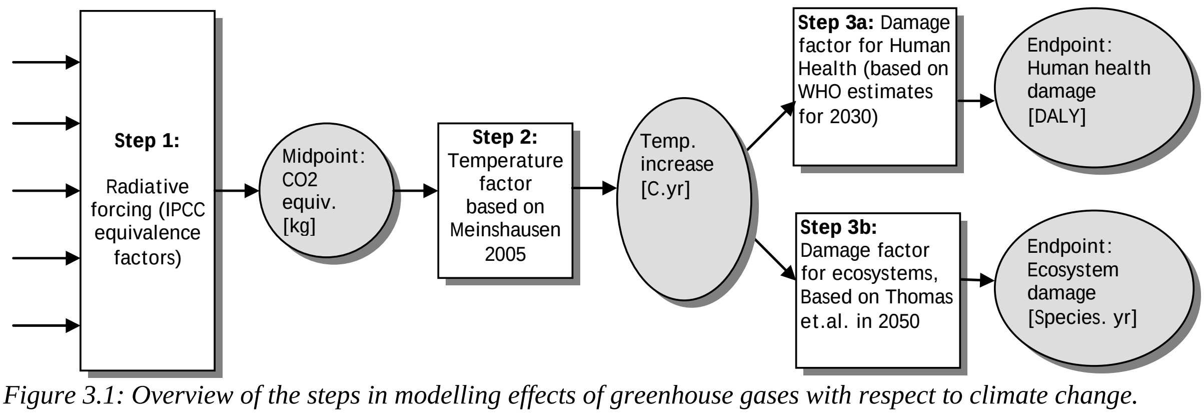


Figure 3.1: Overview of the steps in modelling effects of greenhouse gases with respect to climate change.

[11] Corresponding author (goedkoop@pre.nl).

3.2 STEP 1: RADIATIVE FORCING

3.2.1 GLOBAL WARMING POTENTIALS

For the midpoint methodology, we use the commonly accepted CO_2 equivalency factors published in the IPCC report 2007. These CO_2 equivalency factors are calculated using next formula:

$$GWP_{x,T} = \frac{\int_0^T a_x \times [x(t)]dt}{\int_0^T a_r \times [r(t)]dt} \tag{3.1}$$

Where $GWP_{x,T}$ stands for the global warming potential of substance x, T is the time horizon over which the calculation is considered, a_x is the radiative efficiency due to a unit increase in atmospheric abundance of the substance in question (i.e., Wm-2 kg-1), $[x(t)]$ is the time-dependent abundance of substance x, and the corresponding quantities for the reference gas are in the denominator. The GWP of any substance therefore expresses the integrated forcing of a pulse (of given small mass) of that substance relative to the integrated forcing of a pulse (of the same mass) of the reference gas over some time horizon. The numerator of the equation is the absolute (rather than relative) GWP of a given substance, in this case CO_2. The GWPs of various greenhouse gases can then be easily compared to determine which will cause the greatest integrated radiative forcing over the time horizon of interest. The direct relative radiative forcing per ppbv (part per billion, volume basis) are derived from infrared radiative transfer models based on laboratory measurements of the molecular properties of each substance and considering the molecular weights.

The equivalency factor is dependent on the timeframe considered. If a substance has a lifetime comparable to CO_2, the equivalence factor is relatively insensitive to the timeframe, but for substances with a significant higher or lower lifetime, the equivalency factors vary significantly. For all substances, except CO_2, the lifetime is determined by the atmospheric chemistry. The lifetime for CO_2 is mainly determined by the effectiveness of carbon sinks.

3.2.2 CULTURAL PERSPECTIVES

The selection of the timeframe is a subjective choice that depends on the perspective. We will use the following choices:

- The Hierarchist perspective seeks consensus, and the 100 year timeframe is the most frequently used. For instance it is referenced to in the ISO standards on LCA (14044)
- The Egalitarian world view takes a long term perspective, so we assume the 500 year timeframe. A longer timeframe would even be more desirable in this perspective, but as the atmospheric lifetime of the substances does not exceed 500 years, a longer time perspective would give the same results
- The Individualist perspective assumes a sort time frame, and thus we use the 20 year time frame.

This choice does not affect the characterisation factor of CO_2, but does have significant influence on the importance of methane (more important for individualist perspective) and for instance NF_3 (more important for egalitarian perspective).

3.3 STEP 2, TEMPERATURE FACTOR

The relation between the release of a certain emission flow of CO_2 and the effect on the temperature can be described as:

$$TF = LT_{CO2} \times \frac{\Delta TEMP_t}{\sum_t E_{CO2}} \tag{3.2}$$

With TF the temperature factor for 1kg of CO_2 (in °C.year.kg-1), LT_{CO2} the lifetime of CO_2 (year), $\Delta TEMP_t$ the change in average temperature between the current situation (year 2000) and the situation in year t (°C) and E the annual mass of CO_2 (kg/yr)

The first part of the temperature factor is the lifetime of CO_2. The lifetime of CO_2 is not determined by chemical processes in the atmosphere, but by the effectiveness of sinks. These are dependent on many factors such as the emission levels and the damages already inflicted on the sinks. The IPCC 2001 report specifies an estimated lifetime of CO_2 of 150 years. This figure will be used in our calculations.

The second part of the temperature factor is the change in temperature caused by a certain emission during a certain time period. Meinshausen (2005) investigated this by looking at the impact of mitigation (defined as an avoided emission of carbon over a time period t) on temperature. He found the change in temperature between current situation and the situation in year t, factor $\Delta TEMP_t$, can be calculated as follows:

$$\Delta TEMP_t = c \times \sum_t E_{CO2} \tag{3.3}$$

In which the term *c* (°C/kg) represents the mitigation sensitivity, and *E* the annual mass of carbon mitigated, summed over the period during which the mitigation takes place; the summation of E over t can be interpreted as the cumulative amount mitigated up to year t and thus the term *c* is the factor that represents the change in temperature due to a mitigated mass.

Meinshausen (2005) made a correlation study and analysed the predicted effectiveness of mitigating the emissions of CO_2 (published in Hare and Meinshausen 2006). He compared numerous climate models. Figure 3.2 gives an overview of these studies. The dotted line (labelled "current") shows the mitigation effect at year t. The "equilibrium" line represents the mitigating effect that would hypothetically occur if the climate system would come to equilibrium with the radiative forcing levels in year *t*. Because the latter includes the total temperature effect of a mitigated amount of carbon, we use the equilibrium line.

In the equilibrium situation *c*(carbon) =2.6 E-15 [°C/kg]. This results in *c*(CO_2) = 7.09E-16[°C/kg].

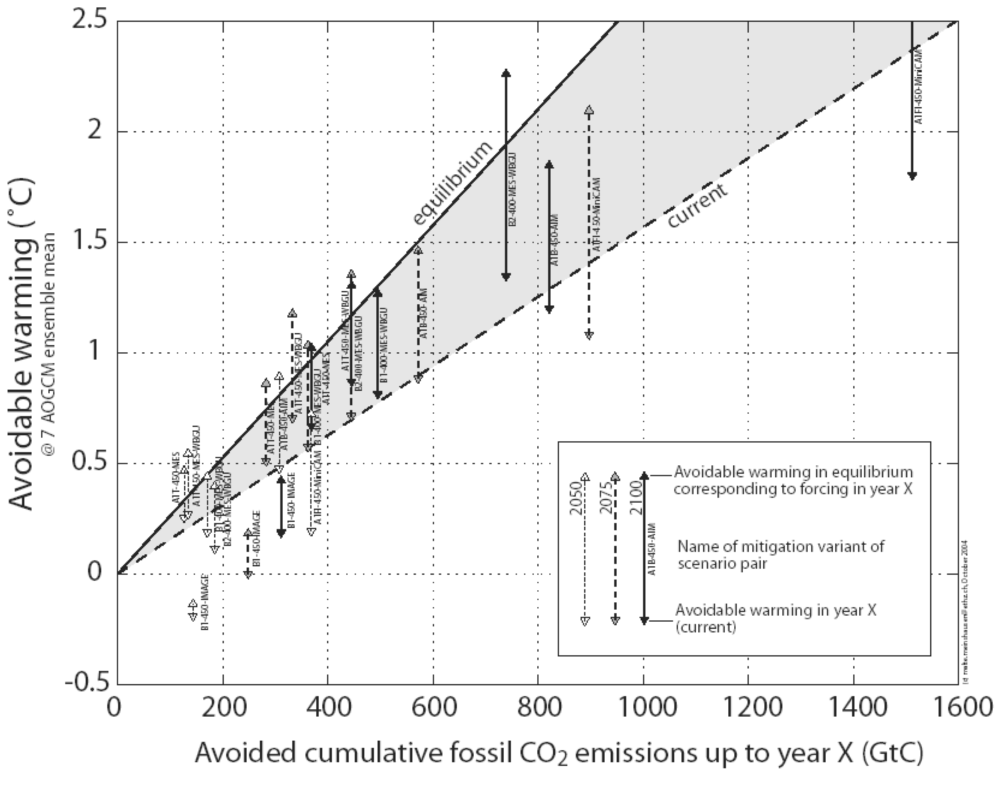


Figure 3.2: Benefits of mitigation by different climate models. The dotted line represents the effect in the current situation in year t, only taking into account the avoidable warming taking place at year t. The full line represents the equilibrium situation, including the growing avoided warming beyond year t of emission, due to the inertia of the system. (figure directly taken from Hare and Meinshausen, 2005).

As a result, the relation between CO_2 emission and temperature change depends on the mitigation sensitivity of CO_2. The second part of the temperature factor can be written as:

$$\frac{\Delta TEMP_t}{\sum_t E} = \frac{c \times \sum_t E_{\mathrm{CO2}}}{\sum_t E_{\mathrm{CO2}}} = c \tag{3.4}$$

The temperature factor for CO_2 can be calculated combining formula (3.2) and (3.4) :

$$TF = 7.09\mathrm{E}-16 \times 150 = 1.064\mathrm{E}-13^{\circ}\mathrm{C} \times \mathrm{yr} \times \mathrm{kg}^{-1} \tag{3.5}$$

De Schryver at al (2008) derived the temperature factor for CO_2 and 62 other greenhouse gases with a flux-based approach:

$$\frac{dTEMP}{dE_x} = \frac{dC_x}{dE_x} \times \frac{dRF}{dC_x} \times \frac{dTEMP}{dRF} = LT_x \times \alpha$$

where dE_x is the emission change of greenhouse gas x to the air (kg/year), dC_x the change in concentration of greenhouse gas x in the air (ppb), dRF is the change in radiative forcing (W/m2) of the atmosphere, and LTx the residence time of greenhouse gas x in the air. The first two factors are based on GHG-specific information given in IPCC (2007), while the change in temperature due to a change in radiative forcing has been calculated with the IMAGE model.

If we assume a lifetime for 150 years for CO_2 , the factor α, which is the increase in temperature per increase in mass in the air, is 0.47E-13ºC.yr /kg_{CO2} , according to De Schryver et al. (2008). Based on the results by Meinshausen, we find a factor of 1.064E-13 ºC.yr/kg_{CO2}, which is a factor 2.5 higher.

The advantage of the method developed by De Schryver et al (2008) is that the calculation procedure links up with the flux-based calculation procedures employed for other impact categories, including toxicity and acidification. Another advantage is that the temperature factors are consistently derived for all greenhouse gases, i.e. using the full atmospheric life time, while the pulse-based approach derived temperature factors with the full life time of CO_2, but using the GWP100 for all other GHGs. Particularly for GHGs with long atmospheric residence times, including N_2O, the temperature factors are underestimated by the pulse-based approach. An important advantage, however, of the pulse-based approach is that the the figure from Meinshausen are based on the grand average of a large number of climate models, while De Schryver et al (2008) based part of there calculations on one climate model only, i.e. IMAGE. Although the conversion factor used in the flux-based calculations of 0.34-0.67 ^{0}C/(Wm−2) falls in the range reported by Fuglestvedt et al. (2003), we prefer the model robustness of the pulse-based approach and recommend this model for further use in LCA practice [12].

3.4 STEP 3A, DAMAGE TO HUMAN HEALTH

Climate change has different effects on human health. Some direct effects are heat waves, air pollution and aeroallergens. Whereas, infectious diseases (vector-borne or water-borne), malnutrition, social and economic disruption are examples of indirect effects. The frequency and intensity of each effect is region and time dependent. Differentiation in the way regions are protected by natural (buffer capacity) or social economic (available income) factors, makes it necessary to calculate the damage of climate change for each region separately. Furthermore, effects taking place on a large timescale can give humans the possibility to adapt, and so create less damage than effects taking place on a small timescale. But overall, it is clear that human health is sensitive to climate variations and that long-term climate change will have some effect, positive or negative, on the global population health.

This chapter outlines the assessment of human health impact caused by climate change at global level, based on five different health effects (see Table 3.2). The main source data and model information is the WHO report ‘climate change and human health’ (McMichael et al., 2003). We selected this basis, as we can assume a broad consensus regarding the assumptions and models. The disadvantage of using such a report is that it does not cover the latest findings, and in some cases more explanation about the assumptions made would be grateful. Another disadvantage is the incorporation of only five health effects, while it is clear that more effects take place. Table 3.1 gives an overview of some important effects and specifies which effects are taken into account. Until now, it is unclear how important the other health effects are.

[12] We thank Olivier Jolliet for helping us to understand the similarities and differences between the pulse-based and flux-based approach better.

Table 3.2: Listed health effects, linked to climate change. Note that this list is incomplete.

Health effects	Analyzed in this report	Not considered
Malnutrition	1.	
Diarrhoea	2.	
Cardiovascular diseases	3.	
Respiratory problems		x
Natural disasters		x
Cyclones		x
Coastal and inland flooding	4.	
Droughts		x
Vector borne diseases		
Malaria	5.	
Dengue		x
Yellow fever		x
Rodent borne diseases		
Leptospirosis		X
Encephalitis		X
Lime		X

3.4.1 DAMAGE FACTOR FOR HUMAN HEALTH

The endpoint damage factor for human damage due to climate change links the marginal changes in temperature to marginal changes in DALY. This factor can be defined as:

$$DF_{HH} = \frac{\Delta IMPACT}{\Delta TEMP} = \frac{\Delta Att.B_{tot}}{\Delta T} \quad (3.6)$$

With DF_{HH} the damage factor for human health [DALY/yr.°C], ΔT the marginal difference in temperature rise between the baseline scenario (1990) and the emission scenario chosen for 2030, and $\Delta Att.B_{tot}$ the marginal change in attributable burden of a population of getting a disease, depending on the scenario chosen for 2030.

The attributable burden can be defined as:

$$Att.B_{r,h} = (RR_{r,h} - 1) * BoD_{r,h} \quad (3.7)$$

With $Att.B_{r,h}$ the attributable burden in region r and for health effect h, during one year, RR the relative risk for the chosen emission scenario and BoD the burden of disease, each for region r and health effect h, during one year. The BoD can be described as the number of DALYs lost to disease for the risk factor of interest, during reference period 1990.

$$Att.B_{tot} = \sum Att.B_{r,h} \quad (3.8)$$

Where $Att.B_{tot}$ represents the global attributable burden, for all health effects, due to a certain temperature rise.

The relative risk factors (RR) depend on the chosen emission scenario. As a result, also Δtemp depends on the emission scenarios chosen. The RR factors are calculated for three different emission scenarios (Hadley Centre, 2002):

- The IS92a or unmitigated scenario, which assumes the current trend is followed. This results in effective CO_2 concentration increasing at 1% per year after 1990.
- The S750 scenario, which assumes that the CO_2 concentration will stabilize on a level of 750 ppm by about 2210. This scenario results in a stabilized temperature increase of about 4 degrees.
- The S550 scenario, which assumes that the CO_2 concentration will stabilize on a level of 550 ppm by about 2170. This scenario results in a stabilized temperature increase of about 3 degrees.

The damage factor represents the slope of the DALY curve as a function of the temperature, which depends of the emission scenarios chosen (see Figure 3.2). Which emission scenarios to chose will be discussed in the perspectives (Section 3.4.2).

The RR factors come from the WHO report ‘climate change and human health’ (McMichael et al., 2003). This report presents RR for six different world regions and five health effects. Because climate change is a global issue, we consider the risk in each region separately. The DALYs of the reference period 1990 are derived from the report ‘The Global Burden of Disease’ (Murray, and Lopez, 1996).

3.4.2 CULTURAL PERSPECTIVES

For some effects of climate change, for example cardiovascular diseases and natural disasters, data is presented that gives us the possibility whether or not to consider the human ability to adapt (see Table 3.3). Two kinds of adaptations are presented by the WHO report: Biological adaptation and socioeconomic adaptation. Socioeconomic adaptation, described as a protection against an effect, evolves over time in proportion with the projected increases in Gross Domestic Product (GDP). For cardiovascular diseases we have data with and without the consideration of human biological adaptation. Although the possibility of this form of adaptation is supported by studies on various United States' cities, it is not yet quantified as a global representation for a range of populations.

Table 3.3: Assumptions on adaptation and vulnerability (McMichael et al., 2003).

	Biological adaptation affecting RRs	**Socioeconomic adaptation affecting RRs**
Direct physiological effects of heat and cold	Yes. Temperature associated with lowest mortality was assumed to change directly with temperature increases driven by climate change	None
Diarrhoea	None	Assumed RR=1 if GDP per capita rises above US$6000/year
Malnutrition	None	Food-trade model assumed future increases in crop yields from technological advances, increased liberalization of trade, and increased GDPb
Disasters: coastal floods	None	Model assumed the RR of deaths in floods decreases with GDP, following Yohe and Tol (2002)
Disasters: inland floods and landslides	None	Model assumed the RR of deaths in floods decreases with GDP, following Yohe and Tol (2002)
Vector-borne diseases: malaria	None	None (for RR)

During the analysis of malnutrition another, unmentioned assumption was discovered. We found that the damage arising for the unmitigated scenario (1,2°C) is lower than for the S750 scenario (0,7°C) (see supporting information). Unfortunately, no clear explanation can be found in the reports, except for a remark that hints at a higher economic growth at an unmitigated emission scenario. This would indicate that the economic development is actually more important than climate change.

When we look at the three perspectives, presented in Table 3.4, three total different assumptions are made.

Table 3.4: Assumptions made for the three perspectives.

Individualist	**Hierarchist**	**Egalitarian**
Full adaptation:	Mean adaptation:	No adaptation:
no cardiovascular risks	Everything included	High cardiovascular risks
no malnutrition	Mean relative risk	High risk for disasters
Low-range RR for natural disasters	Diarrhoea: RR=1 if GDP > 6000 $/yr	High risk for malnutrition

The individualist perspective coincides with the view that mankind has a high adaptive capacity through technological and economic development, that nature is benign and that a short time perspective is justified. For the individualist perspective, we assume a damage factor based on full adaptation. Full adaptation includes a total adaptation to rising temperatures which results in no higher number in heat strokes, a low risk for natural disasters, due to the higher ability of protection and no malnutrition due to high economic growth.

The egalitarian perspective coincides with the view that nature is strictly accountable, that a long time perspective is justified, and that the worst case scenario and preventive thinking are needed (the precautionary principle). For these reasons, ecosystem adaptation is not taken into account, while the management style is preventive. This results in a damage factor based on a maximum risk for cardiovascular diseases, a high risk for natural disasters and a high risk for malnutrition, both without any assumed adaptation. All other effects are set at mid level risk.

The Hierarchist perspective coincides with the view that impacts can be avoided with proper management, and that the choice on what to include in the model is based on the level of (scientific) consensus.. Because a certain level of adaptation is scientifically accepted but the ability of total adaptation is not being proved yet, we assume mean adaptation for the hierarchist perspective.

3.4.3 RESULTS

According to the method, presented above, for each health effect the attributable burden could be calculated. Following our assumptions of the three perspectives the total attributable burden is calculated and presented in Table 3.5.

Table 3.5: The Attributable burden (kDALY/yr = 1000DALY/yr), ΔTemp and damage factor for the three perspectives. The temperature rise, in accordance with the different emission scenarios, derives from Ezzati, M. (2004). Because the data provides only temperature information for the years 1990, 2020 and 2050, a linear relationship is assumed to calculate the temperature rise in 2030.

Item	**Individualist**			**Hierarchist**			**Egalitair**		
Region	S550	S750	Unmit.	S550	S750	Unmit.	S550	S750	Unmit.
Gton C	326	370	436	326	370	436	326	370	436
Temp rise	0.50	0.68	1.20	0.50	0.68	1.20	0.50	0.68	1.20
Scenario	1	2	3	1	2	3	1	2	3
Cardiovasc.	0.0E+00	0.0E+00	0.0E+00	5.4E+02	5.6E+02	8.0E+02	1.1E+03	1.1E+03	1.6E+03
Diarrhoea	1.1E+04	1.2E+04	1.6E+04	1.1E+04	1.2E+04	1.6E+04	1.1E+04	1.2E+04	1.6E+04
Malnutrition	0.0E+00	0.0E+00	0.0E+00	4.3E+03	8.1E+03	5.4E+03	4.3E+03	8.1E+03	1.9E+04 *
Malaria	2.8E+03	3.5E+03	5.4E+03	2.8E+03	3.5E+03	5.4E+03	2.8E+03	3.5E+03	5.4E+03
Nat Disasters	1.4E+00	1.4E+00	1.9E+00	5.2E+02	5.1E+02	4.9E+02	8.7E+02	8.6E+02	8.2E+02
Totaal	1.4E+04	1.5E+04	2.1E+04	1.9E+04	2.5E+04	2.8E+04	2.0E+04	2.5E+04	4.3E+04
ΔScenario	Sc3-1			Sc 3-1			Sc3-1		
ΔTemp	0.7			0.7			0.7		
ΔAtt.b (kDALY)	7800.8			9181.1			23092.3		
DF (kDALY/ °C temp rise)	1.11E+04			1.31E+04			3.30E+04		

** Malnutrition without socioeconomic adaptation, using a linear extrapolation from S550 and S750.*

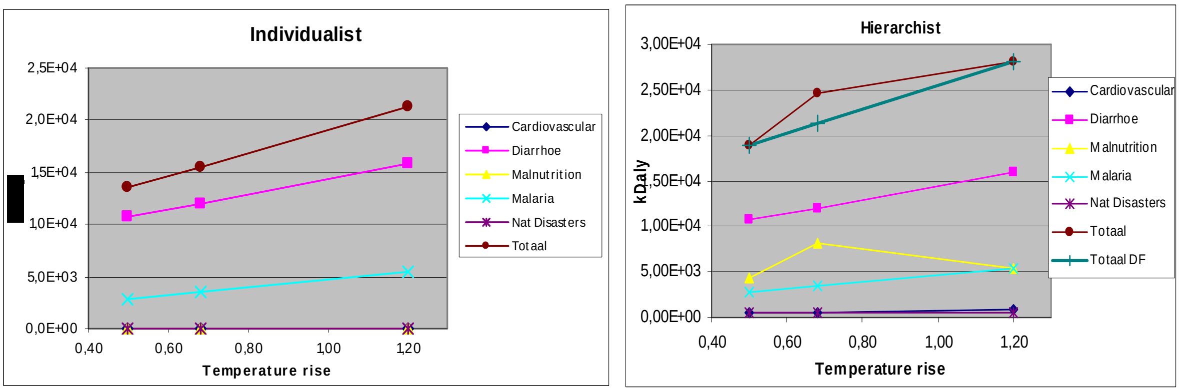


Figure 3.3: Graphical presentation of the damage factor for the individualist and hierarchist perspective.

When we look at Figure 3.3 we can generally conclude that the total attributable burden is caused mainly by the effects of diarrhoea, malaria and malnutrition. Moreover, the effects of diarrhoea play a dominant role with more than 50% of the total burden. The assessment for diarrhoea, used in the WHO report, only addresses the effects of increasing temperatures on the incidence of all-cause diarrhoea. Effects of rainfall patterns are not taken into consideration due to the difficulties in extrapolating the non-linear relationship. This means that the possibility exists that the effect of diarrhoea is even higher than represented, which underlines his dominant role. However, very few studies characterized the exposure-response curve, what results in uncertainties around these figures.

For malnutrition, the WHO used the research of Parry (1999) to predict the number of people at risk of hunger. This work estimates the effects of changes in temperature, rainfall and CO2 on the yield of grain cereals and soybean. Uncertainties around the estimates are difficult to quantify, but derives from regional variation in rainfall and socioeconomic conditions.

The significant contribution of malaria, makes it worth to discus the uncertainty of this effect. Craig et al. (1999) presented the MARA model, which uses a combination of biological and statistical approaches to discover the properties of climate demanded by Falciparum malaria. The WHO used this model to calculate the mid-range risk. Like each model it has several advantages and disadvantages, and the uncertainty is quite high. Some possible sources of uncertainty are the degree to which the African model applies to other regions and, the relationship between the population at risk and the incidence of disease. Due to socioeconomic conditions or climatically unsuitability, most temperate regions are considered to remain insensitive for Malaria. In the absence of uncertainty assessments, the work of Ezzati et al. (2004), defined the lower range as no change in risk in any sub region. This is due to the ability of adaptation. The upper range is a doubling of the mid-range estimate.

Climate change is expected to affect human health by effects of natural disasters and cardiovascular diseases. However, the overall global effect seems to be rather low in comparison with the other three effects described above. For cardiovascular diseases the limited number of studies forced the WHO to use only the changes in mortality attributable to extreme temperature for one or several days. The low burden can be a result of the compensation of cold stroke deaths by less heath stroke deaths. For natural disasters, only the effects of inland flooding, caused by intensive precipitation, and coastal flooding, driven by sea level rise, are taken into account. The estimated Relative Risks incorporate an equal impact for all age and sex groups. Effects of increasing wealth and/or individual adaptation for natural disasters were assumed and are for each perspective presented below.

Table 3.6: Ranges of estimated RR of natural disasters linked to assumptions.

Assumptions	**RR for coastal flooding**	**RR for inland flooding**
Low-range (individualist)	90% lower risk than the mid-range by highly efficient coastal defences or individual adaptation.	No increase in risk is assumed
Mid-range (hierarchist)	Incorporated increasing wealth which allows better adaptive capacity	Incorporated increasing wealth which allows better adaptive capacity
High-range (egalitarian)	No adaptation is assumed	A 50% greater risk than the mid-range and no adaptation with GDP
Comments	Uncertainties in the model relate to the degree and manner to which individuals respond.	Greater uncertainty over adaptive responses than coastal flooding, due to magnitude and temporal variation in precipitation.

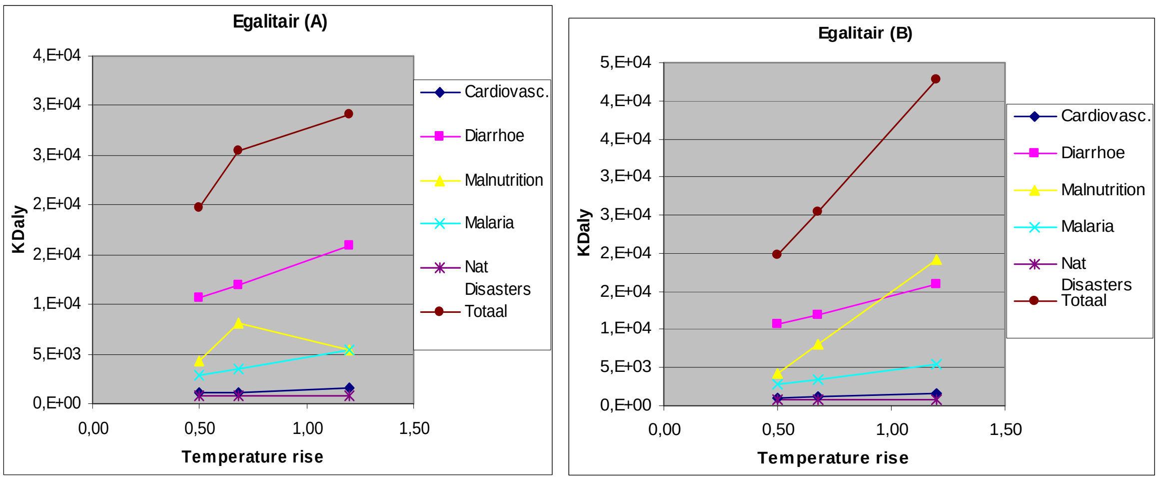


Figure 3.4: Graphic presentation of the damage factor for the egalitarian perspective. A) Presenting the WHO-report figures, B) representing the linear extrapolation for malnutrition and the effect on the total DF.

For the egalitarian perspective, the slope of the damage curve (see Figure 3.4) is steeper than that of the other two perspectives. Here, no adaptation is assumed. The results, based on the WHO-report (Figure 3.4a), makes the socioeconomic adaptation for malnutrition clearly visible. This assumption has a strong effect on the total damage factor. For the egalitarian perspective, no kind of adaptation is assumed. For this reason, an adjustment for malnutrition is made, using a linear extrapolation of the 550 and 750 scenario. This is presented in Figure 3.4b.

To calculate the endpoint characterization factor for climate change health damage [DALY/kgCO2] the temperature factor from step 2 and the damage factor from step 3a is combined:

$$CF_{HH} = TF \times DF_{HH} = LT_{co2} \times \frac{dTEMP_t}{\sum_t E_{co2}} \times \frac{\Delta IMPACT}{\Delta TEMP} \quad (3.9)$$

The endpoint characterisation factors for climate change health damage are presented in Table 3.7.

Table 3.7: Endpoint characterisation factors of human damage, due to climate change, for three perspectives in DALY/kg CO_2.

	Individualist	Hierarchist	Egalitarian
Temperature factor (°C. yr/kg CO_2)	1.064E-13	1.064E-13	1.064E-13
Damage factor ((kDALY/ °C temp rise)	1.11E+04	1.31E+04	3.30E+04
Characterisation factor	1.19E-06	1.40E-06	3.51E-06

3.5 STEP 3B DAMAGE TO ECOSYSTEM DIVERSITY

There are several pathways that link climate change to loss of species. In this chapter we will only develop the mechanism for the relation between temperature increase and loss of species on land, especially plants and butterflies. Other pathways are for instance changes in oceans and seas, the impact of coastal flooding, impacts of extreme weather etc.

We use as single literature reference the paper of Thomas et al. published in Nature in 2004. This paper summarises several studies that link extinction risk of species of several areas in relation to temperature increase in that area. The aim of the paper was to estimate the extinction rate of species in 2050, as a percentage of the total species population.

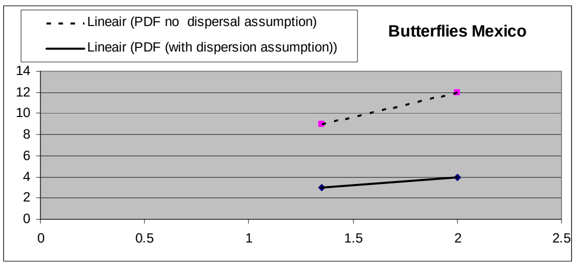
3.5.1 DAMAGE FACTOR FOR ECOSYSTEMS

The endpoint damage factor for ecosystem damage due to climate change links the marginal changes in temperature to marginal changes in disappeared fraction of species. This factor can be defined as:

$$DF_{ES} = \frac{\Delta IMPACT}{\Delta T} \times SD_{terr} = \frac{\Delta Damage_{eco}}{\Delta T} \times SD_{terr} = \frac{\Delta PDF \times area \times SD_{terr}}{\Delta T} \quad (3.10)$$

With DF_{ES} the damage factor for ecosystems [1/°C] and ΔPDF the marginal change in potentially disappeared fraction of species, area the total terrestrial area in the world, excluding areas with no species, and SD_{terr} is the species density, see also paragraph 0.

The extinction is reported for different temperatures and regions. We used these differences to calculate the slope of the extinction curve as function of the temperature. This slope expresses the PDF per ΔC temperature increase. Two examples are presented in Figure 3.5 (numbers from Thomas et al.). The examples illustrate that the slopes do not go through the origin of the graph if we take the slope between two points. As we shall see, some studies present only a single data point. In that case we calculated the slope by connecting the point with the origin. In the background information we discuss the case where all points are connected with the origin.



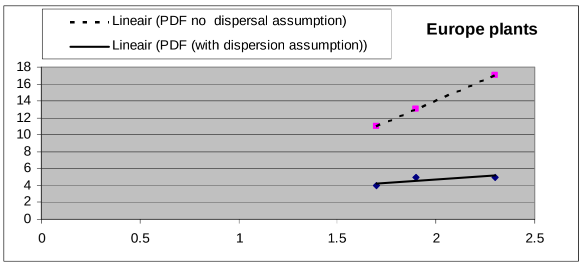


Figure 3.5: Two examples of studies that specify two or three PDF values for different temperatures and the assumed trend line. In both example the case with and without dispersal assumption is represented (graph based on data from Thomas et al., 2004).

We extrapolate the regional PDF's over the total surface of (semi) natural areas of the world, namely $10.8*10^{13}$ m^2. This number is based on the FAO Global Arable-ecological Zones database (see additional information to this chapter).

Methodology used in Thomas et al.

In Thomas et al. the total extinction of species is determined using the species area relationship, also used in Land-use modelling. The key concept is that, with a relatively rapid climate change, many habitats will be changed, and this means that for many species their habitats are reduced in size. The article describes several alternative choices and settings for the model:

- Four assumptions for the species accumulation factor (see the chapter on land use). They assume z=0.15, z=0.25, z=0.35 and z=1. This assumption has significant effects on the outcome. The authors use z=0.25 in their main calculations and we follow this assumption, which is in line with the assumptions in the land-use chapter.
- Three different interpretations for the species area relationship, plus a species area relationship in which only the red list species are included the three interpretations are necessary as climate change can influence the distribution area of each species individually, whereas in the traditional interpretation there is only one distribution area. The three interpretations are:
  1. Method 1 analyses the overall changes in distribution areas, summed across species (n). This is in line with the classical approach, but tends to overweigh specie with a large distribution.

     $$Extinctionrisk = 1 - \left(\sum A_{new} / A_{original} \right)^z \quad (3.11)$$

  2. Method 2 is based on the proportional average distribution loss of the distribution area of each species. This is faithful to the species area relationship, because halving the area will mean halving the distribution area for each species

     $$Extinctionrisk = 1 - \left\{ 1/n \left(\sum A_{new} / A_{original} \right) \right\}^z \quad (3.12)$$

  3. Method 3 estimates the extinction rate of each species in turn, averaging across species

     $$Extinctionrisk = (1/n) \sum \left\{ 1 - \left(A_{new} / A_{original} \right)^z \right\} \quad (3.13)$$

  4. Method 4 is a mixture of expert judgement and modelling. Only the endangered or “red list” species are accounted for.

  We apply method 2 in this project, as it seems most consistent with the use of the species area relationship we apply for land-use. In the additional information section, we do however also calculate the results for the other assumptions.
- Two alternative assumptions on the ability of species to disperse and migrate to other areas. When dispersal is assumed, species are thought to have the ability to disperse, from their original area to a new area that has a favourable habitat. When no dispersal is assumed, species are thought to remain where they are, and only survive in areas that show overlap between the situation before and after the climate change takes place. The difference in extinction risk under these different assumptions is significant and will be handled by the cultural perspectives.

The extinction rate is presented as a percentage of the total number of species. The article is not explicit if extinction is assumed to relate to final extinction of the species from the earth. As the studies do not cover the entire earth, we assume that extinction cannot necessarily mean total extinction, but only disappearance from the region investigated. A similar problem also occurs in other impact categories that relate to species diversity, there is always a certain change that an increase of acidification or toxicity contributes to the final extinction of a species. In the case of climate, this chance seems to be larger; especially when we would assess species in the Polar Regions, as there is no alternative habitat. As it is impossible to say to what extend the reported extinction rate is indeed a final extinction, we shall assume that the extinction simply means disappearance, and with that, we can assume that the extinction rate is similar to the Potential Disappeared Fraction (PDF).

3.5.2 CULTURAL PERSPECTIVES AND RESULTS

The paper of Thomas et al. is used to calculate the damage factor for ecosystems. Because the presented PDF values with or without the ability of dispersal are significant different, this assumption needs to be considered. We handle this uncertainty using the cultural perspectives. For the Individualist and Hierarchist perspective, we assume dispersal will take place. For the egalitarian perspective, we do not assume this.

Table 3.8 summarises the slopes for the assumptions with and without dispersal and the chosen interpretation for the species area relations (method 2). In the additional information for this chapter, also the other methods are specified.

Table 3.8: Potential disappeared fraction per 1degree temperature increase. The column with title "note" indicates how the slope is determined.

Region	**Sample (# species)**	**Assumed temperature (°C)**			**PDF[%]/°C**		**note**	**Used in final result**
		low	mid	high	With dispersal	Without dispersal		
Queensland: Mammals	11	1		3.5	16.4		1	
Queensland: Birds	13	1		3.5	18.0		1	
Queensland: Frogs	23	1		3.5	14.0		1	
Queensland: Reptiles	18	1		3.5	15.2		1	
Australia: butterflies	24	0.9	1.8	2,6	8.8	12.4	2	x
Mexico: mammals	96	1.35	2		1.5	1.5	4	
Mexico, birds	186	1.35	2		1.5	0.0	4	
Mexico: butterflies	41	1.35	2		1.5	4.6	4	x
South Africa: Mammals	5			3	10.7	12.0	3	
South Africa: Birds	5			3	9.7	11.7	3	
South Africa: Reptiles	26			3	7.3	12.0	3	
South Africa: Butterflies	4			3	2.3	15.0	3	x
Basil: Cerrado plants	163	1.35	2			13.8	4	x
Europe: birds	34			3	1.6	6.8	1	
South Africa: Proteaceae	243		2		10.5	15.0	3	x
Europe: plants	192	1.7	1.9	2.3	1.7	10.0	2	x
Average for all studies	1084				8.1	10.4		
Average for sample>100	784				4.6	12.9		
Average for plants only	598				4.6	10.9		
Average for plants and butterflies	667				5.0	11.8		

1. Difference between high and low assumption for local temperature.
2 Difference between high and low temperature for global temperature increase.
3 Only one temperature available, therefore the slope is determined by comparing zero temperature and damage with high (global) temperature.
4 Difference between mid and low assumption for global temperature.

Looking at Table 3.8, we see that in a few cases only a single temperature increase was analysed. In these cases it was impossible to create a damage curve through two points. We solved this by assuming the reference situation (no temperature increase, no damage) as the second point. The second last column indicates what we have done to determine the slope.

We averaged to the extinction rates to get a final extinction rate per ΔC, but there are a number of issues that are not satisfactory in this procedure.

- In other impact categories the PDF was calculated for plants and lower organisms only, and not mammals, reptiles and birds. One of the reasons why this choice was thought to be acceptable was that plants are generally at the start of the food chain, and disappearance of plants would have impacts on higher organisms. In the data we have, it is unclear if higher species disappear because plants disappear, or because of direct reasons.
- Several studies use a very low sample size, which means these few species get a very high weight in the average result. Especially the studies in South Africa and Queensland have very low species numbers. These studies do refer to higher organisms, and one reason for having low species numbers could be that there are fewer higher organism species than plants. As a percentage, the observed population of species may be quite reasonable.
- The data from Queensland seem to give extinction rates that are significantly higher that for other regions. In the text some references are made to destructions of habitats that are caused by other reasons, but it is not too clear if the high extinction rate is affected by these other mechanisms. In the Mexican bird study we find the surprising effect that the extinction rate is zero if no dispersal is assumed, while there is damage if dispersal is assumed.

To investigate this further we also calculated the same results while excluding all studies that use a sample size of less than 100, and that thus only includes Birds in Mexico, Cerrado plants, Proteaceae and European plants. This range does include the somewhat surprising Mexican bird study. Another calculation excluded all species except plants, in order to be more consistent with other impact categories. The disadvantage of this approach is that for the dispersal assumption we have only two studies (Europe and South Africa) while for the no dispersal assumption three studies are available (Brazilian Cerrado plants are added). To avoid having to rely on only two or three studies we added the three studies on butterflies. This does have the disadvantages that the extinction of butterflies may be related to the disappearance of plants, and that the sample sizes are small. It however, broadens the base, as now we also see the damages in Australia end Mexico. These subsets seem to give reasonable stable results, and cover more than 55% of the investigated species. We selected the results for plants and butterflies as the final choice. The result is that the PDF per ΔC is 5% when dispersal is assumed and 11.8% when no dispersal is assumed.

The damage factor for ecosystems is calculated using formula 3.10. Here we combine the results of PDF per one degree temperature increase and the amount of natural area the effect takes place. This gives the following results:
DF_{es} (with dispersal) = 0,05 (PDF/°C) * 108×10^{12} (area, m^2) * 1.38×10^{-8} (species/m^2)= 75×10^6
DF_{es} (with dispersal) = 0,118 (PDF/°C) * 108×10^{12}(area, m^2) * 1.38×10^{-8} (species/m^2) = 177×10^6

3.5.3 Endpoint characterization factor for ecosystems

To calculate the endpoint characterization factor for climate change ecosystem damage [yr/ kg CO_2] the temperature factor from step 2 and the damage factor from step 3b is combined:

$$CF_{ES} = TF \cdot DF_{ES} \tag{3.14}$$

In which TF is the temperature factor (°C.yr/kg CO_2) and DF the damage factor (1/°C)

The endpoint characterisation factors for ecosystem damage are presented in Table 3.9. For the Individualist and Hierarchist perspective, we assume dispersal will take place. For the egalitarian perspective, we do not assume this.

Table 3.9: Endpoint characterisation factors of ecosystem damage, due to climate change, for three perspectives.

Aspect	**Individualist**	**Hierarchist**	**Egalitarian**
Dispersal of species	yes	yes	no
Temperature factor (°C.yr/kg CO_2)	1.064×10^{-13}	1.064×10^{-13}	1.064×10^{-13}
Damage factor (1/°C)	75×10^6	75×10^6	177×10^6
Characterisation factor (yr/kg CO_2)	8.73×10^{-6}	8.73×10^{-6}	18.8×10^{-6}

3.5.4 DISCUSSION ABOUT THE DATA USED

To analyze the robustness of the data used, a comparison of the results of Thomas et al. with other recent published papers is made. Looking at the paper of Thuiller et al. (2005), we see that his figures are within the same range as the figures produces by Thomas et al.(2004). Although, Thuiller et al. projects distributions to 2080, while Thomas et al. projects the same temperature increase at 2050. This may indicate an overestimation of the results of Thomas et al. (2004).

The same conclusion can be drawn from the work of Malcolm et al. (2006) and van Vuuren et al. (2006). Here also, a comparison indicates high range results of Thomas et al. However, the figures of Malcom, which range from 2 to 26% extinction percentage under perfect migration and 3 to 43% under zero migration, have a very large range. This can also suggest an underestimation of the results of Malcom et al. (2006). Furthermore, Malcom et al. (2006) observed the same importance of migration at Thomas did. He observed a 1.7 fold increase in extinction rate when no migration is compared with perfect migration capabilities, which is very comparable to the 2.0 fold increase Thomas et al. observed.

Van Vuuren et al. (2006) indicates a 2-4% of species losses for 2050, which is clearly lower than the results of Thomas et al. (2004). Both studies used a species area approach. One reason for the difference is that Thomas et al. (2004) looked at case studies of individual animal and plant species, while Van Vuuren et al. (2006) looked at a global scale and the response of whole biomes to estimate the damage.

Looking at the results of other studies, we can conclude that in our figures above an overestimation of the reality is possible.

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3.7 SUPPORTING INFORMATION

Additional information on step 1: Midpoint characterisation factors

Additional information on step 3a: Human Health
Additional information on step 3b: Ecosystems

3.8 SUMMARY TABLE

Entity	**Content**
impact category	climate change
LCI results	greenhouse gases (GHG): CFCs, HCFCs, HALONs, etc.
midpoint indicator(s) (with abbreviation)	climate change (CC)
unit of midpoint indicator(s)	kg (CO_2 to air)
midpoint characterisation factor (with abbreviation)	GWP
unit of midpoint characterisation factor	– (or kg/kg)
endpoint indicator(s) (with abbreviation)	damage to human health (HH) damage to ecosystem diversity (ED)
unit of endpoint indicator(s)	HH: yr ED: yr
endpoint characterisation factor	HH: $1.19\times10^{-06\dagger}$ (I) HH: 1.40×10^{-06} (H) HH: 3.51×10^{-06} (E) ED: $8.73x10^{-6}$ (I+H) ED: $18.8x10^{-6}$ (E)
unit of endpoint characterisation factor	HH: yr/kg ED: yr/kg

4 OZONE DEPLETION

Jaap Struijs[13]*, Harm J. van Wijnen, Arjan van Dijk and Mark A.J. Huijbregts*

4.1 INTRODUCTION

The so-called “ozone hole” was detected over Antarctica in 1985 (Farman et al., 1985). Ozone is continuously formed and destroyed by the action of sunlight and chemical reactions in the stratosphere. Ozone depletion occurs if the rate of ozone destruction is increased due to fugitive losses of anthropogenic substances which persist in the atmosphere. Stratospheric ozone, which is 90% of the total ozone in the atmosphere, is vital for life because it hinders harmful solar ultraviolet UV-B radiation. If not absorbed, UV-B radiation below 300 nanometers will reach the troposphere and the surface of the earth where it can increase human health risk of skin cancer and cataract if the body and eyes are not adequately protected by clothes or other precautions. It may also cause premature aging and suppression of the immune system and it may damage terrestrial plant life and aquatic ecosystems (Fahey, 2002) as well.

The characterization factor for ozone layer depletion accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances (ODS). These are recalcitrant chemicals that contain chlorine or bromine atoms. Because of their long atmospheric lifetime they are the source of Cl and Br reaching the stratosphere. Chlorine atoms in chlorofluorocarbons (CFC) and bromine atoms in halons are effective in degrading ozone due to heterogeneous catalysis, which leads to a slow depletion of stratospheric ozone around the globe. The chlorine and the bromine atoms that are released from these reactions have the ability to destroy a large quantity of ozone molecules in the stratosphere because they act as free radical catalysts (WMO, 2003):

$$ClO + O \rightarrow Cl + O_2$$
$$Cl + O_3 \rightarrow ClO + O_2$$
$$ClO + BrO \rightarrow Cl + Br + O_2$$
$$Cl + O_3 \rightarrow ClO + O_2$$
$$Br + O_3 \rightarrow BrO + O_2$$

Although the ozone concentration in the stratosphere is very low, the layer thickness to be passed by the photons is about 25 km and the absorption of short wavelength radiation is therefore complete. The absorption capacity of this layer is at stake if ozone is depleted.

The Ozone Depletion Potential (ODP) has been defined as a relative measure of the ozone depletion capacity of an ODS and uses CFC-11 (trichlorofluoromethane) as a reference. In LCIA the ODP is used as equivalency factors, characterizing ODSs at the midpoint level. Goedkoop and Spriensma (1999) have evaluated the damage to human health caused by stratospheric ozone depletion. Hayashi et al. (2006) recently used a damage function for LCIA, taking into account impacts on human health (skin cancer and cataract), ecosystems (primary productivity) and social assets (crop and timber production).

In ReCiPe 2008, only damage to human health is addressed because uncertainty regarding other areas of protection was considered too large. In a new approach we have evaluated the fate of a marginal increase of emission of ODSs and the resulting worldwide increase of UVB exposure, taking into account population density, latitude and altitude (Van Dijk, 2007a). For characterization of damage, protective factors are accounted for like skin colour (Van Dijk, 2007b) and culturally determined habits such as clothing.

4.2 RELEVANT SUBSTANCES AND PROSPECTIVE EMISSION REDUCTION

4.2.1 GROUPS OF ODSS THAT DEPLETE STRATOSPHERIC OZONE

Seven groups of ODSs can be distinguished. Of these, methylchloride (CH_3Cl) is the most abundant halocarbon in the atmosphere, however as it is largely derived from natural sources it is not considered a controlled gas. Anthropogenic ODSs are controlled substances and subdivided into six groups according to both chemical relationship and emission reduction policies:

- chlorofluorocarbons (CFCs);
- hydrochlorofluorocarbons (HCFCs) and hydrobromofluorocarbons (HBFCs);
- halons (brominated chlorofluorocarbons);

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carbontetrachloride (CCl_4);
methylchloroform (CH_3CCl_3);
methylbromide (CH_3Br).

CFCs, once highly popular as propellants and for other applications, were to first regulated ODSs. HCFCs and HBFCs have been widely applied as commercial solvents and also in refrigeration and air conditioning and as such allowed for some time to replace CFCs. Halons have been widely used in fire extinguishing equipment. The principle use of carbontetrachloride is identified as precursor for the production of CFC-11 and CFC-12. Industrial production of methylchloroform declined dramatically in the 1990s. Emissions of methylbromide and methylchloride are almost entirely of natural origin, however part of the methylbromide emissions is of anthropogenic origin (see Figure 4.1).

4.2.2 PROTECTIVE EMISSION REDUCTION

Global cooperation began with the negotiation of the Vienna Convention for the Protection of the Ozone Layer in 1985. The Montreal Protocol on Substances that Deplete the Ozone Layer has set the details of the international agreement. In 1990 it was agreed in London to phase out “controlled substances”, i.e. the anthropogenic share of all ODSs, including all chemicals of the list above, except methylchloride which is almost entirely of natural origin (see Figure 4.1). In 1992 a meeting was held in Copenhagen to accelerate the phase out schedules of controlled substances: total halons phase out in developed countries was mandated for the beginning of 1994 and CFCs and carbon tetrachloride and methyl chloroform by 1 January 1996. For developing countries a special agreement was reached because otherwise unbridled production of these substances by developing countries was envisaged.

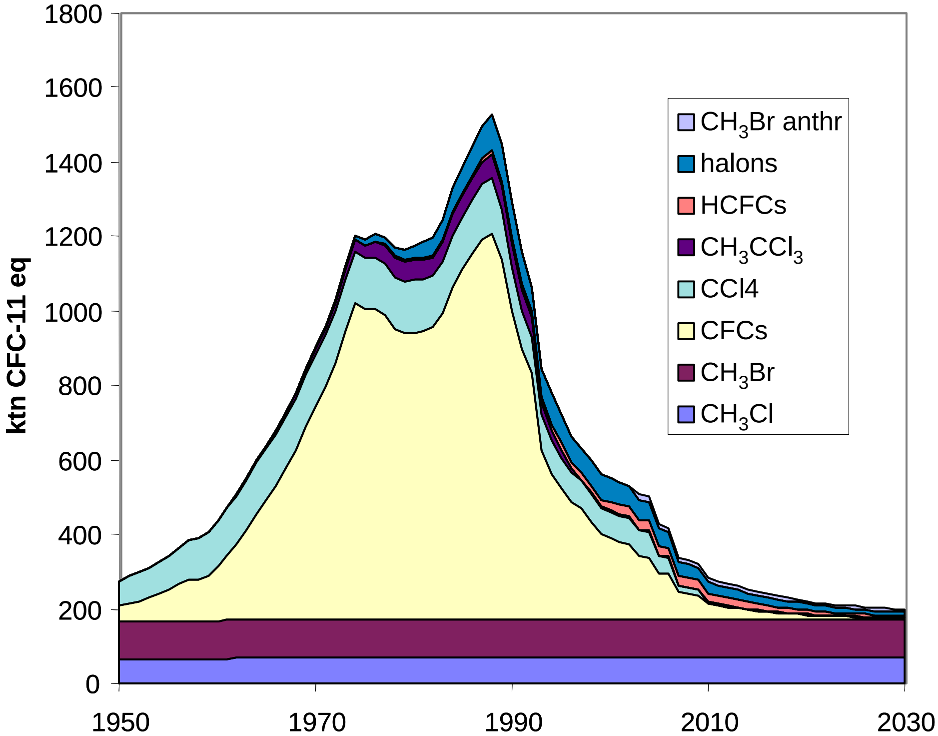

Figure 4.1: Most probable emission scenario (A1: the best guess scenario) of controlled ozone depleting substances (WMO 2003).

In 1995 in Vienna a phase out schedule for HCFCs in developed countries was agreed upon as follows: 35% reduction in 2004, through 65% in 2010, 90% in 2015, 99.5% in 2020 and finally 100% in 2030 (see also Box 1 developing countries). The Copenhagen Amendments had called for a freeze of HCFC production in 1996 in developed countries.

4.3 METHOD

4.3.1 CAUSALITY CHAIN

The causality chain is the modelling procedure is given by Figure 4.2. Calculation of the damage to human health is complicated due to the fact that measures of phasing out some ODS groups, the ultimate fate of halogen and effects of changed UVR exposure are attributed by lag phases. This requires considering the expected changes due to phasing out policies with respect to different ODS groups and dynamic fate modelling of ODSs up to the level of cumulative halogen loading or EESC, which is the Equivalent Effective Stratospheric Chlorine (Daniel et al., 1995). The resulting changes in UV radiation and demographic developments have to evaluated and combined with dose response information for the various human health effects.

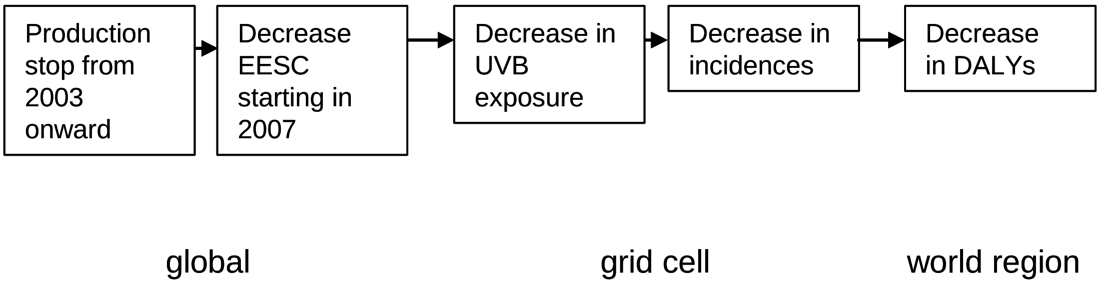

Figure 4.2: Causality chain of the model to assess impacts of ODSs.

4.3.2 PRODUCTION STOP OF ODS GROUPS IN 2003

Different time tables for emission reduction are set for the different groups of these chemicals. HFCFs, for example, are necessary to allow the rapid phasing out of the CFCs. The agreements on control measures define the emission per ODS class integrated over time. We consider the emissions of the six groups, according to the "best guess scenario", abbreviated as A1 (WMO, 2003), shown in Figure 4.1 as the reference. This reference scenario shows that at the beginning of the 21st century the total emission, aggregated as CFC-11 equivalents, had declined to less than half of the peak emission in 1990. The year 2003 was taken as the starting point of the modulation with respect to scenario A1. In this context modulation means that at 2003 the production of group *j* ceases prematurely compared to A1. So quantities preceded by the symbol Δ, we will use hereafter to indicate a change in ODS emission or in stratospheric halogen or in human health damage (DALY), will have a negative sign. For several groups a production stop does not immediately lead to an emission stop. Old equipments and installations will – perhaps for decades – release ODSs after a complete phasing out of that particular ODS group. Methylchloride (with group number *j*=7) is excluded as a group because the anthropogenic contribution is considered nil.

Figure 4.1 shows that in 2003 emission in equivalence units (ktn CFC-11) is already in a sharp decline. Therefore, an extra reduction due to an entire production stop of group *j* from 2003 onward will lead to a marginal difference compared to scenario A1 (see Figure 4.2). In that scenario the WMO (2003) forecasts decreasing emissions of CFCs. At the same time emission of will be continued as a result of abandoning equipment and devices after 2003. Although it will be lower than foreseen in the scenario A1 in which production is scheduled to be phased out in a less drastic manner, allowing other chemicals like HCFC to replace the CFCs for an agreed period of time. Only for tetracarbonchloride and methylbromide production stop has the same effect as emission stop. The difference in CFC-11 equivalents is summed until 2040 to compute the emission reduction of group *j*. This is referred to as the modulation of the total emission in A1 by group *j*. Figure 4.3 shows that the result of this summation will not change significantly if a moment later date than 2040 was chosen, with the exception of methylbromide which will be explained in the discussion.

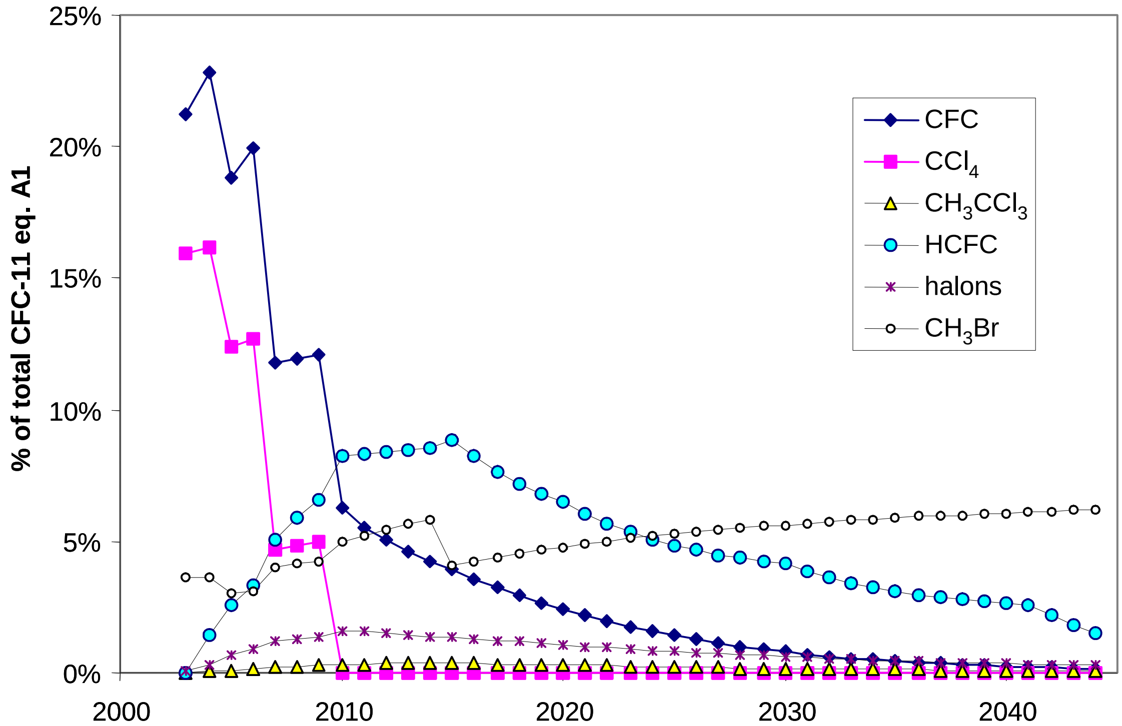

Figure 4.3: Reduction of total CFC-11 equivalents relative to A1 scenario (WMO) 2003 if the production/emission of group j *from 2003 onward ceases.*

4.3.3 DECREASE IN EESC FROM 2007 ONWARD

The concentration of EESC is expressed in units of equivalent chlorine (ppt). This concentration is numerically simulated on the basis of all natural and anthropogenic ODS emissions (WMO, 2003). Both EESC and the modulation due to an emission stop of a certain ODS group in 2003 are evaluated on a global scale. Figure 4.4 displays the temporal trend in total EESC concentration as response of the stratosphere. The EESC aggregates all these emissions. It is forecasted that according to scenario A1 the EESC concentration will drop below a threshold value of 1780 ppt ($EESC_0$) in 2044. This threshold was exceeded in 1980 and it is assumed that below the $EESC_0$ level UV damage to human health equals the natural background.

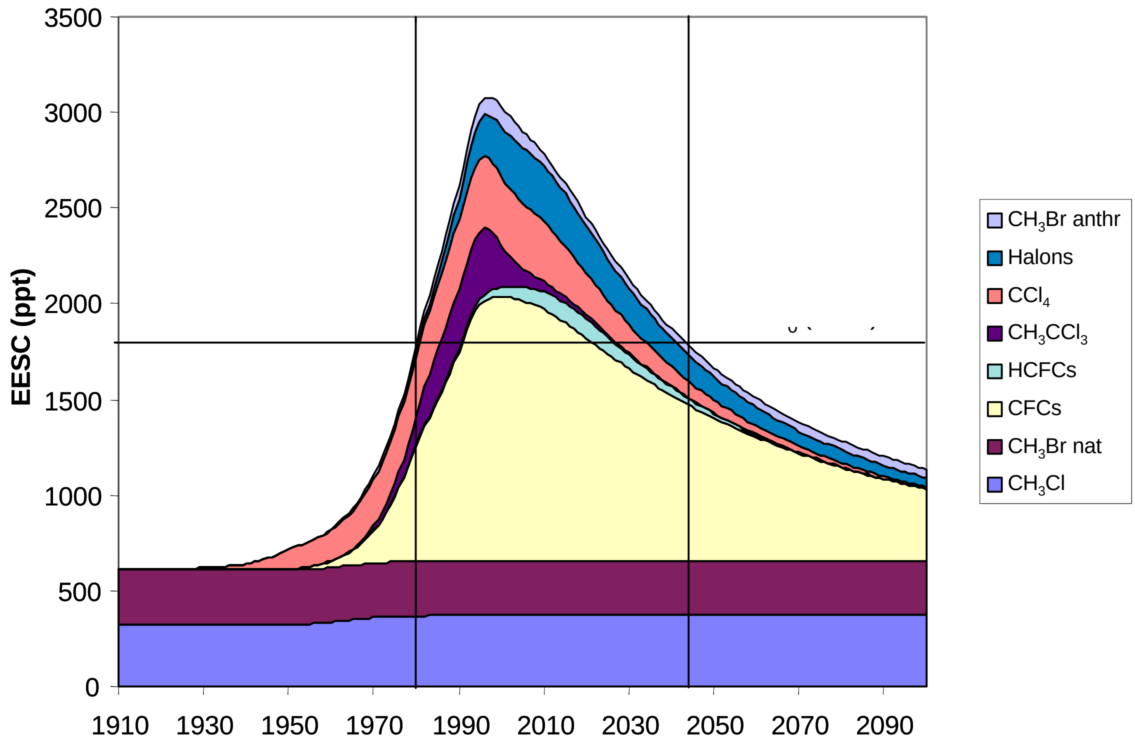

Figure 4.4: The temporal trend in EESC concentration caused by natural and anthropogenic emissions of ODSs according to reference scenario A1 (WMO 2003). The horizontal line at $EESC_0$=1780 ppt is the threshold value of the year 1980.

The modulations of ODS group *j* will cause only marginal changes in EESC. The justification to consider the applied emission modulations marginal is given by Table 4.1 which displays the maximum modulation values of ΔEESC in the year when it occurs. The third column demonstrates that ΔEESC is always less than 2% of the total EESC concentration at that time.

Three different time frames are defined to evaluate the characterization factor and the fate and damage factors it is based upon: the accumulation of ΔODS_j, of $\Delta EESC_j$ and of damage. The latter will be evaluated in terms of ΔDALYs. The change in $EESC_j$ lags 4 years behind the change in ODS_j and therefore the first possible effect in DALYs is also lagging 4 years behind but can in principle be expressed as damage in the year 2100. The cumulative value of ΔODS_j due to an emission stop of group *j* within scenario A1, has to be counted from 2003 until 2040.

Any ODS emitted after 2040 will lead to an increase of EESC after 2044 but that will not contribute to an additional damage to be accounted for in LCIA because damage due to increased UV radiation attributed to anthropogenic emission after 2044 is ignored because of the threshold of 1780 ppt. The avoided amount of cumulated $\Delta EESC_j$ that reduces damage to human health, due to an emission cessation of group *j* in 2003, is counted from 2007 to 2044 (see Figure 4.5). This has consequences for the calculation of effects and therefore also for the computation of the fate factor, which we evaluate only over the time period until 2044. This choice affects the outcome of the calculation of the fate factor of ODS group *j*.

Table 4.1: Maximum reduction EESC due to ceasing the production/emission from 2003 onward.

Year	ΔEESC (ppt)	EESC A1 (ppt)	Modulation of scenario A1
2023	–29	2351	No production of CFCs from 2003 onward
2013	–28	2694	No emission of CCl_4 from 2003 onward
2020	–4	2453	No production of CH_3CCl_3 from 2003 onward
2023	–9	2351	No production of halons from 2003 onward
2023	–52	2351	No production of HCFCs from 2003 onward
2008	–45	2841	No emission of CH_3Br from 2003 onward

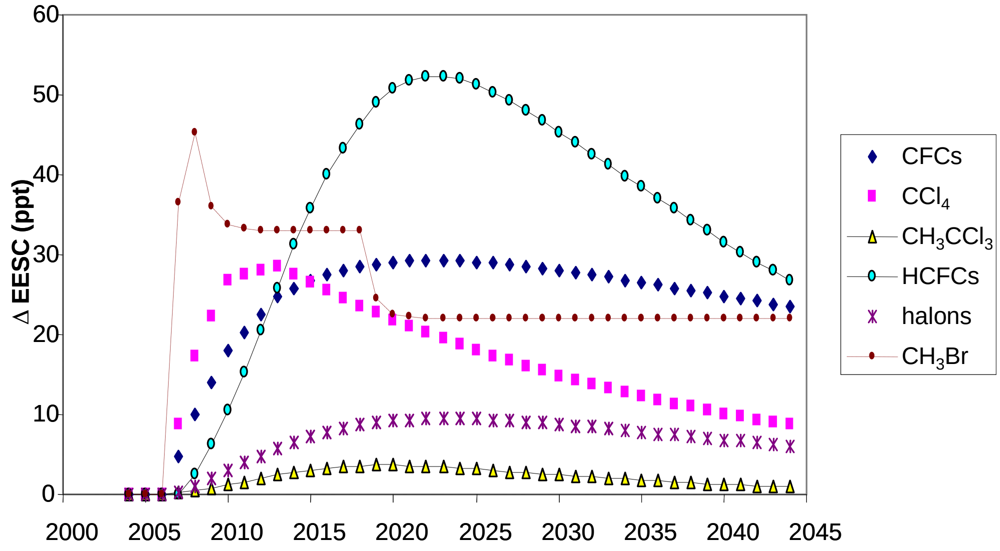

Figure 4.5: Reduction of EESC relative to A1 scenario (WMO 2003) if the production/emission of group j *from 2003 onward ceases.*

4.3.4 DECREASE IN HUMAN EXPOSURE FROM UV-B

Exposure from UV radiation is calculated for each grid cell taking into account the altitude exposed people are living. Also demographic characteristics and the trends therein are included: the population density, the average age and the life expectancy. Also skin colour is taken into account because it is a protection factor against exposure from UV radiation.

The incidence rate is grid-specific, dependent on the type of disease and on demographic characteristics. In the model we have assumed that there is one universal protection factor for all types of skin cancer. In AMOUR 2.0 (Van Dijk et al., 2007a) the resulting protection factors are related to the local skin-reflectance (skin colour). This leads to the following relation for the protection factor as function of skin-reflectance:

$$f_{\text{prot}} = 10^{-0.0321(SkinRefl-66)} \qquad (4.1)$$

here *SkinRefl* is the skin reflectance in percent. 66 refers to 66% skin reflectance in calibration point Amsterdam, where we have chosen $f_{\text{prot}}=1$. For details behind this model we refer to Van Dijk et al. (2007a). For cataract it is assumed that such a protection factor is absent.

In two steps the exposure factor is developed. First, the global decrease of halogens in the stratosphere is converted to a increase of ozone, which is dependent on the latitude (φ). From the marginal increase of ozone, the decrease of UV-B radiation per latitude band is calculated. As emission reduction measures are taken the stratospheric halogen content develops according to Best Guess scenario A1 and as a result the ozone layer and UV radiation. Second, human exposure to decreased UV-B radiation is evaluated, taking into account the latitude dependency of the UV radiation and grid wise, the population density and the altitude. According to the foreseen demographic development, also the population density and composition change in time.

UV-radiation mapping

Exposure modelling requires specific action spectra for skin cancer which differs from cataract. The radiative transfer model TUVRIVM.f was applied for the production of UV-maps. The so-called “table-ozone-angle” provides the weighted UV-dosis in $W.m^{-2}$ for a collection of thicknesses of the ozone layer (in Dobson units) and for a collection of solar zenith angles (SZA, in degrees). The table with “reflection-ozone-angle” gives the fraction of upwelling light that is reflected back to the earth by the atmosphere (see for more details the manual of AMOUR 2.0, Van Dijk et al, 2006). Long-term time-dependency of UV-B radiation is accounted for, regarding the different scenarios of the Montreal Protocol and the Copenhagen Amendments.

Population-mapping.

Population estimates from 1950-2050 (2030 for the USA) for each country in the world were adopted from U.S. Census Bureau (2004). For the years 1900 – 1950, estimates of the total world population were taken from United Nations (1999). To derive the population for each country in these years, population numbers were calculated by taking the relative contribution of each country to the total population in 1950, multiplied with the total population between 1900 and 1950 from United Nations (1999). Linear interpolation was used for years where no population estimates were available. Population estimates between 2050 (2030 for the USA) and 2100 were adopted from CIESIN (2002), where the medium-fertility population scenario was used (United Nations, 1998). Years in which population estimates were missing, were added using linear interpolation (Figure 4.6).

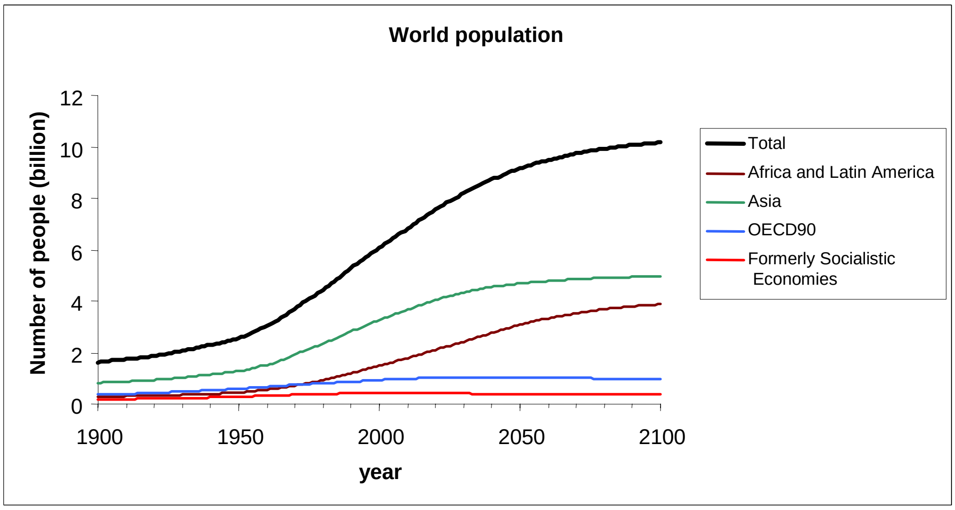

Figure 4.6: Scenario for the world population, aggregated over 4 world regions.

The population density will change over the time delay between emission of ODS and accumulated UV-B exposure. This delay between cause and effect (f.i. people contract skin disease) may be in the range or even beyond the time horizon normally chosen in LCIA.

The population composition (age-distribution) for each country and each year was adopted from the U.S. Census Bureau (2004). The period for which data were available varied between countries and can be roughly subdivided between 1980 and 2050. In total, 17 age classes are defined: 0-4, 5-9, 10-14, 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64, 65-69, 70-74, 75-79, 80+. If no data was available, the population composition was estimated through interpolation or extrapolation.

Skin colour mapping

The present-day skin colour of the world population was derived from the predicted skin reflectance of the indigenous population that was modelled by Chaplin (2004) and Jablonski and Chaplin (2000) (Figure 4.7, left panel). Reflectance was modelled at the 685 nm wavelength. A clear latitudinal and elevational gradient in skin colour can be observed. These predictions were combined with data on ethnic composition in each country (CIA, 2005) to obtain the skin colour of the present-day human population (Figure 4.7, right panel):

$$SkinRefl_{\mathrm{PRED}} = (f_{IND} \times SkinRefl_{\mathrm{IND}}) + (f_A \times SkinRefl_{\mathrm{A}}) + (f_B \times SkinRefl_{\mathrm{B}}) \quad (4.2)$$

where $SkinRefl_{\mathrm{PRED}}$ is the predicted present-day skin reflectance, f_{IND} is the fraction of the population that is indigenous, $SkinRefl_{\mathrm{IND}}$ is the skin reflectance of the indigenous population, f_A is the fraction of the population that is from ethnic group *A*, $SkinRefl_A$ is the average skin reflectance of ethnic group *A*, f_B is the fraction of the population that is from ethnic group *B*, $SkinRefl_B$ is the average skin reflectance of ethnic group *B*. All skin reflectances are at 685 nm; $f_{IND} + f_A + f_B = 1$. When more ethnic groups were present, they were added to the formula. The geographical distribution of modelled skin reflectance worldwide is indicated in Figure 4.7. Especially in areas with a large former immigration rate, such as Latin America, Indonesia and Australia, the skin reflectance differs from what would be expected given the distance to the equator and the elevation.

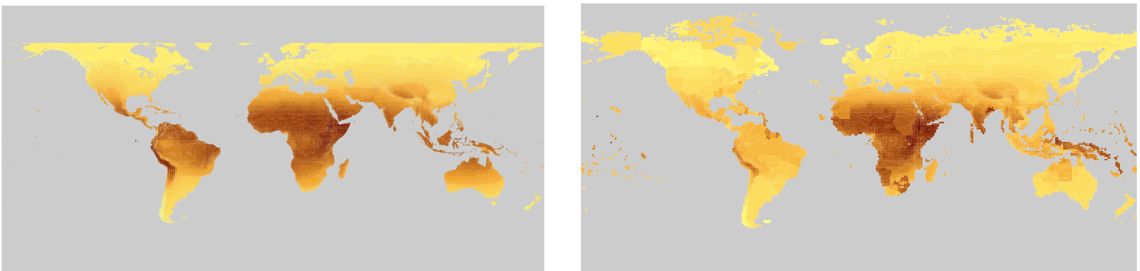

Figure 4.7: Predicted shading of skin reflectance at 685 nm for the indigenous human population (left panel) and for the present-day population (right panel), ranging from 23 (dark shade and dark skin colour) to 76 (light shade and light coloured skin). Left panel reproduced with permission from Chaplin (2004).

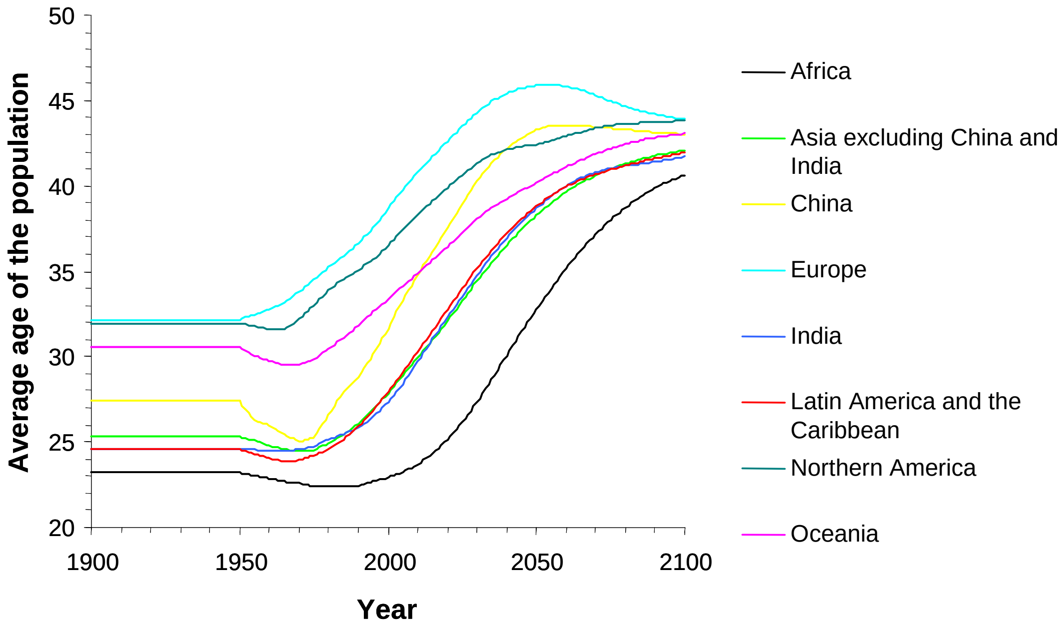

Figure 4.8: The development of average age.

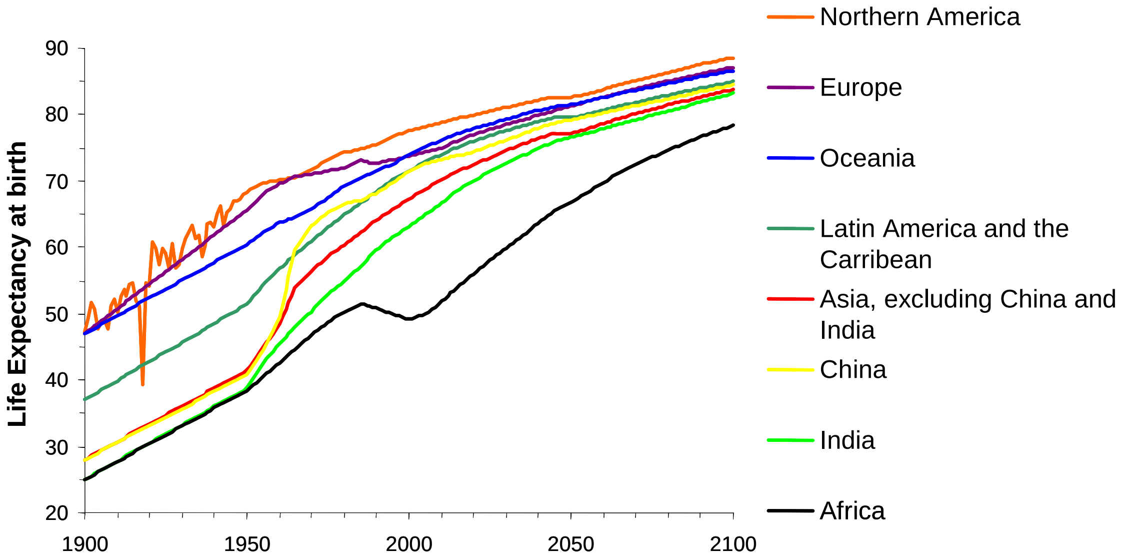

Figure 4.9: Forecasted life expectancy.

4.3.5 DECREASE IN HUMAN HEALTH EFFECTS

Skin cancer

Three types of skin cancer encompass almost all incidences: 70% basal cell carcinoma (BCC), 20% squamous cell carcinoma (SCC) and 10% melanoma (CM). An increase of UV-exposure does not have an immediate effect due to long latency periods (Slaper, 1996; Kelfkens, 2002). The cumulative UV-dose for the induction of SCC spans a period of 30-50 years before diagnosis. Mortality of BCC is negligible in EME countries.

AMOUR 2.0 uses the dose-effect relations for BCC, SCC and CM according to Kelfkens et al. (2002). A protection factor f_{prot} is applied as a measure for the dose-reduction by variation in skin-type and culture. A correction for underrating is described by Van Dijk et al. (2007b).

UV induced cataract

Cataract is world-wide a major cause of blindness. From Murray and Lopez (2001) it can be derived that on a global scale the damage in terms of DALYs is approximately ten times higher than for skin cancer. In developed countries cataract is adequately treated with a surgery. However in developing countries it may have grave social/economic consequences and may even lead to premature death.

Unfortunately, the etiology of cataract is complicated and involves many risk factors such as alcohol abuse, heavy smoking, severe diarrhoea, diabetics and chronic steroid use. There is an analogy to age-dependency of cancers and it is believed that cataract is a senile change (ageing) caused by oxidative processes. Therefore, UV radiation may be a factor because it generates reactive oxygen species. In a literature survey De Gruijl and Van der Leun (in: Kelfkens et al., 2002) found a substantial association of the cataract in people older than 50 years with the time spent outdoors (mostly professionally by males) which is a surrogate for UV exposure. Nevertheless, most studies suggest that "age" appears to be the main independent risk factor. Evidence for the relation between the incidence of cataract and annual erythema UVB has been provided by Sasaki et al. (1999) who compared in an epidemiological study cataract prevalence with age for four areas from low to high latitudes (from Iceland to Singapore).

Three types of cataract are distinguished but can occur in mixed forms: cortical cataract (CC), nuclear cataract (NC) and posterior subcaspular cataract (PSCC). In pure form one out of three cataracts is CC (range 18-49%) and approximately 40% is mixed. With the assumption that of the mixed forms 33% includes CC, we may estimate that ~ 40% contains CC. This type of cataract seems more abundant in populations living in temperate climates while NC is more abundant in tropical regions. From retrospective surveys and epidemiological studies it was found that lifetime exposure of individuals with CC was significantly higher than for cataract-free controls and no association of UV exposure and NC was found. De Gruijl en Van der Leun (2002) concluded that about ⅓ of the total cataracts are UV-sensitive CC. They also decided that "the balance of evidence would presently favour that the main cataractogenic action in sunlight resides in the UV-B, and the erythemal or carcinogenic dose would therefore be a good first approximation". It could reasonably be assumed that UV radiation affects CC development continuously throughout life, similar to SCC. Tentatively, for ReCiPe 2008, cataract has been integrated in AMOUR 2.0 (Van Dijk, 2006) according to a dose-response model proposed by De Gruijl en Van der Leun (2002). In the supporting information more details are given.

4.3.6 DECREASE IN DAMAGE

The damage is calculated on a world region scale. Scenarios for 8 world-regions can be differentiated according to Murray and Lopez (1996). With respect to skin colour, these world-regions seem more homogeneous than a subdivision according to (sub)continents. The results of the marginal reduction of DALYs due to a marginal modulation of scenario A1 as calculated with the model AMOUR are given in the supporting information.

4.3.7 PERSPECTIVES

The use of cultural perspectives accounts for perceived uncertainties in results produced by these models (Hofstetter, 1998). According to the Eco-indicator 99 (Goedkoop and Spriensma, 1999) we aggregate the *hierarchical* version with the *egalitarian* version for a precautionary approach. The individualist version accepts only modeling results on the basis of proven effects. There is wide agreement on the causal relationship between UV radiation and several forms of skin cancer. Three types were considered basal cell carcinoma (BCC), squamous cell carcinoma (SCC) and cutaneous melanoma (CM). These skin cancers were included in all cultural perspectives. The relationship between cataracts and UV exposure is much less univocal than for skin cancer. A proper impact assessment requires a dose-response relationship which is not available for UV-induced cataract in humans. Therefore damage due to cataract is not included in the Individualistic perspective.

4.3.8 MODEL OUTPUT

The characterization factor for different ODS groups

It is not necessary to evaluate the cumulative $\Delta EESC_j$ if only the endpoint characterization factor (CF_j) is to be derived. Only the change in the number of DALYs, attributed to the avoided amount of ODS_j from 2003 onward is necessary. These (negative) increments relative to scenario A1 should be integrated over time and summed over 8 world regions (see box 2):

$$CF_j = \sum_{S=1}^{8} \frac{\int_{2007}^{2100} \Delta DALY_{j,S}\,dt}{\int_{2003}^{2040} \Delta OD_j\,dt} \tag{4.3}$$

in which

CF_j = endpoint characterization factor (yr/kg CFC-11 equivalents) for ODS group *j*

$\Delta DALY_{j,S}$ = the avoided number of DALYs (yr) in world region S, attributed to a global emission stop of all ODSs of group *j*
S = world region
ΔOD_j = the avoided emission of ODSs of group *j* (kg CFC-11 equivalents)

For a better understanding and to check the plausibility, CF_j may be resolved into the fate factor and the damage factor, according to:

$$CF_j = FF_j \times DF_j \tag{4.4}$$

where
FF_j = the fate factor for group *j* (ppt chlorine/kg CFC-11 equivalents)
DF_j = the damage factor which ΔDALYs per ΔEESC (yr/ppt chlorine)

The Fate Factor FF_j for different groups
The fate factor is conducted from manipulations of data retrieved from WMO (2003). The longevity of many ODSs in the troposphere (supporting information) is sufficient to survive the period of approximately 4 years before they enter the stratosphere. Therefore, only the fact that they are emitted is relevant, not the region or environmental compartment. The ultimate fate of ODSs encompasses all events between emission and the moment that chlorine or bromine has terminated its catalytic role in the stratosphere. In the causality chain different ODSs can be compared by the amount of chlorine (or bromine) that ultimately is delivered to the stratosphere. The fate factor relates the total produced or emitted amount, according to a chosen scenario (for example the London Amendment of the Montreal Protocol), to the time integrated EESC

Figure 4.1 shows that emission of controlled ODSs will almost completely come to an end already in the year 2030. The difference (in units of ktn CFC-11 equivalents) between best guess scenario A1 and the same scenario without emission of ODS group *j* from 2003 onward is chosen as a marginal change (ΔOD_j). Figure 4.1 clearly shows that even for CFCs this cumulative amount can be chosen as a marginal modulation and that they will barely differ for other time horizons beyond 2030. In the former section it was already stated that the modulation of ODSs is expressed in units of kg CFC-11 equivalents, denoted as ΔOD. This implies that if group *j* contains more than one chemical (CFCs, HCFCs and halons), the marginal change in ΔOD_j is the weighted sum of the avoided emissions of ODSs belonging to group *j*:

$$\Delta OD_j = \sum_{i \in j} \Delta m_i \cdot ODP_i(\infty) \tag{4.5}$$

with
Δm_i = the avoided amount (kg) of ODS *i* of group j from 2003 onward
$ODP_i(\infty)$ = the equivalence factor of ODS *i* (kg CFC-11 eq per kg of ODS *i*)

The equivalence factor in Eqn 4.5 is the Ozone Depletion Potential (ODP) which is a relative measure for the potency of a substance to destroy the ozone layer. Here the steady state ODP is used (see the supporting information) which reflects the constant ratio between ΔEESC and the resulting depletion of stratospheric ozone ($\Delta[O_3]$). It encompasses the atmospheric residence time (both in the troposphere and stratosphere), the formation of EESC and the resulting stratospheric ozone depletion. The steady state ODP_i is identical to the midpoint characterization factor. For reasons of consistency, ODP values were used identical to the ones reported as “Updated Model-Derived” and “Updated Semi-empirical” in Chapter 1 of WMO (2003).

The halogen loading in terms of EESC, caused by emission of all ODSs in the past and predicted by the best guess scenario A1 was used to evaluate $\Delta EESC_j$. $\Delta EESC_j$ is integrated over time from 2007 until 2044 and is related to the ceased release of all ODSs of group *j* from 2003 until 2040. Because of the delay of 4 yr, emissions after 2040 will obviously not cause changes in EESC before 2044 which is the year EESC drops below the threshold value. If it alters EESC after 2044 it has no effect because after 2044 the EESC concentration will be below the threshold $EESC_0$ (1780 ppt) as it was before 1980. Hence the fate factor is defined as:

$$FF_j = \frac{\int_{2007}^{2044} \Delta EESC_j \, dt}{\int_{2003}^{2040} \Delta OD_j \, dt} \tag{4.6}$$

with
FF_j = the fate factor for group *j* (ppt·yr/ktn CFC-11 eq yr, or ppt/ktn)

The Damage Factor DF_j for group j

We have chosen the following causality chain: decrease in EESC (as long it is above $EESC_0$) → increase of stratospheric ozone (but still not restored to the 1980 level) → decrease of UV radiation (but still above the natural background) → decrease of human health effects. If the EESC threshold is taken into account, a consistent damage factor is obtained, i.e. constant over all ODS groups. We prefer this approach over adhering to a true fate factor. Most importantly, the characterization factor is defined as the summed incremental DALYs divided by the summed incremental amounts of ODS. In this approach, the de-numerator in the equation of the characterization factor (see Eqn 4.3) is not affected by tailing.

In order to be compatible with the derived fate factor, having $\Delta EESC_j$ accumulated until 2044 in the numerator, the damage factor $DF_{j,E}$ for health effect type *E* should have the same in the denominator. Note that $DF_{j,E}$ of group *j* integrates all temporal and spatial elements of the damage due to a (marginal) change in $EESC_j$ attributed to a change in emission of group *j* as a result of a complete production (or emission) stop of ODS_j in 2003:

$$DF_{j,E} = \sum_{S=1}^{8} \frac{\int_{2007}^{2100} \Delta DALY_{S,j,E}\,dt}{\int_{2007}^{2044} \Delta EESC_j\,dt} \qquad (4.7)$$

with:

$DF_{j,E}$ = damage factor for disease E (yr/ppt)

S = 8 world regions (see Box 2)

E = 4 illness types (BCC, SCC, CM or cataract)

$\Delta DALY_{S,j,E}$ = number of extra DALYs (yr) due to illness *E* in region *S* as a result of a complete emission stop of group *j* from 2003 onward

The change in burden of disease due to a deviation of UV exposure from the Best Guess scenario A1 is calculated for skin cancer. The relationship between cataracts and UV exposure is much less univocal than for skin cancer. A proper impact assessment requires a dose-response relationship which is not available for UV-induced cataract in humans as it is for occurrence of skin cancer in the Caucasian population. Suppression of the immune system is not taken into account due to insufficient data. Both for skin cancer and cataract, a rise in prevalence is apparent in the age groups of 40-49 years and older. The share of these age groups differs across the world regions as also the average age of the population differs. Within one century these differences tend to converge as shown in Figure 4.8, as does the life expectancy, shown in Figure 4.9.

The damage factor for each ODS group j and human health effect E is calculated according to eqn 4.7. Results are given in Table 4.5. The damage factor DF_j for ODS group *j* is the summation over all diseases *E*. The final results (Table 4.6) depend on the chosen perspective which implies in our approach the choice whether or not cataract is included in the summation:

$$DF_j = \sum_{E=1}^{4} DF_{j,E} \qquad (4.8)$$

The characterization factor for a compound of a group

As such a characterization factor for a group of ODSs, CF_j, according to eqns 4.3 and 4.4, has only limited relevance in LCA practice, as most inventories report substance-specific emissions. The evaluation of the “group CF” is indispensable to formulate the characterization factor at the endpoint level. In fact, CF_j is the factor by which a characterization factor at the midpoint level, ODP_i, has to be multiplied to yield the characterization factor at the endpoint level. For a chosen perspective, the characterization factor CF_i for an individual substance *i* belonging to group *j*, is obtained as the product of the CF_j and the equivalency factor ODP_i of compound *i* of group *j*:

$$CF_i = ODP_i(\infty) \times CF_j \qquad (4.9)$$

Equation 4.9 could also be formulated as *Endpoint* CF_i = *Midpoint*·CF_j, illustrating that the endpoint indicator score is inline with the midpoint indicator score.

4.4 RESULTS AND DISCUSSION

4.4.1 THE FATE FACTOR OF J

It was expected that all fate factors (Table 4.2) would be in a narrow range because the de-numerator in Eqn 6 has the (steady state) equivalency factor already incorporated, i.e. the ozone depletion potential of each member of group j. This is closely related to the "EESC formation potential". As all ODPs are relative to CFC-11, the variation in the fate factor is higher than expected. Especially for the CFCs and the halons the fate factors appear rather low.

Table 4.2: Fate factors for the six groups of ODSs, ΔODP in units of ktn CFC-11 eq•yr.

ODS group	∫ EESC (ppt·yr)	∫ ODP (ktn·yr)	Fate factor (ppt/ktn)
CFCs	-955.62	-531.4	1.80
CCL_4	-666.26	-176.8	3.77
CH_3CCl_3	-84.08	-17.1	4.92
Halons	-272.45	-98.3	2.77
HCFCs	-1367.4	-337.4	4.05
CH_3Br	-990.8	-206.9	4.79

The variation in the fate factor may be caused by uncertainty in ODP values (due to uncertainty in atmospheric lifetimes) and non-linearity (due to non-marginal changes, both in the numerator and the de-numerator). The main reason, however, is the early cut-off of the large tail in $\Delta EESC_j$ already in the year 2044. This especially affects the fate factor of CFCs (see Figure 4.5). Δ EESC was calculated for the whole period for which data WMO (2003) were available, that is up to the year 2100. It appeared that for the period 2050 to 2100, Δ EESC displays a perfect exponential decay. These data were used to conduct a linear regression of the log transformed data ($R^2 > 0.998$), from which accumulated figures could be derived (third column in Table 4.2).

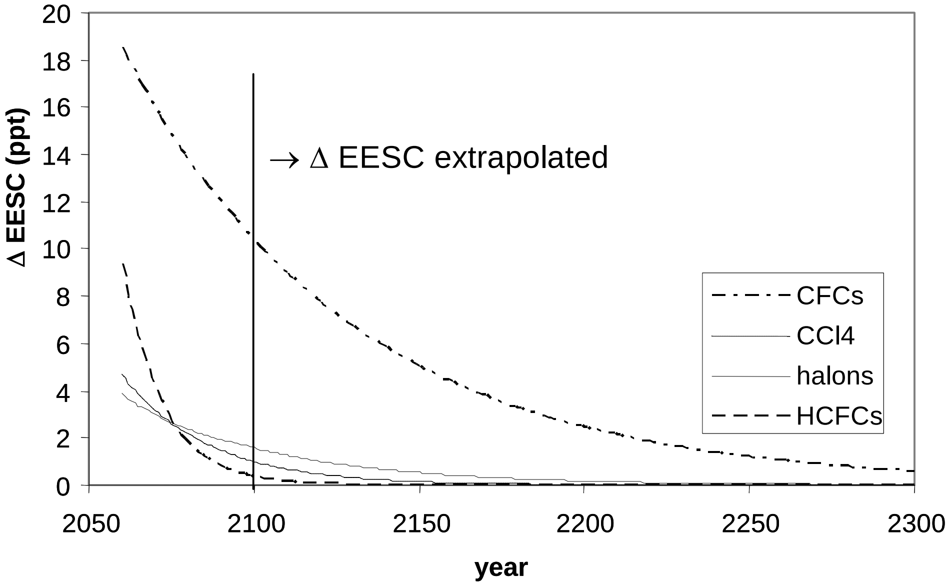

Figure 4.10: Reduction of EESC relative to A1 scenario (WMO 2003) until 2300 if the production/emission of group j from 2003 onward ceases.

If the integral of $\Delta EESC_j$ elapsed from 2007 to 2300, the accumulated difference for CFCs would be -2516.6 ppt·yr in stead of -955.6 ppt·yr, while ΔODP_j would not change at all as it has reached the zero emission level already in 2035. This would result in a higher fate factor for the CFCs (4.7 ppt/ktn), for the halons (4.8 ppt/ktn) and for CCl_4 (5.0 ppt/ktn). The coefficient of variation in Table 4.2 is 33% but would decrease drastically to 5%. The average value would be 4.85 ppt/ktn if the integration over time is conducted over the whole period until the year 2300 (see Table 4.3).

Table 4.3: Influence of the time scale on the fate factor of ODS group j.

ODS group	∫ EESC (ppt·yr)		Fate factor (ppt/ktn)	
	until 2044	until 2300	until 2044	until 2300
CFCs	-955.62	-2516.6	1.80	4.72
CCL_4	-666.26	-887.3	3.77	5.02
CH_3CCl_3	-84.08	-96.7	4.92	5.17
Halons	-272.45	-517.6	2.77	4.83
HCFCs	-1367.4	-1749.7	4.05	4.90
CH_3Br	-1480.5	-6620.2	4.54	4.54

This provides confidence to consider the values in last column of Table 4.8 as *true* fate factors. Obviously, this was expected because all emitted substances were normalized by their (steady state) ODP equivalency factors before they were aggregated to ∫ΔODP in units of ktn CFC-11 eq·yr. Integration over a period as long as to 2300 would yield a genuine fate factor because the long tail of anthropogenic EESC is included. Nevertheless, we do not make use of the true fate factor because the long tail after 2044 does not have any effect on human health above the background. The accumulated increments in EESC after 2044 are not included in the calculation of the damage factor in Table 4.4 because there is no causal relationship between the ΔEESC curve after 2044 and a change in human damage. Moreover, time scale for ∫ΔEESC is not important because the characterization factor equals the product of the fate factor and the damage factor and *provided that the same time scale is used*, ∫ΔEESC cancels.

4.4.2 MODEL OUTPUT OF DAMAGE: DISABILITY ADJUSTED LIFE YEARS

For basal cell carcinoma (BCC), squamous cell carcinoma (SCC), cutaneous melanoma (CM) and cataract the model AMOUR provided results in terms of avoided DALYs per ODS group j (Table 4.4). This output is applied to calculate the damage factors for each group j (Table 4.5). Note that the damage factor for a certain disease is constant over all ODS groups, provided that ΔEESC is summed until 2044 and not beyond. This is in agreement with the particular causal role EESC plays in ozone depletion if the threshold of 1780 ppt is exceeded.

If the damage factors are aggregated, the results depend on the chosen perspective (Table 4.6), i.e. for the egalitarian and the hierarchist all 4 diseases are summed, for the individualist only the 3 types of skin cancer.

Table 4.4: AMOUR output: globally avoided DALYs (yr) due to ceased ODSj emission from 2003 onward.

ODS group	ΔDALYs BCC	ΔDALYs SCC	ΔDALYs CM	ΔDALYs Cataract
CFCs	-5963	-78285	-135458	-713505
CCL_4	-4249	-48370	-93299	-437865
CH_3CCl_3	-539	-6174	-11922	-56688
Halons	-1686	-21488	-38321	-197726
HCFCs	-8336	-100726	-188645	-934148
CH_3Br	-6352	-83278	-142091	-745897

Table 4.5: Damage factors DFj,E (yr/ppt) for each illnesses E.

ODS group	DF BCC	DF SCC	DF CM	DF Cataract
CFCs	6.24	81.92	141.75	746.64
CCL_4	6.38	72.60	140.03	657.20
CH_3CCl_3	6.41	73.43	141.79	674.22
Halons	6.19	78.87	140.65	725.73
HCFCs	6.10	73.66	137.96	683.16
CH_3Br	6.41	84.05	143.41	752.84
Average	6.29	77.42	140.93	706.63
Coeff of Var	1.9%	6%	1.2%	5.2%

Table 4.6: Aggregated damage factors DFj (yr/ppt) for ODS group j for the different perspectives.

ODS group	**DF egalitarian /hierarchist**	**DF individualist**
CFCs	976.6	229.9
CCL_4	876.2	219.0
CH_3CCl_3	895.8	221.6
Halons	951.4	225.7
HCFCs	900.9	217.7
CH_3Br	986.7	233.9
Average	931.3	224.6
Coeff of Var	5%	3%

The method to derive the endpoint characterization factor, i.e. at the damage level, is based upon the evaluation of the factor that comprises all ODSs of group j. This "group CF", CF_j, depends only on the diseases that are included. CF_j is determined by the chosen perspective and is the connecting factor between midpoint and endpoint characterization factors. The final results for these group CFs are given in Table 4.7. These characterization factors pertain to ΣODS_j which is a functional aggregation in modelling the cause-effect chain because forecasted emission scenarios affect a group of ODSs rather than an individual substance.

Table 4.7: Characterization factors CFj (yr/kg CFC-11 eq.) at the endpoint level.

ODS group j	**CF_j egalitarian / hierarchist**	**CF_j individualist**
CFCs	$1.76 \cdot 10^{-3}$	$4.13 \cdot 10^{-4}$
CCL_4	$3.30 \cdot 10^{-3}$	$8.25 \cdot 10^{-4}$
CH_3CCl_3	$4.41 \cdot 10^{-3}$	$1.09 \cdot 10^{-3}$
Halons	$2.64 \cdot 10^{-3}$	$6.26 \cdot 10^{-4}$
HCFCs	$3.65 \cdot 10^{-3}$	$8.82 \cdot 10^{-4}$
CH_3Br	$4.72 \cdot 10^{-3}$	$1.12 \cdot 10^{-3}$

The final results for individual ODSs are given in Table 4.8 which lists the midpoint and endpoint characterization factors for individual compounds.

Table 4.8: Midpoints and endpoints (egalitarian/hierarchist + individualist).

ODS	**CF midpoint kg CFC-11 eq./kg ODS_i**	**CF endpoint yr/kg ODS_i**	
	$ODP_{i \in j}$ (∞)	egalitarian / hierarchist	individualist
CFC-11	1	$1.76 \cdot 10^{-3}$	$4.13 \cdot 10^{-4}$
CFC-12	1 [a]	$1.76 \cdot 10^{-3}$	$4.13 \cdot 10^{-4}$
CFC-113	1 [a]	$1.76 \cdot 10^{-3}$	$4.13 \cdot 10^{-4}$
CFC-114	0.94 [b]	$1.65 \cdot 10^{-3}$	$3.89 \cdot 10^{-4}$
CFC-115	0.44 [b]	$7.73 \cdot 10^{-4}$	$1.82 \cdot 10^{-4}$
HCFC-123	0.02 [a]	$7.30 \cdot 10^{-5}$	$1.76 \cdot 10^{-5}$
HCFC-124	0.02 [a]	$7.30 \cdot 10^{-5}$	$1.76 \cdot 10^{-5}$
HCFC-141b	0.12[a]	$4.38 \cdot 10^{-4}$	$1.06 \cdot 10^{-4}$
HCFC-142b	0.07[a]	$2.56 \cdot 10^{-4}$	$6.18 \cdot 10^{-5}$
HCFC-22	0.05 [a]	$1.83 \cdot 10^{-4}$	$4.41 \cdot 10^{-5}$
HCFC-225ca	0.02[a]	$7.30 \cdot 10^{-5}$	$1.76 \cdot 10^{-5}$
HCFC-225cb	0.03[a]	$1.10 \cdot 10^{-4}$	$2.65 \cdot 10^{-5}$
Halon-1201 (HBFC 1201)	1.4 [c]	$3.69 \cdot 10^{-3}$	$8.76 \cdot 10^{-4}$
Halon-1202	1.3 [a]	$3.43 \cdot 10^{-3}$	$8.14 \cdot 10^{-4}$
Halon-1211	6 [a]	$1.58 \cdot 10^{-2}$	$3.76 \cdot 10^{-3}$
Halon-1301	12 [a]	$3.17 \cdot 10^{-2}$	$7.51 \cdot 10^{-3}$
Halon-2311 (HBFC 2311)	0.14 [c]	$3.69 \cdot 10^{-4}$	$8.76 \cdot 10^{-5}$
Halon-2401 (HBFC 2401)	0.25 [c]	$6.60 \cdot 10^{-4}$	$1.56 \cdot 10^{-4}$

Halon-2402	6 [a]	$1.58 \cdot 10^{-2}$	$3.76 \cdot 10^{-3}$
Carbontetrachloride	0.73[a]	$2.41 \cdot 10^{-3}$	$6.02 \cdot 10^{-4}$
Methylchloroform	0.12[a]	$5.29 \cdot 10^{-4}$	$1.26 \cdot 10^{-4}$
Methylbromide	0.38[a]	$1.80 \cdot 10^{-3}$	$4.26 \cdot 10^{-4}$

[a] *Updated semiemperical from Table 1-5 Ch 1 (WMO, 2003)*
[b] *Updated model derived from Table 1-5 Ch 1 (WMO, 2003)*
[c] *(WMO, 1999)*

4.5 COMPARISON WITH OTHER METHODS

The endpoint characterization factors derived by ReCiPe 2008 are in the same order of magnitude but also systematically higher compared to LIME (Hayashi et al., 2006) and the Eco-indicator 99 (Goedkoop & Spriensma, 1999).

Table 4.9: Endpoint characterization factors (only egalitarian/hierarchist) of ReCiPe 2008 compared to LIME and Eco-indicator 99 in the hierarchist perspective.

ODS	**CF endpoint (yr/kg ODS$_i$)**		
	ReCiPe 2008	**LIME**	**Eco-indicator 99**
CFC-11	$1.76 \cdot 10^{-3}$	$1.34 \cdot 10^{-3}$	$1.05 \cdot 10^{-3}$
CFC-12	$1.76 \cdot 10^{-3}$	$1.41 \cdot 10^{-3}$	$8.63 \cdot 10^{-4}$
CFC-113	$1.76 \cdot 10^{-3}$	$1.44 \cdot 10^{-3}$	$9.48 \cdot 10^{-4}$
CFC-114	$1.65 \cdot 10^{-3}$	$1.34 \cdot 10^{-3}$	$8.95 \cdot 10^{-4}$
CFC-115	$7.73 \cdot 10^{-4}$	$8.07 \cdot 10^{-4}$	$4.21 \cdot 10^{-4}$
HCFC-123	$7.30 \cdot 10^{-5}$	$3.49 \cdot 10^{-6}$	$1.47 \cdot 10^{-5}$
HCFC-124	$7.30 \cdot 10^{-5}$	$2.08 \cdot 10^{-5}$	$3.16 \cdot 10^{-5}$
HCFC-141b	$4.38 \cdot 10^{-4}$	$1.20 \cdot 10^{-4}$	$1.05 \cdot 10^{-4}$
HCFC-142b	$2.56 \cdot 10^{-4}$	$8.24 \cdot 10^{-5}$	$5.26 \cdot 10^{-5}$
HCFC-22	$1.83 \cdot 10^{-4}$	$5.41 \cdot 10^{-5}$	$4.21 \cdot 10^{-5}$
HCFC-225ca	$7.30 \cdot 10^{-5}$	$2.46 \cdot 10^{-5}$	$2.11 \cdot 10^{-5}$
HCFC-225cb	$1.10 \cdot 10^{-4}$	$3.25 \cdot 10^{-5}$	$2.11 \cdot 10^{-5}$
Halon-1201 (HBFC 1201)	$3.69 \cdot 10^{-3}$		$1.47 \cdot 10^{-3}$
Halon-1202	$3.43 \cdot 10^{-3}$		$1.32 \cdot 10^{-3}$
Halon-1211	$1.58 \cdot 10^{-2}$	$3.38 \cdot 10^{-3}$	$5.37 \cdot 10^{-3}$
Halon-1301	$3.17 \cdot 10^{-2}$	$1.97 \cdot 10^{-2}$	$1.26 \cdot 10^{-2}$
Halon-2311 (HBFC 2311)	$3.69 \cdot 10^{-4}$		$1.47 \cdot 10^{-4}$
Halon-2401 (HBFC 2401)	$6.60 \cdot 10^{-4}$		$2.63 \cdot 10^{-4}$
Halon-2402	$1.58 \cdot 10^{-2}$	$6.76 \cdot 10^{-3}$	$7.37 \cdot 10^{-3}$
Carbontetrachloride	$2.41 \cdot 10^{-3}$	$1.30 \cdot 10^{-3}$	$1.26 \cdot 10^{-3}$
Methylchloroform	$5.29 \cdot 10^{-4}$	$9.15 \cdot 10^{-5}$	$1.26 \cdot 10^{-4}$
Methylbromide	$1.80 \cdot 10^{-3}$	$6.53 \cdot 10^{-6}$	$6.74 \cdot 10^{-4}$

Table 4.10 helps to recognize that ReCiPe 2008 produces higher characterization factors than Eco-indicator 99 if the egalitarian and hierarchic perspective is chosen. For the individualist perspective ReCiPe 2008 provides lower factors for the majority of the substances. The reason is that in Eco-indicator 99 the cultural perspectives are based on the time horizon, whereas in ReCiPe 2008 it relies on the choice to include cataract (egalitarian/hierarchist) or not (individualist). For most of the HCFCs and for methylchloroform, ReCiPe 2008 gives higher characterization factors for all perspectives.

With respect to LIME there is more divergence: for HCFC-123 the difference is twenty-fold, however, also with respect to Eco-indicator 99 the characterization factor of LIME was 4 times lower. Most striking is the discrepancy for methylbromide between ReCiPe 2008 and Eco-indicator on one side and LIME on the other. The explanation given by Hayashi et al. (2006) is not satisfactory. Our calculations are based on the data of WMO (2003) in which also an atmospheric lifetime of 0.7 year was applied. It should be emphasized that the major part of methylbromide is of natural origin. Also the difference between Eco-indicator and LIME is a factor of 100. A probable explanation for this large difference might be that in LIME the number of DALYs is divided by the total methylbromide emission, including the natural background. Today approximately 12 % is anthropogenic but in the future it will be below 5 %.

For cataract we applied in the model AMOUR 2.0 (Van Dijk[a] et al., 2007), however, with the action spectrum for skin cancer. This is an approximation according to De Gruijl & Van der Leun (2002) to estimate the effects due to exposure of the eye from UV radiation. In the near future we will improve the damage factor for cataract by repeating the calculations with AMOUR with a more appropriate action spectrum.

The main reason why ReCiPe 2008 produces much higher endpoint characterization factors is probable the demographic development that was taken into account. In the Eco-indicator and in LIME this was, to our knowledge, ignored. If a higher fraction of the population falls in the categories of 50 years and older and if also the increase of the whole world population is taken into account, it is plausible that higher damage factors are calculated because a higher number of incidences of skin cancer and cataract are predicted.

Table 4.10: Ratios of endpoint characterization factors for a comparison between ReCiPe 2008 and Eco-indicator 99 and between ReCiPe 2008 and LIME.

ODS	**ReCiPe 2008/EI99**		**ReCiPe 2008/LIME**	
	H & E	**I**	**H & E**	**I**
CFC-11	1.67	0.49	1.31	0.31
CFC-12	2.03	0.59	1.25	0.29
CFC-113	1.85	0.54	1.22	0.29
CFC-114	1.84	0.54	1.23	0.29
CFC-115	1.84	0.54	0.96	0.23
HCFC-123	4.97	1.48	20.93	5.06
HCFC-124	2.31	0.69	3.51	0.85
HCFC-141b	4.17	1.25	3.65	0.88
HCFC-142b	4.86	1.45	3.10	0.75
HCFC-22	4.34	1.30	3.37	0.82
HCFC-225ca	3.46	1.04	2.97	0.72
HCFC-225cb	5.19	1.56	3.37	0.81
Halon-1201 (HBFC 1201)	2.51	0.74		
Halon-1202	2.60	0.77		
Halon-1211	2.95	0.87	4.68	1.11
Halon-1301	2.51	0.74	1.61	0.38
Halon-2311 (HBFC 2311)	2.51	0.74		
Halon-2401 (HBFC 2401)	2.51	0.73		
Halon-2402	2.15	0.63	2.34	0.56
Carbontetrachloride	1.91	0.59	1.85	0.46
Methylchloroform	4.20	1.28	5.78	1.43
Methylbromide	2.66	0.78	274.95	65.17

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4.7 SUPPORTING INFORMATION

Substance properties and ODPs
Background information as to human health effects and demographic data

4.8 SUMMARY TABLE

Entity	Content
impact category	ozone depletion
LCI results	ozone depleting substances (ODS): CFCs, HCFCs, HALONs, etc.
midpoint indicator(s) (with abbreviation)	ozone depletion (OD)
unit of midpoint indicator(s)	kg (CFC-11 to air)
midpoint characterisation factor (with abbreviation)	ODP
unit of midpoint characterisation factor	– (or kg/kg)
endpoint indicator(s) (with abbreviation)	damage to human health (HH)
unit of endpoint indicator(s)	yr
endpoint characterisation factor (with abbreviation)	See table 4.7
unit of endpoint characterisation factor	yr/kg

5 ACIDIFICATION[14]

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5.1 INTRODUCTION

Atmospheric deposition of inorganic substances, such as sulfates, nitrates, and phosphates, cause a change in acidity in the soil. For almost all plant species there is a clearly defined optimum of acidity. A serious deviation from this optimum is harmful for that specific kind of species and is referred to as acidification. As a result, changes in levels of acidity will cause shifts in species occurrence (Goedkoop and Spriensma, 1999, Hayashi et al. 2004). Major acidifying emissions are NO_x, NH_3, and SO_2 (Udo de Haes et al., 2002; Hayashi et al., 2004).

This chapter describes the calculation of characterization factors for acidification for plant species in forest ecosystems on a European scale. Fate factors, accounting for the environmental persistence of an acidifying substance, can be calculated with an atmospheric deposition model, combined with a dynamic soil acidification model. Effect factors, accounting for ecosystem damage caused by an acidifying substance, can be calculated with a dose-response curve of the potential occurrence of plant species, derived from multiple regression equations per plant species.

Base Saturation (BS) was used as an indicator to express acidity. BS is the degree to which the adsorption complex of a soil in is saturated with basic cations, cations other than hydrogen and aluminum. It is defined as the sum of basic cations (BC in equivalents/kg soil) divided by the total Cation Exchange Capacity (CEC equivalents/kg soil) of the soil and multiplied by 100 (De Vries et al., 2002):

$$BS = \frac{BC}{CEC} = \frac{[\mathrm{K}]+[\mathrm{Ca}]+[\mathrm{Mg}]+[\mathrm{Na}]}{[\mathrm{H}]+[\mathrm{K}]+[\mathrm{Ca}]+[\mathrm{Mg}]+[\mathrm{Na}]} \tag{5.1}$$

For higher BS, more basic cations are present, which enhances the buffer capacity of the soil for acidic equivalents. Changes in BS in mineral soil can influence the occurrence of plant species in forests (De Vries et al., 2002).

5.2 FATE FACTOR

The fate factor was calculated in two steps. First, changes in acid deposition in Europe, derived from continental changes in air emission, were calculated with the model EUTREND (Van Jaarsveld, 1995). Second, changes in BS, derived from changes in acid deposition, were calculated with the model SMART2 (Kros, 2002).

The marginal change in deposition in forest area j ($dDEP_j$ in $eq \cdot ha^{-1} \cdot yr^{-1}$) due to a marginal change in the emission of acidifying substance x (dM_x in $kg \cdot yr^{-1}$) was defined as the atmospheric part of the Fate Factor, $FF_{atm,j}$ in $eq \cdot ha^{-1} \cdot kg^{-1}$ (Van Zelm et al., 2007):

$$FF_{atm,j} = \frac{dDEP_j}{dM_x} = T_{x,Europe \to j} \tag{5.2}$$

where $T_{x,Europe \to j}$ is the transfer of acidifying substance *x* from source area Europe to forest area *j* ($eq \cdot ha^{-1} \cdot kg^{-1}$). Europe was divided in 8064 receptor areas of about 50×50 km, each area characterized by its unique deposition data, coordinates, land use class, roughness length, and forest area. The atmospheric fate model EUTREND (Van Jaarsveld, 1995) was used to calculate depositions for each receptor area caused by European emissions of acidifying substances. Europe is modeled as an open system. Emissions can be exported out of Europe. Emissions occurring outside the system and being transported into Europe are not taken into account. $T_{x,Europe \to j}$ for NO_x, NH_3, and SO_2 was obtained as a source-receptor vector, containing $dDEP_j/dM_x$ for each receptor area.

The marginal change in *BS* in forest area j due to a marginal change in the deposition in forest area *j* was defined as the soil part of the fate factor, FF_{soil} (in $ha \cdot yr \cdot eq^{-1}$) (Van Zelm et al., 2007):

[14] This chapter is based on a paper by Rosalie van Zelm, Mark A.J. Huijbregts, Hans A. van Jaarsveld, Gert Jan Reinds, Jaap Struijs & Dik van de Meent. Time horizon dependent characterization factors for acidification in life-cycle assessment based on forest plant species occurrence in Europe. Environmental Science & Technology 41 (2007), 922-927.

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$$FF_{soil,j} = \frac{dBS_j}{dDEP_j} \approx \frac{\Delta BS_j}{\Delta DEP_j} \tag{5.3}$$

As put in equation (5.3), the soil fate factor depends on multiple parameters, e.g. deposition of the acidifying substance, climate, hydrology, and biogeochemistry, in a potentially non-linear way. Therefore the dynamic Simulation Model for Acidification's Regional Trends, version 2 (SMART2; Kros, 2002) was used to numerically estimate $\Delta BS_j/\Delta DEP_j$. Total emission increases of 1, 5 and 10% from the reference year 2000 were assumed to check for linearity in this range. Variation between emission increases was found to be negligible and therefore only the obtained factors for 1% emission increase are taken into account in this chapter. As acidification is a process that can occur over a long time scale (>100 years), fate factors were calculated for a number of time horizons (20, 50, 100, and 500 years); see Section 5.4.

5.3 EFFECT FACTOR

The marginal change in the Potentially Disappeared Fraction of plant species in European forest area *j* (PDF_j) due to a marginal change in the BS_j in forest area *j* was defined as the dimensionless effect factor, *EF* (Van Zelm et al., 2007):

$$EF_j = \frac{dPDF_j}{dBS_j} \tag{5.4}$$

A dose-response relationship is created that relates the PDF to BS. This relationship is found to be location-independent. Figure 5.1 shows the dose-response relationship of the added fraction of species disappeared in European forests as a function of BS of the soil. The obtained best fit follows the equation:

$$PDF_{\text{added}} = 0.27 - 0.26 \times BS \tag{5.5}$$

with an explained variance (R^2) of 1.00. It can be seen that the linear function holds for BS larger than approximately 0.15.

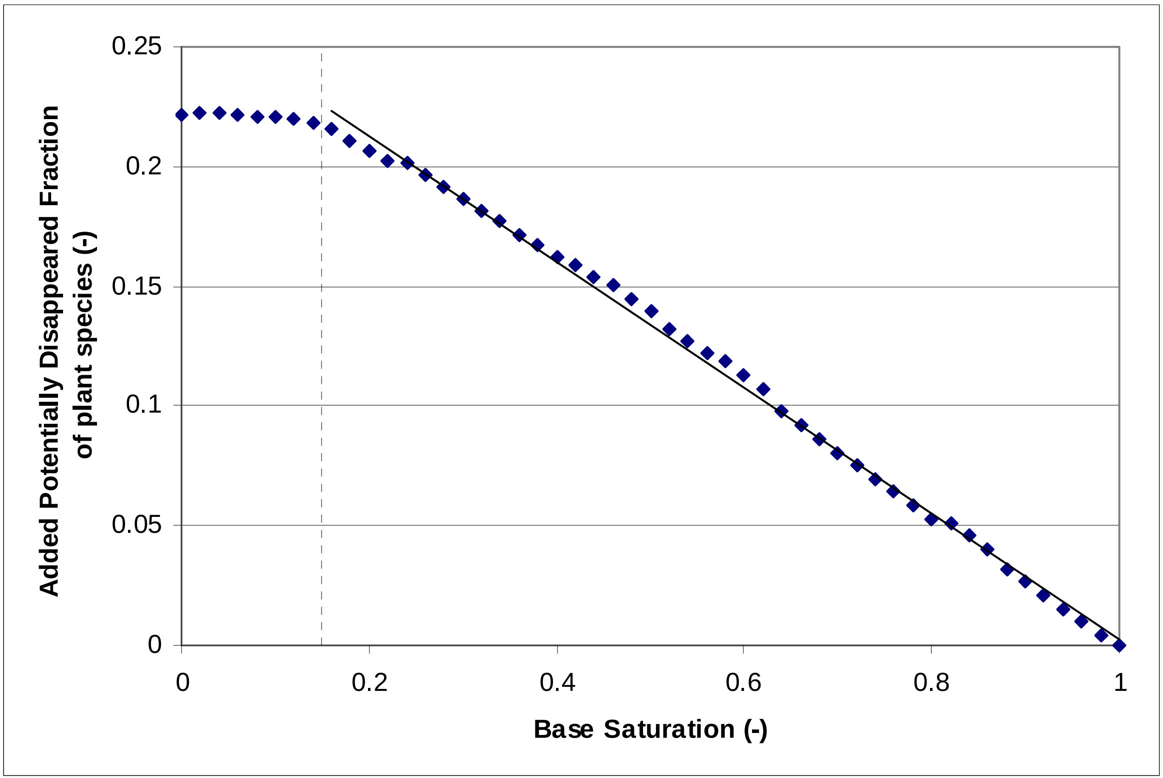

Figure 5.1: A dose response function of the Potentially Disappeared Fraction of plant species due to acidifying emissions (PDF_{added}) as a function of Base Saturation (BS) in mineral soil. The fitted linear function follows $PDF_{added} = 0.27-0.26 \cdot BS$ with an explained variance $R^2 = 1.00$, and holds for BS larger than 0.15

5.4 ENDPOINT CHARACTERIZATION FACTOR

Calculation of endpoint Characterization Factors for acidification of acidifying substance *x* ($CF_{endpoint,x}$ in $yr \cdot kg^{-1}$) for the total forest area consists of a fate and an effect factor The size of forest area *j* (A_j in m^2) and the average terrestrial species density (species/m2) is applied as a weighing factor:

$$CF_{endpoint,x} = \frac{dSpecies}{dM_x} = SD_{terr} \cdot \sum_j A_j \cdot \frac{dDEP_j}{dM_x} \cdot \frac{dBS_j}{dDEP_j} \cdot \frac{dPDF_{added}}{dBS_j} \quad (5.6)$$

where A_j is the size of forest area j (m^2) and $SD_{terr.}$ the species density.

Characterization factors were calculated for *BS*>0.15, since the effect factor can only be applied for this range. Factors were calculated for the total BS range as well to check whether significant differences are observed from the calculations for the range BS > 0.15. Characterization factor outcomes are 1 % higher for NO_x and NH_3 emissions, and 2 to 3 % higher for SO_2 emissions, inclining no significant distinction. The forest area in Europe where BS is below 0.15 appears to have a low influence on the fate factors and characterization factors compared to the area where BS is larger than 0.15

To analyze the endpoint characterization factors, three time perspectives were separated according to the three archetypes used in Cultural Theory. This idea is outlined by Goedkoop and Spriensma (1999). From the individualist perspective only the near future is important and therefore the chosen time-perspective is short-term, 20 year time horizon. From the hierarchic perspective there is no scientific reason to choose a specific time horizon and the chosen time perspective is long term, 100 years. From the egalitarian perspective all the future generations over the next few hundreds to thousands years are considered equally important as the present population. Therefore the time perspective should be very long term and a time horizon of 500 years is chosen. Table 5.1 shows the endpoint characterization factors for acidification for the different time horizons.

Table 5.1: Potentially dissapeared fraction of species for acidification due to SO_2 in European forests (in $m^2 \times yr \times kg^{-1}$).

	Time horizon (years)			
	20	**50**	**100**	**500**
NO_x to air	0.03	0.06	0.12	0.37
NH_3 to air	0.11	0.27	0.52	1.49
SO_2 to air	0.06	0.12	0.21	0.51

To scale the characterization factors, calculated for European forest area, to the total European ecosystem area, $CF_{endpoint}$ is multiplied by the ration between the total European ecosystem area and the European forest area. This ratio was calculated from Posch et al. (2001, 2003 and 2005) and equals 2.0. The average species density for terrestrial ecosystems was included as well. Table 5.2 shows the endpoint characterization factors for acidification of the total European ecosystem area in terms of number of disappeared species.

Table 5.2: Endpoint characterization factors for acidification in European ecosystems

Perspective	**Individualist**		**Hierarchist**	**Egalitarian**
Time horizon	**20 yr**	**50 yr**	**100 yr**	**500 yr**
NO_x to air	$0.69x10^{-9}$	$1.79x10^{-9}$	$3.31x10^{-9}$	$10.1x10^{-9}$
NH_3 to air	$3.04x10^{-9}$	$7.45x10^{-9}$	$14.2x10^{-9}$	$41.1x10^{-9}$
SO_2 to air	$1.52x10^{-9}$	$3.31x10^{-9}$	$5.80x10^{-9}$	$14.2x10^{-9}$

The table also identifies the three different cultural perspectives that are using different time horizons

5.5 MIDPOINT CHARACTERIZATION FACTOR

On midpoint level only the fate factor, dBS_j/dM_x, is of importance. As the acidification effect factor for *BS* appears to be location-independent for *BS*>0.15, a location-independent fate factor for acidification ($m^2 \cdot yr \cdot kg^{-1}$) was calculated:

$$FF_x = \frac{\sum_j \left(\Delta BS_j \times A_j \right)}{\Delta M_x} \quad (5.7)$$

Terrestrial acidification potentials (TAP) are expressed in SO_2-equivalents, and therefore area independent.

$$TAP = \frac{FF_x}{FF_{SO_2}} \quad (5.8)$$

See Table 5.3 for the resulting TAPs.

Table 5.3: Terrestrial acidification potentials for Europe (in kg SO_2-equivalents/kg).

Pollutant	Time horizon (years)			
	20	**50**	**100**	**500**
NO_x to air	0.49	0.52	0.56	0.71
NH_3 to air	1.99	2.23	2.45	2.89
SO_2 to air	1.00	1.00	1.00	1.00

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5.7 SUPPORTING INFORMATION

Fate model characteristics
Effect factor calculations

5.8 SUMMARY TABLE

Entity	Content
impact category	acidification
LCI results	acidifying substances: NO_x, NH_3, SO_2
midpoint indicator(s) (with abbreviation)	terrestrial acidification (TA)
unit of midpoint indicator(s)	kg (SO_2 to air)
midpoint characterisation factor (with abbreviation)	TAP
unit of midpoint characterisation factor	– (or kg/kg)
endpoint indicator(s) (with abbreviation)	damage to ecosystem diversity (ED)
unit of endpoint indicator(s)	yr
endpoint characterisation factor (with abbreviation)	1.52×10^{-9} (I) 5.8×10^{-9} (H) 14.2×10^{-9} (E)
unit of endpoint characterisation factor	yr/kg

6 EUTROPHICATION

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6.1 INTRODUCTION

Aquatic eutrophication can be defined as nutrient enrichment of the aquatic environment. Eutrophication in inland waters as a result of human activities is one of the major factors that determine its ecological quality. On the European continent it generally ranks higher in severity of water pollution than the emission of toxic substances. The long-range character of nutrient enrichment, either through air or rivers, implies that both inland and marine waters are subject to this form of water pollution, although due to different sources and substances and with varying impacts.

Characterization of aquatic eutrophication in Life Cycle Impact Assessment (LCIA) typically only takes into account those nutrients that are limiting the yield of aquatic biomass, which is merely phytoplankton (algae) but also duckweed. "Limiting" implies that only one nutrient is controlling the growth of these primary producers and that there is an excess of the other nutrients. Growth of algae is governed by many factors, however if substances are concerned, the availability of the so-called macro-nutrients phosphorus and nitrogen is dominating. Algal bloom has seasonal dimensions that vary according to geographic region. In northern Europe algal growth is greatly reduced or negligible during the winter period of low light and temperature. Other requirements for growth such as carbon dioxide, (bi)carbonates and sulphates are seldom limiting. Hydrogen, oxygen and nutrients like calcium, potassium, sodium, magnesium and chloride are usually abundant. The natural nitrogen and phosphorus cycle is the predominant source of P and N. Hence, growth of phytoplankton depends on the availability of P and N (and on the season in colder regions). In large regions industrial and agricultural sources exceed natural inputs by far (Kristensen and Hansen. 1994). As a result, an additional amount may lead to increased growth of phytoplankton causing a chain of adverse ecological effects. Whether aquatic eutrophication with nutrients leads to an environmental problem depends on local factors like topography and the physical and chemical nature of the receiving water bodies.

Emissions of N or P can be converted into biomass on the basis of the molecular composition of algae (Redfield et al, 1963). This enables aggregation and provides universal characterization factors that are independent of local environmental conditions. Characterization factors for aquatic eutrophication have been proposed by Heijungs et al. (1992) without a further differentiation between the initial emission compartments and regions involved. Therefore, this approach can be regarded worst case. First attempts to account for region-specific fate factors were made by Huijbregts and Seppälä (2000). They used long-range transport transfer matrices to model the fate of NO_x and NH_3 emissions from air to the marine environment. For inland waters this approach is of minor importance because phosphorus is most often the limiting nutrient. In an extended fate approach, Huijbregts and Seppälä (2001) employed "partial fate factors" to estimate simple transport factors from air to soil, from soil to air and from soil to water due to leaching and run-off to assess the fraction reaching the marine environment. For the northern hemisphere their estimations are 32 % for NO_2 and 17 % for NH_3. Potting and Hauschild (2005) applied a more sophisticated model to approach the fate factor of nutrient emitted from each region or country in Europe separately. Using the integrated assessment model CARMEN (acronym for CAuse effect Relation Model to support Environmental Negotiations), Potting and Hauschild (2005) calculated fractions of the N/P emission flux that actually reach freshwater or coastal seas. Their EDIP 2003 approach can be regarded a realistic worst case as the fraction of nutrients that is not available for surface waters is indeed excluded from the characterization. Worst case characterization by Heijungs et al. (1992) ignores that only a fraction of the eutrophying emissions will be transported to the aquatic environment. The EDIP 2003 report showed that for agricultural nitrogen differences among the countries are not greater than a factor 3. For phosphorus the range is a factor of 7.

In ReCiPe 2008 also CARMEN is used but it differs from EDIP 2003 in two respects:

- As it appeared from the EDIP methodology that country-specificity does not enhance accuracy considerably compared to uncertainty in emission regions, which is usually encountered in the inventory, we developed site generic fate factors for Europe. The dimensions of the fate factor are different with respect to the EDIP 2003 methodology. Our approach allows characterization at the endpoint level by multiplication with the effect or damage factor.

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- Instead of net emissions, we have applied CARMEN to compute fate factors related to gross emissions due to direct supply of manure or fertilizer. Most often only gross supply of N or P in agricultural production is known.

6.2 EMISSION OF RELEVANT SUBSTANCES

As in the EDIP 2003 methodology, Europe is considered the emitting region where aquatic eutrophication can be caused by emissions to air, water and soil. In practice the relevant substances include phosphorus and nitrogen compounds emitted to water and soil as well as ammonia (NH_3) and nitrogen oxide (NO_x) emitted to air. Airborne phosphorus accounts less than 3 percent of the waterborne emission (Berdowski and Jonker, 1994).

The supporting information chapter presents eutrophying substances containing P or N, including equivalent amounts of N and NO_3 – for several nitrogen containing substances that are relevant for freshwater systems. For some P containing substances this table gives equivalent amounts of P as well as the corresponding equivalents of nitrate. The latter is calculated according to the so-called Redfield ratio (Redfield et al., 1993) which refers to the typical composition of aquatic phytoplankton ($C_{106}H_{263}O_{110}N_{16}P$) indicating that for each molecule of P there are 16 molecules of N required.

There are various routes along which P and N containing compounds can enter the water compartment. Diffuse emission through nutrient supply on agricultural land is distinguished from point emission by wastewater treatment plants (N and P). In agricultural nutrient supply, a distinction is made between manure and fertilizer as they differ in fractions of N that is released to the air during application. Default fractions of 21 % for manure and 7 % for fertilizer, have been proposed by Bouwman et al. (2002). Due to diffuse emission nutrients enter water bodies by surface run-off/erosion (N and P), leaching from soils after agricultural supply (N) or atmospheric deposition (relevant mainly for airborn NH_y and NO_x) and subsequent transport to surface water through groundwater drainage. Communal and - of minor importance - industrial wastewater treatment plants are the main point sources of both P and N. Both emission routes dominate the input of nutrients to freshwater systems. Direct deposition of airborne nitrogen on inland surface waters is of minor importance.

Usually, in life cycle assessment both the agricultural topsoil and wastewater treatment plants are considered part of the technosphere (Potting and Hauschild, 2005). As a consequence, inventory data for N or P are deemed proper if they include emission rates from the technosphere into the receiving environment. For point sources such as communal wastewater treatment plants such net emission data are readily available and suitable in environmental fate analysis. For N and P supply to agricultural soil, however, this can be troublesome as most often only gross supply in terms of kg nitrogen/ha/year is known, i.e. emission to the topsoil or to the technosphere. Conversion from gross supply to agricultural soil into emission from the topsoil accounting for uptake by plants, binding to topsoil and erosion, then seems inevitable. Annex B contains factors for nitrogen and phosphorus in manure and fertilizer applied to agricultural fields. These processes, however, vary highly with the texture of the soil, slope, landuse etc. and the conversion factors in Annex B are a preliminary representation of the environmental mechanism. Therefore, a more accurate fate factor can be derived by means of the GIS based CARMEN model when dealing with gross supply of manure and fertilizer while accounting for widely varying agricultural fields in Europe.

6.3 FATE

CARMEN calculates the change in nutrient loads in ground water, inland waters and coastal seas from changes in net nutrient emissions or gross supplies. It models the transport of nutrients from agricultural supply and atmospheric deposition through groundwater drainage and surface runoff spatially resolved over 124320 grid elements of 1/6 X 1/6 degree (555 columns and 224 rows). It also models in a straightforward way the transport of nutrients that are emitted by wastewater treatment plants. CARMEN can be applied to establish fate or exposure factors for aquatic eutrophication. The European continent (32 countries where emission takes place) is subdivided into•101 river catchments and 41 coastal seas. CARMEN models three sources categories (Figure 6.1): agricultural supply of manure and fertilizer (diffuse sources), N and P from effluent (point sources) of communal and industrial waste water treatment plants and airborn nitrogen depositions. As CARMEN does not contain the relationships between emission of N to air and depositions elsewhere, the model EUTREND is applied to calculate depositions on land and coastal seas. From the combined computations with CARMEN and EUTREND in which the gross N deposition either due to manure or fertilizer supply is marginally increased with respect to the reference scenario, the attribution of the nitrogen emission from the topsoil of agricultural land could be derived: 31 % is due to atmospheric NH_y and NO_x deposition, 28 % is due to manure and 41 % to fertilizer supply.

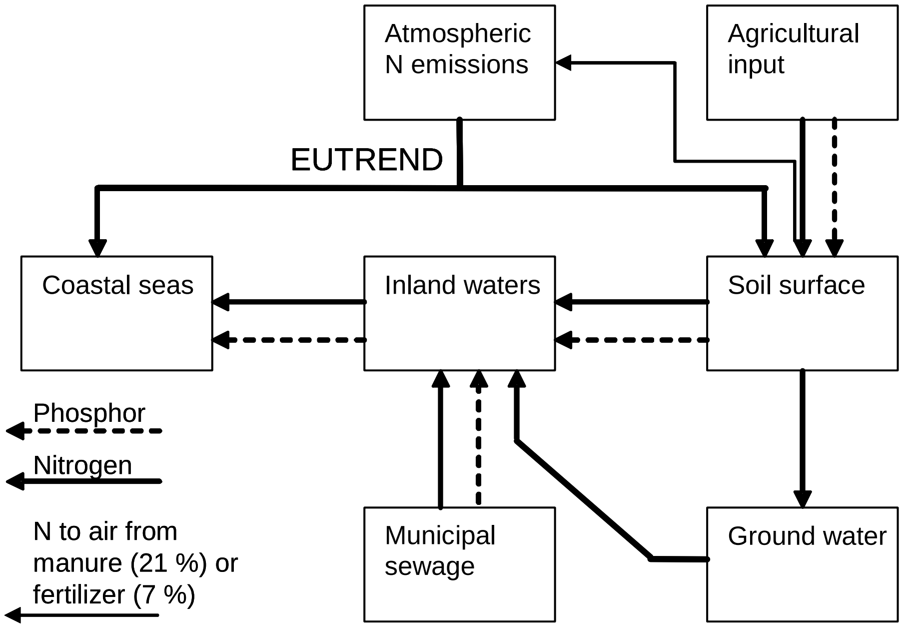

Figure 6.1: Main sources for N and P emission to soil, groundwater, surface waters and transport routes to the aquatic environment in the CARMEN model supplemented with EUTREND (Beusen, 2005).

Elimination due to denitrification in anaerobic zones in freshwaters is treated in CARMEN as a constant with a generic removal of 30 %. Hence 70 % of the nitrogen input transports to sea.

With CARMEN it is possible to evaluate the fate factor (FF_x in yr/km3) for aquatic eutrophication of nutrient x emitted in Europe. It can be written as the marginal concentration increment $dC_{x,j}$ in tn/km^3 in exposed aquatic system j due to a marginal increase of emission rate dM_x (tn/yr):

$$FF_x = \frac{dC_{x,j}}{dM_x} \tag{6.1}$$

The aquatic system j may be one of the 101 river catchments or one of the 41 coastal seas as defined by CARMEN (Beusen, 2005), see supporting information.

Fate factors were derived on the bases of the summed increments in steady state concentration in every water system (ΣdC), calculated with CARMEN, if the considered intervention dM, i.e. the marginal increase of emission rate (manure supply to soil or emissions from sewage treatment plants (STPs) or other emissions of P and N), is evenly increased by 1 % in all 32 countries of Europe ().

The fate of N and P in manure and fertilizer that enters the soil compartment is calculated with the CARMEN model. Air emissions of NH_3 and NO_2, mainly due to agricultural activities but also from industry and transport, are input for EUTREND to compute deposition both on the European continent and on coastal seas. In turn, deposition on soil is again input for CARMEN. Equation (6.1) is applied to evaluate the fate factor of seawater and freshwater separately. If nutrient x is emitted directly to the water compartment, dMx is evaluated in a straightforward manner: tn x/yr with x = N or P. If the nutrient is applied as manure or fertilizer, fate and transport in the soil and freshwater compartment are evaluated with respect to gross supply of either manure or fertilizer to the soil (source category i). The concentrations are normalized with respect to the area occupied by the water systems. The summation of the concentration of nutrient x over j seas is area weighted in order to be consistent with the impact of aquatic toxicity in marine systems. This results in the following calculation of the fate factor for nutrients:

$$FF_x^k = \frac{\frac{1}{\sum_j A_j^k} \cdot \sum_j dC_{x,j}^k \cdot A_j^k}{\sum_i dM_{x,i}} \tag{6.2}$$

with A_j^k is the surface (km2) of water system j. The superscript k is used to discriminate inland water from coastal sea. The denumerator of Eqn (6.2) equals 1 % of the total annual emission of nutrient x. We distinguish the following interventions, referred to the year 1995:

- Gross supply of manure or fertilizer to agricultural soil. Fate factors for N for this intervention can be evaluated in two fashions:
    - o dC_j is computed with CARMEN for all processes occurring in soil and water that affect the fate of N. Due to volatilization, only a fraction of the gross application of N to soil will reach the topsoil. According to Bouwman et al. (2002), 79 % of total N in manure and 93 % of total N in fertilizer will enter the topsoil;
    - o The complementary fractions of nitrogen in manure and fertilizer are emitted to the air as NH_3. Deposition of NH_3 on sea and soil is modeled with EUTREND. Deposited on soil N is subjected to fate processes, modeled in CARMEN, that contribute to concentrations in coastal seas. dC_j is the resultant of outputs from both models;
- Both routes produce a concentration increment of N in coastal seas due to 1 % increase of gross manure or fertilizer supply, taking all fate processes in soil, air and water into account. Taking this into account a composite fate factor is evaluated.
- Derivation of the fate factor for P is less complex as emission to air during manure or fertilizer supply is neglected. Only CARMEN is used to calculate dC_j^k.
- Emission of N and P from the outlet of STPs. The average of N and P emission per capita is 4.6 and 1.06 kg/yr in Europe, respectively. The environmental intervention regarding this point source is the emission of nutrients from the technosphere, i.e. emission after treatment in STPs.
- EUTREND is applied to convert emissions of NH_3 and NO_x to air into deposition on sea and soil. In 1995 this was 6.81·106 tn NH_3 and 1.99·107 tn NO_2 in Europe. These values were taken for 1 % emission increments for whole Europe. Deposition on European soils was converted into concentration in coastal seas with CARMEN.

For freshwater also the summation of concentrations in rivers is also area weighted.

The fate factors for the year 1995 are summarized in Table 6.1. Note that for N supply, either manure or fertilizer, a composite fate factor is given, i.e. both routes (through air and soil) to the receiving water compartments are included. The values of these composite fate factors are specific for the default percentages of N volatilization. In the supporting information, a differentiation is made between air and soil for nitrogen emission due to supply of manure and fertilizer. Fate factors regarding aquatic eutrophication due to supply of manure or fertilizer are related to gross supply of P or N. Net supply of N and P takes only the share into account that is available to eutrophy surface water after uptake by plants and crops in the topsoil.

Table 6.1: Fate factors for aquatic eutrophication. Interventions are agricultural P or N emissions to soil due to gross supply of manure or fertilizer. Midpoints are printed in bold.

Intervention			**Fate factor**	
emission type	compartment	dimension	seawater	Freshwater
manure P	Soil	yr/km^3	$3.27·10^{-6}$	**$1.72·10^{-5}$**
fertilizer P	Soil	yr/km^3	$2.55·10^{-6}$	**$1.83·10^{-5}$**
manure N	soil + air	yr/km^3	**$5.69·10^{-6}$**	$2.21·10^{-5}$
fertilizer N	soil + air	yr/km^3	**$5.21·10^{-6}$**	$3.16·10^{-5}$
N from STP	Freshwater	yr/km^3	**$7.17·10^{-5}$**	$3.42·10^{-4}$
P from STP	Freshwater	yr/km^3	$7.28·10^{-5}$	**$3.44·10^{-4}$**
emission NH_3	Air	(yr·tn N)/(km^3·tn NH_3)	**$6.60·10^{-6}$**	$1.51·10^{-5}$
emission NO_2	Air	(yr·tn N)/(km^3·tn NO_2)	**$2.79·10^{-6}$**	$4.95·10^{-6}$

If only *net* agricultural N or P emissions to the receiving water systems are available (i.e. after uptake by plants in the top soil), the fate factors of the upper half of Table 6.1 are not appropriate. In that case the fate factors should be multiplied with the factors given in Table 6.2. The fate factors for the upper half of Table 6.1 pertain to supply of N/P to agricultural soil, however, when multiplied with the relevant factors of Table 6.2, fate factors are obtained that are appropriate for *net* N/P emissions from agricultural activities, i.e. if the net release from top soil to water bodies is given.

Table 6.2: Net/gross correction factors for fate factors of agricultural emissions in Table 6.1.

Emission	**compartment**	**net/gross ratio**
manure P	soil	19.33
fertilizer P	soil	19.33
manure N	soil + air	14.46
fertilizer N	soil + air	8.57

If volatilization percentages of NH_3 during the application of manure and fertilizer differ from the defaults, i.e. 21 % and 7 %, respectively, the data in Table 6.1 and Table 6.2 are not valid. In case other volatilization percentages are more realistic, a method for this conversion is provided in the supporting information. It is common practice in LCA impact assessment to combine characterization with normalization. Composite characterization factors (for soil and air emissions) are inconvenient as normalization requires a characterization factor that is based upon a single emission compartment. Therefore, also emission compartment resolved fate factors are provided. These fate factors require the amount N emitted to air and soil in a straightforward fashion. Composite fate factors that cover both transport routes are given in case only net emissions are available and volatilization percentages deviate from the defaults.

6.4 MIDPOINT CHARACTERIZATION

6.4.1 FATE FACTORS WITH RESPECT TO RELEVANT WATER SYSTEMS

Biomass growth in different aquatic ecosystems may be limited by different nutrients. Most of the time, aquatic ecosystems are saturated by either nitrogen or phosphorus, and only the non-saturated element (the limiting factor) will cause eutrophication (e.g. Kristensen and Hansen. 1994, Crouzet et al. 1999). In temperate and subtropical regions of Europe, freshwaters are typical limited by phosphorus, whereas nitrogen usually limits production of algal biomass in marine waters (e.g., Crouzet et al. 1999). Here we assume that the limiting nutrient is N in all coastal waters and P in all freshwaters and therefore marine and inland waters are treated as two subcategories under aquatic eutrophication. Therefore, only the fate factors printed in bold (Table 6.2) are considered midpoints.

6.4.2 AQUATIC EUTROPHICATION POTENTIALS

In European regions, where moderate climate conditions prevail, sea and freshwater have distinct limiting nutrients, being nitrogen and phosphorus, respectively. This divides eutrophication into two different impact categories: one for nitrogen enrichment of seawater and one for phosphor enrichment of freshwater. For both impact categories it is convenient, f.i. for normalization purposes, to relate different fate factors to direct emissions to water. For seawater eutrophication, reference can be made to emission of N from STPs to freshwater (which will reach coastal waters) and P emission from STP to freshwater for freshwater eutrophication. This requires that all fate factors have the same units. For emission of NH_3 and NO_2 to air in Table 6.1 the fate factor should also expressed in yr/km3 by multiplying with the factors 17/14 and 46/14, respectively. For gross N supply to agricultural land, the eutrophication potentials in Table 6.3 are only valid for default volatilization fractions of N supply. In the supporting information a calculation routine is provided for deviating volatilization rates.

The fate factors in Table 6.3 and Table 6.4 are the characterization factors (CF) at the midpoint level.

Table 6.3: Fate factors (midpoint CF) and eutrophication potentials (EP seawater)

Intervention		**fate factor**	**EP seawater**
emission type	compartment	**yr/km^3**	**(-)**
manure N	soil + air	5.69×10^{-6}	0.079
fertilizer N	soil + air	5.21×10^{-6}	0.073
N from STP	freshwater	7.17×10^{-5}	1
emission NH_3	Air	8.01×10^{-6}	0.112
emission NO_2	Air	9.18×10^{-6}	0.128

For P in freshwater, the eutrophication potentials are given in Table 6.4.

Table 6.4: Fate factors (midpoint CF) and eutrophication potentials (EP freshwater)

Intervention		**fate factor**	**EP freshwater**
emission type	compartment	**yr/km^3**	**(-)**
manure P	Soil	1.72×10^{-5}	0.050
fertilizer P	Soil	1.83×10^{-5}	0.053
P from STP	freshwater	3.44×10^{-4}	1

6.5 ENDPOINT CHARACTERIZATION

Until now, it has not been feasible to formulate a damage function in dimensions of “potentially vanished fraction” or “potentially disappeared fraction” (PDF) per concentration increase, or the total speciesloss. Such a damage function can be attached to the midpoint through multiplication yielding an endpoint characterization factor. Here we make an attempt to evaluate a damage factor for eutrophication of freshwater due to the emission of phosphor.

Whether aquatic nutrient enrichment leads to an environmental problem or not depends on local factors like topography, physical and chemical nature of water bodies. Here we make an attempt to assess ecological damage due to eutrophication of freshwater caused by too high concentrations of phosphorus. Aquatic species as well as chemical and physical parameters are monitored in various Dutch surface waters on a regular basis. We selected the combination of phosphorus concentration and the number of macrofauna species to analyze aquatic eutrophication in freshwaters. In Figure 6.2 the number of species per location is plotted against the phosphorus concentration. The dome shaped cloud of points indicates that many stressors may affect the species diversity at varying levels. In the left part (< 30 µg/L) the number of species decreases with lower P concentrations due to phosphorus deficiency. In the range of P concentrations between 30 and 300 µg/L freshwater may have any number of macrofauna species between zero and the optimal number of 129. This number reflects the absence of environmental stressors, whereas zero indicates a great influence of all other possible stressors. The cloud of points enables interpretation by drawing a contour line (for example the 95th percentile of the number of species per P concentration) which indicates impairment of most invertebrates due to disturbing conditions in freshwater. A concentration as high as 10,000 µg/L (point B), inhibits the occurrence of any macrofauna species, even if all other conditions are optimal. In the range between 300 and 10,000 µg/L a declining number of species due to an increasing dominancy of eutrophication becomes visible as a contour line, indicating P enrichment that decreases essential requirements for aquatic life of invertebrates. Point B indicates that nutrient enrichment has pushed the ecosystem over the edge. The unbalanced growth of phytoplankton and macrophytes causes the water to become obfuscated and depleted from oxygen and macrofauna life has become virtually impossible.

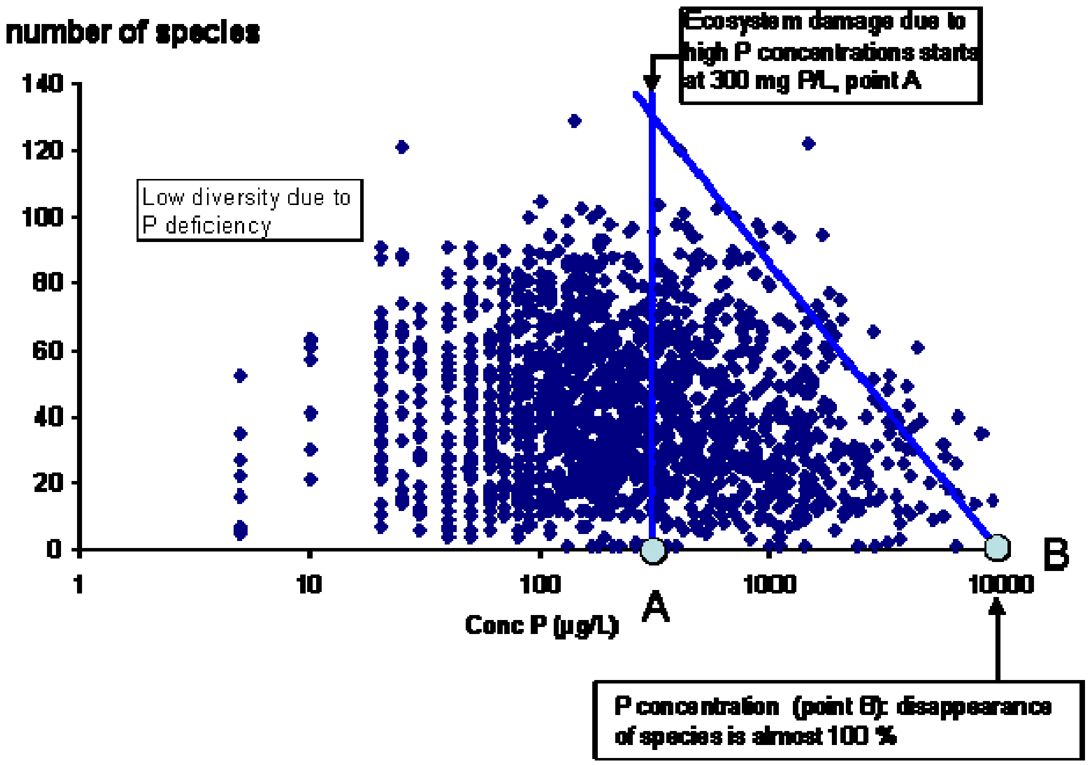

Figure 6.2: Number of macrofauna species in Dutch freshwater systems monitored during the summer period. (source: STOWA, 2005).

Figure 6.2 is, however, not suitable to derive a quantitative relationship between the P concentration and the occurrence of macrofauna. We discarded all biosurvey data with a P concentration below 100 µg/L and aggregated species into genera (total 251). For each genus the relative abundance (Abu_{rel}) was evaluated for 20 intervals of log C_P. $Abu_{rel} < 0.05$ is considered absence (= 0) otherwise the species is present (= 1). The variation among 251 genera in response to log C_P is regarded a Species Sensitivity Distribution (SSD). For each concentration interval the Potentially Disappeared Fraction (PDF) is computed according to: PDF = 1 – (number present/251) and plotted versus C_P as in Figure 6.3.

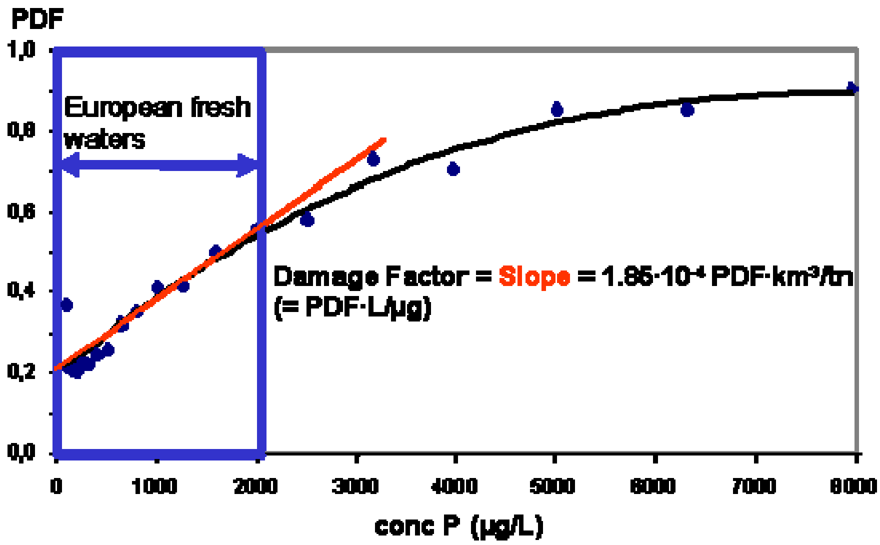

Figure 6.3: Potentially Disappeared Fraction (of macrofauna genera) vs the concentration P in freshwater.

Phosphor concentrations in almost all European freshwaters are in the range between 0 and 2000 µg/L (or tn/km^3)which is in the more or less linear part of the PDF curve. The damage factor (DF) is obtained from the slope and because PDF is dimensionless DF has units of km^3/tn. The characterization factor at the endpoint level is the product of the fate factor in Table 6.4 and this damage factor in Figure 6.3. This gives results in units of PDF.yr per ton in the one but last column of Table 6.5. This damage occurs in a volume that is as large as the entire freshwater volume in CARMEN. This volume is estimated by multiplying the entire freshwater surface in the model (2.95x10^{11} m^2) with an average water depth of 3 meter. This results in a volume of 8.85x10^{11} m^3.

Table 6.5: Endpoint characterization for freshwater eutrophication.

		Dissapeared fraction (PDF)		Characterisation factor
emission type	**emission compartment**	**PDF.yr/tn**	**PDF.yr·m^3/kg**	**Species.yr/kg**
manure P	Soil	3.2×10^{-9}	2.81	2.22x10^{-9}
fertilizer P	Soil	3.4×10^{-9}	2.99	2.36x10^{-9}
P from STP	**Freshwater**	**6.4×10^{-8}**	**56.3**	**4.44x10^{-8}**

6.6 DISCUSSION AND CONCLUSIONS

In the designation of fate factors for aquatic eutrophication, the concept of limiting nutrient can be denied, in principal. Fate factors for N and P were evaluated for inland and coastal waters (Table 6.1) ignoring the fact one or the other nutrient is always limiting algae or duckweed growth. Application of the Redfield ratio (Redfield et al., 1993) referring to the typical composition of aquatic phytoplankton ($C_{106}H_{263}O_{110}N_{16}P$), allows conversion of all fate factors into exposure factors by multiplication with the Redfield ratio. Table 6.6 converts the mass of a nutrient into plant biomass. Multiplication would convert fate factors (in yr/km^3) into in exposure factors in terms of (ton algae/ton nutrient)·(yr/km^3).

Table 6.6: Conversion factors for phosphorus and nitrogen, based on the Redfield ratio

Nutrient	**tn algae/tn nutrient**
P	114.5
N	15.8

For the midpoints, however, we adopt the concept of limiting nutrients and only the fate factors printed in bold in Table 6.1 are considered appropriate characterization factors for the relevant water systems. As a consequence, this would result in exposure factors as given in supporting information. If the concept of the limiting nutrient is abandoned, both N- and P-nutrients in one receiving compartment can be aggregated by multiplying the fate factors for both P and N with the Redfield ratios of Table 6.6.

Further aggregation is feasible because in principle, the produced phytoplankton also requires a certain amount of oxygen due to bacterial degradation of the biomass (see e.g. Samuelsson 1993). Accordingly, emissions of phosphorus and nitrogen compounds may be expressed in units of biological oxygen demand (BOD) or COD to indicate the loading of surface water with organic material. Phosphorus, nitrogen and organic waste can thus be aggregated into a single score by characterization factors related to the impact indicator of oxygen depletion in water systems that are naturally aerobic.

At the midpoint, we have chosen to consider the fate factor to be equal to the characterization factor only for the limiting nutrient. A comparison with the EDIP 2003 midpoint for aquatic eutrophication is not well feasible. Potting and Hauschild (2005) applied the CARMEN model in a different fashion. Even in their "site generic" approach their results express the emitted fraction of nutrient that is available to eutrophy surface water and as such can not be used to compare to a fate factor in units of year/km^3.

The impact score in the EDIP 2003 method is fraction multiplied by nutirient emission (intervention) and has dimensions of ton nutrients per year that eutrophy surface water, whereas in our approach the impact score has the dimensions of concentration (tn/km^3) in the surface water of protection: fate factor (yr/km^3) multiplied by nutrient emission (tn/yr).

In the formulation of fate factors for nitrogen that enters seawater exclusively via air, exclusively through soil or via both routes, for practical reasons we prefer additivity with respect to the impacts score over additivity with respect to fate factors. Thus the sum of fate factors for N to air and soil is not equal to the composite fate factor. However, the impact scores are additive, provided that the emission of N can be split up into fractions emitted to air and to soil. For example, if the intervention is 100 tn manure N per year supplied to agricultural land, the sum of the impact scores calculated with fate factors is equal to $79 \times 4.31 \times 10^{-6} + 21 \times 1.09 \times 10^{-5} = 5.69 \times 10^{-4}$ tn/km^3 for the default scenario. This is similar to 100 multiplied by the composite fate factor (5.69×10^{-6} yr/km^3).

The assumed volatilization percentages are average values for all regions. This is also true for the assumption that 30 % of N in lakes and rivers is converted into N due to denitrification. Other sources of uncertainty and variability are the neglect of any emission of phosphorus to air and the assumption that there is no import from outside of Europe.

6.7 LITERATURE

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6.8 SUPPORTING INFORMATION

Redfield ratio based conversion factors (last column)

Conversion factors for inventory data that refer to loading the technosphere (agricultural topsoil and wastewater treatment), according to EDIP 2003 (Potting and Hauschild, 2005)

Alternative scenarios of N supply to agricultural fields

Exposure factors

Characteristics of European freshwater systems in CARMEN

Characteristics of European coastal seas in CARMEN

Countries in Europe as emission regions considered in CARMEN

6.9 SUMMARY TABLE

Entity	**Content**
impact category	Eutrophication
LCI results	eutrophying substances: N and P compounds
midpoint indicator(s) (with abbreviation)	freshwater eutrophication (FE) marine eutrophication (ME)
unit of midpoint indicator(s)	kg (P to freshwater) kg (N to freshwater)
midpoint characterisation factor (with abbreviation)	FEP MEP
unit of midpoint characterisation factor	– (or kg/kg) – (or kg/kg)
endpoint indicator(s) (with abbreviation)	
unit of endpoint indicator(s)	Yr
endpoint characterisation factor (with abbreviation)	**$4.44x10^{-8}$**
unit of endpoint characterisation factor	yr/kg

7 TOXICITY[17]

Mark A.J. Huijbregts[18], Rosalie van Zelm, Linda Rombouts, Ad Ragas, Jaap Struijs, Mark Goedkoop, Reinout Heijungs, Jasper Harbers, Arjen Wintersen, Leo Posthuma, Jan Hendriks, Dik van de Meent

7.1 INTRODUCTION

The characterisation factor of human toxicity and ecotoxicity accounts for the environmental persistence (fate) and accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. Fate and exposure factors can be calculated by means of ‘evaluative’ multimedia fate and exposure models, while effect factors can be derived from toxicity data on human beings and laboratory animals (Hertwich et al., 1998; Huijbregts et al., 2000). A commonly applied multimedia fate, exposure and effects model is USES-LCA, the Uniform System for the Evaluation of Substances adapted for LCA purposes (Huijbregts et al., 2000). The present chapter outlines an update of the fate, exposure, effect and damage part of USES-LCA, based on Huijbregts et al. (2005a, b), Van de Meent and Huijbregts (2005) and Van Zelm et al. (2007,2008). The update is referred to as USES-LCA 2.0.

7.2 FATE AND EXPOSURE FACTOR

The marginal change in the steady state concentration in an environmental compartment due to a marginal emission change is defined as the compartment-specific fate factor (Huijbregts et al., 2005a):

$$F_{j,i,x} = \frac{\partial C_{j,x}}{\partial M_{i,x}} \tag{7.1}$$

in which $F_{j,i,x}$ represents the compartment-specific fate factor that accounts for the transport efficiency of substance x from compartment i to and persistence in compartment j (year.m^{-3}), $C_{j,x}$ is the marginal change in the steady state dissolved concentration of substance x in compartment j (kg.m^{-3}), and $M_{i,x}$ is the marginal change in the emission of substance x to compartment i (kg.year^{-1}). USES-LCA 2.0 calculates compartment-specific fate factors for 1 freshwater, 1 sea, 3 oceanic and 7 soil compartments. Emission compartments identified were urban air, rural air, freshwater, seawater, agricultural soil and industrial soil on the Western European scale.

The marginal change in steady state intake of substance x in the total human population at scale g via intake route r due to a marginal emission change in compartment i is defined as the route-specific intake fraction of the human population (Huijbregts et al., 2005a):

$$iF_{r,i,x,g} = \frac{\partial I_{r,x,g}}{\partial M_{i,x}} == \frac{\partial I_{r,x,g}}{\partial C_{j,x}} \times \frac{\partial C_{j,x}}{\partial M_{i,x}} \tag{7.2}$$

in which $iF_{r,i,x,g}$ represents the human population intake fraction at geographical scale g that accounts for transport of substance x via intake route r from emission compartment i (dimensionless), and $\partial I_{r,x,g}$ is the marginal change in the intake of substance x by the human population via intake route r (kg.day^{-1}) at scale g. Table 7.1 shows the emission compartments, the environmental receptors and human intake routes identified in the fate factor calculations are also shown in Table 7.1.

Table 7.1: Emission compartments, environments and human exposure routes included

Emission compartments	Environmental receptors	Human exposure routes
Urban air	Terrestrial environment	Inhalation
Rural air	Freshwater environment	Ingestion via root crops
Freshwater	Marine environment	Ingestion via leaf crops

[17] The text of this chapter was based on the following papers:
- Huijbregts MAJ, Struijs J, Goedkoop M, Heijungs R, Hendriks AJ, Van de Meent D. 2005. Human population intake fractions and environmental fate factors of toxic pollutants in Life Cycle Impact Assessment. Chemosphere 61 (10): 1495-1504.
- Huijbregts MAJ, Rombouts LJA, Ragas AMJ, Van de Meent D. 2005. Human-toxicological effect and damage factors of carcinogenic and non-carcinogenic chemicals for life cycle impact assessment. Integrated Environmental Assessment and Management 1 (3): 181-244.
- Van Zelm R, Huijbregts MAJ, Harbers JV, Wintersen A, Struijs J, Posthuma L, Van de Meent D. 2007. Uncertainty in msPAF-based ecotoxicological freshwater effect factors for chemicals with a non-specific mode of action in life cycle impact assessment. Integrated Environmental Assessment and Management 3 (2): 203-210.
- Van Zelm R, Huijbregts MAJ, Wintersen A, Posthuma L, Van de Meent D. 2008. msPAF-based Ecotoxicological Effect Factors of Pesticides for Freshwater Ecosystems. Int. J. LCA (submitted)

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Sea water	Ingestion via meat products
Agricultural soil	Ingestion via dairy products
Industrial soil	Ingestion via eggs
Natural soil	Ingestion via freshwater fish
	Ingestion via marine fish
	Ingestion via drinking water

The nested multimedia fate model Simplebox 3.0, developed by Den Hollander et al. (2004) and included in the newest version of EUSES (EC, 2004), forms the basis of the update of USES-LCA. The SimpleBox fate model has four spatial scales (local, regional, continental and hemispheric) and three climate zones, reflecting arctic, moderate and tropic climatic zones of the Northern hemisphere. The model structure of Simplebox has been adapted to meet LCA-specific demands. These changes are discussed below.

Discarding the local and regional scale

In almost all current life cycle inventories, emissions are summed up per pollutant regardless of their geographical place of occurrence. This results in an inventory outcome that lacks any retrievable relation with a particular region. Consequently, the local and regional scales are not used in the calculation of fate factors.

Urban and rural area at the continental scale

To model the consequences of multimedia fate and exposure in high and low density populated areas, the continental scale is subdivided into a (sub)urban and rural scale. The (sub)urban scale is nested in the rural scale and has two compartments, air and urban soil. The number of people on the (sub)urban scale is approximately 100 million persons in Western Europe. Assuming a population density of 2000 persons.km^{-2}, the urban area equals 5,000 km^2. The rural scale includes the compartments air, freshwater, freshwater sediment, sea water, sea water sediment, natural soil, agricultural soil and industrial soil. In the fate and exposure calculations, emissions to air are specified for the urban and rural air, respectively. Emissions to industrial soil are modelled as emissions to ‘industrial soil’ in the rural area.

Soil depth-dependent intermedia transport

In standard multimedia mass balance models, the soil compartment is modeled as a box with uniform concentrations, which often does not correspond with actual field situations. Therefore, the theoretically expected decrease of soil concentrations with depth was implemented in USES-LCA 2.0. Soil-related intermedia processes, such as volatilisation, leaching, run off, drainage and transpiration by vegetation were modelled with depth-specific soil concentrations (Hollander et al., 2004).

Rain – no rain conditions

Hertwich (2001) found that under continuous rain conditions, particularly air concentrations are not appropriately estimated for substances with a low gas/water partition coefficient (<10^{-5} at 25 °C). Therefore, following Hertwich et al. (2001), a weighted average of marginal environmental concentration and human intake changes is calculated at conditions with (20%) and without (80%) rainfall.

Vegetation at the hemispeheric scale

For the assessment of human population intake fractions, marginal concentration changes in above and below ground crops are needed. Therefore, vegetation compartments were included at the three zones at the hemispheric scale.

Ecological soil depth

The average concentration of the top 20 cm of the soil is included in the calculation of terrestrial fate factors, assuming that terrestrial species are exposed to contaminants in the top 20 cm of the soil only.

Drinking water concentrations

The calculation of the marginal concentration change in drinking water on the continental scale is added to Simplebox 3.0, using both the marginal surface water concentration change after purification and the marginal groundwater concentration change. It is assumed that drinking water from ground water comes from agricultural soil, natural soil and industrial soil, aggregated by the soil surface area fractions of the three soil types. For the human exposure assessment, concentrations in ground water were calculated at 1 m.

Egg, dairy and meat product concentration

Simplebox 3.0 does not calculate concentrations in eggs, dairy and meat products. The equations applied to calculate concentrations in these media are, however, needed in the human population intake fraction calculations. For these animal-derived food items concentrations are calculated following Hertwich et al. (2001).

Human transfer factors
Region-specific food item production rates for the year 2000 have been derived from food production statistical databases provided by the Food and Agriculture Organisation of the United Nations (FAO, 2004). These production statistics were corrected to reflect the amount produced for human consumption. Additionally, for fruits, treenuts, pulses, leafy vegetables and root crops a second correction factor is introduced to reflect the edible part of the human food produced. Table 7.2 shows the effective human production rates of the food items included. Population numbers, average human intake rates of air and drinking water are also listed.

pH-dependency
pH-dependency of (a) the Henry coefficient of dissociating substances (Shiu et al., 1994), (b) soil-water partitioning coefficients for a number of metals (Sauvé et al., 2000) and (c) rates of hydrolysis in water, soil and sediments of dissociating substances were taken into account in the model calculations.

Table 7.2 Human consumption rates for drinking water and inhalation, and effective food production rates applied in the human population intake fraction calculations

Parameter	Unit	C	M	A	T	Source
Number of humans		$2.7{\cdot}10^{8}$ (R) $1.0.10^{8}$ (U)	$2.2{\cdot}10^{9}$	$9.8{\cdot}10^{7}$	$2.7{\cdot}10^{9}$	a
Drinking water intake	$m^3.capita^{-1}.y^{-1}$	$5.1.10^{-1}$	$5.1.10^{-1}$	$5.1.10^{-1}$	$5.1.10^{-1}$	b
Inhalation	$m^3.capita^{-1}.y^{-1}$	$4.9.10^{3}$	$4.9.10^{3}$	$4.9.10^{3}$	$4.9.10^{3}$	b
Freshwater fishery production	$kg_{wwt}.y^{-1}$	$8.3.10^{8}$	na	na	Na	c
Marine fishery production	$kg_{wwt}.y^{-1}$	$1.5.10^{9}$	41.10^{10}	ng	$1.4.10^{10}$	c
Cereal production	$kg_{wwt}.y^{-1}$	$1.2.10^{11}$	$5.3.10^{11}$	$3.0.10^{10}$	$3.3.10^{11}$	c
Fruit production	$kg_{wwt}.y^{-1}$	$4.4.10^{10}$	$1.1.10^{11}$	$1.6.10^{9}$	$1.2.10^{11}$	c
Vegetable production	$kg_{wwt}.y^{-1}$	$4.0.10^{10}$	$3.0.10^{11}$	$6.0.10^{9}$	$1.5.10^{11}$	c
Treenuts production	$kg_{wwt}.y^{-1}$	$6.1.10^{8}$	$2.8.10^{9}$	$2.1.10^{4}$	$1.4.10^{09}$	c
Pulses production	$kg_{wwt}.y^{-1}$	$2.2.10^{9}$	$7.9.10^{9}$	$1.1.10^{9}$	$1.3.10^{10}$	c
Roots and tubers production	$kg_{wwt}.y^{-1}$	$2.3.10^{10}$	$1.3.10^{11}$	$9.9.10^{9}$	$1.0.10^{11}$	c
Meat production	$kg_{wwt}.y^{-1}$	$3.6.10^{10}$	$1.1.10^{11}$	$3.9.10^{9}$	$4.3.10^{10}$	c
Milk production	$kg_{wwt}.y^{-1}$	$1.1.10^{11}$	$1.7.10^{11}$	$1.8.10^{10}$	$1.1.10^{11}$	c
Egg production	$kg_{wwt}.y^{-1}$	$4.8.10^{9}$	$2.8.10^{10}$	$1.1.10^{9}$	$1.1.10^{10}$	c

C= Continental scale; M = Moderate zone; A = Arctic zone; T = Tropic zone; R = rural area; U = urban area
na = not applicable; ng = negligible
[a] Haub (2003); [b] USEPA (1999); [c] FAO (2004)

Degradation half lifes
Degradation rates in water were specified as hydrolysis, photo-degradation and biodegradation separately. Biodegradation half lifes in sea water were set 3 times higher compared to freshwater (EC, 2004). In case no quantitative information on biodegradation rates was available, primary degradation classes, estimated by the EPIWIN software (US-EPA, 2005), were used to derive biodegradation half lifes.. For degradation half lifes in vegetation no estimation routine was found in the literature. Based on empirical information for 34 substances on degradation half lifes in soil (Howard et al., 1991) and degradation half lifes derived from standardised plant cell culture tests (Komoßa et al., 1995), degradation half lifes in vegetation were set 15 times lower compared to soil.

7.3 ECOTOXICOLOGICAL EFFECT FACTOR

For ‘ecotoxicity’, calculation of the combined ecotoxicological effects of mixtures of toxic chemicals on sets of species, as described by Traas *et al.* (2002), assumes independence of the different toxic modes of action:

$$PDF_{tox} = 1 - \prod_{k}\left(1 - PDF_k\right) \qquad (7.3)$$

where the mode of action-specific disappearance of species, PDF_k, can be approximated by an L(E)C50-based species sensitivity distribution per mode of action *k* (Posthuma and De Zwart, 2006):

$$PDF_k \approx PAF_k^{L(E)C50} \qquad (7.4)$$

As the focus is on marginal changes in ecological and human damage due to marginal changes in the production of goods and services, the ecotoxicological effect factor for substance *x* is obtained by partial differentiation of the msPDF-equation (Huijbregts et al., 2002). The partial derivative $\partial msPDF/\partial C_x$ for ecotoxic pollutants is split into three factors:

$$\frac{\partial PDF_{tox}}{\partial C_x} = \frac{\partial PDF_{tox}}{\partial TU_k} \cdot \frac{\partial TU_k}{\partial C_x} \tag{7.5}$$

where TU_k represents the effective toxicity (in toxic units) of a group of pollutants with the same mode of action and C_x is the environmental concentration of substance *x* with mode of action *k*.

Starting from concentration addition for chemicals with the same toxic mode of action *k* (De Zwart and Posthuma 2005, Könemann and Pieters 1996) and a lognormal Toxic Unit (TU)-response function, $\partial PDF_{tox}/\partial TU_k$ is summarized by (Van Zelm et al., 2007):

$$\frac{\partial PDF_{tox}}{\partial C_x} = \underbrace{\left\{ \frac{1-PAF_{tox}}{(1-PAF_k)\cdot\sigma_k\cdot\sqrt{2\cdot\pi}\cdot TU_k\cdot\ln 10}\cdot\exp\left(-\frac{1}{2}\cdot\left(\frac{\log(TU_k)}{\sigma_k}\right)^2\right)\right\}}_{TMoA-specific}\cdot\underbrace{\frac{1}{HC50_x}}_{Chemical-specific} \tag{7.6}$$

This derivation shows that $\partial PDF_{tox}/\partial C_x$ consists of a TMoA-specific part ($\partial PDF_{tox}/\partial TU_k$) and a chemical-specific part ($\partial TU_k/\partial C_x$). Based on Van Zelm et al. (2007) and Van Zelm et al (2008), we derived an average *∂msPAF/∂TU* from 22 modes of action in freshwater ecosystems of 0.55 effect unit per toxic unit. The *∂PDFtox/∂TUk* is set at a typical value of 0.55 effect unit per toxic unit added, without a further specification per mode of action or ecosystem type due to lack of data.

7.4 HUMAN-TOXICOLOGICAL EFFECT AND DAMAGE FACTOR

As shown by Hofstetter (1998), the concept of DALY is a powerful concept to address human health damages in LCA. The overall human population damage, expressed as DALY caused by a number of diseases ($DALY_{ov}$), can be estimated by:

$$DALY_{ov} = N_{pop}\cdot\sum_e DALY_e\cdot R_e \tag{7.7}$$

where N_{pop} is the total population number, $DALY_e$ is the DALY for disease type *e* and R_e is the probability of occurrence of disease type *e* in the human population.

Taking $DALY_{ov}$ as a measure of overall human population damage, the derivative *∂Damage/∂Intake* can be described by:

$$\frac{\partial DALY_{ov}}{\partial I_x} = \frac{\partial DALY_{ov}}{\partial R_e}\cdot\frac{\partial R_e}{\partial TU_e}\cdot\frac{\partial TU_e}{\partial I_x} \tag{7.8}$$

The damage factor *∂D/∂R* can be calculated by (Huijbregts et al., 2005b)

$$\frac{\partial DALY_{ov}}{\partial R_e} = DALY_e \tag{7.9}$$

where $DALY_e$ is the sum of Years of Life Lost (YLL_e) and Years of Life Disabled (YLD_e) caused by disease type *e*:

$$DALY_e = YLL_e + YLD_e \tag{7.10}$$

Damage factors were derived from the extensive burden of disease and health statistics provided by Murray and Lopez (1996a, b) on a world level for 1990. Applying equal weightings for the importance of 1 year of life lost for all ages and no discounting for future damages. For carcinogenic substances, the typical cancer damage factor is 11.5 years of life lost per incidence case, ranging from 4 years lost for prostate cancer to 28 years lost due to leukemia. The typical non-carcinogenic damage factor is 2.7 years of life lost per incidence case, ranging from 0.1 years lost for panic disorder to 80 year lost due to a number of congenital anomalies, such as renal agenesis (Huijbregts et al., 2005b).

Starting from dose addition (joint action or simple similar action) for chemicals with the same mode of action (Plackett and Hewlett 1952; Könemann and Pieters 1996; Wilkinson et al. 2000; Chen et al. 2001) and a lognormal human relative dose-response function (Hattis 1996, 1997; Renwick and Lazarus 1998), The derivative $\partial R_e/\partial I_x$, representing the mode of action specific-part of the human-toxicological effect factor, can be calculated by (Huijbregts et al., 2005b):

$$\frac{\partial R_e}{\partial I_x} = \underbrace{\left\{\frac{1}{\sigma_{\log,e}\cdot\sqrt{2\cdot\pi}\cdot TU_e\cdot\ln 10}\cdot e^{-\frac{1}{2}\cdot\left(\frac{\log(TU_e)}{\sigma_{\log,e}}\right)^2}\right\}}_{Disease-specific}\cdot\underbrace{\frac{1}{ED50_x}}_{Chemical-specific} \tag{7.11}$$

where $\partial R_e/\partial I_x$ indicates the marginal change in the probability of occurrence of human health effect *e* by a marginal change in the Intake of chemical *x* (kg^{-1}).

To derive $\partial R_e/\partial TU_e$ for the 49 disease types identified, we assumed for all carcinogenic effect types a σ_{log} of 0.59 and for all non-carcinogenic effect types a σ_{log} of 0.26. Disease probability of occurrence statistics were provided by Murray and Lopez (1996b) on a world level for 1990. The average $\partial R_e/\partial TU_e$, weighted by life-time incidence cases, of carcinogenic effects is 0.22. The average non-cancer $\partial R_e/\partial TU_e$ is 0.66. These numbers are higher than reported in Huijbregts et al (2005b) due to the fact that disease prevalence data were previously used instead of life time incidence rates. The latter are preferable.

The carcinogenic chronic dose affecting 50% of a laboratory species of the substance added (ED50) was obtained from the Carcinogenic Potency Database (CPDB), developed by Gold and Zeiger (1997). ED50s were reported as an average of all exposure routes considered (Gold and Zeiger 1997; Gold 2004). If the CPDB reports for a substance a carcinogenic ED50 for more than 1 species, the order of preference is monkey, than dog, rat, hamster and mouse. For substances lacking a carcinogenic ED50 in the CPDB, the carcinogenic low dose slope factor qx^* was used to estimate the carcinogenic ED50 (Huijbregts et al., 2005b).

In case of non-carcinogenic effects, chronic ED50s were not readily available. Based on dose-response data reported in the Integrated Risk Information System (IRIS) of the USEPA (2004), we calculated ingestion ED50s for 12 substances and inhalation ED50s for 9 substances. The ED50 of the binary dose-response data was determined by fitting a probit model to the data. The ED50 of the continuous dose-response data was determined by fitting a linear dose-response model to the data using USEPA's benchmark dose software (BMDS), version 1.3.2 (USEPA 2000). For most of the substances, however, insufficient data were available to derive a non-carcinogenic ED50 with dose-response models. In these cases, the ED50 has been estimated from the No Observed Effect Level (NOEL) or the Lowest Observed Effect Level (LOEL).

After deriving the ED50 for laboratory species, the life-time ED50 for humans can be calculated by extrapolation from test species to humans and extrapolation from sub-acute or semi-chronic exposure to chronic exposure:

$$ED50_{x,r} = \frac{ED50_{a,t,x,r} \cdot X_r \cdot LT \cdot N}{CF_a \cdot CF_t} \qquad (7.12)$$

where $ED50_{x,r}$ is the life-time dose of substance *x* via exposure route *r* affecting 50% of the human population (kg), $ED_{50,a,t,x,r}$ is the effect dose of substance *x* via exposure route *r* affecting 50% of the population test species *a* for exposure duration *t* ($kg.kg^{-1}.day^{-1}$ or $kg.m^{-3}$), CF_a the conversion factor for interspecies differences (–), CF_t is the conversion factor for differences in time of exposure (–), X_r is the average body weight of humans (70 kg) or the average breath intake of humans (13 $m^3.day^{-1}$), *LT* is the average lifetime of humans (75 years), *N* the number of days per year (365 $days.year^{-1}$).

Table 7.3: Interspecies conversion factors

Species	CF interspecies (-)	Average bodyweight (kg)	Source
human	1.0	70	-
pig	1.1	48	Baird, 1996
dog	1.5	15	Vermeire *et al.*, 2001
monkey	1.9	5	Vermeire *et al.*, 2001
cat	1.9	5	Expert judgement
rabbit	2.4	2	Vermeire *et al.*, 2001
hen	2.6	1.6	Baird, 1996
mink	2.9	1	Expert judgement
guinea pig	3.1	0.750	Vermeire *et al.*, 2001
rat	4.1	0.250	Vermeire *et al.*, 2001
hamster	4.9	0.125	Baird, 1996
gerbil	5.5	0.075	Expert judgement
mouse	7.3	0.025	Vermeire *et al.*, 2001

The combined human effect and damage factor can be approximated by

$$E_{r,x,c/nc} = \frac{\partial DALY_e}{\partial I_{r,x}} = \left[\frac{\partial DALY_e}{\partial R_e}\right] \cdot \left[\frac{\partial R_e}{\partial TU_e}\right] \cdot \left[\frac{\partial TU_e}{\partial I_{r,x}}\right] \approx 1.9 \cdot \frac{1}{ED50_{r,x,c/nc}} \qquad (7.13)$$

where *Er,x,c/nc* represents the human effect and damage factor of substance *x* via intake route *r* in terms of loss of disability adjusted life years per kg of intake for carcinogenic or non-carcinogenic efect ($yrlost.kg^{-1}$). Combining disease-specific ∂DALY/∂R and ∂R/∂TU outcomes, the average ∂DALY/∂TU for carcinogens is 2.5 yrlost and for non-carcinogens 1.3 yrlost. Because of the relatively high uncertainty in these numbers (see Huijbregts et al., 2005b for further details) we prefer to work with one default ∂DALY/∂TU for all chemicals and effects which is set equal to the average of the carcinogens and non-carcinogens (1.9 yrlost).

7.5 ENDPOINT CHARACTERISATION FACTOR

The compartment-specific ecotoxicological characterisation factor consists of a fate factor, an effect factor and a species density factor:

$$CF_{j,i,x} = F_{j,i,x} \cdot E_{j,x} \tag{7.14}$$

where $CF_{j,i,x}$ is the compartment-specific environmental characterisation factor of chemical *x* emitted to compartment *i* and transported to compartment *j* (year.kg^{-1}).

In a next step, the compartment-specific characterisation factors were aggregated on the basis of the compartment's volume and area to an environment-specific characterisation factor for the marine and terrestrial environment, respectively:

$$CF_{j,i,x} = SD_q \cdot \sum_j CF_{j,i,x} \cdot W_{j \in q} \tag{7.15}$$

where $CF_{q,i,x}$ represents the environment-specific characterisation factor for substance *x* emitted to compartment *i* causing effects in environment *q* (m2.year.kg^{-1}), W_j is the area or volume of compartment *j* (m2 or m3) in environment *q* and SD_q the species density of enviromment q (1/m2 or 1/m3).

The scale-specific human characterisation factor consists of a fate factor and combined effect and damage factor:

$$CF_{r,i,x,g,c/nc} = F_{r,i,x,g} \cdot E_{r,x,c/nc} \tag{7.16}$$

where $CF_{r,i,x,g,c/nc}$ represents the human characterisation factor for carcinogenic or non-carcinogenic effects at scale *g* that accounts for transport of substance *x* via intake route *r* (ingestion, inhalation) from emission compartment *i* (year.kg^{-1}). For substances that lack relevant effect data on the exposure route of interest, route-to-route extrapolation with help of allometric scaling factors, and oral and inhalatory absorption factors was performed (EC, 2004). In case chemical-specific information on absorption factors was lacking, complete oral and inhalatory absorption was assumed.

The route-specific (oral, inhalation), scale-specific (continental, moderate, tropic, arctic) and effect-specific (carcinogenic, non-carcinogenic) human characterisation factors were aggregated to an overall human population characterisation factor of substance *x* emitted to compartment *i*:

$$CF_{i,x} = \sum_{n/nc} \sum_r \sum_k CF_{n/nc,r,i,x,g} \tag{7.17}$$

7.6 MIDPOINT CHARACTERISATION FACTOR

The midpoint characterisation factor for ecotoxicity includes the fate factor, *∂C/∂M*, and the chemical-specific part of the effect factor, *∂TU/∂C*. The step towards the marginal change in the disappeared fraction of species, *∂msPDF/∂TU*, has been excluded. This has been modelled as a constant (0.55) due to lack of data, implying that there are no chemical-specific and ecosystem-specific differences introduced by this factor.

The midpoint characterisation factor for human includes the fate and exposure factor, *∂I/∂M*, and the chemical-specific part of the human-toxicological effect and damage factor, *∂TU/∂I*. The step towards the marginal change in the disability adjusted life years, *∂DALY/∂TU*, has been excluded. This has also been modelled as a constant (1.9 yrlost) due to lack of chemical-specific data.

The chemical 1,4-dichlorobenzene was used as a reference substance in the midpoint calculations (to urban air for human toxicity, to freshwater for freshwater ecotoxicity, to seawater for marine ecotoxicity and to industrial soil for terrestrial ecotoxicity).

7.7 UNCERTAINTIES AND CHOICES: PERSPECTIVES

Table 7.4: Choices made in the three perspectives

Item	E +H	I

Time horizon	Infinite	100 years
Exposure routes for human toxicity	All exposure routes for all chemicals	Organics: all exposure routes Metals: drinking water and air only
Environmental compartments for marine ecotoxicity	Sea + ocean for all chemicals	Sea + ocean for organics and non-essential metals. for essential metals the sea compartment is included only, excluding the oceanic compartments
Carcinogenity	All chemicals with reported TD50	Only chemicals with TD50 classified as 1, 2A, 2B by IARC

Time horizon
As shown by Huijbregts et al (2001), the impact of metals largely depend on the time horizon of interest. We choose to define the egalitarian and hierarchistic scenario with an infinite time horizon, while the individualistic scenario takes a time horizon of 100 years as a starting point..

Exposure routes
USES-LCA assumes in the calculation of human population intake fractions for metals that the concept of bioconcentration, generally applicable for organic pollutants, also holds for inorganics. However, this assumption may be doubtful. For instance, McGeer et al. (2003) found an inverse relationship between the bioconcentration factor and exposure concentration of metals in the environment. Hendriks and Heikens (2001) also showed that internal body concentrations of metals increase less than proportional with increasing environmental concentrations. To include the sensitivity of the human population intake fractions for metals in the calculations, we assumed in the egalitarian and hierarchic scenario that human exposure via all intake routes (air, drinking water, food) occurs. In contrast, the more conservative individualistic scenario assumes human exposure via air and drinking water only.

Marine ecotoxicity
USES-LCA includes potential fate and effects of metals in the oceans. However, in a recent LCA workshop on non-ferro metals the potential effect of essential metals in oceans has been critised (Ligthart, 2004). The potential impact in the marine environment may strongly depend on the statement that additional inputs of (essential) metals to oceans also lead to toxic effects (Ligthart, 2004). To test the sensitivity of this model assumption, the egalitarian and hierarchic scenario include the sea and oceanic compartments in the calculation of the marine ecotoxicological impacts, while the individualistic scenario excludes the oceanic environment in the calculations for essential metals. Essential metals are Cobalt, Copper, Manganese, Molybdenum and Zinc.

Carcinogenity
Concerning the carcinogenity of a substance, it should be noted that not all substances with a carcinogenic ED50 are necessarily known carcinogenics to humans. The International Agency for Research on Cancer (IARC), part of the WHO, evaluated the carcinogenic risk of 844 substances (mixtures) to humans by assigning a carcinogenity class to each substance (IARC 2004). The classes reflects the strength of the evidence for carcinogenity derived from studies in humans and in experimental animals and from other relevant data. This information can be readily used to define the two scenarios. The egalitarian and hierarchic scenario include the substances with insufficient evidence of carcinogenity (IARC-category 1, 2A, 2B, 3 or no classification). The individualistic scenario includes the substances with strong evidence of carcinogenity (IARC-category 1, 2A and 2B) only.

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7.9 SUPPORTING INFORMATION

No supporting information available

7.10 SUMMARY TABLE

Entity	Content
impact category	toxicity
LCI results	human toxic and ecotoxic substances (very many)
midpoint indicator(s) (with abbreviation)	human toxicity (HT) terrestrial ecotoxicity (TET) freshwater ecotoxicity (FET) marine ecotoxicity (MET)
unit of midpoint indicator(s)	kg (14DCB to urban air) kg (14DCB to soil) kg (14DCB to freshwater) kg (14DCB to freshwater)
midpoint characterisation factor (with abbreviation)	HTP TETP FETP METP
unit of midpoint characterisation factor	– (or kg/kg) – (or kg/kg) – (or kg/kg) – (or kg/kg)
endpoint indicator(s) (with abbreviation)	damage to human health (HH) damage to ecosystem diversity (ED)
unit of endpoint indicator(s)	yr $m^2 \times yr$
endpoint characterisation factor (with abbreviation)	HTP 7.0×10^{-7} (I, H, E) TETP 1.3x10-7 (I, H, E) FETP 2.6 10–10 (I, H, E) METP 4.2 10–14 (I, H, E)
unit of endpoint characterisation factor	yr/kg $m^2 \times yr/kg$

8 HUMAN HEALTH DAMAGE DUE TO PM_{10} AND OZONE[19]

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8.1 INTRODUCTION

Fine Particulate Matter with a diameter of less than 10 µm (PM_{10}) represents a complex mixture of organic and inorganic substances. PM_{10} causes health problems as it reaches the upper part of the airways and lungs when inhaled. Secondary PM_{10} aerosols are formed in air from emissions of sulfur dioxide (SO_2), ammonia (NH_3), and nitrogen oxides (NO_x) among others (World Health Organization, 2003). Inhalation of different particulate sizes can cause different health problems. From recent WHO studies, the effects of chronic PM exposure on mortality (life expectancy) seem to be attributable to $PM_{2.5}$ rather than to coarser particles. Particles with a diameter of 2.5–10 µm ($PM_{2.5–10}$), may have more visible impacts on respiratory morbidity (World Health Organization, 2006). PM has both anthropogenic and natural sources. Although both may contribute significantly to PM levels in the atmosphere, this chapter focuses on attributive effects of PM from anthropogenic sources, since only this fraction may be influenced by human activity.

Ozone is not directly emitted into the atmosphere, but it is formed as a result of photochemical reactions of NO_x and Non Methane Volatile Organic Compounds (NMVOCs). This formation process is more intense in summer. Ozone is a health hazard to humans because it can inflame airways and damage lungs. Ozone concentrations lead to an increased frequency and severity of humans with respiratory distress, such as asthma and Chronic Obstructive Pulmonary Diseases (COPD). Ozone formation is a non-linear process which depends on meteorological conditions and background concentrations of NO_x and NMVOCs (European Environment Agency, 2005).

To express the life years affected by respiratory health damage due to exposure to PM_{10} and ozone, Disability Adjusted Life Years (DALYs) is used as a measure.

8.2 FATE FACTOR

The fate factor for human health damage due to PM_{10} and ozone was defined as the marginal change in Intake rate of pollutant *x* (dI_x in kg·yr^{-1}) due to a marginal change in emission of pollutant x (dM_x in kg·yr^{-1}), which equals the Intake Factor of pollutant *x* for the European population ($IF_{pop,x}$). Fate factors for PM_{10} and ozone were calculated with a steady-state and a dynamic model respectively. Fate factors for ozone were calculated for 1, 5, and 10% emission changes to check for linearity in this range. Europe is modeled as an open system. Emissions can be exported out of Europe. Emissions occurring outside the system that are transported into Europe are not taken into account

$IF_{pop,x}$ per gridcel is defined as the marginal increase in population Intake rate of pollutant *k*, per grid cell *i* ($dI_{pop,k,i}$) induced by a marginal increase in emission of *x* (dM_x), e.g. increase in intake of PM_{10}, caused by emission of SO_2 (Van Zelm et al., 2008):

$$IF_{pop,x,i} = \frac{dI_{pop,k,i}}{dM_x} = (IH \cdot N_i)\frac{dC_{k,i}}{dM_x} \tag{8.1}$$

where N_i is the Number of inhabitants of grid cell *i* (derived from Oak Ridge National Laboratory (2004)), $C_{k,i}$ is the yearly average Concentration of pollutant *k* in grid cell *i* (kg·m^{-3}), and IH is the average human breath intake rate (4745 m^3·yr^{-1}; (U. S. EPA, 1997).

The atmospheric fate model EUTREND (Van Jaarsveld, 1995; Van Jaarsveld et al., 1997) was used to calculate intake fractions of PM_{10} from SO_4^{2-}, NH_4^+, NO_3^-, and PM_{10} aerosols, which result from SO_2, NH_3, NO_x, and PM_{10} emissions respectively.

The chemistry and (non-)linearity of ozone formation is relatively complex as it depends on the presence of precursors and meteorological factors and due to the short lifetime of ozone under specific conditions. Therefore the dynamic model LOTOS-EUROS was applied to calculate intake fractions for ozone due to emissions of NO_x and

[19] This chapter is based on a paper by Rosalie van Zelm, Mark A.J. Huijbregts, Henri A. den Hollander, Hans A. van Jaarsveld, Ferd J. Sauter, Jaap Struijs, Harm J. van Wijnen and Dik van de Meent. European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. Atmospheric Environment 42 (2008): 441-453.

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NMVOCs (Schaap et al., 2008). Population intake factors in year 2000 of ozone were calculated from modeled maximum daily 8-hour average ozone concentrations. Since the ozone concentration is calculated over 8 hours the breath intake refers to 1/3rd of a year.

Table 8.1 shows intake fractions for health damage due to PM_{10} and ozone exposure. Intake fractions for ozone for 1% emission increase are reported here. Since Intake factors for NMVOC and NOx-induced ozone are comparable for 1, 5, and 10% emission increases, no distinction is made for the different emission increases.

Table 8.1: European population intake factors (–) due to emissions of PM_{10} and ozone.

Pollutant		Intake fractions
PM_{10}	NH_3	$1.5 \cdot 10^{-6}$
	NO_x	$1.0 \cdot 10^{-6}$
	SO_2	$9.3 \cdot 10^{-7}$
	PM_{10}	$4.9 \cdot 10^{-6}$
Ozone	NO_x	$1.2 \cdot 10^{-7}$
	NMVOC	$1.2 \cdot 10^{-7}$

8.3 EFFECT AND DAMAGE FACTOR

No thresholds for PM_{10} and ozone effects were assumed in the effect calculations. After thorough examination of all available evidence, a review by a WHO working group (World Health Organization, 2004) concluded that most epidemiological studies on large populations have been unable to identify a threshold concentration below which ambient PM and ozone have no effect on mortality and morbidity.

The Effect Factor ($EF_{e,k,i}$ in kg^{-1}), links marginal changes in intake to marginal changes in the Attributable Burden of a population of getting disease *e* due to exposure to pollutant *k* per year of exposure ($AB_{e,k}$ in yr^{-1}). The Damage Factor ($DF_{e,k}$ in yr), links marginal changes in the attributable burden to marginal changes in DALY. The combined human effect and damage factor for pollutant *k* in grid cell *i* was defined as (Van Zelm et al., 2008):

$$EF_{e,k,i} \cdot DF_{e,k,i} = \sum_{e} \left(\frac{\partial AB_{e,k,i}}{\partial I_{pop,k,i}} \cdot \frac{\partial DALY_{e,k,i}}{\partial AB_{e,k,i}} \right) \tag{8.2}$$

with the Effect Factor for pollutant *k* and disease *e* in grid cell *i* defined as:

$$EF_{e,k,i} = \frac{dAB_{e,k,i}}{dI_{k,i}} = \frac{dAB_{e,k,i}}{IH \cdot dC_{k,i}} = \frac{\left(RR_{e,k} - 1\right) \cdot F_{inc,e}}{IH \cdot \left(\left(RR_{e,k} - 1\right) \cdot C_{k,i} + 1\right)^2} \tag{8.3}$$

and the Damage Factor for pollutant *k* and disease *e* defined as:

$$DF_{e,k} = \frac{dDALY_{e,k,i}}{dAB_{e,k,i}} = YLL_e + D_e \cdot S_e \tag{8.4}$$

$RR_{e,k}$ is the Relative Risk to obtain disease *e* from pollutant *k* (per $\mu g \cdot m^{-3}$), $F_{inc,e}$ is the incidence rate of the population to get disease *e* per year of exposure (yr^{-1}), C_k is the Concentration of pollutant *k* ($kg \cdot m^{-3}$), *YLL* is the Years of Life Lost due to disease *e* per incidence case (YLL_e in yr), D_e is the Duration of disease *e* (yr) and S_e is the Severity of disease *e* (–). Both D_e and S_e are related to hospital admissions. More information on calculation and data input for the effect factor and the damage factor can be found in the supporting information. Effect and damage factors attributable to PM_{10} and ozone exposure are in Table 8.2. Mortality due to chronic PM_{10} exposure has a dominant contribution to the calculated characterization factors compared to short term mortality and morbidity. More than 99.5% of the DALYs due to a kg intake of PM_{10} is attributed to chronic mortality.

Table 8.2: Average European effect and damage factors attributable to PM_{10} and ozone concentrations in air.

Pollutant	Disease	Effect and damage factors ($yr \cdot kg^{-1}$)
PM_{10}	Chronic mortality	57.59
	Acute mortality	0.21
	Acute respiratory morbidity	0.02
	Acute cardiovascular morbidity	0.02
Ozone	Acute mortality	0.31

8.4 ENDPOINT CHARACTERIZATION FACTOR

Calculation of endpoint Characterization Factors for human health damage of emitted substance *x* ($CF_{endpoint,x}$ in yr/kg) for Europe consists of the intake factor and the combined effect and damage factor:

$$CF_{endpoint,x} = \sum_i \left(IF_{pop,x,i} \cdot \sum_e \left(EF_{e,k,i} \cdot DF_{e,k} \right) \right) = \sum_i \left(\frac{dI_{pop,k,i}}{dM_x} \cdot \sum_e \left(\frac{dAB_{e,k,i}}{dI_{pop,k,i}} \cdot \frac{dDALY_{e,k}}{dAB_{e,k}} \right) \right) \quad (8.5)$$

Endpoint characterization factors for PM_{10} and ozone emissions, related to human health effects, are in Table 8.3.

Table 8.3: Characterization factors (yr·kg^{-1}) for mortality and morbidity due to emissions of PM_{10} and ozone.

Pollutant	Emitted substance	Endpoint characterization factors (yr·kg^{-1})				
		Mortality		Morbidity (acute)		Total
		chronic	acute	respiratory	cardiovascular	
PM_{10}	NH_3	$8.2\cdot10^{-5}$	$3.2\cdot10^{-7}$	$2.7\cdot10^{-8}$	$2.3\cdot10^{-8}$	$8.3\cdot10^{-5}$
	NO_x	$5.7\cdot10^{-5}$	$2.2\cdot10^{-7}$	$1.8\cdot10^{-8}$	$1.6\cdot10^{-8}$	$5.7\cdot10^{-5}$
	SO_2	$5.1\cdot10^{-5}$	$2.0\cdot10^{-7}$	$1.6\cdot10^{-8}$	$1.4\cdot10^{-8}$	$5.1\cdot10^{-5}$
	PM_{10}	$2.6\cdot10^{-4}$	$1.0\cdot10^{-6}$	$8.6\cdot10^{-8}$	$7.4\cdot10^{-8}$	$2.6\cdot10^{-4}$
Ozone	NO_x		$3.9\cdot10^{-8}$			$3.9\cdot10^{-8}$
	NMVOC		$3.9\cdot10^{-8}$			$3.9\cdot10^{-8}$

8.5 MIDPOINT CHARACTERIZATION FACTOR

On the midpoint level the intake fraction of PM10 is of importance, as the effect and damage factors are substance independent. Particulate matter formating potentials (*PMFP*) are expressed in PM_{10}-equivalents:

$$PMFP = \frac{iF_x}{iF_{PM10}} \quad (8.6)$$

The midpoint characterization factor for ozone formation of substance *x* should be representative for both potential ecosystem and human health effects and is therefore defined as the marginal change in the 24h-average European concentration of ozone (dC_{O3} in kg·m^{-3}) due to a marginal change in emission of substance *x* (dM_x in kg·year^{-1}) expressed as NMVOC-equivalents:

$$OFP = \frac{\overline{dC_{O3}/dM_x}}{\overline{dC_{O3}/dM_{NMVOC}}} \quad (8.7)$$

where *OFP* is the Ozone Formation Potential.

The average European ozone concentration change in ozone is calculated by averaging the grid-specific concentrations over land (sea grids are excluded). Midpoint characterization factors for pollutants causing particulate formation and/or ozone formation are in Table 8.4.

Table 8.4: Midpoint Characterization Factors for particulate matter formation and tropospheric ozone formation of substance x

Emitted substance	Particulate Matter Formation Potential (PM10-eq/kg)	Ozone Formation Potential NMVOC-eq/kg
PM_{10} to air	1	
NH_3 to air	0.31	
NO_x to air	0.21	1.0
SO_2 to air	0.19	
NMVOC to air		1

8.6 CHARACTERIZATION FACTORS FOR INDIVIDUAL NMVOCS

The midpoint and endpoint characterisation factors of NMVOCs do not differentiate between ozone formation by single hydrocarbons. Reactivity among single hydrocarbons however, varies widely. To evaluate the contribution of individual substances to ozone formation, the concept of Photochemical Ozone Creation Potentials (POCPs) was introduced (Derwent and Jenkin, 1991). POCPs are relative reactivities, calculated for ozone formation in a volume of air, with ethylene as a reference substance. The POCP of a VOC is the ratio between the change in ozone concentration due to a change in emission (*M*) of that VOC *x* and the change in ozone concentration due to an equal relative change in emission of ethylene (Derwent et al., 1998). To couple total NMVOC characterization factors to individual classes of NMVOCs, POCPs from Derwent et al. (1998) can be used. The following equation can be used to calculate the characterization factor for a specific hydrocarbon:

$$CF_x = \frac{POCP_x}{POCP_{NMVOC}} \cdot CF_{NMVOC} \quad (8.8)$$

8.7 REFERENCES

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8.8 SUPPORTING INFORMATION

Fate model characteristics
Effect and damage factor calculations

8.9 SUMMARY TABLE

Entity	Content
impact category	health damage due to PM_{10} and ozone
LCI results	particulate matter and ozone creating substances: PM_{10}, NH_3, SO_2, NO_x and NMVOC
midpoint indicator(s) (with abbreviation)	photochemical oxidant formation (POF) particulate matter formation (PMF)
unit of midpoint indicator(s)	kg (NMVOC to urban air) kg (PM_{10} to air)
midpoint characterisation factor (with abbreviation)	Ozone Formation Potential (OFP) Particulate Matter Formation Potential (PMFP)
unit of midpoint characterisation factor	– (or kg/kg) – (or kg/kg)
endpoint indicator(s) (with abbreviation)	damage to human health (HH)
unit of endpoint indicator(s)	yr
endpoint characterisation factor (with abbreviation)	OFP3.9E10–8 PMFP 2.6E10–4
unit of endpoint characterisation factor	yr/kg

9 IONISING RADIATION

Mark Goedkoop[21]

9.1 INTRODUCTION

This chapter describes the damage to Human Health related to the routine releases of radioactive material to the environment. It is a summary of a paper that has been written for our project by Frischknecht, Suter, Hofstetter and Braunschweig (Frischknecht et al, 1999). Some parts of this paragraph have been quoted directly. The endpoint factors are identical to those used in the Eco-indicator 99; the midpoint is chosen at the level of exposure; the unit is Sievert per Becquerel. At this level the relative contribution of each substance can be determined; the effect and damage analysis is the based on the Sievert exposure level. This means that the characterisation is different from the one used in the CML guide, where effect and damage were included.

Figure 9.1 gives an overview of the entire assessment method of health effects of ionising radiation introduced in this paragraph. The model starts with the release at the point of emission, expressed as Becquerel (Bq). One Becquerel is equivalent with one decay per second.

Phase of the Model	***Stage of Pathway***	***Units***
Inventory Analysis	Radioactive releases	Becquerel, Bq; Bq/FU [1])
↓	↓	
Fate Analysis	*Transport, dispersion and deposition* Contamination in environment	Bq/kg, Bq/l, Bq/m^2, Bq/m^3
↓	↓	
Exposure Analysis	Standard characteristics of people Inhalation, consumption of food and water Absorbed Dose Effective and Average Individual Dose Collective Dose	m^3, kg, l gray, 1Gy=1J/kg Sievert, Sv man.Sievert, man.Sv
↓	↓	***Midpoint level***
Effect Analysis	Dose response relationship Fatal, non-fatal cancer, severe hereditary effects	Number of cases/man.Sv
↓	↓	
Damage Analysis	Disability weighting scale Disability adjusted life years (DALYs)	YLD, YLL, DA-LYs/fatal cancer
↓	↓	
Damage Assessment and Cultural Theory	Value-laden assumptions value weighted DALYs	DALYs/kBq ***Endpoint level***

Figure 9.1: Overview of impact pathway stages of radioactive releases in the assessment described in this paper, based on [Dreicer et al 1995:19] and [Hofstetter 1998]. [1]) FU: Functional unit

9.2 MIDPOINTS

The fate and exposure model has been based on [Dreicer et al 1995], who described the routine[22] atmospheric and liquid discharges in the French nuclear fuel cycle. Data of discharges from the sites (mining and milling, conversion, enrichment, fuel fabrication, electricity production, and reprocessing) and of the surrounding condi-

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22 Routine emissions: Emissions due to normal operation excluding the low probability of severe accidents.

tions (population density, lifestyles of that population, meteorology, etc.) refer to the French situation. The models use a time horizon of 100,000 years in order to consider significant impacts of the different pathways[23]. For the assessment of long-term global impacts the world population is assumed to remain at a constant 10^{10} people for 100,000 years.

Two models are used; a Gaussian dispersal model for substances with a short lifetime and thus a limited dispersal area, and a Global dispersal model for substances with long life times.

- For dispersion of atmospheric discharges a Gaussian plume model is used. For liquid releases into rivers a simple box model is used assuming instantaneous mixing in each section and representing the radionuclide concentration in a compartment with a differential equation. The uncertainty in the fate analysis is approximately a factor 2 to 4.
- For globally dispersed radionuclides, i.e., Tritium, Carbon-14, Krypton-85, and Iodine-129, simplified models over a time horizon of 100'000 years are applied. For H-3 the global hydrological cycle is modelled dynamically based on seven compartments. For C-14 four environmental compartments are used in a dynamic model. For Kr-85 a dynamic model with two compartments (for the two hemispheres) is used. For I-129 a dynamic model with nine compartments is applied. The confidence in the results of the global assessments for Carbon-14, Tritium, Iodine-129, and Krypton-85 is low "due to the extremely general models that are used and the propagation of very small doses over a large population for very long periods of time" [Dreicer et al 1995:310]. For the global assessment the uncertainty is probably greater than an order of magnitude, except for Carbon-14. As we will see the latter uncertainty is disturbingly high, as the global effects turn out to be very significant.

In the exposure analysis we calculate what dose human actually absorb, given the radiation levels that are calculated in the fate analysis. The measure for the effective dose is the Sievert (Sv), based on human body equivalence factors for the different ionising radiation types (α-, β-, γ-radiation, neutrons). 1 Sv = 1 J/kg body weight.

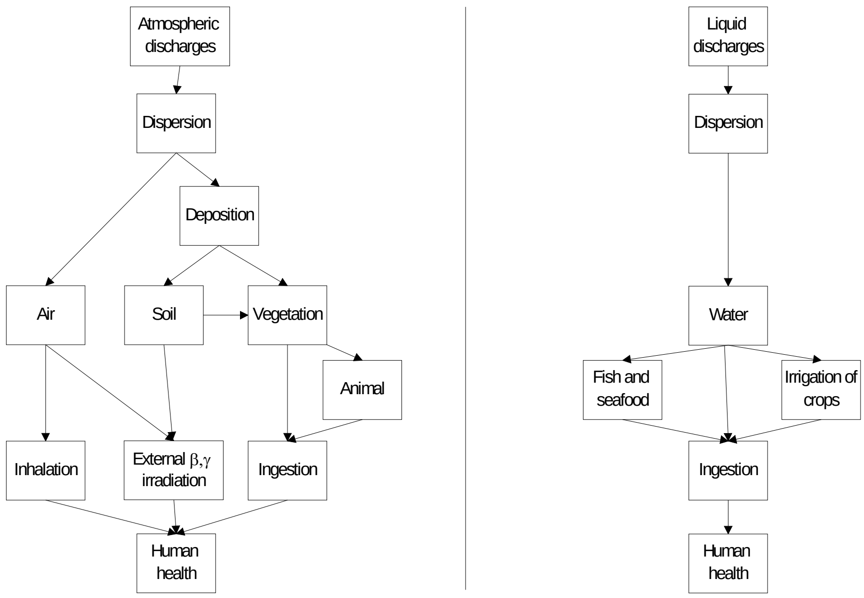

Figure 9.2: The exposure pathways that are taken into account. Also here a difference is made between exposure from atmospheric and liquid releases through the local/regional fate modelling and global exposure

Data expressed in Sievert contain physical data on energy doses and biological data on the sensitivities of different body tissues. An intermediate stage in the calculations of doses is often expressed as Gray (Gy). This is the measure of absorbed dose without considering the different reaction types of body tissues. In order to link the emissions (Bq) to immissions (Sv), we need to draw up the exposure routes.

The global exposure of Tritium, Carbon-14, Krypton-85, and Iodine-129 have been calculated for a time horizon of 100.000 and 100 years. The uncertainties for the global exposure is considerable. A σ_g^2 of 10 to 50 has to be assumed.

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23 With half-lifes of 1.6·107 years for Iodine-129 or 7.1·108 for Uranium-235 additional impacts are to be expected beyond 100,000 years. According to [Dreicer 1995:52] only about 15% of the collective effective dose of Iodine-129 occur during the first 100,000 years compared to an assessment until infinity.

The midpoint characterisation factors are below. The first table is derived from the Gaussian plume model, the second from the global exposure model.

Table 9.1: Combined fate and Exposure factors (collective dose per activity released) of radionuclides. The squared geometric standard deviation σ_g^2 for each exposure factor is 10 (Assumption based on qualitative information). Dividing and multiplying the best estimate by σ_g^2 spans the 95% confidence interval

Exposure factor [man.Sv/kBq]	**Atmospheric releases**	**Liquid releases into rivers**	**Liquid releases into the ocean**	**Reference[3)]**
Silver-110 (Ag-110m)	-	3.30E-10	-	D
Americium-241 (Am-241)	-	-	2.10E-08	D
Carbon-14 (C-14)	-	-	7.80E-10	D
Curium alpha (Cm alpha)	-	-	3.80E-08	D
Cobalt-58 (Co-58)	2.80E-10	2.70E-11	-	D
Cobalt-60 (Co-60)	1.10E-08	2.90E-08	2.60E-10	D
Cesium-134 (Cs-134)	7.90E-09	9.50E-08	5.20E-11	D
Cesium-137 (Cs-137)	8.90E-09	1.10E-07	5.20E-11	D
Iodine-131 (I-131)	1.00E-10	3.30E-10	-	D
Iodine-133 (I-133)	6.20E-12	-	-	D
Manganese-54 (Mn-54)	-	2.10E-10	-	D
Lead-210 (Pb-210)	1.00E-09	-	-	U
Polonium-210 (Po-210)	1.00E-09	-	-	U
Plutonium alpha (Pu alpha)	5.50E-08	-	4.90E-09	D
Plutonium-238 (Pu-238)	4.40E-08	-	-	D
Radium-226 (Ra-226)	6.0E-10 [1)]	8.5E-11 [2)]	-	
Radon-222 (Rn-222)	1.60E-11	-	-	D
Ruthenium-106 (Ru-106)	-	-	9.50E-11	D
Antimony-124 (Sb-124)	-	5.40E-10	-	D
Antimony-125 (Sb-125)	-	-	9.80E-12	D
Strontium-90 (Sr-90)	-	-	2.70E-12	D
Thorium-230 (Th-230)	3.00E-08	-	-	U
Uranium-234 (U-234)	6.40E-08	1.60E-09	1.50E-11	D
Uranium-235 (U-235)	1.40E-08	1.50E-09	1.60E-11	D
Uranium-238 (U-238)	5.40E-09	1.50E-09	1.50E-11	D
Xenon-133 (Xe-133)	9.40E-14	-	-	D

[1)]: [UNSCEAR 1993]

[2)]: based on the assumption that the ^{226}Ra-emission of 2 kBq/kg natural uranium released during mining and milling [ESU 1996:VII:56] leads to the ^{226}Ra concentration in rivers of 40 Bq/m^3 used in [DREICER 1995:109]

[3)]: D = Dreicer, 1995; U = UNSCEAR, 1993

Table 9.2: Combined fate and exposure factors (collective dose per activity released) of radionuclides based on Dreicer et al. (1995) considering local and regional effects, excluding and including global collective doses with different time horizons. Dividing and multiplying the best estimate by σ_g^2 spans the 95% confidence interval

	Hierarchist and Egalitarian		Individualist	
	Local and regional exposure and exposure from global dispersion during 100'000 years		Local and regional exposure and exposure from global dispersion during 100 years	
	Exposure factor [man.Sv/kBq]	assumed standard deviation σ_g^2	Exposure factor [man.Sv/kBq]	assumed standard deviation σ_g^2
Atmospheric releases:				
Carbon-14 (C-14)	1.40E-07	10	1.30E-08	10
Tritium (H-3)	9.50E-12	20	9.50E-12	20
Iodine-129 (I-129)	6.20E-07	50	1.90E-07	20
Krypton-85 (Kr-85)	9.30E-14	20	9.30E-14	20
Liquid releases:				
Tritium (H-3) into river	3.00E-13	20	3.00E-13	20
Tritium (H-3) into the sea	4.60E-14	20	4.60E-14	20
Iodine-129 (I-129)	6.60E-08	50	1.50E-08	20

9.3 EFFECT AND DAMAGE ANALYSIS

In the damage analysis we concentrate on carcinogenic and hereditary effects, as these appear to be the most significant [Dobris 1996].

Two issues are important:

- Establishing the number of cases that occur as a result of the calculated exposure.
- Establishing the number of DALYs per case.

An important discussion is whether and how epidemiological findings at medium and high exposure may be extrapolated to low doses[24]. Linear, supralinear, sublinear, threshold models and even beneficial effects of low radiation levels thanks to a hormetic[25] effect have been suggested.
Most international advisory boards assume a linear no threshold (LNT) behaviour for low doses of ionising radiation. The slope including high dose-rates can be best described as S-shaped and the section where no acute effects are observed is supposed to follow a linear-quadratic function. Most of the epidemiological information is available from the quadratic intersection.[26]

[Frischknecht et al 1999] list the DALYs for the same types of cancers we have used in previous calculations. In total they found 0.5 fatal and 0.12 non-fatal cases per Man.Sv. The σ_g^2 is a value of 3. [Frischknecht et al 1999] also assume that the radiation induced cancer cases occur at the same age pattern as for other cancer causes. Frischknecht et al also present the cases with and without age weighting. The method of calculation of the number of DALY per cancer case is identical to the one used for carcinogenic effects.

The number of severe hereditary effects is assumed to be 0.01 case per Man.Sv [ICRP 1999] This number is very uncertain (σ_g^2=5), as it was derived from animal tests. For hereditary effects it is much less clear how one case should be expressed in DALYs. Frischknecht et al quote [Dreicer 1995], who assumes severe hereditary effects either result in immediate death or severely impaired life. [Murray et al 1996] suggest disability weights of about 0.2 to 0.6 for serious disabilities, including genetic defects. Frischknecht et al assume that 50% of the cases result in immediate death, while the rest lives with a disability weighted as an average of 0.4. This results in 57 DALY per case with age weighting and 61 DALYs per case without age weighting. This factor contributes about 50% of the effect and damage step. The carcinogenic effects contribute the other 50%.

The following Table 9.3 summarises the number of fatal and non-fatal cases for both carcinogenic and hereditary effects per man Sievert

24 Low doses are equivalent doses resulting from absorbed doses below 0.2 Gray (ICRP 1999:19).
25 Hormetic effects are effects stimulating the immune system.
26 In order to correct for the slope for low doses a so-called 'dose and dose-rate effectiveness factor' (DDREF) is used which was found to be between less than 2 and 10 [ICRP 1999]. for example, A DDREF of 5 means that the risk increase per man.Sv observed at high doses is divided by 5 to assess risks at low doses. All higher DDREF stem from animal tests. Epidemiological data on the association between exposure doses and cancer cases are available from a still ongoing study with the survivors of the atomic bomb attacks in Hiroshima and Nagasaki. This study includes survivors with a large range of exposure up to low doses as well. A dose and dose-rate effectiveness factor of 2 is the best estimate for the extrapolation to low doses although the ICRP "recognises that the choice of this value is somewhat arbitrary and may be conservative" [ICRP 1999:19]. This factor corrects for the epidemiological and toxicological findings that effects are lower at lower dose-rates.

Table 9.3: Lethality fractions and probabilities of occurrence for the different cancers considered [ICRP 1990], and level of association based on epidemiological studies (atomic bomb survivors and medical radiation) reported in [Ron & Muirhead 1998:170]. The squared geometric standard deviation (lognormal distribution) is estimated to be a factor of 3 for all tumour types and 5 for hereditary effects. Per man Sv we calculated 1,17 DALY,s will result

	Lethality fraction	**Fatal cases**	**Non-fatal cases**	**Average disability**	**Average age of onset a_m**	**$DALYs_m$ [a/fatal can-**	**Average duration of**	**YLD_m**	**YLL/man Sv**	**YLD/ man Sv**	**DALY/ man Sv**	
Tissue or organ	[-]	[10^{-2} cases per man.Sv]	[10^{-2} cases per man.Sv]	[-]	[a]		[a]	[a]				
Bladder Cancer	0.5	0.003	0.003	0.087	67.2	7.3	4.7	0.29	2.19E-02	7.57E-05	2.20E-02	2%
Bone marrow Cancer	0.99	0.005	0.00005	0.06	58.5	11.9	3.8	0.2	5.95E-02	1.00E-05	5.95E-02	5%
Bone surface Cancer	0.7	0.0005	0.00021	0.136	62.6	12.1	3.4	0.38	6.05E-03	7.98E-05	6.13E-03	1%
Breast Cancer	0.5	0.002	0.002	0.084	60.3	14.6	4.3	0.31	2.92E-02	6.20E-04	2.98E-02	3%
Colon Cancer	0.55	0.0085	0.00695	0.217	67.5	9.7	3.9	0.61	8.25E-02	4.24E-03	8.67E-02	7%
Liver Cancer	0.95	0.0015	0.00008	0.239	64.3	10.9	1.77	0.34	1.64E-02	2.72E-05	1.64E-02	1%
Lung Cancer	0.95	0.0085	0.00045	0.146	66.7	10.6	2	0.22	9.01E-02	9.90E-05	9.02E-02	8%
Oesophagus Canc.	0.95	0.003	0.00016	0.217	66.2	10.6	1.8	0.3	3.18E-02	4.80E-05	3.18E-02	3%
Ovary Cancer	0.7	0.001	0.00043	0.095	59	12.5	3.3	0.28	1.25E-02	1.20E-04	1.26E-02	1%
Skin Cancer	0.002	0.0002	0.0998	0.045	55.4	15.4	4.4	0.19	3.08E-03	1.90E-02	2.20E-02	2%
Stomach Cancer	0.9	0.011	0.00122	0.217	66.6	13.2	3	0.48	1.45E-01	5.86E-04	1.46E-01	12%
Thyroid Cancer	0.1	0.0008	0.0072	0.136	62.6	12.1	3.4	0.38	9.68E-03	2.74E-03	1.24E-02	1%
Other Cancers	0.71	0.005	0.00204	0.136	62.6	12.1	3.4	0.38	6.05E-02	7.75E-04	6.13E-02	5%
Hereditary effects	0.5	0.005	0.005	0.4	birth	82.5	82.5	33	4.13E-01	1.65E-01	5.78E-01	49%
Total									9.81E-01	1.93E-01	**1.17E+00**	

The damage factor is 1.17 DALY per Man Sv.

9.4 THE ROLE OF CULTURAL PERSPECTIVES

For the calculation of the whole cause and effect chain, we run into a number of value-laden choices, which are dealt with using the cultural perspectives. Frischknecht et al mention the following aspects:

- The time horizon for the integration of exposure to people.
- The area to be considered in the fate and exposure analysis.
- The necessary evidence for an association between low-level radiation and cancer cases.
- The extrapolation model to be used for estimating health effects at very low doses.
- The dose and dose-rate effectiveness factor that should be applied if linear no-threshold extrapolation methods are used.

Frischknecht at al argue that the decades long debate has resulted in sufficient agreement on fate and exposure analysis, the necessary evidence, and the dose-rate effectiveness.

The remaining disagreement may therefore be seen as technical uncertainties. The choices on the time horizon and the choices within the DALY system, especially the age weighting are dealt with through cultural perspectives:

- The *egalitarian* and the *hierarchist* perspectives use the longest time horizon (100,000 years)
- The *individualist* perspective integrates the exposure over 100 years

With these choices Frischknecht et al [27] calculate the DALYs per emission (Bq) for 31 nuclides, which are supposed to be the most important in nuclear power plant operations.

9.5 RESULTS

Table 9.4 summarises the midpoint characterisation factors, taken at the fate and exposure level [manSv/kBq] or alternatively [U235 equivalent], and the endpoint characterisation factors [DALY/kBq] or alternatively [U235 equivalent]. These are obtained by multiplying the midpoint factors with 1.17, as calculated in the table above

[27] Contrary to the implementation in the Eco-indicator 99 method, we do not differentiate between age weighting or no age weighting, as this difference is also not made in other impact categories.

[DALY/man.Sv] or 1.64E-08 [DALY/U235 equivalent]. The columns for the individualist perspective only differ for the factors printed in bold. These are calculated in Table 9.4.

Table 9.4: Damage factors and characterisation factors for three scenarios following three world views

	Midpoints				**Endpoints**	
	Hierarchist/ egalitarian [man.Sv/kBq]	Hierarchist/ egalitarian [U235 equivalents]	Individualist [man.Sv/kBq]	Individualist [U235 equivalents]	Hierarchist/ egalitarian [DALY/kBq]	Individualist [DALY/kBq]
Atmospheric releases						
Carbon-14 (C-14)	1.40E-07	1.00E+01	1.30E-08	9.29E-01	1.64E-07	1.53E-08
Cobalt-58 (Co-58)	2.80E-10	2.00E-02	2.80E-10	2.00E-02	3.29E-10	3.29E-10
Cobalt-60 (Co-60)	1.10E-08	7.86E-01	1.10E-08	7.86E-01	1.29E-08	1.29E-08
Cesium-134 (Cs-134)	7.90E-09	5.64E-01	7.90E-09	5.64E-01	9.28E-09	9.28E-09
Cesium-137 (Cs-137)	8.90E-09	6.36E-01	8.90E-09	6.36E-01	1.05E-08	1.05E-08
Iodine-129 (I-129)	6.20E-07	4.43E+01	1.90E-07	1.36E+01	7.28E-07	2.23E-07
Iodine-131 (I-131)	1.00E-10	7.14E-03	1.00E-10	7.14E-03	1.17E-10	1.17E-10
Iodine-133 (I-133)	6.20E-12	4.43E-04	6.20E-12	4.43E-04	7.28E-12	7.28E-12
Krypton-85 (Kr-85)	9.30E-14	6.64E-06	9.30E-14	6.64E-06	1.09E-13	1.09E-13
Lead-210 (Pb-210)	1.00E-09	7.14E-02	1.00E-09	7.14E-02	1.17E-09	1.17E-09
Polonium-210 (Po-210)	1.00E-09	7.14E-02	1.00E-09	7.14E-02	1.17E-09	1.17E-09
Plutonium alpha (Pu alpha)	5.50E-08	3.93E+00	5.50E-08	3.93E+00	6.46E-08	6.46E-08
Plutonium-238 (Pu-238)	4.40E-08	3.14E+00	4.40E-08	3.14E+00	5.17E-08	5.17E-08
Radium-226 (Ra-226)	6.00E-10	4.29E-02	6.00E-10	4.29E-02	7.05E-10	7.05E-10
Radon-222 (Rn-222)	1.60E-11	1.14E-03	1.60E-11	1.14E-03	1.88E-11	1.88E-11
Thorium-230 (Th-230)	3.00E-08	2.14E+00	3.00E-08	2.14E+00	3.52E-08	3.52E-08
Tritium (H-3)	9.50E-12	6.79E-04	9.50E-12	6.79E-04	1.12E-11	1.12E-11
Uranium-234 (U-234)	6.40E-08	4.57E+00	6.40E-08	4.57E+00	7.51E-08	7.51E-08
Uranium-235 (U-235)	1.40E-08	1.00E+00	1.40E-08	1.00E+00	1.64E-08	1.64E-08
Uranium-238 (U-238)	5.40E-09	3.86E-01	5.40E-09	3.86E-01	6.34E-09	6.34E-09
Xenon-133 (Xe-133)	9.40E-14	6.71E-06	9.40E-14	6.71E-06	1.10E-13	1.10E-13
Liquid releases into rivers						
Antimony-124 (Sb-124)	5.40E-10	3.86E-02	5.40E-10	3.86E-02	6.34E-10	6.34E-10
Cesium-134 (Cs-134)	9.50E-08	6.79E+00	9.50E-08	6.79E+00	1.12E-07	1.12E-07
Cesium-137 (Cs-137)	1.10E-07	7.86E+00	1.10E-07	7.86E+00	1.29E-07	1.29E-07
Cobalt-58 (Co-58)	2.70E-11	1.93E-03	2.70E-11	1.93E-03	3.17E-11	3.17E-11
Cobalt-60 (Co-60)	2.90E-08	2.07E+00	2.90E-08	2.07E+00	3.41E-08	3.41E-08
Iodine-129 (I-129)	6.60E-08	4.71E+00	1.50E-08	1.07E+00	7.75E-08	1.76E-08
Iodine-131 (I-131)	3.30E-10	2.36E-02	3.30E-10	2.36E-02	3.87E-10	3.87E-10
Manganese-54 (Mn-54)	2.10E-10	1.50E-02	2.10E-10	1.50E-02	2.47E-10	2.47E-10
Radium-226 (Ra-226)	8.50E-11	6.07E-03	8.50E-11	6.07E-03	9.98E-11	9.98E-11
Silver-110 (Ag-110m)	3.30E-10	2.36E-02	3.30E-10	2.36E-02	3.87E-10	3.87E-10
Tritium (H-3)	3.00E-13	2.14E-05	3.00E-13	2.14E-05	3.52E-13	3.52E-13
Uranium-234 (U-234)	1.60E-09	1.14E-01	1.60E-09	1.14E-01	1.88E-09	1.88E-09
Uranium-235 (U-235)	1.50E-09	1.07E-01	1.50E-09	1.07E-01	1.76E-09	1.76E-09
Uranium-238 (U-238)	1.50E-09	1.07E-01	1.50E-09	1.07E-01	1.76E-09	1.76E-09
Liquid releases into the ocean						
Americium-241 (Am-241)	2.10E-08	1.50E+00	2.10E-08	1.50E+00	2.47E-08	2.47E-08
Antimony-125 (Sb-125)	9.80E-12	7.00E-04	9.80E-12	7.00E-04	1.15E-11	1.15E-11
Carbon-14 (C-14)	7.80E-10	5.57E-02	7.80E-10	5.57E-02	9.16E-10	9.16E-10
Cesium-134 (Cs-134)	5.20E-11	3.71E-03	5.20E-11	3.71E-03	6.11E-11	6.11E-11
Cesium-137 (Cs-137)	5.20E-11	3.71E-03	5.20E-11	3.71E-03	6.11E-11	6.11E-11
Cobalt-60 (Co-60)	2.60E-10	1.86E-02	2.60E-10	1.86E-02	3.05E-10	3.05E-10
Curium alpha (Cm alpha)	3.80E-08	2.71E+00	3.80E-08	2.71E+00	4.46E-08	4.46E-08
Plutonium alpha (Pu alpha)	4.90E-09	3.50E-01	4.90E-09	3.50E-01	5.75E-09	5.75E-09
Ruthenium-106 (Ru-106)	9.50E-11	6.79E-03	9.50E-11	6.79E-03	1.12E-10	1.12E-10
Strontium-90 (Sr-90)	2.70E-12	1.93E-04	2.70E-12	1.93E-04	3.17E-12	3.17E-12
Tritium (H-3) into the sea	4.60E-14	3.29E-06	4.60E-14	3.29E-06	5.40E-14	5.40E-14
Uranium-234 (U-234)	1.50E-11	1.07E-03	1.50E-11	1.07E-03	1.76E-11	1.76E-11
Uranium-235 (U-235)	1.60E-11	1.14E-03	1.60E-11	1.14E-03	1.88E-11	1.88E-11
Uranium-238 (U-238)	1.50E-11	1.07E-03	1.50E-11	1.07E-03	1.76E-11	1.76E-11

9.6 SUPPORTING INFORMATION

No supporting information

9.7 SUMMARY TABLE

Entity	**Content**
impact category	ionising radiation
LCI results	radionuclides
midpoint indicator(s) (with abbreviation)	absorbed dose
unit of midpoint indicator(s)	Man.Sievert
midpoint characterisation factor (with abbreviation)	ionising radiation potential (IRP)
unit of midpoint characterisation factor	kg (U235 to air)
endpoint indicator(s) (with abbreviation)	damage to Human health (HH)
unit of endpoint indicator(s)	yr
endpoint characterisation factor (with abbreviation)	1.64E-08
unit of endpoint characterisation factor	Yr/Sv

10 IMPACTS OF LAND USE

An De Schryver and Mark Goedkoop[28]

The land use impact category reflects the damage to ecosystems due to the effects of occupation and transformation of land. Although there are many links between the way land is used and the loss of biodiversity, we concentrate on the following mechanisms:

1. occupation of a certain area of land during a certain time;
2. transformation of a certain area of land.

Both mechanisms can be combined, often occupation follows a transformation, but often occupation occurs in an area that has already been converted (transformed). In such cases we do not allocate any of the transformation impact to the production system that occupies an area.

10.1 INVENTORY ASPECTS OF LAND USE

Land use is often referred to as an impact. In this chapter, we will consistently refer to land use impacts when we are speaking of the impacts, and to land use in the forms of occupation and transformation as analogous to an emission or a resource extraction, i.e. as the items that show up in the inventory analysis.

10.1.1 LCI PARAMETER FOR OCCUPATION

Many production processes need a certain area of land. For instance, for the production of a certain amount of corn a certain area of land is occupied during one year (if there is only one crop per year). Also for other production processes space is needed. A car factory will need a certain area, and if we know that area and we know how many cars are made in one year, we can determine how many hectares×year are needed per car. Please note that we only know the combination of area and time. We can choose to assume if a single car occupies the entire area during a millionth of a year or so, or that we assume a millionth of the area is occupied during a year. Area and time are interchangeable, only their combination is given. This means the unit of the occupation LCI parameter is $m^2 \times yr$.

Not all types of occupation have the same effect on the biodiversity, this means the LCI data should also contain an indication of the type of land-use. In crop fields the farmer takes every measure to reduce the number of species to just one, the crop; in production forests there will be significant more species than in a cropland. We shall define a number of archetypical land use types in this chapter.

10.1.2 LCI PARAMETER FOR TRANSFORMATION

Transformation of land is not always easy to allocate to production systems. For instance, an area of agricultural land that was transformed into a factory can produce from then on a steady amount of products every year, which cumulates into an infinte number of products. Per unit of product, the area transformed is zero. But there are a few clear cases in which it makes sense to allocate the transformation to a product, for instance in mining we can determine a link between the production of a kilogram ore and the area size of the mine. With each ton a number of square metres of area are converted from the existing land-use type to a mining area. Similar situations occur in land filling, each ton land filled will occupy an additional area.

Transformed areas will have a different species diversity. The damage to ecosystems can be calculated by taking into account the time needed for the transformed area to restore to a land-use type with a similar diversity. The restoration times for natural areas can be very long; some estimates are that natural areas can take thousands of years to recover, if they recover at all. We have chosen not to require the LCI practitioner to include estimates for the restoration time. Instead we use a set of restoration times that differ depending on the land use types before and after transformation. This means the unit of the LCI parameter for transformation is only m^2. However, we shall also give factors that can be used if a better restoration time estimate is available. In that case LCI practitioners can correct the assumed restoration times we have provided.

Like in the case of occupation, the LCI parameter should also contain information about the type of land use before and after transformation. We have developed a set of archetypical land-use conversion cases that we consider to be practicable in LCI. We have deliberately limited ourselves to the most relevant cases for production processes. LCAs are not intended to be used for very detailed conversion descriptions.

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10.1.3 COMBINATION OF OCCUPATION AND TRANSFORMATION

After transformation, an area is often occupied for some time, before the restoration can start. As there are no general rules about the length of the occupation, the LCI practitioner has to specify the transformation and the occupation parameters separately, so they can be both multiplied with the appropriate characterisation factors and added to get the total damage to ecosystem. Another reason that they must be specified separately, of course, is that they have a different unit ($m^2 \times yr$ and m^2), and that occupation requires a specification of the land use type during the activity, whereas transformation requires a specification of the land use type before and during the activity.

10.2 MIDPOINT CHARACTERISATION

For the midpoint characterisation we have chosen to use the competition approach, as is currently used in the CML methodology (Guinée et al., 2002). This approach adds all different types of land uses and includes LCI parameters defined as $m^2 \times yr$. To improve this method we introduce three midpoints categories instead of one, see Table 10.1

Table 10.2: Midpoint characterisation factors for three midpoint IC on land use

Midpoint impact category	**CF**	**LCI**	**With:**
Agricultural land occupation (ALO)	$CF_{agr}= 1$	$A_{o(agr)} \cdot t$	$A_{o(agr)}$ the amount of agricultural area occupied (in m2) and t the time of occupation in years.
Urban land occupation (ULO)	$CF_{urban}= 1$	$A_{o(urban)} \cdot t$	With $A_{o(urban)}$ the amount of urban area occupied (in m2) and t the time of occupation in years.
Natural land transformation (NLT)	$CF_{trans}= 1$	$A_{o(trans)} \cdot t$	With $A_{o(trans)}$ the amount of transformed area (in m2) and t the time of occupation in years.

To calculate this midpoint methodology, only the amount of area occupied or transformed [m2.yr] is needed. At midpoint level, no differentiation to land use types is made, due to the uncertainties. While at endpoint level, uncertainties are accepted and so a differentiation to several land use types is made. This means that the midpoint indicators can not directly be used in the endpoint methodology.
Section 10.6 shows the resulting characterisation factors for the three impact categories and how the Ecoinvent land use types have been assigned for these purposes.

10.3 ENDPOINT CHARACTERISATION

This section describes the calculation of endpoint characterisation factors for loss of species diversity, caused by land use.

- The endpoint indicator for land occupation is the Potential Disappeared Fraction (PDF) of species. The damage is calculated by multiplying this factor with the LCI parameter expressed in $m^2 \times yr$ and the species density SD.
- The endpoint indicator for land transformation is PDF multiplied by restoration time (PDF×yr) and the species density SD. The time is determined by the restoration time. The damage is calculated by multiplying this factor with the LCI parameter, expressed as in m^2.

In both cases the damage is expressed as PDF×yr, or, as PDF is dimensionless, yr. This is compatible with the other endpoints linking to ecosystem damage. Observe that the integration of midpoint and endpoint indicators has not been attained for impacts of land use. At the midpoint level, different land use types are aggregated; for the endpoint characterisation this information is needed again.

10.3.1 SPECIES AREA RELATIONSHIP

The potential disappeared fraction of species is influenced by the area-species relationship, also called the island bio-geographical theory of McArthur and Wilson (1967). This relationship describes the rising number of species present due to a rising area size:

$$S = cA^z \qquad (10.1)$$

in which S represents the number of plant species, A is the size of the area (m^2), c stands for the species richness factor and z is the species accumulation factor.

The factors c and z are specific for each land use type, while the factor z is also dependent of the area size. This species area relationship complicates the model, because we cannot link a certain land-use type to a number of species, as that number depends on the size of the area. The work of Crawley and Harral (2001) investigated this effect in Great Britain and produced for different land use types some interesting numbers. These numbers will be used to determine the species accumulation factor z. The species richness factors c will be calculated using the work of Köllner (2001) and the Countryside Survey 2000 of the UK. More information about these papers can be found in the Supporting information B.3.

Application of the species area relationship and some assumptions
When a certain area is occupied we assume it causes damage to the ecosystem, as it cannot return to a reference state. If the number of species in the occupied area is lower than the number of species in the reference situation we consider occupation to be a damage. If the occupied area has a higher number of species, we consider it to cause a negative damage. The magnitude of the damage depends on the species area relationship, described in formula 10.1 . This formula tells us that the number of species directly depends on the size of the area. This is both true for natural areas and for non natural areas. Enlarging non natural areas will be at the expense of a decreasing natural area.

This may seem simple, but there are a number of complications:

- If we have data on a certain land-use type that tells us there are 200 species, on 100 km^2 we do not know if this is due to the effect of *C* or the effect of *z*, so how do we determine *z* and *C*? The obvious answer is that we need to have data from different area sizes, but as we shall see this does not always provides us with clear answers. One complication is that z itself seems to be dependent on the area size. This problem is described in Section 10.4.1.
- Are used areas isolated form other areas or are they connected? In the latter case they become part of a greater entity, and this influences the results, as we shall see in Section 10.3.3.
- It is not clear how to define the reference land-use type. In some studies the reference is considered to be the natural area, whereby the question arise "what is the natural area". In some studies it is assumed to be the mixtures of all land-use types, including nature.

10.3.2 THE REFERENCE LAND-USE TYPE

Before producing any formula or analyzing any results, a decision about the reference area must be made. The reference area represents the potential vegetation, or the type of land that will arise without human distortion. This kind of land type can be named "Nature". Unfortunately, it is not easy to describe and indicate the term "Nature", which still causes many discussions. To analyze the question "which land use type should be used as reference?" and to make a proper decision, we looked at the potential land use types of Europe, which would appear when no human influence takes place (see Figure 10.1).

Figure 10.1: Illustration of how Europe would look without human intervention or environmental changes (D. Stanners and P. Bourdeau, 1995).

Figure 10.1 illustrates that within Europe, without any human intervention, 80-90% of the land would be covered by forest. In Northern Europe boreal forest would be most present, while Great Britain, Central and Southern Europe would be dominated by deciduous trees, like oaks and beech. Based on this information, the reference area for this impact category is chosen to be the land use type "woodland".

10.3.3 IMPACTS OF OCCUPATION

In this section we shall develop the mathematical relationships that determine the impact of occupation on the species number. With occupation we refer to the continuous use of land, for instance the occupation of land by a cornfield that is needed to produce a certain amount of corn. We leave aside the question how that cornfield was made and what it was before, as in such cases there is no data available. In Section 10.3.4 we discuss cases, where we do know which conversion and restoration processes take place.

When we assess the effect of occupation, we assess the differences between the situation when an area is occupied and the situation in which the occupied area is in the reference state. During the period an area is occupied, there are two effects:

1. The regional effect, this is the effect due to the difference in area size if there is or there is no occupation. To be more precise, there are two regional effects:
    a. The occupation restricts the size of the reference land-use type (nature), but does not increase the size of the land-use type *i*. This means that the size of the reference area is lower compared to the situation where no occupation takes place. According to the

species area relationship, the number of species in the reference area decreases somewhat.

   b. The number of species in other areas with the same land-use type *i* is influenced by the occupation due to the connection of the occupied area to the other regions with the same land-use type.

2. The local effect, this is the effect of the occupation on the occupied area itself. The number of species in the occupied area is solely dependent on the occupied area and the values of C and z for that land-use type i. If the area would not be occupied, we would expect this area to have a species diversity determined by the values of z and C for the reference area, and the size of the occupied area.

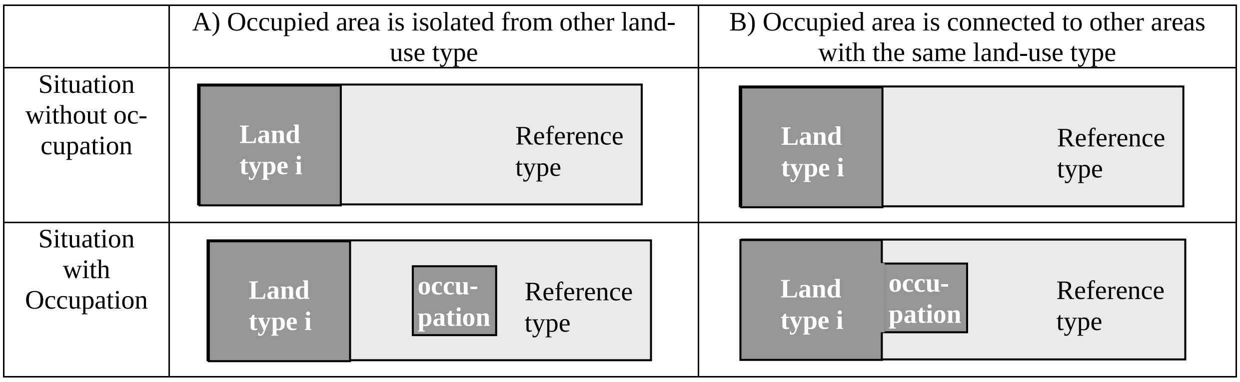

Figure 10.2:Illustration of the unconnected and the connected form of changing a reference land-use type into land-use type i.

The issue mentioned under point 1 deserves some further analysis. In Figure 10.2 we have illustrated two assumptions:

- The occupied area does not have any linkage to similar land-use types. For instance, when a meadow is made in the middle of a forest. Under this assumption there is no second regional effect as mentioned under the first point.
- The occupied area can be assumed to be connected to other similar land-use types, and will be a part of a greater habitat; in this case there is a second regional effect.

For the calculations below, it is important to carefully define the parameters:

- area size of the reference area A_r without occupation;
- area size of land-use type i: A_i without occupation (is zero under assumption A);
- area size of the occupied area: A_o;
- species number in the reference area without occupation: S_r;
- species number in land-use type i without occupation: S_i;
- species number decrease in the reference area when occupation takes place: ΔS_r;
- species number increase in land-use type i when occupation takes place: ΔS_i (is zero under assumption A).
- time during which the occupation takes place: t.

Due to occupation there is a small marginal decrease of the area size A_r to $A_r – A_o$, and according to the species area relationship, this will mean a marginal decrease of the species richness in this area. Under assumption B, it also means an increase of the area A_i to $A_i + A_o$, and thus a marginal species increase in this area.

In area A_0, the species richness is equal to S_r as long as the area is not occupied. In case of occupation, the species richness is $S_i + \Delta S_i$ (with $\Delta S_i = 0$ under assumption A). For calculating the ecosystem damage, we cannot use ΔS, as this represents an absolute species number. We must use the relative decrease of species; relative to what the species richness is without occupation.

Regional damage factor for occupation

The regional damage describes the marginal species loss in the surrounded area, due to the fact that occupation reduces the size of the surrounding area and thus the number of species found in that area. This effect is named the “species loss” due to occupation.

Under assumption A, the occupied area is not linked with the area of the same land use type. The marginal species loss is multiplied by area and time to get the damage caused by the occupation:

$$ED_{occ} = t \times A_r \frac{\Delta S_r}{S_r} \tag{10.2}$$

With ED_{occ} representing the environmental damage due to occupation, A_r the area size of the reference area, S_r the species number in the region and ΔS_r the difference between natural and current number of species. Figure 10.3 below illustrates this.

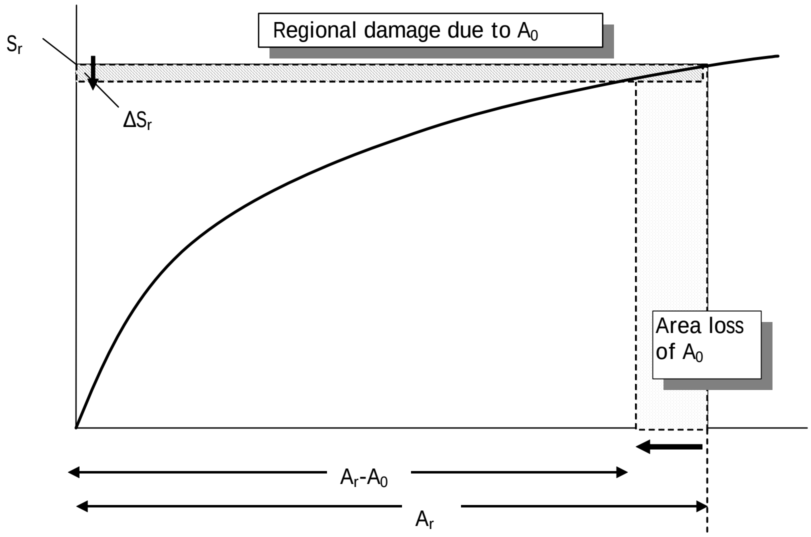

Figure 10.3: The regional damage for region A_r. *can be represented as the shaded area in the top of the figure.*

To get the marginal species decrease ΔS_r, the first derivative of formula (10.1) is calculated:

$$\Delta S_r = A_0 c_r z A_r^{z_r - 1} \tag{10.3}$$

Using formula (10.2) and (10.3), we get:

$$ED_{occ-A}(regional_{assumptionA}) = t \times A_r \times A_0 \frac{z_r c_r A_r^{z_r-1}}{c_r A_r^{z}} = t \times A_0 \times z_r \tag{10.4}$$

Apparently, under assumption A the regional damage is independent of the size of the region, only the size of the occupation plays a role. One can interpret z_r as the characterisation factor that is used to get the regional damage:

$$CF_{occ-A}(regional_{assumptionA}) = Z_r * ED \tag{10.5}$$

Under assumption B, the occupied area is linked with the area of the same land use type and thus enlargement of that land use type is assumed. The regional damage, under this assumption, describes not only the marginal species loss in the reference area, but also the marginal gain in the enlarged land use type *i*.

Under assumption B, the marginal loss in the surrounded area is the same as formula (10.4) . To calculate the marginal gain, the reasoning is exactly the same as above. The result in ecosystem damage is:

$$ED_{occ-gain}(regional_{assumptionB}) = -t \times A_i \times A_0 \frac{c_i z_i A_i^{z_i-1}}{c_i A_i^{z}} = -t \times A_0 \times z_i \tag{10.6}$$

Under assumption B, the environmental damage factor is the sum of the marginal gain of the occupied area (formula 10.4 and the marginal loss of the surrounded area (formula 10.4)

$$ED_{occ-B}(regional_{assumptionB}) = (z_r - z_i) \times t \times A_o \tag{10.7}$$

The characterization factor is thus:

$$CF_{occ-B}(regional_{assumptionB}) = (z_r - z_i) \times SD \tag{10.8}$$

The results of these calculations are remarkable simple. They only important factor is the *z* value, often referred to as the species accumulation factor. Note that under assumption B the characterisation factor can become negative if z_i is larger than z_r.

Local damage for occupation

If the area was not occupied, we would find the number of species on that area using the species area relationship (see Figure 10.4). The species number found on the area A_o before occupation is:

$$S_{occ}(local) = c_r A_0^{z_r} \tag{10.9}$$

After occupation, we can expect a number of species (in the occupied area A_o) that is characterised by:

$$S_{i\_local} = c_i A_0^{z_i} \tag{10.10}$$

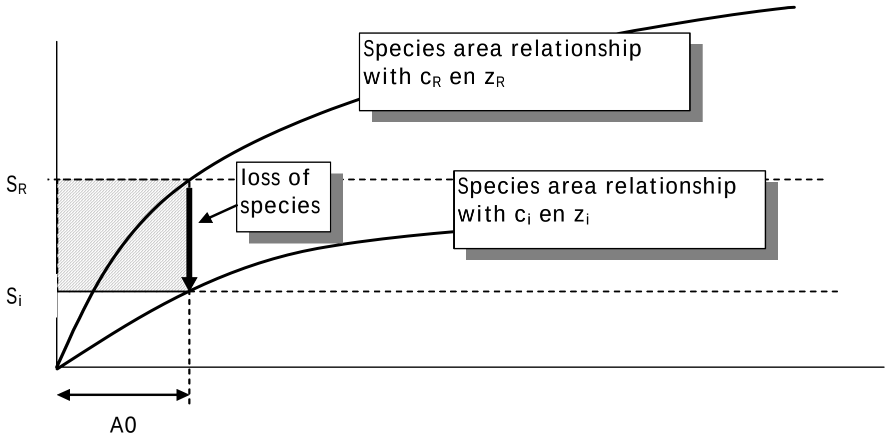

Figure 10.4: Local effect of area A$_o$*, can be illustrated as the shaded area in this graph; note that there can also be an increase of species, so the local damage can become negative.*

Using formula (10.9) and (10.10) we can now determine the species loss on the area A_o:

$$\Delta S_{local} = c_R A_0^{z_R} - c_i A_0^{z_i} \tag{10.11}$$

The local environmental damage in area A_0 can be summarized as:

$$ED_{occ}(local) = t \times A_0 \frac{S_{r\_local} - S_{r\_local}}{S_{r\_local}} = t \times A_0 \frac{c_r A_0^{z_r} - p_i A_0^{z_i}}{c_r A_0^{z_r}} = t \times A_0 \frac{c_r - c_i A_0^{z_i - z_r}}{c_r} \tag{10.12}$$

The characterization factor is thus:

$$CF_{occ}(local) = \frac{c_r - c_i A_0^{z_i - z_r}}{c_r} \times SD \tag{10.13}$$

This means, the local characterisation factor depends on the area size of occupation. Because in the LCI data practitioners do not know the occupied area size, a practical solution is needed. Some authors (Köllner) have simplified this relationship by standardising the area size to one square meter. In this case the values of *z*, have no impact anymore, and the characterisation factor becomes only dependent on the values of *c*. In Goedkoop and Spriensma (1999) the assumption was made that the differences between the *z* values are small, and can be assumed to be equal in most cases. In Section 10.4.1 we will further discuss this, as there are a number of complications with this approach.

Combined damage factor for occupation

The combined damage factor of occupation consists of the sum of regional effects and local effects. Under assumption A, the damage factor is calculated combining formula (10.4) and (10.13):

$$ED_{occ.}(assumptionA) = (z_r + \frac{c_r - c_i A_0^{z_i - z_r}}{c_r}) \times A_o \times t \tag{10.14}$$

Under assumption B, the damage factor is calculated combining formula (10.7) and (10.13)

$$ED_{occ.}(assumptionB) = (z_r - z_i + \frac{c_r - c_i A_0^{z_i - z_r}}{c_r}) \times A_o \times t \tag{10.15}$$

In Section 10.4.1, we shall describe how *z* and *c* can be determined for the reference and for the specific land-use type. First we shall discuss the case of transformation.

10.3.4 IMPACTS OF TRANSFORMATION

As discussed in Section 10.1.2, the LCI parameter for transformation is given in square meters. The characterisation factor is the combination of the species loss integrated over the time the species loss occurs. This indicates that the characterisation factor in fact describes a combination of two processes: conversion and restoration.

The term 'conversion' describes the active conversion from one state to the other, for instance when a mine or landfill is expanded, or when a forest is clear cut for wood production. The conversion process will also take some time, but in practice this time is short compared with the time needed for restoration of the land to an original or close to original state. Restoration can be a completely natural process, or it can be helped, by taking appropriate measures that speeds up the natural restoration processes.

Between the conversion and the restoration, there will usually be an occupation time. As discussed in Section 10.1.3 the LCI practitioner is supposed to specify the transformation and occupation parameters separately. In this chapter we shall therefore ignore the occupation. In case the assumption that the conversion process takes little time, one can add a factor for occupation of the area.

The damage from converting an area is determined by the difference in species richness of the area before and after transformation, and by the assumed restoration time (t_{rest}). Also for transformation there is a local and regional effect, and also here we have an assumption A and an assumption B.

The characterisation factor for transformation can be computed in a very similar way as in the case of occupation. Below we have rewritten formula (10.14) and (10.15) to calculate the ecosystem damage. In this formula we have made the following replacements:

- the index *r* (reference) has been replaced by the index *o* (original);
- the area A_o representing the occupied area, has been replaced by A_{trans}, representing the transformed area size; this is the LCI parameter;
- the time *t* (which is given as a part of the LCI parameter in the case of occupation), has been replaced by t_{rest} (which is not part of the LCI parameter in the case of transformation.

Under assumption A, the environmental damage for transformation is:

$$ED_{trans.}(assumption\_A) = (z_O + \frac{c_O - c_i A_0^{z_i - z_O}}{c_O}) \times A_{trans.} \times t_{rest} \qquad (10.16)$$

Under assumption B, the environmental damage for transformation is based on formula (10.15):

$$ED_{trans.}(assumption\_B) = (z_O - z_i + \frac{c_O - c_i A_0^{z_i - z_O}}{c_O}) \times A_{trans.} \times t_{rest} \qquad (10.17)$$

If we take out the LCI parameter A_{trans}, we can write the characterisation factor as

$$CF_{trans.}(assumption\_A) = (z_O + \frac{c_O - c_i A_0^{z_i - z_O}}{c_O}) \times t_{rest} \times SD \qquad (10.18)$$

The characterisation factor due to transformation, under assumption B, can be summarized as:

$$CF_{trans.}(assumption\_B) = (z_O - z_i + \frac{c_O - c_i A_0^{z_i - z_O}}{c_O}) \times t_{rest} \times SD \qquad (10.19)$$

Section 10.4.3 gives an overview of the restoration times we can apply.

10.4 DATA FOR DETERMINING THE CHARACTERISATION FACTORS

As the characterisation factors are determined by the values of the species accumulation factor *z* and the species richness factor *c*, we now need to determine these values for different land-use types. Furthermore, for transformation, we need to determine the restoration times.

Three important sources have been used to collect the data on the species richness factor *c* and for the species accumulation *z* factor:

- Crawley (2001) provides an in depth analysis of the variability of the species accumulation factors at different land area sizes in the UK. It provides data both for the *z* values and the c values, but the number of land use types is rather limited.

- CS2000 which gives species counts for land-use types in the UK, for different area sizes, witch a good separation of main land use types and verges and boundaries. This source does not provide values for *z* and *c*, but we shall describe how we could derive these.
- Köllner 2001, which gives *c* values for a wide range of land use types in Switzerland, but assumes a uniform value for *z* of 0.21, irrespective of the land use type.

10.4.1 DETERMINATION OF THE SPECIES ACCUMULATION FACTOR Z

According to several sources, the value of the species accumulation factor *z* in formula (10.1) can vary between 0.1 and 0.4, depending of the size of the area and the type of land. Hereby, 0.25 is often quoted as a good assumption for *z*. This range is quite large, and therefore difficult to use. Köllner (2001) solves this by taking an average value for *z* of 0.21.

Interrelation between z and the area size

In the research of M.J Crawley (2001), British species diversity data, for different land use types and at different scales, were collected and used to determine the variability of factor *z*. Comparing six different land use types, six different *z* factors were found. Moreover, the research also found different *z* factors for different area scales. At small scales (0.01 m^2 – 10 m^2) and extreme high scales (>100 km^2) *z* is lower than at mid-range scale (0.01 km^2 – 10 km^2) areas. In a linear model as an LCA, we cannot know the actual size of the area being occupied, as the LCI parameter only specifies the product of area and time. For some land-use types the characterisation factors are heavily affected by the instability of *z* over different area sizes, while for others the instability of the *z* value is not so significant. In the additional information the land-use types which have a relatively stable characterisation value are determined. Furthermore, as default area for our characterisation factors an area size of an hectare (10,000 m^2) is chosen. This choice is based on several considerations further discussed in the supporting information B.3.

10.4.2 DETERMINATION OF THE SPECIES RICHNESS FACTOR C

Interpretation of the Köllner data

In Köllner (2001) the species richness factor is given. Köllner calculates these from species observation data using a fixed value of *z* = 0.21.

Interpretation of the CS2000 data:

The Countryside Survey CS2000 gives species counts in arable land use types for three kinds of plots in Great Brittan:

- The X plots are located in the middle of each field, and measure 200×200 m.
- The A plots are located just at the border, but inside the field, and measure 1×100 m.
- The B plots are located just outside the border, and measure 1×10m.

It also specifies species diversity for other features such as road verges, water verges, etc. We will not apply these, as they do not have much meaning for LCA applications.

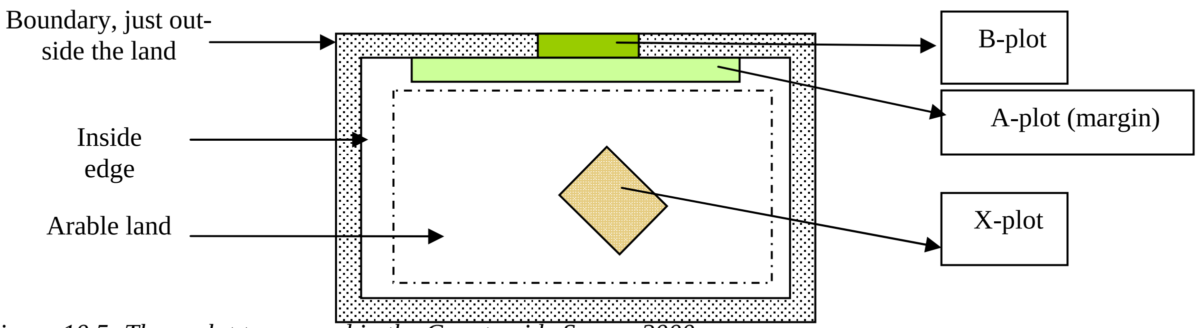

Figure 10.5: Three plot types used in the Countryside Survey 2000.

The CS2000 data does not specify a value for *z* or *c*, it merely provides species counts. These average species counts have been combined with the *z* values (Table 10.3) provided by Crawley (2001), to calculate the values for *c*. We did take into account the difference in plot sizes.

Table 10.3: Species accumulation factor (z values) given by Crawley (2001) for the main land use types.

	Area size (m^2)				
Land use type	**1**	**10***	**100**[†]	**1000**	**10000**
Grasland	0.238	0.15	0.207	0.184	0.349

Woodland	0.173	0.242	0.193	0.437	0.439
Built	0.054	0.174	0.385	0.406	0.214
Bracken	0.058	0.094	0.274	0.423	
Heath	0.192	0.233	0.349	0.64	0.123
Fallow	0.141	0.119	0.256	0.225	0.32

** Applied to plot type B.*
† Applied to plot type X and A.

Boundary effects in agricultural areas
The CS2000 data confirms that the main richness of the plots is relatively independent of what grows on the field, but it is determined by the edges. The diversity in an area with many edges and borders will thus be significantly higher than the diversity in large monocultures, with very few edges.

For LCA practitioners, agricultural landscapes are an important and rather specific land use type, as they are often part of the production systems of products. In agricultural land use significant differences occur between the diversity of the edges, and the harvested part of the land. In modern agricultural practices the harvested land just contains the target species, with hardly any weed. This means that it is hardly worthwhile to distinguish between different crops, as the number of species will be kept artificially low with weed control techniques applied by the farmer. In fact the purpose of farming is to reduce the number of species to one, or a few desirable species.

We propose to use three archetypes of land use intensiveness:
- Monocultures, with no edges (corn fields in Nebraska). We find it safe to assume that the species diversity in the entire area is represented by the diversity found in the X plots.
- Intensive arable areas with plots of more than a few hectares that are separated by just narrow edges. We find it safe to assume that the species diversity in the entire area is represented by the diversity found in the margins, the A plots.
- Extensive arable areas with small fields and plenty of edges, and small natural plots in between. We find it safe to assume that the species diversity in the entire area is represented by the diversity found in the boundary areas just outside the land, the B plots.

10.4.3 RESTORATION TIMES
The restoration times are derived from the work of Bastian and Schreiber (1999). They indicated restoration times for six different land-use types. These times refer to the time needed for an area to be restored back into the original state. See Table 10.4.

Table 10.4: Restoration times for six different ecosystems (Bastian and Schreiber, 1999).

Ecosystem being transformed	**Restoration time (yr)**
vegetation of arable land, pioneer vegetation	< 5
species poor meadows and tall-herb communities, mature pioneer vegetation	5 – 25
species poor immature hedgerows and shrubs, oligotroph vegetation of areas silting up, relatively species rich marshland with sedges, meadows, dry meadows and heath land	25 – 50
forests quite rich in species, shrubs and hedgerows	50 – 200
low and medium (immature) peatbogs, old dry meadows and heathland	200 – 1000
high (mature) peatbogs, old grow forests	1000 – 10000

For application in LCA the most relevant restoration time is the time for natural areas that are transformed for operations such as mining. In general LCAs will not be suitable to monitor subtle transformations between the other land-use types.

In the following section we shall further describe how we will interpret these ranges.

10.5 CALCULATED CHARACTERISATION FACTORS UNDER DIFFERENT PERSPECTIVES
The cultural perspectives (Van Assalt M. and Rotmans J.,1995; Hofstetter P., 1998) are used to deal with assumptions on the regional effects and restoration times. In this impact category we are confronted with the following choices.

- Should we apply assumption A or assumption B regarding the connection between an occupied area and an area with a similar land use type?
- Which assumptions can we make for restoration times? Is it realistic to take the full restoration time into account?

The choice for assumption A or B is related to the question if we can assume that the positive effect of expanding the land area for land-use type i may indeed be taken into account. In the egalitarian perspective we do not assume such positive effects and choose assumption A. In the individualist perspective we can make this assumption B. In the hierarchist perspective we also select assumption A. The hierarchist perspective has a high confidence in policy measures that are aimed to connect ecosystems of different types; clearly it sees fragmentation of areas as a problem.

Table 10.5: Overview of the choices under the three perspectives.

Aspect	**Egalitarian**	**Individualist**	**Hierarchism**
Restoration times	Maximum restoration times	Mean restoration time, with a maximum of 100 year	Mean restoration times
Regional effect Assumption A (Isolated) or B (not isolated)	Assumption A	Assumption B	Assumption A (We assume that fragmentation is an overall problem that has to be considered)

The restoration time interpretation can be translated in Table 10.6.

Table 10.6: Translation of the restoration time ranges into single values for the three perspectives.

Ecosystem being transformed	**Restoration times (year)**			
	Value given	**Egalitarian**	**Individualist**	**Hierarchist**
Vegetation of arable land, pioneer vegetation	< 5	5	2.2	2.2
Species poor meadows and tall-herb communities, mature pioneer vegetation	5 – 25	25	11	11
Species poor immature hedgerows and shrubs, oligotroph vegetation of areas silting up, relatively species rich marshland with sedges, meadows, dry meadows and heath land.	25 – 50	50	35	35
Forests quite rich in species, shrubs and hedgerows	50 – 200	200	100	100
Low and medium (immature) peat bogs, old dry meadows and heath land	200 – 1000	1000	100	450
High (mature) peat bogs, old grow forests	1000 – 10000	10000	100	3300

10.5.1 CHARACTERIZATION FACTORS FOR IMPACTS OF OCCUPATION

The characterization factors for occupation can be calculated using formulas for the local and regional effects, as they are combined in formulas 10.14 and 10.15. The local effect is calculated using formula 10.13. As we discussed above, the regional effect can be calculated under different assumptions. Formula 10.5 refers to assumption A, the occupied area is not connected to similar areas. This assumption is used in the Hierarchist and the Egalitarian perspective. Formula 10.8 is used for assumption B, the individualist perspective.

These formulas require values for the *z* and *c* factor, for each land use type. The *z* factors are in principle taken from Crawley, considering an area size of 10.000 m^2. In a few cases we do not have data from Crawley, and we use Köllner instead; he assumes a fixed value of 0.21 for all land-use types. The factors for *c* are taken from both Köllner and CS2000. A problem with these two sources is that they give different values for *c* for the same land-use types. We have solved this, by normalizing the Köllner data for the reference land-use type. This is chosen to be extensive broadleaf forest, as discussed in Section 10.3.2. In the CS2000 data this reference is called: “Extensive Broadleaf, mixed and yew LOW woodland” and in Köllner it is called “broadleaved forest”.

Table 10.7: Characterization factors for occupation for the egalitarian and hierarchistic perspectives, for 18 different land use types. The damage caused by occupation of a certain area of land can be found by multiplying the proper CF-value with the area and time of occupation.

Land use type	**Z**	**c**	**Local effect** PDF.m^2.yr	**Regional effect** PDF.m^2.yr	**Total effect** PDF.m^2.yr	**CF_{occ} * 10^{-9}**

Monoculture Crops/Weeds[1]	0.210[3]	2.0[1]	0.95	0.44	1.39	19.2
Intensive Crops/Weeds[1]	0.210[3]	4.6[1]	0.89	0.44	1.33	18.4
Extensive Crops/Weeds[1]	0.210[3]	6.2[1]	0.85	0.44	1.29	17.8
Monoculture Fertile Grassland[1]	0.349	3.7[1]	0.69	0.44	1.13	15.6
Intensive Fertile Grassland[1]	0.349	6.2[1]	0.48	0.44	0.92	12.7
Extensive Fertile Grassland[1]	0.349	7.9[1]	0.25	0.44	0.69	9.5
Monoculture Infertile Grassland[1]	0.349	7.1[1]	0.41	0.44	0.85	11.7
Extensive Infertile Grassland[1]	0.349	10.5[1]	0.00	0.44	0.44	6.1
Monoculture Tall Grassland/Herb[1]	0.349	0.9[1]	0.92	0.44	1.36	18.8
Intensive Tall Grassland/Herb[1]	0.349	4.7[1]	0.61	0.44	1.05	14.5
Extensive Tall Grassland/Herb[1]	0.349	7.2[1]	0.31	0.44	0.75	10.4
Monoculture Broadleaf, mixed forest and woodland[1]	0.439	3.1[1]	0.19	0.44	0.63	8.7
Extensive Broadleaf, mixed and yew LOW woodland[1,*]	0.439	5.2[1]	0.00	0.00	0.00	-
Broad-leafed plantation[2]	0.439	3.3[2]	0.37	0.44	0.81	11.2
Coniferous plantations[2]	0.439	2.8[2]	0.47	0.44	0.91	12.6
Mixed plantations[2]	0.439	1.8[2]	0.76	0.44	1.10	15.2
Continuous urban[2]	0.214	1.4[2]	0.96	0.44	1.4	19.3
Vineyards[2]	0.210[3]	2.8[2]	0.42	0.44	0.86	11.9

** Reference land use type; [1] data of CS2000; [2] data of Köllner; [3]* z *values taken from Köllner*

Table 10.8: Characterization factors for the individualistic perspective, for 18 different land use types. The damage caused by occupation of a certain area of land can be found by multiplying the proper CF-value with the area and time of occupation.

Land use type	**z**	**c**	**Local effect** $PDF.m^2.yr$	**Regional effect** $PDF.m^2.yr$	**Total effect** $PDF.m^2.yr$	$CF_{occ} * 10^{-9}$
Monoculture Crops/Weeds[1]	0.210[3]	2.0[1]	0.95	0.23	1.18	16.3
Intensive Crops/Weeds[1]	0.210[3]	4.6[1]	0.89	0.23	1.12	15.5
Extensive Crops/Weeds[1]	0.210[3]	6.2[1]	0.85	0.23	1.08	14.9
Monoculture Fertile Grassland[1]	0.349	3.7[1]	0.70	0.09	0.79	10.9
Intensive Fertile Grassland[1]	0.349	6.2[1]	0.50	0.09	0.59	8.1
Extensive Fertile Grassland[1]	0.349	7.9[1]	0.27	0.09	0.36	5.0
Monoculture Infertile Grassland[1]	0.349	7.1[1]	0.43	0.09	0.52	7.2
Extensive Infertile Grassland[1]	0.349	10.5[1]	0.03	0.09	0.12	1.7
Monoculture Tall Grassland/Herb[1]	0.349	0.9[1]	0.93	0.09	1.02	14.1
Intensive Tall Grassland/Herb[1]	0.349	4.7[1]	0.62	0.09	0.71	9.8
Extensive Tall Grassland/Herb[1]	0.349	7.2[1]	0.33	0.09	0.42	5.8
Monoculture Broadleaf, mixed and yew LOW woodland[1]	0.439	3.1[1]	0.40	0.00	0.19	2.6
Extensive Broadleaf, mixed and yew LOW woodland[1,*]	0.439	5.2[1]	0.00	0.00	0.00	-
Broad-leafed plantation[2]	0.439	3.3[2]	0.37	0.00	0.37	5.1
Coniferous plantations[2]	0.439	2.8[2]	0.47	0.00	0.47	6.5
Mixed plantations[2]	0.439	1.8[2]	0.66	0.00	0.66	9.1
Continuous urban[2]	0.214	1.4[2]	0.97	0.22	1.19	16.4
vineyards[2]	0.210[3]	2.8[2]	0.42	0.23	0.65	9.0

Reference land use type; [1] data of CS2000; [2] data of Köllner; [3] z *values taken from Köllner*

10.5.2 CHARACTERIZATION FACTORS FOR IMPACTS OF TRANSFORMATION

The characterisation factors for transformation are given in formulas (10.18) and (10.19). The main difference with occupation is the use of the restoration time. It is possible to develop huge conversion matrices between all kind of land use types, but for LCA it is especially relevant to be able to express environmental damages due to the transformation of natural areas into an artificial area. Conversion of agricultural land-use type A into an agricultural land-use type B is probably less interesting.

The characterisation factors provided below are based on this self limitation. We have assumed that the conversion takes place in a more or less natural area, to an artificial area; for formula (10.18) and (10.19) this means that the index *o* (original) is assumed equal to *r* (reference). As a result, the PDF is independent of the area type that will be transformed (the first column in Table 10.9, Table 10.10, and Table 10.11) and only differentiates for the land use types that occur due to transformation. For the agricultural land use types we have only calculated the impact for the intensive land use, not for the monocultures or the extensive land-use types. The second row has the PDF value that occurs after conversion. It is taken from the values calculated in Section 10.3.3. These PDF values are multiplied with the assumed restoration times, which depends of the original state. If more data on the actual restoration times are available anyone can use this actual restoration time in stead of the defaults.

Table 10.9: Characterisation factors (PDF.Yr) per square meter converted area for the hierarchist perspective (assumption A and average restoration times).

	Restoration time	**Crops and weeds**	**Grassland**	**Broad-leaved plantation**	**Coniferous plantation**	**continous urban**
PDF		1.3	0.8	0.9	1.1	1.4
Species poor immature hedgerows and shrubs + [a]	35	46	28	32	39	49
Forests, shrubs and hedgerows	100	130	80	90	110	140
Low and medium[b] peat bogs, old dry meadows and heath land	450	585	360	405	495	630
High (mature) peat bogs, old grow forests	3300	4290	2640	2970	3630	4620

[a] *oligotroph vegetation of areas silting up, relatively species rich marshland with sedges, meadows, dry meadows and heath land.*
[b] *immature*

Table 10.10: Characterisation factors (PDF.Yr) per square meter converted area for the egalitarian perspective (assumption A and average restoration times). These values still need to be multiplied with the terrestrial species density factor, we have not done so as this makes the results less clear

	Restoration time	**Crops and weeds**	**Grassland**	**Broad-leaved plantation**	**Coniferous plantation**	**Continous urban**
PDF		1.3	0.8	0.9	1.1	1.4
Species poor immature hedgerows and shrubs + [a]	50	65	40	45	55	70
Forests quite rich in species, shrubs and hedgerows	200	260	160	180	220	280
Low and medium[b] peat bogs, old dry meadows and heath land	1000	1300	800	900	1100	1400
High (mature) peat bogs, old grow forests	10000	13000	8000	9000	11000	14000

[a] *oligotroph vegetation of areas silting up, relatively species rich marshland with sedges, meadows, dry meadows and heath land.*
[b] *immature*

Table 10.11: Characterisation factors (PDF.Yr) per square meter converted area for the individualist perspective (assumption B and average restoration times, limited to 100 years). These values still need to be multiplied with the terrestrial species density factor, we have not done so as this makes the results less clear.

	Restoration time	**Crops and weeds**	**Grassland**	**Broad-leaved plantation**	**Coniferous plantation**	**Continous urban**
PDF		1.12	0.65	0.37	0.47	1.2

Species poor immature hedge-rows and shrubs, + [a]	35	39	23	13	16	42
Forests quite rich in species, shrubs and hedgerows	100	112	65	37	47	120
Low and medium[b] peat bogs, old dry meadows and heath land	100	112	65	37	47	120
High (mature) peat bogs, old grow forests	100	112	65	37	47	120

[a] *oligotroph vegetation of areas silting up, relatively species rich marshland with sedges, meadows, dry meadows and heath land.*
[b] *immature*

10.6 LAND USE OCCUPATION WITH ECOINVENT

A. Land occupation midpoints

Table 10.12shows the resulting characterisation factors for agricultural and urban land occupation and how the Ecoinvent land use types have been assigned for these purposes. The land use type 'unknown' from Ecoinvent is handled differently, as it is an average between natural and non-natural land. Based on the fact that 61% of all land is non-natural and 39% is natural land, it receives for both ALO the characterisation factor 0.4 and ULO the characterisation factor 0.6.

Table 10.12: Midpoint characterisation factors for impacts of land occupation.

Land use type in Ecoinvent	**ALOP ($m^2 \times yr/m^2 \times yr$)**	**ULOP ($m^2 \times yr/m^2 \times yr$)**
Occupation, arable	1	0
Occupation, arable, integrated	1	0
Occupation, arable, non-irrigated	1	0
Occupation, arable, non-irrigated, diverse-intensive	1	0
Occupation, arable, non-irrigated, fallow	1	0
Occupation, arable, non-irrigated, monotone-intensive	1	0
Occupation, arable, organic	1	0
Occupation, construction site	0	1
Occupation, dump site	0	1
Occupation, dump site, benthos	0	1
Occupation, forest	1	0
Occupation, forest, extensive	1	0
Occupation, forest, intensive	1	0
Occupation, forest, intensive, clear-cutting	1	0
Occupation, forest, intensive, normal	1	0
Occupation, forest, intensive, short-cycle	1	0
Occupation, heterogeneous, agricultural	1	0
Occupation, industrial area	0	1
Occupation, industrial area, benthos	0	1
Occupation, industrial area, built up	0	1
Occupation, industrial area, vegetation	0	1
Occupation, mineral extraction site	0	1
Occupation, pasture and meadow	1	0
Occupation, pasture and meadow, extensive	1	0
Occupation, pasture and meadow, intensive	1	0
Occupation, pasture and meadow, organic	1	0
Occupation, permanent crop	1	0
Occupation, permanent crop, fruit	1	0
Occupation, permanent crop, fruit, extensive	1	0
Occupation, permanent crop, fruit, intensive	1	0
Occupation, permanent crop, vine	1	0
Occupation, permanent crop, vine, extensive	1	0
Occupation, permanent crop, vine, intensive	1	0
Occupation, sea and ocean	0	0
Occupation, shrub land, sclerophyllous	1	0
Occupation, traffic area	0	1
Occupation, traffic area, rail embankment	0	1
Occupation, traffic area, rail network	0	1
Occupation, traffic area, road embankment	0	1

Occupation, traffic area, road network	0	1
Occupation, tropical rain forest	1	0
Occupation, unknown	0.4	0.6
Occupation, urban, continuously built	0	1
Occupation, urban, discontinuously built	0	1
Occupation, urban, green areas	0	1
Occupation, water bodies, artificial	0	0
Occupation, water courses, artificial	0	0

B. Land occupation endpoints

Table 10.13 shows the resulting characterisation factors for land occupation on endpoint level and how the ecoinvent land use types have been assigned for these purposes. The land use type 'unknown' from Ecoinvent is handled differently, it is calculated as an average between 61% non-natural and 39% natural land.

Table 10.13: Endpoint characterisation factors in PDF.m^2.yr, and the charaterisation factors which are the result of caluclating with the species density for impacts of land occupation. The table distinguishes the individualist (I) perspective and the combined hierarchist and egalitarian perspective (H)+(E)

Land use type in Ecoinvent	**Corresponding land use type from ReCiPe**	**PDF.m^2.yr (H)+(E)**	**PDF.m^2.yr (I)**	**LOP [yr] (H)+(E)**	**LOP [Yr] (I)**
Occupation, arable	Intensive Crops/Weeds[1]	1.3	1.12	1.79E-08	1.55E-08
Occupation, arable, integrated	Intensive Crops/Weeds[1]	1.33	1.12	1.84E-08	1.55E-08
Occupation, arable, non-irrigated	Intensive Crops/Weeds[1]	1.33	1.12	1.84E-08	1.55E-08
Occupation, arable, non-irrigated, diverse-intensive	Monoculture Crops/Weeds[1]	1.39	1.18	1.92E-08	1.63E-08
Occupation, arable, non-irrigated, fallow	Extensive Crops/Weeds[1]	1.29	1.08	1.78E-08	1.49E-08
Occupation, arable, non-irrigated, monotone-intensive	Monoculture Crops/Weeds[1]	1.39	1.18	1.92E-08	1.63E-08
Occupation, arable, organic	Extensive Crops/Weeds[1]	1.29	1.08	1.78E-08	1.49E-08
Occupation, construction site	Continuous urban[2]	1.4	1.19	1.93E-08	1.64E-08
Occupation, dump site	Continuous urban[2]	1.4	1.19	1.93E-08	1.64E-08
Occupation, dump site, benthos	Continuous urban[2]	1.4	1.19	1.93E-08	1.64E-08
Occupation, forest	Monoculture Broadleaf, mixed forest and woodland[1]	0.63	0.19	8.69E-09	2.62E-09
Occupation, forest, extensive	Monoculture Broadleaf, mixed forest and woodland[1]	0.63	0.19	8.69E-09	2.62E-09
Occupation, forest, intensive	Broad-leafed plantation[2]	0.81	0.37	1.12E-08	5.11E-09
Occupation, forest, intensive, clear-cutting	Mixed plantations[2]	1.1	0.66	1.52E-08	9.11E-09
Occupation, forest, intensive, normal	Broad-leafed plantation[2]	0.81	0.37	1.12E-08	5.11E-09
Occupation, forest, intensive, short-cycle	Mixed plantations[2]	1.1	0.66	1.52E-08	9.11E-09
Occupation, heterogeneous, agricultural	Extensive Crops/Weeds[1]	1.29	1.08	1.78E-08	1.49E-08
Occupation, industrial area	Continuous urban[2]	1.4	1.19	1.93E-08	1.64E-08
Occupation, industrial area, benthos	Continuous urban[2]	1.4	1.19	1.93E-08	1.64E-08
Occupation, industrial area, built up	Continuous urban[2]	1.4	1.19	1.93E-08	1.64E-08
Occupation, industrial area, vegetation	Continuous urban[2]	1.4	1.19	1.93E-08	1.64E-08
Occupation, mineral extraction site	Continuous urban[2]	1.4	1.19	1.93E-08	1.64E-08
Occupation, pasture and meadow	Intensive Fertile Grassland[1]	0.92	0.59	1.27E-08	8.14E-09
Occupation, pasture and meadow, extensive	Intensive Fertile Grassland[1]	0.92	0.59	1.27E-08	8.14E-09
Occupation, pasture and meadow, intensive	Monoculture Fertile Grassland[1]	1.13	0.79	1.56E-08	1.09E-08
Occupation, pasture and meadow, organic	Extensive Fertile Grassland[1]	0.69	0.36	9.52E-09	4.97E-09
Occupation, permanent crop	Mixed plantations[2]	1.1	0.66	1.52E-08	9.11E-09
Occupation, permanent crop, fruit	Mixed plantations[2]	1.1	0.66	1.52E-08	9.11E-09
Occupation, permanent crop, fruit, extensive	Broad-leafed plantation[2]	0.81	0.37	1.12E-08	5.11E-09
Occupation, permanent crop, fruit, intensive	Mixed plantations[2]	1.1	0.66	1.52E-08	9.11E-09
Occupation, permanent crop, vine	Vineyards[2]	0.86	0.65	1.19E-08	8.97E-09
Occupation, permanent crop, vine, extensive	Vineyards[2]	0.86	0.65	1.19E-08	8.97E-09
Occupation, permanent crop, vine, intensive	Vineyards[2]	0.86	0.65	1.19E-08	8.97E-09
Occupation, sea and ocean		0	0	0.00E+00	0.00E+00
Occupation, shrub land, sclerophyllous	Intensive Tall Grassland/Herb[1]	1.05	0.71	1.45E-08	9.80E-09
Occupation, traffic area	Continuous urban[2]	1.4	1.19	1.93E-08	1.64E-08
Occupation, traffic area, rail embankment	Continuous urban[2]	1.4	1.19	1.93E-08	1.64E-08
Occupation, traffic area, rail network	Continuous urban[2]	1.4	1.19	1.93E-08	1.64E-08
Occupation, traffic area, road embankment	Continuous urban[2]	1.4	1.19	1.93E-08	1.64E-08

Occupation, traffic area, road network	Continuous urban²	1.4	1.19	1.93E-08	1.64E-08
Occupation, tropical rain forest	Monoculture Broadleaf, mixed forest and woodland¹	0.63	0.19	8.69E-09	2.62E-09
Occupation, unknown		1.10	0.80	1.52E-08	1.10E-08
Occupation, urban, continuously built	Continuous urban²	1.4	1.19	1.93E-08	1.64E-08
Occupation, urban, discontinuously built	Continuous urban²	1.4	1.19	1.93E-08	1.64E-08
Occupation, urban, green areas	Continuous urban²	1.4	1.19	1.93E-08	1.64E-08
Occupation, water bodies, artificial	0	0	0	0.00E+00	0.00E+00
Occupation, water courses, artificial	0	0	0	0.00E+00	0.00E+00

*Calculated as 0.6 continuous urban and 0.4 mixed forest.

10.7 LAND USE TRANSFORMATION WITH ECOINVENT

For the land transformation impact category, land is transformed from one state to the other, namely from land use type x to land use type y. Land use type x and y can be defined as natural land or non-natural land. Non-natural land can be defined as those land use types describing high human intervention, like urban land, arable fields or traffic area. Natural land is more difficult to define. Following the conventions of Ecoinvent, the land use types 'forest', 'tropical forest' and 'sea and ocean' can be recognize as natural land. As a result four transformation processes can take place:

- Transformation from natural land to non-natural land
- Transformation from non-natural land to natural land
- Transformation from non-natural land to non-natural land
- Transformation from natural land to natural land

In ReCiPe, the first transformation process is characterised with a positive characterisation factor, referring to environmental damage. The second transformation process produces environmental improvement, accounted with a negative characterisation factor. The transformation processes from nature to nature and from non-natural to non-natural have no meaning in the ReCiPe method. We assume no effect takes place, what corresponds to a characterisation factor of 0 for these two transformation processes.

In the Ecoinvent inventory database however, for each land transformation process mentioned above, the state before transformation and the state after land transformation is defined separately in two LCI data points. The final result of one land transformation process is produced when adding both transformation states:

- Transformation, from land use type x
- Transformation, to land use type y.

Eco-invent considers the transformation from land use type x to a reference land use type and the transformation to land use type y from a reference land use type. It does not define what that reference land use type is exactly, but leaves this to the LCIA developer. The use of two conversions, from and to a reference state, is a different concept from the ReCiPe methodology. In ReCiPe we developed factors for the transformation process. This conceptual difference forces us to link the characterisation factor to one of the two transformation states given by Eco-invent. The most logical choice is to have only a characterisation factor for transformations from and to natural land-use types, as the environmental damage of land transformation depends on the restoration time needed to restore the natural land.

For each state a characterisation factor is produced. In order to be consistent with Ecoinvent and taking into account the distinction between natural and non-natural land, the characterisation factors are produced as follows:

Transformation, to non-natural land: CF = 0;
Transformation, from non-natural land: CF = 0;
Transformation, to natural land: CF= negative value;
Transformation, from natural land: CF= positive value.

A. Land transformation midpoints

For the different land use types of Ecoinvent, the NLTPs (the natural land transformation potentials) have been listed in Table 10.14.The land use type 'unknown' from Ecoinvent is handled differently, as it is an average between natural and non-natural land. Based on the fact that 61% of all land is non-natural and 39% is natural land, it receives the following characterisation factors[29]:

[29] Combining these characterisation factors in the above transformation processes, it gives following results: Transformation from natural land to unknown land: CF=0.6; Transformation from unknown land to natural land: CF=-0.6; Transformation from non-natural land to unknown land: CF=-0.4; Transformation from unknown land to non-natural land: CF=0.4.

Transformation, to unknown: CF = -0.4;
Transformation, from unknown: CF = 0.4;

Table 10.14: Midpoint characterisation factors for impacts of land transformation.

Land use type	**NLTP (m^2/m^2)**
transformation, from forest	1
transformation, from sea and ocean	1
transformation, from tropical rain forest	1
transformation, from unknown	0.4
transformation, from *'any type of non-natural land'*	0
transformation, to forest	-1
transformation, to sea and ocean	-1
transformation, to tropical rain forest	-1
transformation, to unknown	-0.4
transformation, to *'any type of non-natural land'*	0

The midpoint indicators can not directly be used in the endpoint methodology. At midpoint level, no differentiation to land use types is made, due to the uncertainties. While at endpoint level, uncertainties are considered and so a differentiation to several land use types is made.

B. Land transformation endpoints

For the different land use types of ecoinvent, the endpoint characterisation factors for land transformation have been listed in . As discussed previously, the endpoint characterisation factors for land use are determined by the difference in species richness before and after transformation, and the time needed to restore the land.

- As the effect of transformation is determined by the type of natural land the transformation is coming from or going to, the restoration time chosen is the time needed to restore the natural land.

Restoration time	Hierarchist & individualist	Egalitarian
Forests, shrubs and hedgerows	100	200
Tropical forest	3300	10000

- In principle, the restoration time is multiplied with the difference in species richness before and after transformation. This species difference is difficult to define as the non-natural land use type, where the land will be transformed to or is coming from, is unknown (as when using Ecoinvent each possible combination can be made). Furthermore, the restoration time is incorporated in the CF of the natural land and thus also here the species difference should be implemented. The difference in species richness chosen, is an average of the different non-natural land use types the transformation is coming from or going to. We realize this is a rough assumption that eliminates a lot of land use specific factors that are available.

Difference in species richness (PDF)	Hierarchist & egalitarian	Individualist
Between natural and non-natural land	1.05	0.8

We tried to compensate for the use of 'an average factor' by implementing land type specific information multiplied with the restoration time for natural land, in the CFs of the non-natural land use types. This would solve our rough average in transformations from natural land to non-natural land or visa versa. However, within Ecoinvent next to transformations from natural to non-natural, also transformation from non-natural to non-natural appears, and this can give problems. To test we calculated the environmental damage, using a sample size of 40 agricultural processes from Ecoinvent. For transformations from non-natural land to non-natural land, using the exact same land use types, both effects are compensated and the net effect is zero (like we want). However, small asymmetries in transformations such as 'transformation from arable to arable, non-irrigated' resulted in an environmental load much larger than the load due to occupation of the arable land. This is clearly not consistent with what we want to express. The high damage derived from the restoration time which applies for the natural land, what is not correct as in this case we have a transformation from non-natural to non-natural land. As a result, we decided to give a CF of 0 to all transformations from and to non-natural land use types.

Table 10.15: Endpoint characterisation factors for impacts of land transformation, expressed both as PDF.m^2.yr as in species.yr, the characterisation factor.

Land use type	**PDF. m^2. yr (H)**	**PDF. m^2. yr (E)**	**PDF. m^2. yr (I)**	**LTP [yr] (H)**	**LTP [yr] (E)**	**LTP [yr] (I)**
transformation, from forest	130	260	110	3.59E-06	1.52E-06	4.95E-14
transformation, from tropical rain forest	4290	13000	3630	1.79E-04	5.01E-05	2.48E-12
transformation, from unknown*	51	5070	43	7.00E-05	5.93E-07	9.66E-13
transformation, from *'any type of non-natural land'*	0	0	0	0	0	0
transformation, to forest	-130	-260	-110	-3.59E-06	-1.52E-06	-4.95E-14
transformation, to tropical rain forest	-4290	-13000	-3630	-1.79E-04	-5.01E-05	-2.48E-12
transformation, to unknown*	-51	-5070	-43	-7.00E-05	-5.93E-07	-9.66E-13
transformation, to *'any type of non-natural land'*	0	0	0	0	0	0

*Calculated as mixed forest multiplied with 0.4.

The land use type 'unknown' from Ecoinvent is handled differently. Based on the fact that 39% of all land is natural land, it receives a different characterisation factor. For the Hierarchist and Individualist perspective we assume that 40% natural land is covered by Forests, shrubs and hedgerows. For the Egalitarian perspective a worst case scenario is considered, where the characterisation factor of 'tropical forest' is multiplied with 0.4.

10.8 REFERENCE

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10.9 SUMMARY TABLE

Entity	**Content**
impact category	land use
LCI results	land occupation, land transformation
midpoint indicator(s) (with abbreviation)	agricultural land occupation (ALO) urban land occupation (ULO) natural land transformation (NLT)
unit of midpoint indicator(s)	$m^2 \times yr$ $m^2 \times yr$ m^2
midpoint characterisation factor (with abbreviation)	agricultural land occupation potential (ALOP) urban land occupation potential (ULOP) natural land transformation potential (NLTP)
unit of midpoint characterisation factor	$m^2 \times yr/m^2 \times yr$ $m^2 \times yr/m^2 \times yr$ m^2/m^2
endpoint indicator(s) (with abbreviation)	damage to ecosystem diversity (ED)
unit of endpoint indicator(s)	yr
endpoint characterisation factor (with abbreviation)	No direct link with midpoint
unit of endpoint characterisation factor	yr/m^2

11 WATER DEPLETION

Mark Goedkoop[30] and An De Schryver

Water is a scarce resource in many parts of the world, but also a very abundant resource in other parts of the world. Unlike other resources there is no global market that ensures a global distribution. The market does not really work over big distances as transport costs are too high. Extracting water in a dry area can cause very significant damages to ecosystems and human health, but so far no models are available to express the damage on the endpoint level. We do propose however to have a midpoint indicator that simply expresses the total amount of water used.

11.1 THE MIDPOINT INDICATOR

An important issue is to consider which types of water uses do result in water shortages. If water evaporates or is used as input for the production of concrete, used as an input in production processes, etc., one can assume the water is lost from an area. If the water is consumed, but also released very close to the point of consumption, one may argue the water is not lost, and in that case the water use does not result in any shortages. There are also more complex causes of water shortages. For instance sewer systems along roads and cities are designed to quickly remove water from surfaces, without giving the water to opportunity to add to the groundwater table.
To give some guidance, we selected five water types used in the ecoinvent data that should be used as default, but we recommend assessing on a case by case basis if more water use types should be included.

Table 11.1: Midpoint characterisation factors for the midpoint impact category freshwater depletion. No endpoint modelling is available at present.

Resources	**$CF_{midpoint}$ (m^3/m^3)**	**$CF_{endpoint}$**
Water, lake	1	NA*
Water, river	1	NA
Water, well, in ground	1	NA
Water, unspecified natural origin	1	NA
Water, unspecified natural origin (kg)	0.001†	NA

** NA = not available*
† in m^3/kg

11.2 REFERENCE

none

11.3 SUPPORTING INFORMATION

none

11.4 SUMMARY TABLE

Entity	**Content**
impact category	freshwater depletion
LCI results	freshwater use
midpoint indicator(s) (with abbreviation)	water depletion (WD)
unit of midpoint indicator(s)	m^3
midpoint characterisation factor (with abbreviation)	water depletion potential (WDP)
unit of midpoint characterisation factor	m^3/m^3
endpoint indicator(s) (with abbreviation)	–
unit of endpoint indicator(s)	–
endpoint characterisation factor (with abbreviation)	–
unit of endpoint characterisation factor	–

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12 MINERAL RESOURCE DEPLETION

Mark Goedkoop[31] *and An De Schryver*

Minerals are naturally occurring substances formed through geological processes that have a characteristic chemical composition, a highly ordered atomic structure and specific physical properties (Wikipedia). Minerals were present when the earth was formed, and when cooling down, geologic processes created areas in which minerals were concentrated.

12.1 AVAILABLE DATA ON COMMODITIES AND DEPOSITS

A mineral is in nature extracted from a deposit (that is extracted in a mine) and most deposits contain several minerals (Verhoef et. al. 2004). Eventually, the minerals or metals are the economic output of a mining operation and therefore also called commodities. One mineral can be found in different deposits and several mines can produce the same deposit type (producing the same metal). Although mines are often named after the primarily metal ("nickel mine") in fact they do not mine copper but a deposit, like Dunitic, that contains nickel, but also often silver, and copper. Some metals are always mined as a by product like molybdenum, gallium and indium. Because inventory data produces information based on metals instead of deposits, the increased costs of the deposits are being recalculated individually per commodity.

One of the most important data source for this method is the selected world metal deposits database of US geological survey (Singer et al., 1997). This database contains historical data from over 3000 mines on 50 deposits. Grade and tonnage data are not available for all mines or deposits. The commodities found in the different deposits are given in Table 12.1.

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Table 12.1: Commodities in deposits. Number of mines between brackets

Deposit[a]	**Commodities**
Besshi (44)	Ag-Au-Cu-Zn
Carbonatite[b](31)	Nb_2O_5,RE_2O_5[c],P_2O_5
climax-mo_(9)	Mo
Comstock(41)	Ag-Au-Cu-Pb-Zn
Creede(27)	Ag-Au-Cu-Pb-Zn
cu-skarn(64)	Ag-Au-Cu
cuban-mn(93)	Fe-Mn
cyprus-mn (49)	Ag-Au-Cu-Pb-Zn
cyprus-mn-rev (7)	Fe-Mn
distal-dissem-ag-au(10)	Ag-Au
dunitic-ni(22)	Au-Co-Cu-Ir-Ni-Pd
epithermal-qtz-alunite-au(9)	Ag-Au-Cu
epithermal-mn_(59)	Mn
fe-skarn(168)	Cu-Fe
franciscan-mn_(184)	Mn
homestake-au(118)	Ag-Au
hot-spring-au(17)	Ag-Au
karst-bauxite_(41)	Al
komatiitic-ni(31)	Au-Co-Cu-Ir-Ni-Pd-Pt
kuroko-sier(19)	Ag-Au-Cu-Pb-Zn
kuroko-rev(457)	Ag-Au-Cu-Pb-Zn
laterite-bauxite_(122)	Al
lateritic-ni(71)	Co-Ni
olympic-penn-mn(17)	Fe-Mn
phosphate-upwelling_(60)	P_2O_5
phosphate-warm-current_(18)	P_2O_5
placer-pt-au(83)	Au-Ir-Os-Pd-Pt
podiform-cr-minor(435)	Cr-Ir-Pd-Pt-Rh-Ru
podiform-cr-major(174)	Cr-Ir-Pd-Pt-Rh-Ru
polymetallic-repl(52)	Ag-Au-Cu-Pb-Zn
porphyry-cu-ak-bc(56)	Ag-Au-Cu-Mo
prophyry-mo-low-f_(33)	Mo
replacement-mn(37)	Cu-Fe-Mn-P
replacement-sn_(6)	Sn
rhyolite-hosted-sn_(132)	Sn
sado-epithermal-au(20)	Ag-Au-Cu-Pb-Zn
sediment-hosted-au(39)	Ag-Au
sediment-hosted-cu(58)	Ag-Co-Cu
sedimentary-exhalative(44)	Ag-Cu-Pb-Zn
sandstone-hosted-pb-zn(20)	Ag-Au-Cu-Pb-Zn
sediment-mn_(38)	Mn
sn-greisen_(10)	Sn
sn-skarn_(4)	Sn
sn-vein_(43)	Sn
superior-algoma-fe(66)	Fe-P
synorogenic-synvol-ni(32)	Au-Co-Cu-Ni-Pd-Pt
unconformity-u_(36)	U
volcanic-hosted-magnetite(39)	Fe-P
volcanogenic-u_(21)	U
zn-pb-skarn(34)	Ag-Au-Cu-Pb–Zn

a: According to USGS metal deposits database [2]
b: Not taken into account: no monetary value available
c: RE: Rare earth metals

This table shows all commodities come from different deposits. The number behind each deposit indicates the amount of mines present in the database producing the same deposit. This is further illustrated in Figure 12.1, where we plotted all yields (in dollars), per deposit and per commodity.

Deposit type	Ag	Al	Au	Co	Cr	Cu	Fe	Ir	Mn	Mo	Ni	Os	P	Pb	Pd	Pt	Rh	Ru	Sn	U	Zn
besshi	0%		0%			1%															0%
carbonatite																					
climax-mo_										42%											
comstock	10%		5%			0%								0%							0%
creede	10%		3%			0%								1%							1%
cu-skarn	0%		0%			1%															
cuban-mn							0%		31%												
cyprus-mn	0%		1%			1%								0%							0%
cyprus-mn-rev							0%		3%												
distal-dissem-ag-au	3%		1%																		
dunitic-ni			0%	1%		0%		0%			11%				0%						
epithermal-qtz-alunite-au	0%		2%			0%															
epithermal-mn_									23%												
fe-skarn						2%	14%														
franciscan-mn_									9%												
homestake-au	0%		43%																		
hot-spring-au	0%		4%																		
karst-bauxite_		7%																			
komatiitic-ni			0%	1%		0%		90%			2%				98%	20%					
kuroko-sier	0%		0%			0%								0%							0%
kuroko-rev	19%		16%			20%								19%							42%
laterite-bauxite_		93%																			
lateritic-ni				34%							86%										
olympic-penn-mn									2%												
phosphate-upwelling_																					
phosphate-warm-current_																					
placer-pt-au			0%					8%				####			0%	80%					
podiform-cr-minor					4%			1%							0%	0%	20%	17%			
podiform-cr-major					96%			2%							0%	0%	80%	83%			
polymetallic-repl	9%		1%			0%								12%							6%
porphyry-cu-ak-bc	2%		10%			12%				11%											
prophyry-mo-low-f_										47%											
replacement-mn						0%	0%		32%				0%								
replacement-sn_																			27%		
rhyolite-hosted-sn_																			0%		
sado-epithermal-au	1%		1%			0%								0%							0%
sediment-hosted-au	0%		13%																		
sediment-hosted-cu	26%			64%		60%															
sedimentary-exhalative	16%					1%								56%							46%
sandstone-hosted-pb-zn	0%		0%			0%								8%							1%
sediment-mn_									0%												
sn-greisen_																			27%		
sn-skarn_																			9%		
sn-vein_																			37%		
superior-algoma-fe							78%						30%								
synorogenic-synvol-ni			0%	0%		0%					1%				1%	0%					
unconformity-u_																				90%	
volcanic-hosted-magnetite							7%						70%								
volcanogenic-u_																				10%	
zn-pb-skarn	1%		1%			0%								3%							3%

Figure 12.1: The contribution of each deposit to a resource (as a percentage of the total resource mass)

12.2 FRAMEWORK

In the description of the Area of protection, the damage is defined as the additional costs society has to pay as a result of an extraction. This cost can be calculated by multiplying the marginal cost increase of a resource with an amount that is extracted during a certain period. This could be the annual production of a resource on a global basis, or the apparent consumption of a resource in a region.

$$Damage = \frac{\Delta C_{kg}}{\Delta Y_{kg}} \times P_{kg} \times \Delta Y_{kg} \times NPV_T \qquad (12.1)$$

The damage is expressed in \$, ΔC_{kg} is the cost increase (\$/kg), ΔY_{kg} the extracted mass that caused the price increase (kg), P_{kg} the produced amount of resource over a certain period (kg/yr) and NPV the net present value factor of spending a dollar a year over a time T (yr) (defined in chapter 0).

The damage can also be written when using economic values instead of mass:

$$Damage = \frac{\Delta C_{\$}}{\Delta Y_{\$}} \times P_{\$} \times NPV_T \times \Delta Y_{\$} \qquad (12.2)$$

In this case $\Delta C_{\$}$ is the cost increase per dollar value produced (\$/\$), $\Delta Y_{\$}$ the extracted amount in \$, and $P_{\$}$ the amount produced per year expressed in value (\$/yr).

The characterisation factor for extraction defined in dollar (\$/\$) can thus be defined as:

$$CF_{\$} = \frac{\Delta C_{\$}}{\Delta Y_{\$}} \times P_{\$} \times NPV_T = MCI_{\$} \times P_{\$} \times NPV_T \quad (12.3)$$

With $MCI_{\$}$ the marginal cost increase (1/\$). Similarly, the characterisation factor for extractions defined as mass is:

$$CF_{kg} = \frac{\Delta C_{kg}}{\Delta Y_{kg}} \times P_{kg} \times NPV_T = MCI_{kg} \times P_{kg} \times NPV_T \quad (12.4)$$

With MCI_{kg} the marginal cost increase in \$/ kg^2.

The proposed methodology focuses on the depletion of deposits, instead of individual commodities. By this way we do more justice to the actual geological distribution of metals, and we will be able to cover many more commodities, especially those metals that are always mined as co product. The method uses increased costs as end-point indicator and 'the slope (relation grade-yield) divided by availability' as midpoint indicator.
The environmental mechanism used for this impact category includes the following steps:

Step 1: A marginal increase in yield (in \$), caused by an extraction (the LCI parameter) of a deposit results in a marginal lower grade (in \$/kg) of the deposit. As a deposit usually contains more than one commodity, a value (\$) weighted average yield (\$) and grade (\$/kg) is used.

Step 2: The relation between ore grade and mining cost is established. The value weighted grade (\$/kg), determines how much ore needs to be extracted. A marginal decrease in grade (in \$/kg) results in extra mining cost (\$/kg) . The marginal cost increase (\$/\$) is non linear with the grade decrease and thus depends on the current ore grade. We have chosen to determine the marginal increase at the grade that corresponds with the median of the extracted amount in our dataset.

Step 3: The marginal cost increase on deposit level can be calculated by combining step 1 and 2. This factor can be defined as the marginal average cost increase (\$/\$) due to extracting a dollar value of deposit *d* (1/\$).

Step 4: From the marginal cost increase factor on deposit level we go to the cost increase factor on commodity level. The average weighted yield of the cost increase of all deposits that contribute to the production of the commodity is calculated.

Step 5: Until here the marginal cost increase factors we developed for an extraction is expressed as monetary value. In LCA, resource extractions are usually defined as a mass. Therefore the marginal cost increase must be converted to mass extracted.

From the marginal cost increase factor in step 5, we develop a midpoint characterisation factor,

12.3 STEP 1, LOWER VALUE WEIGHTED GRADE IF VALUE WEIGHTED YIELD INCREASES

The definition of an ore grade in a deposit is difficult to define if a deposit produces different commodities. To solve this we add up the grades of the individual commodities, multiplied with the economic value of the commodities, for each mine.

$$g_{v.m} = \sum_c \left(g_{c,m} \times V_c \right) \quad (12.5)$$

With $g_{v.m}$ the value weighted grade of mine *m*, $g_{c,m}$ the grade of commodity *c* at mine *m* and V_c the market value of commodity *c* (\$/kg). The value weighted grade can be interpreted as the yield per kg of ore (\$/kg).

The data also provides the production amount of each commodity from a resource in hundreds of mines. Also here we use the price to get a total yield from the deposit.

$$Y_{v.m} = \sum_c \left(Y_{c,m} \times V_c \right) \quad (12.6)$$

With $Y_{v.m}$ the value weighted yield of mine *m* (\$), in other words the total yield in dollars per mine, $Y_{c,m}$ the yield of commodity c at mine *m* (kg).

Below we plot an example that illustrates how value weighted yield (cumulative values) and grade are related in the example of Dunitic. Each dot represents a mine of the same deposit Dunitic. A linear function is fitted through the data plots. This is done for each deposit. An overview of all plots can be seen in the supporting information.

Initially we analysed the set using the assumption that there is a lognormal distribution of potential yields versus grade. This assumption is relatively well accepted among geologists, and also used in the Surplus energy concept (Mueller-Wenk). We found a very bad fit if we wanted to plot such a function on the available data. A linear relationship fits better, although the fit is far from perfect, as can be seen in the supporting information.

The misfit can indicate that the dataset is not completely representative for the total distribution in the earth crust. The data only samples mines, and not other geologic formation. In fact it covers only a small part of the variety of ore grades in metals. We use the linear fit, assuming that this linear relationship can be seen as an approximation of the ore-grade relationship, in the range of grades that are presently mined. It is clear that the linear relation cannot be valid at very high or low grades. We will only use the central part of the grade yield relationship, in fact we will use the grade that corresponds with the median yield.

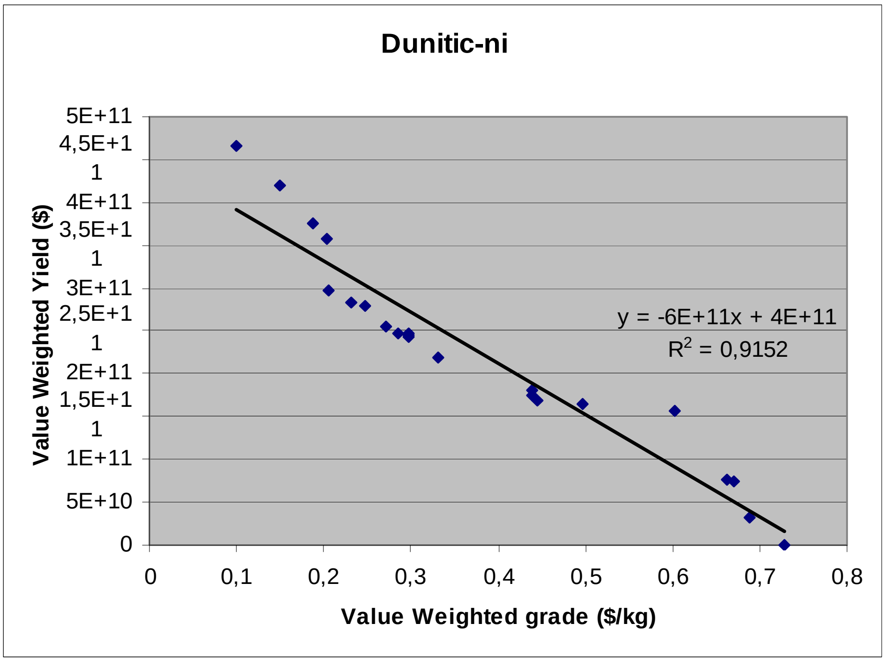

Figure 12.2: The cumulative value weighted yield in relation to the value weighted grade. The values of each dot derives from formula (12.5) and (12.6). The higher the grade, the lower yield at that grade is available. For an overview of all plots, see the supporting information.

A certain amount of extraction ($) will cause a certain change in the value weighted grade ($/kg), determined by the slope M_d (kg) and constant c_d. For each deposit we can write:

$$Y_{v.d} = M_d \times g_{v.d} + c_d \tag{12.7}$$

With $Y_{v.d}$ the cumulative value weighted yield over all mines of deposit d ($), $g_{v.d}$ the value weighted grade of deposit d ($/kg), and M_d the slope (kg), while c_d is a constant ($).

The marginal change in value weighted grade of deposit d due to a marginal change in value weighted yield of deposit d can be defined as:

$$\frac{\partial g_{v.d}}{\partial Y_{v.d}} = \frac{1}{M_d} \tag{12.8}$$

12.4 STEP 2 FROM VALUE WEIGHTED GRADE TO MARGINAL COST INCREASE

For each decrease in grade in $/kg, an extra amount of value weighted yield needs to be mined. The cost grade relationship can be described as follows:

$$C_{d.\$} = \frac{x}{g_{v.d}} \tag{12.9}$$

With $C_{d.\$}$ the cost to mine a certain amount of ore of deposit d ($/$), x the mining costs per kg ore ($/kg), $g_{v.d}$ the value weighted grade of deposit d ($/kg). The cost, $C_{d.\$}$ can be described as the amount of dollar paid to extract an amount of a deposit that contains commodities with a market value of a dollar.

CostMine, formerly Western Mine Engineering, Inc. and now a division of InfoMine, provides advice, publications and software. World Mine Cost Data Exchange is a co-operative internet resource for mining industry analysts. Both internet sources produce data and information on mining costs, operating conditions, wage scales, and unit prices. Costmine presents data typical for western U.S. mining operations. They used as example an open pit mine producing 5,000 tonnes ore and 5,000 tonnes waste per day. InfoMine made a free sample downloadable about Grasberg copper-gold mine located in Irianjaya, Indonesia. Grasberg is a complex operation with a large open pit and underground mine feeding four mills. Both sources give an average mining cost of 0.004 $/kg ore mined. When milling is included, an average cost of 0.013 $/kg ore is derived. Due to limited data we assume this cost applies for all different deposits, without considering a difference in open pit and underground mining.

Based on the function described in formula (12.9) an example of Dunitic illustrates how value weighted grade and increased costs are related. Each dot represents a mine of the same deposit Dunitic.

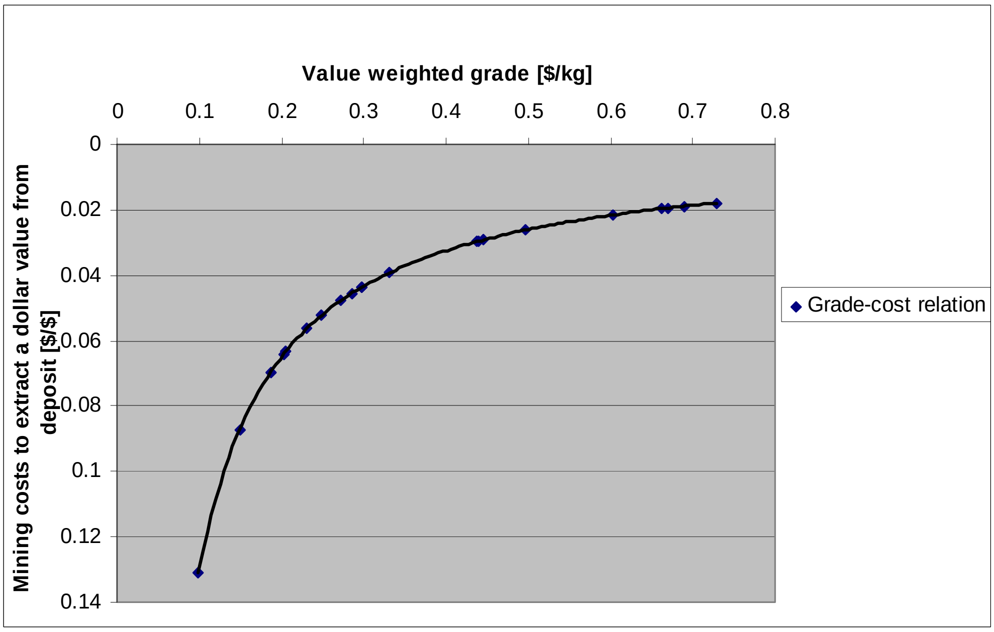

Figure 12.3: Mining costs ($/$) in relation with the value weighted grade ($/kg). We plotted the cost on the negative axis, so this graph can be combined with the previous graph where yield is plotted against grade. The combined graphs allow us to link yield increases to cost increases, with grade as an intermediate variable.

The marginal change in cost of mining deposit *d* ($) due to a marginal change in value weighted grade of deposit *d* ($/kg) can be defined as:

$$\frac{\partial C_{d.\$}}{\partial g_{v.d}} = -\frac{x}{g_{v.d}{}^{2}} \tag{12.10}$$

As noted above, we have chosen to use the grade at the median of the total extracted amount of our database. This can be found at $Y = c/2$. It we substitute this in equation (12.10) we get:

$$\frac{\partial C_{d.\$}}{\partial g_{v.d}} = -\frac{x}{\left(\dfrac{Y_{v,d} - c_d}{M_d}\right)^2} = -\frac{xM_d{}^2}{(-0.5c_d)^2} \tag{12.11}$$

The choice to take the yield at *c*/2 is rather arbitrary, but has no impact at the relative differences between the characterisation factors, although it is directly influencing the absolute values in the endpoint score.

12.5 STEP 3, MARGINAL COST INCREASE ON DEPOSIT LEVEL

The marginal increase of the cost factor $C_{d.\$}$ due to a yield *Y* ($) can now be found, when we combine step one and two, formula (12.8) and (12.9).

$$MCI_{d.\$.} = \frac{\partial C_{d.\$}}{\partial Y_{v.d}} = \frac{\partial C_{d.\$}}{\partial g_{v.d}} \times \frac{\partial g_{v.d}}{\partial Y_{v.d}} = -\frac{xM_d{}^2}{(-0.5c_d)^2} \times \frac{1}{M_d} = -4x \times \frac{M_d}{(c_d)^2} \tag{12.12}$$

With $MCI_{d.\$}$ the marginal cost increase on the deposit level (1/$); M_d the slope on deposit level (kg), *x* the mining costs ($/kg), $Y_{v.d}$ the value weighted yield of the deposit *d* ($) and c_d the constant ($).
This cost increase can also be used to develop a characterisation factor, by substituting MCI in equation (12.3):

$$CF_{d.\$} = MCI_{d.\$} \times P_{d.\$} \times NPV_T = -4x \times \frac{\bar{M}_d}{(\bar{c}_d)^2} \times P_{d.\$} \times NPV_T \quad (12.13)$$

With $P_{c.\$}$ the amount of deposit d, expressed in \$/yr. This can be used if LCI data is specified in monetary value per deposit. The unit of the characterisation factor on this level is \$/\$.

12.6 STEP 4, FROM MARGINAL COST INCREASE ON DEPOSIT LEVEL TO COST INCREASE ON COMMODITY LEVEL

As most commodities come from more than one deposit, we have to calculate the characterisation factor per commodity, using the calculations for deposits. Therefore, the average weighted yield of the characterisation factor of all deposits that contribute to the total yield of the commodity is calculated. To do this, we calculate the average for M_d and c_d separately[32]. We use the contribution to the yield as weighting factor to create the average. The basic assumption here is that if we extract one kg of copper it will come from all the deposits according to the current average production ratios.

$$\overline{M}_c = \frac{\sum_d \left(Y_{c,d} \times M_d\right)}{\sum_d Y_{c,d}} \text{ and } \overline{C}_c = \frac{\sum_d \left(Y_{c,d} \times C_d\right)}{\sum_d Y_{c,d}} \quad (12.14)$$

With M_c and C_c the slope and constant on deposit level recalculated to commodity level *c*, and $Y_{c,d}$ the yield of commodity c in deposit *d* (\$). Substituting both formulas from equation (12.14) into formula (12.12) the marginal cost increase on commodity level can be calculated as follows:

$$MCI_{c.\$.} = -4x \times \frac{\overline{M}_c}{\left(\overline{c}_c\right)^2} \quad (12.15)$$

With $MCI_{c.\$}$ the marginal cost increase on the commodity level (1/\$); M_c the slope on deposit level (kg), *x* the mining costs (\$/kg), c_c the constant (\$). This cost increase can also be used to develop a characterisation factor, by substituting MCI in equation (12.3):

$$CF_{c.\$} = MCI_{c.\$} \times P_{c.\$} \times NPV_T = -4x \times \frac{\bar{M}_c}{(\bar{c}_c)^2} \times P_{c.\$} \times NPV_T \quad (12.16)$$

With $P_{c.\$}$ the amount of commodity c, expressed in \$/yr. NPV_T the net present value factor (yr). This factor can be used if LCI data is expressed in monetary value per commodity. The unit of the characterisation factor on this level is \$/\$.

12.7 STEP 5, FROM MARGINAL COST INCREASE PER DOLLAR TO A CHARACTERISATION FACTOR PER KG

The marginal cost increase for extractions can also be expressed for a mass extraction, and this can also be expressed using equation 12.4, while converting both ΔC_{kg} and ΔY_{kg} into $\Delta C_{\$}$ and $\Delta Y_{\$}$ using the value of the commodity V_c.

$$MCI_{c.kg} = \frac{\Delta C_{c.kg}}{\Delta Y_{c.kg}} = \frac{\Delta C_{c.\$} \times V_c}{\Delta Y_{c.\$} \times V_c^{-1}} = \frac{\Delta C_{c.\$}}{\Delta Y_{c.\$}} \times V_c^2 = MCI_{c.\$.} \times V_c^2 = -4x \times \frac{\overline{M}_c}{\left(c_c\right)^2} \times V_c^2 \quad (12.17)$$

With MCI_{kg} the marginal cost increase expressed as \$/kg/kg; ΔC_{kg} the cost increase (\$/kg) and ΔY_{kg} the extracted mass (kg) and P_{kg} the produced amount of resource (kg) and NPV the net present value factor (yr). We can now write the characterisation factor that expresses the increase in price (\$/kg) as a result of an extraction in kg as.

32 The alternative would be to use a weighted average of M/c2. When we do this, we see that even deposits that give a very small contribution in the total production but that have an unfavourable ratio between M and c dominate the characterisation factor, as the differences in M/c2 can differ several orders of magnitude for the same commodity.

$$CF_{c.kg.end} = MCI_{c.kg.} \times P_{c.kg} \times NPV_T = -4x \times \frac{\overline{M}_c}{(c_c)^2} \times V_c^2 \times P_{c.kg} \times NPV_T \qquad (12.18)$$

The unit of the endpoint characterisation factor is \$/ kg

12.8 MIDPOINT CHARACTERISATION FACTOR

Formula (12.18) also allows for the derivation of a midpoint characterisation factor, by leaving out elements that do not contribute to relative differences between the characterisation factors. The term 4*x* is such a term, x is independent from the commodity. The factor 4 is a leftover from the choice to take the slope on the cost factor at the level of $Y_d = c_d/2$, and can also be left out of the midpoint equation. The midpoint characterisation factor can thus be computed as:

$$CF_{c.kg.mid} = -\frac{\overline{M}_c}{(c_c)^2} \times V_c^2 \times P_{c.kg} \qquad (12.19)$$

The unit of this characterisation factor is 1/\$.yr

If needed, midpoint characterisation factors can also determined on the deposit level and the commodity level per dollar, by taking formula 12.13 and 12.16, while leaving out the factor 4x. In this report, we only specify 20 characterisation factors based on equation 12.18 and 12.19. Similar to all other midpoint impact categories the midpoints are presented as a substance equivalent, in this case iron equivalents.

12.9 MANAGING DIFFERENT PERSPECTIVES

For mineral resource depletion no different assumptions according to time perspective or proven/unproven effects are made. As a result, no choices are handled by using the cultural perspectives. All three perspectives receive the same characterization values on midpoint and endpoint level.

12.10 MIDPOINT AND ENDPOINT CHARACTERIZATION FACTOR FOR MINERAL DEPLETION AND DISCUSSION

Below the midpoint factors are given as Fe-equivalents. The endpoint characterisation factors are given for four different discount rates and a factor is given for the extra cost during one year. The endpoint factors are expressed as \$ per kg extraction. The practical interpretation is that the consequence of extracting a kilo of iron will cause a cost to society of 7 cents when a 3% discount rate is used. The extraction of a kg of Uranium costs \$ 8.77, while the future cost of extracting a kg of platinum is over 11 thousand dollar, which is still less than the market price, but a significant amount.

As reference, the values for the extraction of oil are also provided; these are developed in the next paragraph. It is clear that the values for oil are relatively high compared to these for metals, the future costs are one order of magnitude higher than the current market price. Interestingly the costs are in the same order of magnutude as for the extraction of uranium

Table 12.2: Midpoint and endpoint characterisation factors for mineral and fossil depletion. Although the fossil fuel depletion is describe in the next chapter, we already include the cost of depleting oil in this table to get a better overview.

	Midpoint characterisation factors in FE equivalents	Surplus cost per year per kg.yr	Surplus cost indef, 2% discounting	Surplus cost indef, 3% discounting	Surplus cost indef, 4% discounting	Surplus cost indef, 5% discounting
	-	$/kg.yr	$/kg	$/kg	$/kg	$/kg
Discount rate			2%	3%	4%	5%
Ag	2.86E+02	$ 0.61	$ 30.72	$ 20.48	$ 15.36	$ 12.29
Al	9.01E-02	$ 0.0002	$ 0.0097	$ 0.0064	$ 0.0048	$ 0.0039
Au	6.99E+04	$ 150	$ 7,509	$ 5,006	$ 3,754	$ 3,003
Co	1.01E+00	$ 0.002	$ 0.108	$ 0.072	$ 0.054	$ 0.043
Cr	2.49E+01	$ 0.05	$ 2.68	$ 1.78	$ 1.34	$ 1.07
Cu	4.27E+01	$ 0.09	$ 4.58	$ 3.06	$ 2.29	$ 1.83
Fe	1.00E+00	$ 0.00	$ 0.11	$ 0.07	$ 0.05	$ 0.04
Ir	9.25E+01	$ 0.20	$ 9.93	$ 6.62	$ 4.96	$ 3.97
Mn	7.66E+01	$ 0.16	$ 8.23	$ 5.48	$ 4.11	$ 3.29
Mo	2.08E+02	$ 0.45	$ 22.28	$ 14.85	$ 11.14	$ 8.91
Ni	1.25E+01	$ 0.03	$ 1.34	$ 0.90	$ 0.67	$ 0.54
Os	6.48E+03	$ 13.92	$ 696	$ 464	$ 348	$ 278
P			$ -	$ -	$ -	$ -
Pb	1.77E+00	$ 0.0038	$ 0.19	$ 0.13	$ 0.09	$ 0.08
Pd	3.81E+03	$ 8.19	$ 409	$ 273	$ 205	$ 164
Pt	1.63E+05	$ 349.57	$ 17,478	$ 11,652	$ 8,739	$ 6,991
Rh	2.03E+04	$ 43.65	$ 2,182	$ 1,455	$ 1,091	$ 873
Ru	2.01E+03	$ 4.31	$ 216	$ 144	$ 108	$ 86
Sn	1.27E+03	$ 2.73	$ 136.49	$ 90.99	$ 68.24	$ 54.59
U	1.23E+02	$ 0.26	$ 13.16	$ 8.77	$ 6.58	$ 5.26
Zn	2.25E+00	$ 0.00	$ 0.24	$ 0.16	$ 0.12	$ 0.10
Oil up to 3000 Gb		$ 0.22	$ 10.91	$ 7.28	$ 5.46	$ 4.37
Oil after 2030		$ 0.48	$ 24.11	$ 16.07	$ 12.06	$ 9.64

In Figure 12.4 we compare the midpoint results with the CML 2002 and the Eco-indicator 99 method. The CML method expresses all results in Antimony equivalents, but as we do not have a characterisation factor for this substance, we have converted the CML characterisation results to Fe equivalents. Also the EI99 endpoint characterisation factors were converted to Fe equivalents.

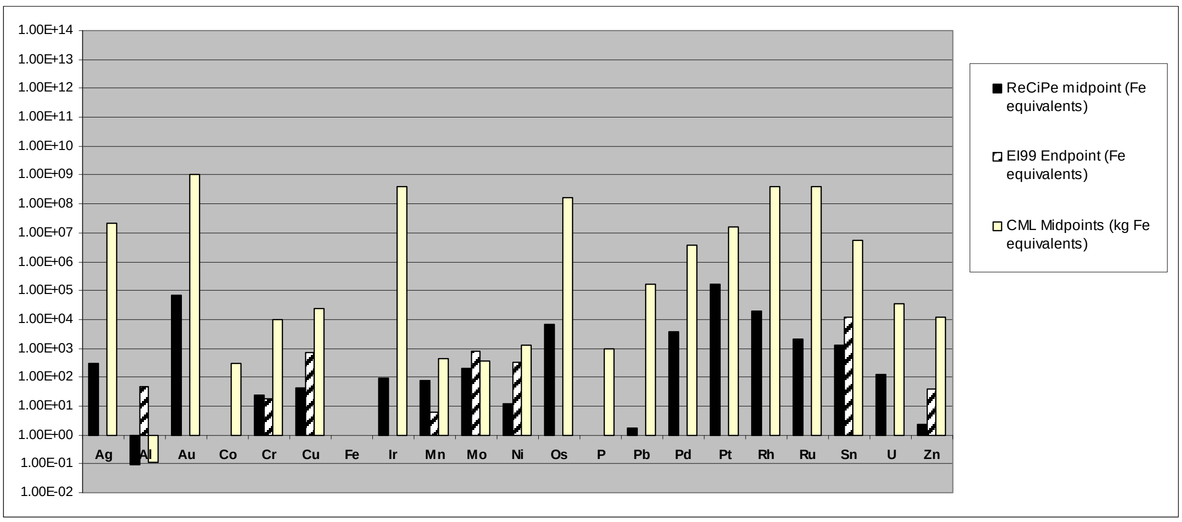

Figure 12.4: Comparison of the characterisation factors of CML 2002, Eco-indicator 99, and ReCiPe 2008.

The comparison shows quite significant differences. In general characterisation factors are relatively low, but this could also mean that the characterisation factor for iron, is relatively high in the ReCiPe method. Commodities that are produced in relatively small amounts result in relatively small cost increases for society as a whole, which is understandable. The production volume has a quite important impact on the characterisation factor. The low factor for lead was not expected, as the production

12.11 SUMMARY TABLE

Entity	Content
impact category	mineral resource depletion
LCI results	extraction of mineral resources
midpoint indicator(s) (with abbreviation)	mineral depletion (MD)
unit of midpoint indicator(s)	kg (Fe)
midpoint characterisation factor (with abbreviation)	mineral depletion potential (MDP)
unit of midpoint characterisation factor	kg/kg
endpoint indicator(s) (with abbreviation)	damage to resource cost (RC)
unit of endpoint indicator(s)	$
endpoint characterisation factor (with abbreviation)	0.0715
unit of endpoint characterisation factor	$/kg

13 FOSSIL FUEL DEPLETION

Mark Goedkoop[33] *and An De Schryver*

The term fossil fuel refers to a group of resources that contain hydrocarbons. The group ranges from volatile materials (like methane), to liquid petrol, to non-volatile materials (like coal).

The origin of liquid and gaseous fossil fuels lies in the late Jurrasic (150 million years ago), the Cretaceous (90 million years ago) and the Permian (230 million years ago). During these time periods, huge amounts of oil and gas were formed in oceans and large lakes, when, during a period of extremely high temperatures huge amounts of plankton and other organisms sank to the bottom. About 1% of the original deposits can still be found in quantities that can be exploited. Coal was formed from forest and other terrestrial plants that formed peat during a period between 300 and 50 million years ago. Coal can be found in many different places, while oil formation only occurred in the warmest regions of the world. The location of these warm regions has been shifted as continents drifted (which explain the oil finds in Alaska and Russia). It is well known where these warm regions are now, which means mankind has little difficulty to look for regions with oil, and has in fact analysed all these potential oil producing regions in rather fine detail.

Unlike metals, we cannot use the concept of grade to express the quality of oil and gas resources. Conventional oil and gas will simply flow out of the well up to a certain point. After that point is reached it is still possible to extract more, but this will increase the production costs and the production energy requirement. Once the energy price increases, it also becomes possible to extract other unconventional resources, such as tar sands, the use of gas liquids, converting gas to oil or coal to oil etc. This means the increase of costs and energy is not caused by a gradual decrease of ore grade, but because more and more mankind will have to switch from conventional resources to unconventional resources.

13.1 MARGINAL COST INCREASE DUE TO FOSSIL FUEL EXTRACTION

When conventional fossil fuel production is limited by scarcity, new, so called unconventional sources will be needed to ensure sufficient supply. These unconventional sources can be unconventional fossil fuels, such as tar sands as well as "alternative" energy sources, such as uranium[34], wind and solar. In our assessment we focus on the replacement of conventional fossil resources with non conventional fossil resources, mainly because in most scenarios these are expected to be much more important on a global scale.

Unconventional fossil resources are generally more energy intensive and more costly to produce, compared to conventional fuels. This means unconventional fuels can only be produced when the overall price level for the fuel is high enough to cover the costs. So in a perfectly balanced market, the price of oil or gas will be determined by the cost of the most expensive unconventional fuel that is needed to satisfy the demand for fuels.

13.2 DATA ON THE AVAILABILITY OF CONVENTIONAL OIL

There is a highly politicized debate on the availability of conventional (liquid) oil, and this makes it difficult to obtain reliable unbiased data. The spectrum of views ranges from the Peak-oil movement (www.aspo.org or peak-oil.com) to international organisations like the International Energy Agency (IEA), or commercial organisations like the Cambridge Energy Research Agency (CERA). The calculations are based on the International Energy Agency. Backgrounds of the two other views can be found in the additional information.

Up to the 2005 outlook the IEA outlooks assumed there would not be any problem in the oil availability. In the 2005 outlook the IEA recognises that oil supply may be scarce and describes the peak oil problem. The major cause for the problem is seen as the lack of adequate investment when oil prices were very low. They do predict however, that the current boost in investments will tackle the problem. The figure below gives an overview of the oil availability in relation to the price. About 1000 Gb of oil have been produced, another 1000 Gb is still available, mainly in the OPEC region. This estimate is in line with the peak oil theory that predicts the peak when half the available conventional oil resource is used. The graph also shows that the alternatives that can fill in the slower production of liquid oil are more expensive.

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34 Uranium was formed in the same way as all other metals, the characterisation factor for Uranium is thus included in the impact category for mineral depletion and not fossil fuels.

The current estimated increase in demand for oil from Asia will require a huge production, almost 1000 billion barrels in just 30 years, which means that in just 30 years the same amount of oil is used, as we used since the production of oil began.

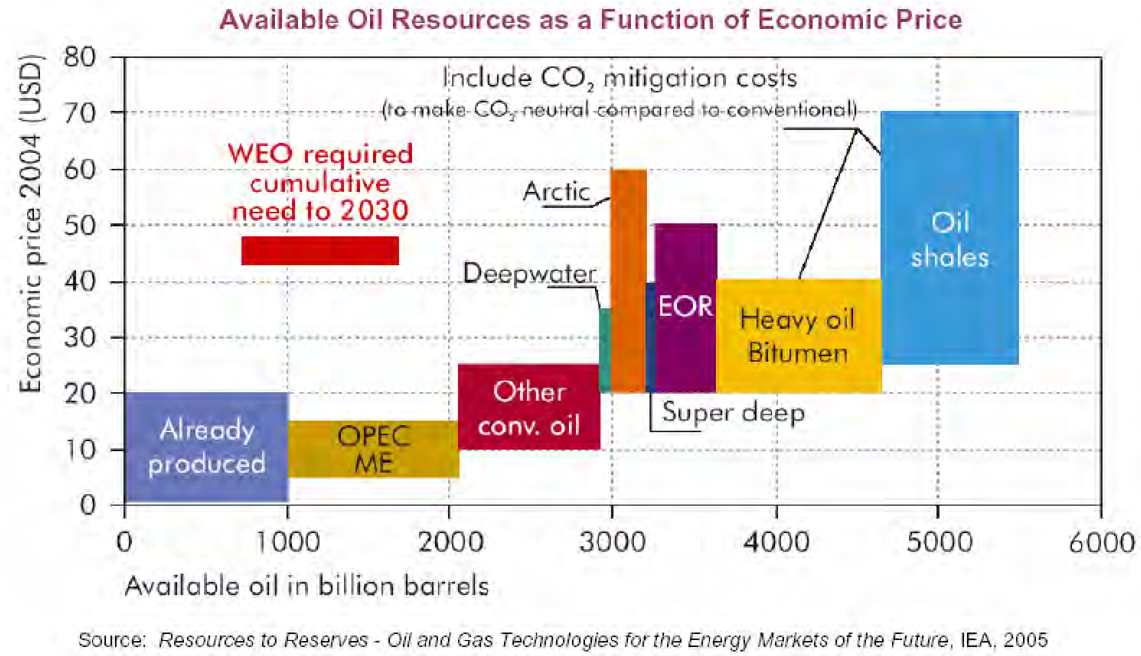

Figure 13.1: Overview of proven reserves and their predicted exploitation costs. For an explanation of the terms see the table below and see section supporting information.

A problem also stated in the IEA is that in many statistics there is no clear definition of all these types of fuel. A summary of definitions given by IEA is in Table 13.1.

Table 13.1: Overview of some terms related to oil statistics.

Term	Meaning
OPEC ME	Oil available in OPEC countries in the Middle East
Other conv. Oil	Oil available in other world regions
Deepwater	Oil in deep waters that are considered to be exploitable
Arctic	Oil available and potentially exploitable in the Arctic regions
Ultra deep	Oil available in ocean floors
EOR	Extension of Oil Recovery
Heavy Oil/Bitumen	Tar sands and other heavy oil
Oil shale	Oil shale (stone like formations with high organic fraction)

In the additional information each of these resources are described in more detail, including some of the factors that determine the costs.

13.3 MARGINAL COST INCREASE FOR FOSSIL FUELS

The IEA data presented in Figure 13.2 can also be plotted in another way, indicating the total liquid oil availability as a function of the oil price. In this graph we can already see the price elasticity of the available liquid oil. For oil resources up to 3000 Gb it seems that for every 1000 Gb production the price of oil needs to go up 10 dollar per barrel. For the next 1000 Gb, the price will need to increase 30 dollar per 1000 Gb or more.

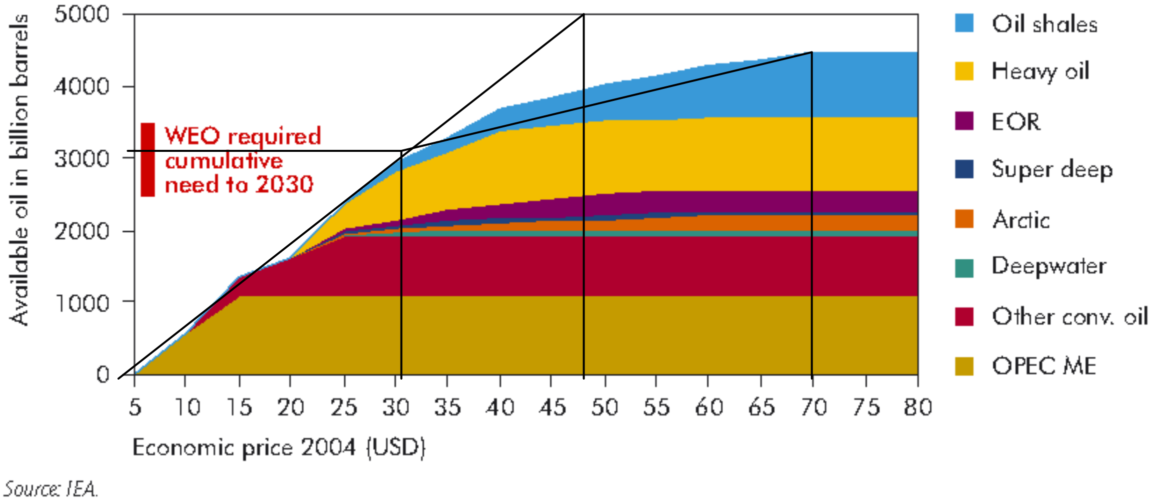

Figure 13.2: Availability of oil as a function of the price of oil.

To express the result per kg of oil, the density is needed. The density depends on the location of extraction and the type of fuel. As average 850kg/m^3 is taken (http://www.simetric.co.uk/si_liquids.htm). If we take cost as a guiding principle, we can have two types of marginal cost increase MCI [35]: Up to a production amount of 3000 Gb, there is a steady increase of production costs, after that the production cost increases faster. As the original data are not available, two lines are constructed in this graph, and we can calcullate the slop of each line

up to a production of 3000Gb, the MCI_{kg} is 6.4E–14 \$/kg/kg;

after 3000 GB have been produced the, the MCI_{kg} is 1.4E–13 \$/kg/kg.

13.4 ENDPOINT CHARACTERISATION FACTOR

With the marginal cost increase known, we can use formula 13.4 to define the endpoint characterisation factor for oil:

$$CF_{kg.oil.end} = MCI_{kg} \times P_{kg} \times \sum_{T} \frac{1}{(1-d)^t}$$

In which P_{kg} is the annual production of oil in a base year (in 2000, this was 3.43E+12). The unit of the characterisation factor is \$.kg, just like for the characterisation factor for minerals

13.5 MANAGING DIFFERENT PERSPECTIVES

The view in the IEA studies typically connect to the world view of the individualist and the hierarchist perspectives:

- The Individualist perspective assumes free market forces and quick development of technology can/ will avoid many problems, as is often stated in the CERA report, and this view is also presented in the IEA report, although they seem to be a little less optimistic about the certainty of supply
- The hierarchist perspective follows consensus models such as described by authoritative bodies such as the in the IEA report.

For these two perspectives, we can apply the findings described above, but we differentiate according to the time perspective:

- The individualist perspective adheres to a short timeframe, and we shall use the marginal price increase for up to a production volume of 3000 Gb.
- For the hierarchist perspective we shall assume the price increase after 3000Gb have been exploited, as the time perspective is basically long

35 The cost estimates provided by the IEA are much lower than the Oil price in the recent history (2005-2007). This seems like an inconsistency, but can be explained by the high increase in demand, which has created a shortage in production capacity. The surplus cost method can thus not be used to predict oil market prices. It only reflects fundamental increases in production costs, and at best it provides a lower limit of future oil prices.

The Peak oil movement seems to have views in line with the egalitarian perspective:

- If the expected growth in the supply of non conventional resources is not proven, it cannot be expected that they will not be developed in time.
- The more or less stable production level of liquid oil that is predicted in the CERA and IEA reports, is contested. The unreliability of the oil reserve data, especially in the OPEC region is a clear example, one cannot rely on this assumption.
- There seems to be a very strong group feeling, and a weak grid feeling as its members seem to portray themselves as an in-group, fighting an out-group, and as the precautionary principle thinking seems to be dominant.

Although we do think these are at least valid arguments, it is very difficult to connect any scenario to this perspective. The suggestion in the senate hearing 2005 that a peak price of 160 dollar is possible when shortages of 4% of the total demand occurs is an indication, but if we do not know how to use this in a model, and what would happen if the shortages is 8% or more, would this double the price?

As we cannot link a scenario to the perspective, we have no other option than to apply the same model as we use for the hierarchist scenario.

13.6 MIDPOINT CHARACTERISATION FACTORS FOR FOSSIL FUEL DEPLETION

The midpoint characterisation factor is based on the energy content (higher heating value):

$$CF_{\text{midpoint},i} = \frac{CED_i}{CED_{ref}} \tag{13.1}$$

With $CF_{midpoint,i}$ the midpoint characterization factor for the non-renewable resource *i* (in kg oil-equivalents/unit of resource *i*) CED_i the cumulative energy demand indicator of non-renewable resource I (in MJ/unit of resource *i*) and CED_{ref} the cumulative energy demand indicator of the reference oil resource (in MJ/kg oil) The midpoint characterisation factor is dimensionless.

We will use the factors used in the ecoinvent database compiled by Frischknecht 2007, as far as fossil fuels are concerned (Uranium is not a fossil fuel, but a metal, and is treated under metals; other energy carriers mentioned in this publication such as hydropower, are also not used). As reference resources we chose “Oil, crude, feedstock, 42 MJ per kg, in ground”.

Table 13.2: Midpoint characterisation factors (individualist, hierarchist and egalitarian perspective) for fossil depletion.

Resource	$CF_{midpoint}$	Unit*
Coal, 18 MJ per kg, in ground	4.29E–01	kg oil-eq/kg
Coal, 26.4 MJ per kg, in ground	6.29E–01	kg oil-eq/kg
Coal, 29.3 MJ per kg, in ground	6.98E–01	kg oil-eq/kg
Coal, brown, 10 MJ per kg, in ground	2.38E–01	kg oil-eq/kg
Coal, brown, 8 MJ per kg, in ground	1.90E–01	kg oil-eq/kg
Coal, brown, in ground	2.36E–01	kg oil-eq/kg
Coal, feedstock, 26.4 MJ per kg, in ground	6.29E–01	kg oil-eq/kg
Coal, hard, unspecified, in ground	4.55E–01	kg oil-eq/kg
Energy, from coal	2.38E–02	kg oil-eq/MJ
Energy, from coal, brown	2.38E–02	kg oil-eq/MJ
Energy, from gas, natural	2.38E–02	kg oil-eq/MJ
Energy, from oil	2.38E–02	kg oil-eq/MJ
Energy, from peat	2.38E–02	kg oil-eq/MJ
Energy, from sulfur	2.38E–02	kg oil-eq/MJ
Gas, mine, off-gas, process, coal mining/kg	1.19E+00	kg oil-eq/kg
Gas, mine, off-gas, process, coal mining/m^3	9.48E–01	kg oil-eq/m^3
Gas, natural, 30.3 MJ per kg, in ground	7.21E–01	kg oil-eq/kg
Gas, natural, 35 MJ per m^3, in ground	8.33E–01	kg oil-eq/m^3
Gas, natural, 36.6 MJ per m^3, in ground	8.71E–01	kg oil-eq/m^3
Gas, natural, 46.8 MJ per kg, in ground	1.11E+00	kg oil-eq/kg
Gas, natural, feedstock, 35 MJ per m^3, in ground	8.33E–01	kg oil-eq/m^3
Gas, natural, feedstock, 46.8 MJ per kg, in ground	1.11E+00	kg oil-eq/kg
Gas, natural, in ground	9.12E–01	kg oil-eq/m^3
Gas, off-gas, oil production, in ground	9.48E–01	kg oil-eq/m^3
Gas, petroleum, 35 MJ per m^3, in ground	8.33E–01	kg oil-eq/m^3
Methane	8.55E–01	kg oil-eq/kg
Oil, crude, 38400 MJ per m^3, in ground	9.14E+02	kg oil-eq/m^3
Oil, crude, 41 MJ per kg, in ground	9.76E–01	kg oil-eq/kg
Oil, crude, 42 MJ per kg, in ground	1.00E+00	kg oil-eq/kg
Oil, crude, 42.6 MJ per kg, in ground	1.01E+00	kg oil-eq/kg
Oil, crude, 42.7 MJ per kg, in ground	1.02E+00	kg oil-eq/kg
Oil, crude, feedstock, 41 MJ per kg, in ground	9.76E–01	kg oil-eq/kg
Oil, crude, feedstock, 42 MJ per kg, in ground	1.00E+00	kg oil-eq/kg
Oil, crude, in ground	1.09E+00	kg oil-eq/kg

** For "kg oil-eq", read "kg oil, crude, feedstock, 42 MJ per kg, in ground-eq".*

13.6.1 ENDPOINT CHARACTERISATION FACTORS FOR FOSSIL FUEL DEPLETION

Based on the characterisation factor of oil, we are able to determine the endpoint characterisation factor for other fossil resources:

$$CF_{\mathrm{end},i} = CF_{\mathrm{mid},i} \times CF_{oil.end.kg} \qquad (13.2)$$

With $CF_{end,i}$ the endpoint characterisation factor for non-renewable resource *i* (in \$/kg.yr of resource *i*), $CF_{oil.end.kg}$, the increased costs for extracting 1kg of resource

The exploitation of natural gas fields is often linked to the exploitation of oil, as they often occur in the same location. We have found far less literature on the possible shortages in natural gas, and the need to exploit unconventional gas resources. It is also clear form the analysis of oil that unconventional oil and gas resources are often linked. If deepwater oil is exploited, and gas is found, it will probably also be exploited. Gas and oil are also to some agree substitutes of each other, especially for non mobile applications (although currently natural gas is offered as fuels for vehicles). As so much is unclear we choose to assume the future increased costs for gas using the same environmental mechanism as for oil, see Section 13.3 and 13.5.

For coal the increased cost is not strongly related to scarcity, but to cost of workforce and for environmental protection. Also here it is very difficult to develop a scenario, and we propose to consider the increased cost in the same way as we do for oil up to the year 2030. After 2030, we assume the increased cost will not rise further and propose to use in this timeframe the same increased cost as used up to 2030, see Section 13.5. The resulting mis to endpoint factors are:

- Costs per kg oil individualist perspective: $ 7.28
- Costs per kg oil for the egalitarian and Hierarchist: 16.07 (H+E)

13.7 LITERATURE

ASPO: Association for the Study of Peak Oil&Gas, whose web site contains extensive references to literature arguing for more conservative estimates of world oil and gas resources, www.peakoil.net

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13.8 SUPPORTING INFORMATION

Description of non conventional oils

13.9 SUMMARY TABLE

Entity	Content
impact category	fossil fuel depletion
LCI results	extraction of fossil resources
midpoint indicator(s) (with abbreviation)	fossil depletion (FD)
unit of midpoint indicator(s)	kg (oil, crude, feedstock, 42 MJ per kg, in ground)
midpoint characterisation factor (with abbreviation)	fossil depletion potential (FDP)
unit of midpoint characterisation factor	MJ/kg, MJ/MJ, or MJ/m^3
endpoint indicator(s) (with abbreviation)	damage to resource cost (RC)
unit of endpoint indicator(s)	$
endpoint characterisation factor (with abbreviation)	7.28 (I) 16.07 (H+E)
unit of endpoint characterisation factor	$/kg, $/MJ. or $/$m^3$

ABBREVIATIONS AND SYMBOLS

Abbreviation or symbol	Explanation	Unit (if applicable)
AB	attributable burden	yr-1
C	Concentration	$kg \times m^{-3}$
CF	characterization factor	$yr \times kg^{-1}$
D	Duration	yr
DALY	Disability adjusted life years	yr
DF	damage factor	yr
EF	effect factor	kg^{-1}
FF	fate factor	-
Finc	Incidence fraction of the population	yr^{-1}
I	Intake	$kg \times yr^{-1}$
iF	intake fraction	-
IH	average human breath intake rate	$m^3 \times d^{-1}$
M	Emission	$kg \times yr^{-1}$
n	number of days per year	–
N	number of inhabitants	–
RR	relative risk	$m^3 \times \mu g^{-1}$
S	Severity	–
t	Time	yr
YLD	years of life disabled	yr
YLL	years of life lost	yr
ODS	ozone depleting susbtance	-
ODP	ozone depletion potential	$kg \times kg^{-1}$
CFC	Chorofluorocarbon	–
HCFC	Hydrochorofluorocarbon	–
HBFC	Hydrobromofluorocarbon	–
EESC	equivalent effective stratospheric chlorine	–
BCC	basal cell carcinoma	–
SCC	squamous cell carcinoma	–
CM	melanoma	–
UV	Ultraviolet	–
CC	cortical cataract	–
NC	nuclear cataract	–
PSCC	Posterior subcaspular cataract	–
BS	base saturation	–
BC	basic cations	$meq \times kg\ soil^{-1}$
CEC	cation exchange capacity	$meq \times kg\ soil^{-1}$

Subscript	meaning
E	disease
I	grid cell
Pop	population
X	pollutant

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