National Institute for Public Health
and the Environment
*Ministry of Health, Welfare and Sport*

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A harmonized life cycle impact assessment method at midpoint and endpoint level
Report I: Characterization

RIVM Report 2016-0104
M.A.J. Huijbregts et al.

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# Colophon



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# Synopsis

**ReCiPe 2016**
A harmonized life cycle impact assessment method at midpoint and endpoint level
Report I: Characterization

Life cycle assessment (LCA) enables the assessment of the pressure a certain (production) process places on the environment. The assessment comprises all phases needed to produce and use a product, from the initial development to the treatment of waste (the total life cycle). The goal of LCA is, for example, to compare alternatives or to identify phases in the production process that place a relatively high level of pressure on the environment. Based on this knowledge, production processes can be optimized.

Within LCA, 'life cycle impact models' (LCIA) are used to estimate the environmental impact. The RIVM is presenting a new, updated version of the life cycle impact (LCIA)-model ReCiPe often used in the Netherlands and Europe. It's called the ReCiPe 2016. The methodologies and data used in the new model are up to date with the current scientific knowledge.

A life cycle impact assessment results in an 'environmental profile': a score list with different environmental effects, such as climate change, water use, land use and soil acidification. This list provides information about the environmental effects that score relatively well or poorly within the life cycle of a product and about the phases in the life cycle that contribute most to the different environmental effects.

The ReCiPe method was first developed in 2008 through cooperation between RIVM, Radboud University Nijmegen, Leiden University and Pré Consultants.

Keywords: ReCiPe, life cycle analysis, LCA, life cycle impact assessment, LCIA, environmental assessment

# Publiekssamenvatting

**ReCiPe 2016.**
Een geharmoniseerde levenscyclus impact assessment methode op 'midpoint' en 'endpoint' niveau
Rapport 1: karakterisatie

Met een zogeheten levenscyclusanalyse (LCA) is het mogelijk om te bepalen in welke mate een productieproces van een product het milieu belast. De analyse omvat alle stadia die nodig zijn om een product te produceren en te gebruiken, dus vanaf het onttrekken van de benodigde grondstoffen tot en met de verwerking van afval. Het doel van een LCA is bijvoorbeeld om alternatieven te vergelijken, of om stappen in het productieproces die een grote milieuschade veroorzaken in kaart te brengen. Op basis van deze kennis kan het productieproces worden geoptimaliseerd.

Binnen LCA worden ‘levenscyclus-impactassessments’ (LCIA) gebruikt om de milieubelasting te bepalen. Het RIVM presenteert een nieuwe, herziene versie van het zowel in Nederland als Europa veelgebruikte levenscyclus-impactassessment ReCiPe: ReCiPe 2016. De methodiek en data zijn hierin aangepast aan de huidige wetenschappelijke stand van zaken.

Een LCIA levert een soort milieuprofiel op: een 'scorelijst' met milieueffecten, zoals klimaatverandering, waterverbruik en –schaarste, landgebruik en bodemverzuring. Aan het milieuprofiel is te zien welke milieuaspecten slecht scoren in de levenscyclus van een product of dienst en welke onderdelen in de levenscyclus de grootste bijdrage leveren aan de verschillende milieueffecten.

De ReCiPe-methode is in 2008 ontwikkeld door een samenwerkingsverband tussen RIVM, Radboud Universiteit Nijmegen, Leiden Universiteit en Pré Consultants.

Kernwoorden: ReCiPe, levenscyclusanalyse, LCA, levenscyclusimpactanalyse, LCIA, milieubeoordeling

# Contents

# Summary

Life Cycle Assessment (LCA) quantifies the environmental impacts of the complete life cycle of products. The life cycle of a product is connected to a very large number of substance emissions and resource extractions, which can substantially vary in their environmental relevance. Life cycle impact assessment (LCIA) helps the interpretation of LCA studies by translating these emissions and resource extractions into a limited number of environmental impact scores (Hauschild and Huijbregts, 2015). This is done by means of so-called characterization factors. Characterization factors indicate the environmental impact per unit of stressor (e.g. per kg of resource used or emission released).

There are two mainstream ways of deriving characterization factors: at midpoint or endpoint. Characterization factors at the midpoint level are located somewhere along the impact pathway, typically at the point after which the environmental mechanism is identical for all environmental flows assigned to that impact category (Goedkoop et al. 2009). Characterization factors at the endpoint level correspond to three areas of protection, i.e. human health, ecosystem quality and resource scarcity. The two approaches are complementary in that the midpoint characterization has a stronger relation to the environmental flows and a relatively low uncertainty, while the endpoint characterization provides better information on the environmental relevance of the environmental flows, but is also more uncertain than the midpoint characterization factors (Hauschild and Huijbregts, 2015).

Goedkoop et al. (2009) developed a life cycle impact assessment method called ReCiPe2008 that provides harmonized characterization factors at midpoint and endpoint levels. The current report describes the update from ReCiPe2008 to ReCiPe2016. The update of ReCiPe provides characterization factors that are representative for the global scale, instead of the European scale, while maintaining the possibility for a number of impact categories to implement characterization factors at a country and continental scale. Consistency in the development of midpoint and endpoint models was enhanced by working with the same time horizon per cultural perspective across the various impact categories. We also expanded the number of environmental interventions and added the impact of water use on human health, the impacts of water use and climate change on freshwater ecosystems, and the impacts of water use and tropospheric ozone formation on terrestrial ecosystems as novel damage pathways.

This first framework chapter provides information about the impact pathways modelled and gives an overview of the value choices, i.e. visions related to environmental decision-making, quantified via clustering into three perspectives. After this framework chapter, individual chapters follow for all the impact categories. Each of them provides information on how the impact pathway affects the environment and the three areas of protection, and explains the value choices and modelling steps for both midpoint and endpoint characterization factors.

# 1 Framework

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## 1.1 Introduction

Life Cycle Assessment (LCA) quantifies the environmental impacts of the complete life cycle of products. The life cycle of a product is connected to a very large number of substance emissions and resource extractions, which can substantially vary in their environmental relevance. Life cycle impact assessment (LCIA) helps the interpretation of LCA studies by translating these emissions and resource extractions into a limited number of environmental impact scores (Hauschild and Huijbregts, 2015). This is done by means of so-called characterization factors. Characterization factors indicate the environmental impact per unit of stressor (e.g. per kg of resource used or emission released). There are two mainstream ways of deriving characterization factors: at midpoint or endpoint. Characterization factors at the midpoint level are located somewhere along the impact pathway, typically at the point after which the environmental mechanism is identical for all environmental flows assigned to that impact category (Goedkoop et al. 2009). Characterization factors at the endpoint level correspond to three areas of protection, i.e. human health, ecosystem quality and resource scarcity. The two approaches are complementary in that the midpoint characterization has a stronger relation to the environmental flows and a relatively low uncertainty, while the endpoint characterization provides better information on the environmental relevance of the environmental flows, but is also more uncertain than the midpoint characterization factors (Hauschild and Huijbregts, 2015).

Goedkoop et al. (2009) developed a life cycle impact assessment method, called ReCiPe2008, that provides harmonized characterization factors at midpoint and endpoint levels. The current report describes the update from ReCiPe2008 to ReCiPe2016. The update of ReCiPe provides characterization factors that are representative for the global scale, instead of the European scale, while maintaining the possibility for a number of impact categories to implement characterization factors at a country and continental scale. Consistency in the development of midpoint and endpoint models was enhanced by working with the same time horizon per cultural perspective across the various impact categories. We also expanded the number of environmental interventions and added the impact of water use on human health, the

impacts of water use and climate change on freshwater ecosystems, and the impacts of water use and tropospheric ozone formation on terrestrial ecosystems as novel damage pathways. Table 1.1 provides an overview of these updates. This framework chapter provides information about the impact pathways modelled (see Section 1.2). It also gives an overview of the value choices, i.e. visions related to environmental decision-making, quantified via clustering into three perspectives (see Section 1.3). Information on the characterization factors at midpoint level and endpoint level is included in Sections 1.4 and 1.5 respectively. After this framework chapter, individual chapters follow for all the impact categories. Each of them provides information on how the impact pathway affects the environment and the three areas of protection, and explains the value choices and modelling steps for both midpoint and endpoint characterization factors. For all impact categories, we provide default midpoint and endpoint characterization factors with a global scope. Note that, for a limited number of impact categories, we also provide midpoint and endpoint characterization factors at a country level (photochemical ozone formation, particulate matter formation, terrestrial acidification, freshwater eutrophication and water use). Finally, Chapter 14 contains information on how characterization factors were derived, to be used when no inventory for individual substances is known, but only for a group of substances.

*Table 1.1. Overview of updates included in ReCiPe2016.*

| **Environmental mechanism** | **Updates** |
|---|---|
| Climate change | - The time horizon for the Egalitarian perspective was explicitly taken as 1,000 years, which is the longest time horizon reported for $CO_2$ response functions in the literature.<br>- A much larger set of greenhouse gas emissions (207 GHGs in total) is included on the basis of the latest IPCC report.<br>- Damage factors for human health and terrestrial ecosystems were updated.<br>- Damage to freshwater (river) ecosystems was now included. |
| Stratospheric ozone depletion | - New semi-empirical ODPs were included with a more detailed specification between various chlorofluorocarbons (CFCs).<br>- A preliminary ODP for $N_2O$ was included.<br>- Three time horizons were consistently implemented: 20 years (Individualist), 100 years (Hierarchist) and infinite (Egalitarian). |
| Ionizing radiation | - Three time horizons were consistently implemented: 20 years (Individualist), 100 years (Hierarchist) and 100,000 years (Egalitarian).<br>- Dose and dose rate effectiveness factors (DDREFs) were specified per cultural perspective.<br>- Updated DALYs per fatal cancer incidence were applied. |

| Environmental mechanism | Updates |
|---|---|
| Fine particulate matter formation | - The European factor was replaced by a world average factor.<br>- Lung cancer and cardiovascular mortality were included as critical effects.<br>- Value choices were added.<br>- World-region specific characterization factors were added. |
| Photochemical ozone formation | - The European factor was replaced by a world average factor.<br>- Respiratory mortality was included.<br>- To derive characterization factors for individual VOCs, the most recent photochemical ozone formation potentials (POCPs) reported in the literature were used.<br>- Damage to terrestrial ecosystems was included as well.<br>- World-region specific characterization factors were added. |
| Terrestrial acidification | - The European factor was replaced by a world average factor, based on grid-specific factors.<br>- Soil sensitivity was based on H+ concentration instead of base saturation.<br>- Effects of all vascular plant species included, not only forest species.<br>- Country-specific characterization factors were provided as well. |
| Freshwater eutrophication | - Fate factors were derived with a state-of-the-art global fate model for phosphorus, instead of a European fate model.<br>- Effect factors were updated based on a global analysis, instead of using information from the Netherlands only.<br>- Country-specific characterization factors were provided as well. |
| Toxicity | - Characterization factors for human cancer and non-cancer effects were separately included.<br>- Fate and exposure for dissociating organics was explicitly modelled.<br>- The USEtox organic and inorganic database was implemented (3094 substances).<br>- A time horizon of 20 years was included for the Individualist perspective.<br>- Only linear effect factors were included for reasons of simplicity.<br>- Effects on agricultural soil were excluded to prevent double counting with the land use impact category. |

| Environmental mechanism | Updates |
|---|---|
| Water use | - Consumption/extraction ratios were provided.<br>- Characterization factors at an endpoint level for human health, terrestrial and aquatic ecosystems were included.<br>- Country-specific characterization factors were provided as well. |
| Land use | - Characterization factors were based on global scale data, whereas the previous factors focused on Europe.<br>- The local impact of land use was covered only, as the modelling of regional impacts in the previous ReCiPe version was considered too uncertain to recommend. |
| Mineral resource scarcity | - Cumulative grade-tonnage relationships and cumulative cost-tonnage relationships were used, based on mine-specific cost and production data.<br>- An estimation of future production was included in the modelling without future discounting. |
| Fossil resource scarcity | - Cumulative cost-tonnage relationships were based on recent cost and future production data.<br>- An estimation of future production was included in the modelling without future discounting. |

## 1.2 Impact pathways and areas of protection

Human health, ecosystem quality and resource scarcity were selected in ReCiPe2008 as the three areas of protection (Goedkoop et al. 2009). It was decided to keep the same three areas of protection for the implementation of the ReCiPe2016 methodology. The endpoints are related to the three areas of protection (see Table 1.2). DALYs (disability adjusted life years), relevant for human health, represent the years that are lost or that a person is disabled due to a disease or accident. The unit for ecosystem quality is the local species loss integrated over time (species year). The unit for resource scarcity is the dollar ($), which represents the extra costs involved for future mineral and fossil resource extraction.

*Table 1.2. Overview of the endpoint categories, indicators and characterization factors.*

| Area of protection | Endpoint | Abbr. | Name | Unit |
|---|---|---|---|---|
| human health | damage to human health | HH | disability-adjusted loss of life years | year |
| natural environment | damage to ecosystem quality | ED | time-integrated species loss | species ×yr |
| resource scarcity | damage to resource availability | RA | surplus cost | Dollar |

The overview of the link between the environmental mechanisms, i.e. the midpoints, and the three areas of protection is shown in Figure 1.1.

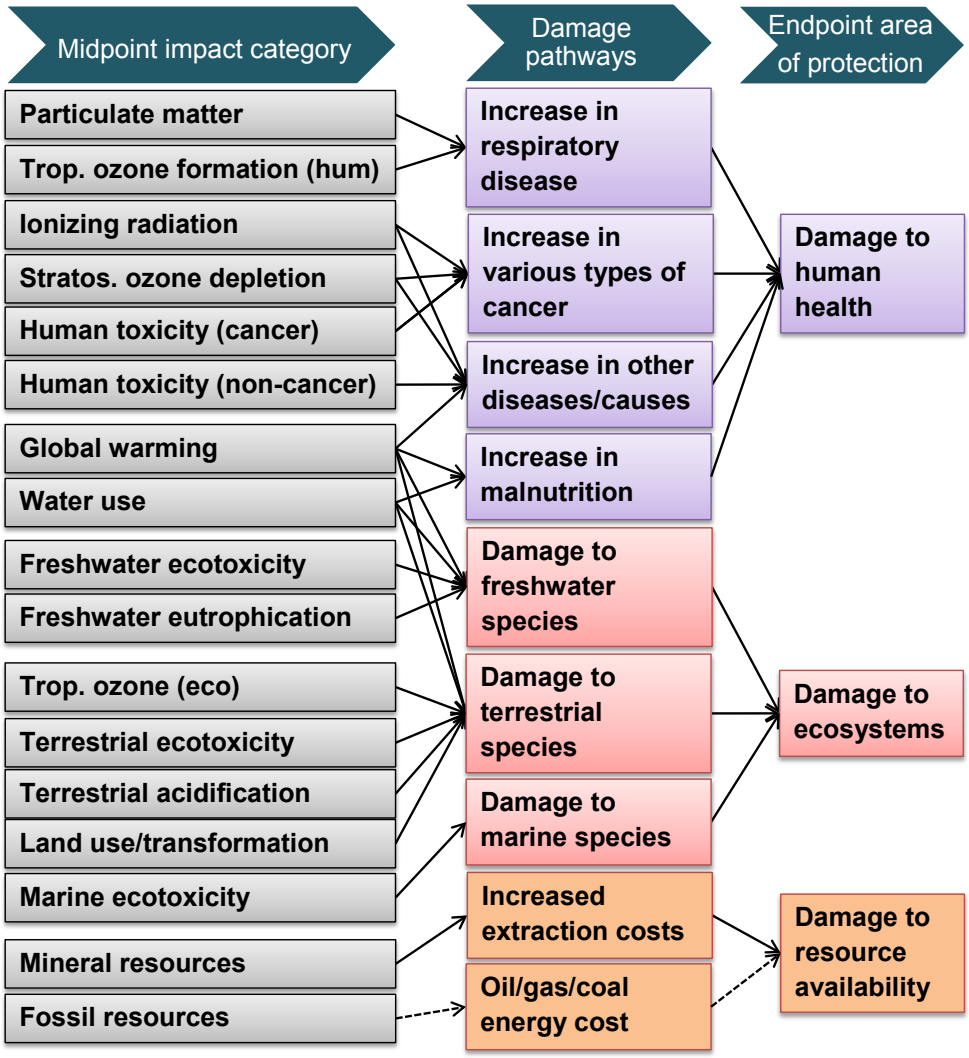


*Figure 1.1. Overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection.*

## 1.3 Value choices

Following the same strategy as in ReCiPe2008, different sources of uncertainty and different choices were grouped into a limited number of perspectives or scenarios, according to the "Cultural Theory" (Thompson et al., 1990). These perspectives do not claim to represent archetypes of human behaviour, they are merely used to group similar types of assumptions and choices. Three perspectives were included in ReCiPe2016:

1. The individualistic perspective is based on the short-term interest, impact types that are undisputed, and technological optimism with regard to human adaptation.
2. The hierarchist perspective is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms.

3. The egalitarian perspective is the most precautionary perspective, taking into account the longest time frame and all impact pathways for which data is available.

Table 1.3 provides an overview of how the perspectives were operationalized per impact category. Note, however, that due to lack of sufficient information, the influence of value choices was not considered in the calculation of characterization factors for photochemical ozone formation, terrestrial acidification, freshwater eutrophication, land use and fossil resource scarcity.

*Table 1.3. Value choices in the derivation of characterization factors, as included in ReCiPe2016.*

| | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|
| **Climate change** | | | |
| Time horizon[1] | 20 years | 100 years | 1,000 years |
| Climate-carbon feedbacks non-$CO_2$ | No | Yes | No |
| Future socio-economic developments[2] | Optimistic | Baseline | Pessimistic |
| Adaptation potential[2] | Adaptive | Controlling | Comprehensive |
| **Ozone depletion** | | | |
| Time horizon[1] | 20 years | 100 years | Infinite |
| Included effects[2] | Skin cancer | Skin cancer | Skin cancer and cataract |
| **Ionizing radiation** | | | |
| Time horizon[1] | 20 years | 100 years | 100,000 years |
| Dose and dose rate effectiveness factor (DDREF)[2] | 10 | 6 | 2 |
| Included effects[2] | -Thyroid, bone marrow, lung and breast cancer<br>-Hereditary disease | -Thyroid, bone marrow, lung, breast, bladder, colon, ovary, skin, liver, oesophagus and stomach cancer<br>-Hereditary disease | -Thyroid, bone marrow, lung, breast, bladder, colon, ovary, skin, liver, oesophagus, stomach, bone surface and remaining cancer<br>-Hereditary disease |
| **Fine particulate matter formation** | | | |
| Included effects[2] | Primary aerosols | Primary aerosols, secondary aerosols from $SO_2$ | Primary aerosols, secondary aerosols from $SO_2$, $NH_3$ and $NO_x$ |
| **Toxicity** | | | |
| Time horizon[1] | 20 years | 100 years | Infinite |

| | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|
| Exposure routes for human toxicity[1] | Organics: all exposure routes. Metals: drinking water and air only | All exposure routes for all chemicals | All exposure routes for all chemicals |
| Environmental compartments for marine ecotoxicity[1] | Sea + ocean for organics and non-essential metals. For essential metals, the sea compartment is included only, excluding the oceanic compartments. | Sea + ocean for all chemicals | Sea + ocean for all chemicals |
| Carcinogenity[1] | Only chemicals with carcinogenicity classified as 1, 2A, 2B by IARC | All chemicals with reported carcinogenic effects | All chemicals with reported carcinogenic effects |
| Minimum number of tested species for ecotoxicity[1] | 4 | 1 | 1 |
| **Water use** | | | |
| Regulation of stream flow[2] | High | Standard | Standard |
| Water requirement for food production[2] | 1000 $m^3$/yr/capita | 1350 $m^3$/yr/capita | 1350 $m^3$/yr/capita |
| Impacts on terrestrial ecosystems considered[2] | No | Yes | Yes |
| **Mineral resource scarcity** | | | |
| Future production | Reserves | Ultimate recoverable resource | Ultimate recoverable resource |

## 1.4 Characterization factors at midpoint level

Categories and indicators at the midpoint level are presented in Table 1.4. There is a difference in the unit of the indicator for each category and the unit of the midpoint characterization factor (CFm).This is because a reference substance has been introduced, so that the characterization factor is a dimensionless number that expresses the strength of an amount of a substance relative to that of the reference substance. For all emission-based impact categories and resource scarcity, this is a kg reference substance to one specific environmental compartment, while for land use it is the area and time integrated for one type of land use.

*Table 1.4. Overview of the midpoint categories and related impact indicators.*

| **Impact category** | **Indicator** | **Unit** | **$CF_m$** | **Abbr.** | **Unit** |
|---|---|---|---|---|---|
| climate change | Infra-red radiative forcing increase | W×yr/$m^2$ | global warming potential | GWP | kg $CO_2$ to air |
| ozone depletion | stratospheric ozone decrease | ppt×yr | ozone depletion potential | ODP | kg CFC-11 to air |
| ionizing radiation | absorbed dose increase | man×Sv | ionizing radiation potential | IRP | kBq Co-60 to air |
| fine particulate matter formation | PM2.5 population intake increase | kg | particulate matter formation potential | PMFP | kg PM2.5 to air |
| Photochemical oxidant formation: ecosystem quality | tropospheric ozone increase (AOT40) | ppb.yr | Photochemical oxidant formation potential: ecosystems | EOFP | kg NOx to air |
| Photochemical oxidant formation: human health | tropospheric ozone population intake increase (M6M) | kg | Photochemical oxidant formation potential: humans | HOFP | kg NOx to air |
| terrestrial acidification | proton increase in natural soils | yr×$m^2$×mol/l | terrestrial acidification potential | TAP | kg $SO_2$ to air |
| freshwater eutrophication | phosphorus increase in fresh water | yr×$m^3$ | freshwater eutrophication potential | FEP | kg P to fresh water |
| human toxicity: cancer | risk increase of cancer disease incidence | - | human toxicity potential | HTPc | kg 1,4-DCB to urban air |
| human toxicity: non-cancer | risk increase of non-cancer disease incidence | - | human toxicity potential | HTPnc | kg 1,4-DCB to urban air |
| terrestrial ecotoxicity | hazard-weighted increase in natural soils | yr×$m^2$ | terrestrial ecotoxicity potential | TETP | kg 1,4-DCB to industrial soil |
| freshwater ecotoxicity | hazard-weighted increase in | yr×$m^3$ | freshwater ecotoxicity potential | FETP | kg 1,4-DCB to fresh |

| Impact category | Indicator | Unit | $CF_m$ | Abbr. | Unit |
|---|---|---|---|---|---|
| | fresh waters | | | | water |
| marine ecotoxicity | hazard-weighted increase in marine water | yr×$m^3$ | marine ecotoxicity potential | METP | kg 1,4-DCB to marine water |
| land use | occupation and time-integrated transforma-tion | yr×$m^2$ | agricultural land occupation potential | LOP | $m^2$×yr annual crop land |
| water use | increase of water consumed | $m^3$ | water consump-tion potential | WCP | $m^3$ water con-sumed |
| mineral resource scarcity | ore grade decrease | kg | surplus ore potential | SOP | kg Cu |
| fossil resource scarcity | upper heating value | MJ | fossil fuel potential | FFP | kg oil |

## 1.5 From midpoint to endpoint

Endpoint characterization factors (CFe) are directly derived from the CFm, with a constant midpoint to endpoint factor per impact category by

$$CFe_{x,c,a} = CFm_{x,c} \times F_{M\rightarrow,E,c,a}$$

Whereby c denotes the cultural perspective, a denotes the area of protection (human health, terrestrial ecosystems, freshwater ecosystems, marine ecosystems or resource scarcity), x denotes the stressor of concern and $F_{M\rightarrow,E,c,a}$ is the midpoint to endpoint conversion factor for cultural perspective c and area of protection a. These midpoint to endpoint factors are constant per impact category, because environmental mechanisms are considered to be identical for all stressors after the midpoint impact location on the cause-effect pathway. Table 1.5 provides the midpoint-to-endpoint factors for human health damage, terrestrial ecosystem damage, freshwater ecosystem damage, marine ecosystem damage, and resource scarcity for the three cultural perspectives. For all impact categories, we were able to establish constant global midpoint to endpoint factors, except for fossil resource scarcity, due to a lack of understanding about the full cause-effect pathway. Derivation of these factors is explained in the individual chapters.

*Table 1.5. Midpoint to endpoint factors for the Individualist (I), Hierarchist (H) and Egalitarian (E) perspectives.*

| | Unit[1,2] | I | H | E |
|---|---|---|---|---|
| **Human health** | | | | |
| climate change | yr/kg $CO_2$ to air | 8.1E-08 | 9.3E-07 | 1.3E-05 |
| ozone depletion | yr/kg CFC11 to air | 2.4E-04 | 5.3E-04 | 1.3E-03 |
| ionizing radiation | yr//kBq Co-60 to air | 6.8E-09 | 8.5E-09 | 1.4E-08 |
| fine particulate matter formation | yr/kg PM2.5 to air | 6.3E-04 | 6.3E-04 | 6.3E-04 |
| photochemical ozone formation | yr/kg NOx to air | 9.1E-07 | 9.1E-07 | 9.1E-07 |
| cancer toxicity | yr/kg 1,4-DCB to air | 3.3E-06 | 3.3E-06 | 3.3E-06 |
| non-cancer toxicity | yr/kg 1,4-DCB to air | 6.7E-09 | 6.7E-09 | 6.7E-09 |
| water use | yr/$m^3$ water | 3.1E-06 | 2.2E-06 | 2.2E-06 |
| **Ecosystem quality: terrestrial** | | | | |
| climate change | species.yr/kg $CO_2$ to air | 5.3E-10 | 2.8E-09 | 2.5E-08 |
| photochemical ozone formation | species.yr/kg $NO_x$ to air | 1.3E-07 | 1.3E-07 | 1.3E-07 |
| acidification | species.yr/kg $SO_2$ to air | 2.1E-07 | 2.1E-07 | 2.1E-07 |
| toxicity | species.yr/kg 1,4-DCB to industrial soil | 5.4E-08 | 5.4E-08 | 5.4E-08 |
| water use | species.yr/$m^3$ water consumed | 0 | 1.4E-08 | 1.4E-08 |
| land use | species/$m^2$ annual crop land | 8.9E-09 | 8.9E-09 | 8.9E-09 |
| **Ecosystem quality: fresh water** | | | | |
| climate change | species.yr/kg $CO_2$ | 1.5E-14 | 7.7E-14 | 6.8E-13 |
| eutrophication | species.yr/kg P to fresh water | 6.1E-07 | 6.1E-07 | 6.1E-07 |
| toxicity | species.yr/kg 1,4-DCB to fresh water | 7.0E-10 | 7.0E-10 | 7.0E-10 |
| water use | species.yr/$m^3$ water consumed | 6.0E-13 | 6.0E-13 | 6.0E-13 |
| **Ecosystem quality: marine** | | | | |
| toxicity | species.yr/kg 1,4-DCB | 1.1E-10 | 1.1E-10 | 1.1E-10 |
| **Resource scarcity** | | | | |
| minerals | $US_{2013}$ $/kg Cu | 0.16 | 0.23 | 0.23 |
| fossils[3] | $US_{2013}$ $/kg crude oil | 0.46 | 0.46 | 0.46 |
| | $US_{2013}$ $/kg hard coal | 0.03 | 0.03 | 0.03 |
| | $US_{2013}$ $/$Nm^3$ natural gas | 0.30 | 0.30 | 0.30 |

1 The unit for human health damage refers to the disability adjusted life years lost in the human population; 2 the units for ecosystem damage refer to the number of species lost integrated over time; 3 fossil resource scarcity is the only midpoint category which do not have a constant midpoint to endpoint factor.

# 2 Climate change

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This chapter is based on information from the latest IPCC report 5 (IPCC, 2013), Joos et al. (2013), Hanafiah et al. (2011), De Schryver et al. (2009) and Urban (2015). The major changes from the previous version are:

- The time horizon for the Egalitarian perspective is explicitly taken as 1,000 years, which is the longest time horizon reported for $CO_2$ by Joos et al. (2013).
- A much larger set of greenhouse gas emissions (207 GHGs in total) is included on the basis of the latest IPCC report.
- Climate-carbon feedbacks are now included for the hierarchist perspective.
- Midpoint to endpoint factors for human health and terrestrial ecosystems are corrected on the basis of De Schryver et al. (2009) and Urban (2015) respectively.
- Damage to freshwater (river) ecosystems is included, as derived from Hanafiah et al. (2011).

## 2.1 Impact pathways and affected areas of protection

For the impact category climate change, the damage modelling is subdivided into several steps (Figure 2.1). An emission of a greenhouse gas (kg) will lead to an increased atmospheric concentration of greenhouse gases (ppb) which, in turn, will increase the radiative forcing capacity (w/m$^2$), leading to an increase in the global mean temperature (°C). Increased temperature ultimately results in damage to human health and ecosystems. Here, we estimated the damage to human health, terrestrial ecosystems and freshwater ecosystems.

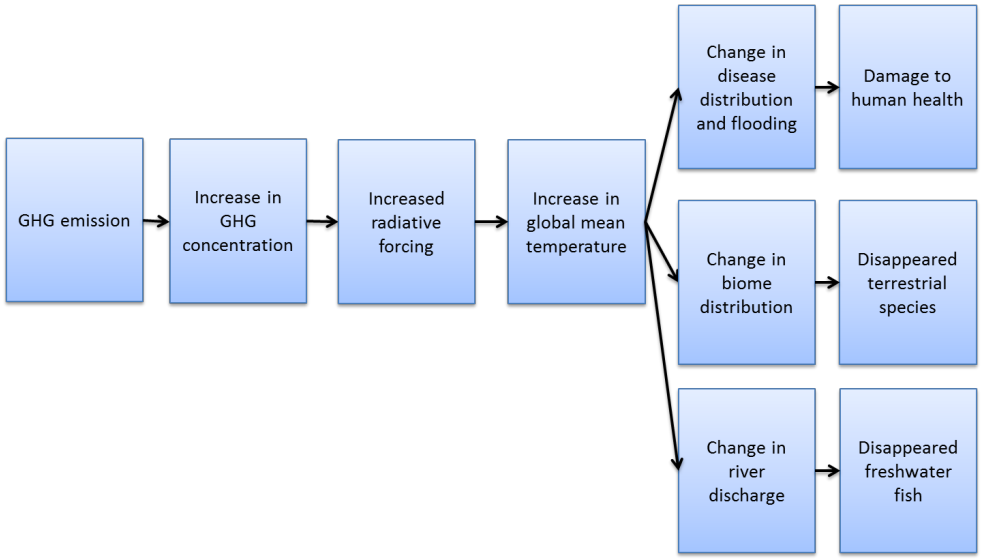


*Figure 2.1. Cause-and-effect chain from greenhouse gas emissions to human health damage and relative loss of species in terrestrial and freshwater ecosystems.*

## 2.2 Value choices

The value choice on the time horizon over which the impacts are integrated affects both the midpoint modelling and endpoint modelling of climate change (Joos et al. 2013). The various GHGs have widely different atmospheric lifetimes, resulting in time-horizon-dependent characterization factors. The decision of whether or not to include climate-carbon feedbacks for non-$CO_2$ GHGs affects their relative importance to $CO_2$ (for which the climate-carbon feedbacks are always included). Including this feedback mechanism adds uncertainty, but it also provides a more consistent midpoint CF. The other value choices considered are relevant for the damage assessment only and include the adaptation potential and the future socio-economic development of human society. The value choices are categorized by means of three cultural perspectives, as summarized in Table 2.1 (see De Schryver et al. 2009).

*Table 2.1. Value choices in the modelling of the effect of GHGs*

| Choice category | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|
| Time horizon | 20 years | 100 years | 1,000 years |
| Climate-carbon feedbacks included for non-$CO_2$ GHGs | No | Yes | No[1] |
| Future socio-economic developments | Optimistic | Baseline | Pessimistic |
| Adaptation potential | Adaptive | Controlling | Comprehensive |

[1] Ideally, Climate-Carbon feedbacks should be included for this perspective; however GWPs including Climate Carbon feedbacks are not available for a 1,000-year time horizon.

## 2.3 Characterization factors at midpoint level

The midpoint characterization factor for climate change is the widely used Global Warming Potential (GWP). The GWP expresses the amount of additional radiative forcing integrated over time (here 20, 100 or 1,000 years) caused by an emission of 1kg of GHG relative to the additional radiative forcing integrated over that same time horizon caused by the release of 1 kg of $CO_2$. The amount of radiative forcing integrated over time caused by the emission of 1 kg of GHG is called the Absolute Global Warming Potential (AGWP) and is expressed in the unit W $m^{-2}$ yr $kg^{-1}$. The midpoint characterization factor of any GHG (x) and any time horizon (TH) can then be calculated as follows:

$$GWP_{x,TH} = \frac{AGWP_{x,TH,}}{AGWP_{CO_2,TH}}$$

Which yields a time-horizon-specific GWP with the unit kg $CO_2$ eq/kg GHG. The GWPs for 20 and 100 years are directly provided by the latest IPCC report (IPCC, 2013). Values reported as <1 are rounded to 0 or 1, based on the reported AGWPs of the substance and that of $CO_2$. The GWP for a 1,000-year time horizon was derived in a different way. We directly used the AGWP for $CO_2$ for a 1,000-year time horizon ($=5.48 \cdot 10^{-13}$ $yr \cdot W \cdot m^{-2} \cdot kg^{-1}$), as provided by Joos et al. (2013), and we calculated the AGWP for a 1,000-year time horizon for the other GHGs as follows:

$$AGWP_{x,TH} = RF_x \; cv_x \; LT_x \; (1 - e^{-\frac{TH}{LT_x}})$$

Whereby RF is the radiative efficiency (W $m^{-2}$/ppb), cv is the substance-specific mass to concentration conversion factor (ppb/kg), LT is the lifetime (year) of the substance x and TH is the time horizon (year) of the assessment (in this case 1,000 years). RF and LT were directly available from the fifth assessment report (IPCC 2013). Since the values for cv are not reported separately in the fifth assessment report, these were calculated from the AGWPs that were reported by IPCC (2013). The GWPs of 207 GHGs are listed in Table 2.2.

*Table 2.2. Global Warming Potentials (kg $CO_2$-eq/kg) for the three time perspectives.*

| **Name** | **Formula** | **Indivi-dualist (20 years)** | **Hierarch-ist (100 years)** | **Egalitarian (1,000 years)** |
|---|---|---|---|---|
| Carbon dioxide | $CO_2$ | 1 | 1 | 1 |
| Methane | $CH_4$ | 84 | 34 | 4.8 |
| Fossil methane | $CH_4$ | 85 | 36 | 4.9 |
| Nitrous oxide | $N_2O$ | 264 | 298 | 78.8 |
| **Chlorofluorocarbons** | | | | |
| CFC-11 | CCl3F | 6,900 | 5,352 | 875.4 |
| CFC-12 | CCl2F2 | 10,800 | 11,547 | 2,709.4 |
| CFC-13 | CClF3 | 10,900 | 15,451 | 1,2684.1 |
| CFC-113 | CCl2FCClF2 | 6,490 | 6,586 | 1,409.5 |
| CFC-114 | CClF2CClF2 | 7,710 | 9,615 | 3,492.3 |
| CFC-115 | CClF2CF3 | 5,860 | 8,516 | 8,578.8 |
| **Hydrochlorofluoro-carbons** | | | | |
| HCFC-21 | CHCl2F | 543 | 179 | 24.6 |
| HCFC-22 | CHClF2 | 5,280 | 2,106 | 295.9 |
| HCFC-122 | CHCl2CF2Cl | 218 | 72 | 9.9 |
| HCFC-122a | CHFClCFCl2 | 945 | 312 | 43.2 |
| HCFC-123 | CHCl2CF3 | 292 | 96 | 13.3 |
| HCFC-123a | CHClFCF2Cl | 1,350 | 447 | 61.9 |
| HCFC-124 | CHClFCF3 | 1,870 | 635 | 88.2 |
| HCFC-132c | CH2FCFCl2 | 1,230 | 409 | 56.6 |
| HCFC-141b | CH3CCl2F | 2,550 | 938 | 130.9 |
| HCFC-142b | CH3CClF2 | 5,020 | 2,345 | 332.5 |
| HCFC-225ca | CHCl2CF2CF3 | 469 | 155 | 21.4 |
| HCFC-225cb | CHClFCF2CClF2 | 1,860 | 633 | 87.8 |
| (E)-1-Chloro-3,3,3-trifluoroprop-1-ene | trans-CF3CH=CHCl | 5 | 2 | 0.3 |
| **Hydrofluorocarbons** | | | | |
| HFC-23 | CHF3 | 10,800 | 13,856 | 5,664.5 |
| HFC-32 | CH2F2 | 2,430 | 817 | 113.3 |
| HFC-41 | CH3F | 427 | 141 | 19.5 |
| HFC-125 | CHF2CF3 | 6,090 | 3691 | 546.4 |
| HFC-134 | CHF2CHF2 | 3,580 | 1337 | 186.4 |
| HFC-134a | CH2FCF3 | 3,710 | 1549 | 217.6 |
| HFC-143 | CH2FCHF2 | 1,200 | 397 | 54.9 |
| HFC-143a | CH3CF3 | 6,940 | 5,508 | 913.3 |
| HFC-152 | CH2FCH2F | 60 | 20 | 2.8 |
| HFC-152a | CH3CHF2 | 506 | 167 | 23.0 |
| HFC-161 | CH3CH2F | 13 | 4 | 0.6 |

| Name | Formula | Indivi-dualist (20 years) | Hierarch-ist (100 years) | Egalitarian (1,000 years) |
|---|---|---|---|---|
| HFC-227ca | CF3CF2CHF2 | 5,080 | 3,077 | 455.5 |
| HFC-227ea | CF3CHFCF3 | 5,360 | 3,860 | 607.5 |
| HFC-236cb | CH2FCF2CF3 | 3,480 | 1,438 | 202.4 |
| HFC-236ea | CHF2CHFCF3 | 4,110 | 1,596 | 223.5 |
| HFC-236fa | CF3CH2CF3 | 6,940 | 8,998 | 3918.3 |
| HFC-245ca | CH2FCF2CHF2 | 2,510 | 863 | 119.7 |
| HFC-245cb | CF3CF2CH3 | 6,680 | 5,298 | 879.9 |
| HFC-245ea | CHF2CHFCHF2 | 863 | 285 | 39.4 |
| HFC-245eb | CH2FCHFCF3 | 1,070 | 352 | 48.6 |
| HFC-245fa | CHF2CH2CF3 | 2,920 | 1,032 | 143.7 |
| HFC-263fb | CH3CH2CF3 | 278 | 92 | 12.6 |
| HFC-272ca | CH3CF2CH3 | 530 | 175 | 24.1 |
| HFC-329p | CHF2CF2CF2CF3 | 4,510 | 2,742 | 407.1 |
| HFC-365mfc | CH3CF2CH2CF3 | 2,660 | 966 | 134.7 |
| HFC-43-10mee | CF3CHFCHFCF2CF3 | 4,310 | 1,952 | 276.6 |
| HFC-1132a | CH2=CF2 | 0 | 0 | 0.0 |
| HFC-1141 | CH2=CHF | 0 | 0 | 0.0 |
| (Z)-HFC-1225ye | CF3CF=CHF(Z) | 1 | 0 | 0.0 |
| (E)-HFC-1225ye | CF3CF=CHF(E) | 0 | 0 | 0.0 |
| (Z)-HFC-1234ze | CF3CH=CHF(Z) | 1 | 0 | 0.0 |
| HFC-1234yf | CF3CF=CH2 | 1 | 0 | 0.1 |
| (E)-HFC-1234ze | trans-CF3CH=CHF | 4 | 1 | 0.2 |
| (Z)-HFC-1336 | CF3CH=CHCF3(Z) | 6 | 2 | 0.3 |
| HFC-1243zf | CF3CH=CH2 | 1 | 0 | 0.0 |
| HFC-1345zfc | C2F5CH=CH2 | 0 | 0 | 0.0 |
| 3,3,4,4,5,5,6,6,6-Nonafluorohex-1-ene | C4F9CH=CH2 | 1 | 0 | 0.0 |
| 3,3,4,4,5,5,6,6,7,7,8,8,8-Tridecafluorooct-1-ene | C6F13CH=CH2 | 0 | 0 | 0.0 |
| 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-Heptadecafluorodec-1-ene | C8F17CH=CH2 | 0 | 0 | 0.0 |
| **Chlorocarbons and hydrochlorocarbons** | | | | |
| Methyl chloroform | CH3CCl3 | 578 | 193 | 26.8 |
| Carbon tetrachloride | CCl4 | 3,480 | 2,019 | 296.0 |
| Methyl chloride | CH3Cl | 45 | 15 | 2.0 |
| Methylene chloride | CH2Cl2 | 33 | 11 | 1.5 |
| Chloroform | CHCl3 | 60 | 20 | 2.7 |
| 1,2-Dichloroethane | CH2ClCH2Cl | 3 | 1 | 0.2 |
| **Bromocarbons, hyrdobromocarbons and Halons** | | | | |
| Methyl bromide | CH3Br | 9 | 3 | 0.4 |
| Methylene bromide | CH2Br2 | 4 | 1 | 0.2 |
| Halon-1201 | CHBrF2 | 1,350 | 454 | 62.9 |
| Halon-1202 | CBr2F2 | 848 | 280 | 38.7 |
| Halon-1211 | CBrClF2 | 4,590 | 2,070 | 293.3 |
| Halon-1301 | CBrF3 | 7,800 | 7,154 | 1342.2 |
| Halon-2301 | CH2BrCF3 | 635 | 210 | 29.1 |

| Name | Formula | Indivi-dualist (20 years) | Hierarch-ist (100 years) | Egalitarian (1,000 years) |
|---|---|---|---|---|
| Halon-2311/Halothane | CHBrClCF3 | 151 | 50 | 6.9 |
| Halon-2401 | CHFBrCF3 | 674 | 223 | 30.7 |
| Halon-2402 | CBrF2CBrF2 | 3,440 | 1,734 | 248.0 |
| **Fully Fluorinated Species** | | | | |
| Nitrogen trifluoride | NF3 | 12,800 | 17,885 | 12,816.7 |
| Sulphur hexafluoride | SF6 | 17,500 | 26,087 | 34,368.5 |
| (Trifluoromethyl)sulfur pentafluoride | SF5CF3 | 13,500 | 19,396 | 17,724.5 |
| Sulfuryl fluoride | SO2F2 | 6,840 | 4,732 | 731.9 |
| PFC-14 | CF4 | 4,880 | 7,349 | 11,009.8 |
| PFC-116 | C2F6 | 8,210 | 12,340 | 17,810.2 |
| PFC-c216 | c-C3F6 | 6,850 | 10,208 | 13,315.3 |
| PFC-218 | C3F8 | 6,640 | 9,878 | 12,611.8 |
| PFC-318 | c-C4F8 | 7,110 | 10,592 | 13,921.4 |
| PFC-31-10 | C4F10 | 6,870 | 10,213 | 13,018.1 |
| Perfluorocyclopentene | c-C5F8 | 7 | 2 | 0.3 |
| PFC-41-12 | n-C5F12 | 6,350 | 9,484 | 12,838.0 |
| PFC-51-14 | n-C6F14 | 5,890 | 8,780 | 11,504.8 |
| PFC-61-16 | n-C7F16 | 5,830 | 8,681 | 11,301.3 |
| PFC-71-18 | C8F18 | 5,680 | 8,456 | 11,042.5 |
| PFC-91-18 | C10F18 | 5,390 | 7,977 | 9,686.2 |
| Perfluorodecalin(cis) | Z-C10F18 | 5,430 | 8,033 | 9,759.0 |
| Perfluorodecalin(trans) | E-C10F18 | 4,720 | 6,980 | 8,505.2 |
| PFC-1114 | CF2=CF2 | 0 | 0 | 0.0 |
| PFC-1216 | CF3CF=CF2 | 0 | 0 | 0.0 |
| Perfluorobuta-1,3-diene | CF2=CFCF=CF2 | 0 | 0 | 0.0 |
| Perfluorobut-1-ene | CF3CF2CF=CF2 | 0 | 0 | 0.0 |
| Perfluorobut-2-ene | CF3CF=CFCF3 | 6 | 2 | 0.3 |
| **Halogenated alcohols and ethers** | | | | |
| HFE-125 | CHF2OCF3 | 12,400 | 13,951 | 3,657.5 |
| HFE-134 (HG-00) | CHF2OCHF2 | 11,600 | 6,512 | 946.2 |
| HFE-143a | CH3OCF3 | 1,890 | 632 | 87.5 |
| HFE-227ea | CF3CHFOCF3 | 8,900 | 7,377 | 1,261.5 |
| HCFE-235ca2(enflurane) | CHF2OCF2CHFCl | 2,120 | 705 | 97.6 |
| HCFE-235da2(isoflurane) | CHF2OCHClCF3 | 1,800 | 595 | 82.2 |
| HFE-236ca | CHF2OCF2CHF2 | 9,710 | 4,990 | 715.3 |
| HFE-236ea2(desflurane) | CHF2OCHFCF3 | 5,550 | 2,143 | 300.1 |
| HFE-236fa | CF3CH2OCF3 | 3,350 | 1,177 | 163.8 |
| HFE-245cb2 | CF3CF2OCH3 | 2,360 | 790 | 109.5 |
| HFE-245fa1 | CHF2CH2OCF3 | 2,900 | 997 | 138.5 |
| HFE-245fa2 | CHF2OCH2CF3 | 2,910 | 981 | 135.9 |
| 2,2,3,3,3-Pentafluoropropane-1-ol | CF3CF2CH2OH | 69 | 23 | 3.1 |
| HFE-254cb1 | CH3OCF2CHF2 | 1,110 | 365 | 50.4 |
| HFE-263fb2 | CF3CH2OCH3 | 5 | 2 | 0.2 |
| HFE-263m1 | CF3OCH2CH3 | 108 | 36 | 4.9 |
| 3,3,3-Trifluoropropan-1-ol | CF3CH2CH2OH | 1 | 0 | 0.1 |
| HFE-329mcc2 | CHF2CF2OCF2CF3 | 6,720 | 3,598 | 519.8 |
| HFE-338mmz1 | (CF3)2CHOCHF2 | 5,940 | 3,081 | 442.1 |

| Name | Formula | Indivi-dualist (20 years) | Hierarch-ist (100 years) | Egalitarian (1,000 years) |
|---|---|---|---|---|
| HFE-338mcf2 | CF3CH2OCF2CF3 | 3,180 | 1,118 | 155.5 |
| Sevoflurane (HFE-347mmz1) | (CF3)2CHOCH2F | 795 | 262 | 36.1 |
| HFE-347mcc3 (HFE-7000) | CH3OCF2CF2CF3 | 1,910 | 641 | 88.8 |
| HFE-347mcf2 | CHF2CH2OCF2CF3 | 2,990 | 1,028 | 142.9 |
| HFE-347pcf2 | CHF2CF2OCH2CF3 | 3,150 | 1,072 | 148.7 |
| HFE-347mmy1 | (CF3)2CFOCH3 | 1,330 | 440 | 60.8 |
| HFE-356mec3 | CH3OCF2CHFCF3 | 1,410 | 468 | 64.8 |
| HFE-356mff2 | CF3CH2OCH2CF3 | 62 | 20 | 2.8 |
| HFE-356pcf2 | CHF2CH2OCF2CHF2 | 2,560 | 867 | 120.3 |
| HFE-356pcf3 | CHF2OCH2CF2CHF2 | 1,640 | 540 | 74.7 |
| HFE-356pcc3 | CH3OCF2CF2CHF2 | 1,510 | 500 | 69.2 |
| HFE-356mmz1 | (CF3)2CHOCH3 | 50 | 17 | 2.3 |
| HFE-365mcf3 | CF3CF2CH2OCH3 | 3 | 1 | 0.2 |
| HFE-365mcf2 | CF3CF2OCH2CH3 | 215 | 71 | 9.8 |
| HFE-374pc2 | CHF2CF2OCH2CH3 | 2,260 | 758 | 105.0 |
| 4,4,4-Trifluorobutan-1-ol | CF3(CH2)2CH2OH | 0 | 0 | 0.0 |
| 2,2,3,3,4,4,5,5-Octafluorocyclopentanol | (CF2)4CH(OH) | 47 | 16 | 2.2 |
| HFE-43-10pccc124(H-Galden 1040x,HG-11) | CHF2OCF2OC2F4OCHF2 | 8,010 | 3,353 | 471.7 |
| HFE-449s1 (HFE-7100) | C4F9OCH3 | 1,530 | 509 | 70.4 |
| n-HFE-7100 | n-C4F9OCH3 | 1,760 | 587 | 81.2 |
| i-HFE-7100 | i-C4F9OCH3 | 1,480 | 492 | 68.1 |
| HFE-569sf2 (HFE-7200) | C4F9OC2H5 | 209 | 69 | 9.5 |
| n-HFE-7200 | n-C4F9OC2H5 | 237 | 79 | 10.8 |
| i-HFE-7200 | i-C4F9OC2H5 | 163 | 54 | 7.4 |
| HFE-236ca12 (HG-10) | CHF2OCF2OCHF2 | 11,000 | 6,260 | 912.0 |
| HFE-338pcc13 (HG-01) | CHF2OCF2CF2OCHF2 | 8,430 | 3,466 | 486.9 |
| 1,1,1,3,3,3-Hexafluoropropane-2-ol | (CF3)2CHOH | 668 | 221 | 30.5 |
| HG-02 | HF2C–(OCF2CF2)2–OCF2H | 7,900 | 3,250 | 456.4 |
| HG-03 | HF2C–(OCF2CF2)3–OCF2H | 8,270 | 3,400 | 477.7 |
| HG-20 | HF2C–(OCF2)2–OCF2H | 10,900 | 6,201 | 904.1 |

| Name | Formula | Indivi-dualist (20 years) | Hierarch-ist (100 years) | Egalitarian (1,000 years) |
|---|---|---|---|---|
| HG-21 | HF2C–OCF2CF2OCF2OCF2O–CF2H | 11,100 | 4,628 | 651.9 |
| HG-30 | HF2C–(OCF2)3–OCF2H | 15,100 | 8,575 | 1,250.2 |
| 1-Ethoxy-1,1,2,2,3,3,3-heptafluoropropane | CF3CF2CF2OCH2CH3 | 223 | 74 | 10.1 |
| Fluoroxene | CF3CH2OCH=CH2 | 0 | 0 | 0.0 |
| 1,1,2,2-Tetrafluoro-1-(fluoromethoxy)ethane | CH2FOCF2CF2H | 3,080 | 1,051 | 145.9 |
| 2-Ethoxy-3,3,4,4,5-pentafluorotetrahydro-2,5-bis[1,2,2,2-tetrafluoro-1-(trifluoromethyl)ethyl]-furan | C12H5F19O2 | 204 | 68 | 9.3 |
| Fluoro(methoxy)methane | CH3OCH2F | 46 | 15 | 2.1 |
| Difluoro(methoxy)meth-ane | CH3OCHF2 | 528 | 175 | 24.1 |
| Fluoro(fluoromethoxy)-methane | CH2FOCH2F | 479 | 159 | 21.9 |
| Difluoro(fluoromethoxy)-methane | CH2FOCHF2 | 2,260 | 748 | 103.3 |
| Trifluoro(fluoromethoxy)-methane | CH2FOCF3 | 2,730 | 909 | 125.8 |
| HG'-01 | CH3OCF2CF2OCH3 | 815 | 269 | 37.0 |
| HG'-02 | CH3O(CF2CF2O)2CH3 | 868 | 287 | 39.4 |
| HG'-03 | CH3O(CF2CF2O)3CH3 | 812 | 268 | 37.0 |
| HFE-329me3 | CF3CFHCF2OCF3 | 7,170 | 5,241 | 829.6 |
| 3,3,4,4,5,5,6,6,7,7,7-Undecafluoroheptan-1-ol | CF3(CF2)4CH2CH2OH | 2 | 1 | 0.1 |
| 3,3,4,4,5,5,6,6,7,7,8,8,9,9,9-Pentadecafluorononan-1-ol | CF3(CF2)6CH2CH2OH | 1 | 0 | 0.1 |
| 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,11-Nonadecafluoroundecan-1-ol | CF3(CF2)8CH2CH2OH | 1 | 0 | 0.0 |
| 2-Chloro-1,1,2-trifluoro-1-methoxyethane | CH3OCF2CHFCl | 449 | 149 | 20.4 |
| PFPMIE(perfluoropoly-methylisopropyl ether) | CF3OCF(CF3)CF2OCF2OCF3 | 7,500 | 10,789 | 9,861.9 |
| HFE-216 | CF3OCF=CF2 | 1 | 0 | 0.0 |
| Trifluoromethylformate | HCOOCF3 | 2,150 | 712 | 98.3 |
| Perfluoroethylformate | HCOOCF2CF3 | 2,130 | 703 | 97.1 |
| Perfluoropropylformate | HCOOCF2CF2CF3 | 1,380 | 456 | 63.0 |

| Name | Formula | Indivi-dualist (20 years) | Hierarch-ist (100 years) | Egalitarian (1,000 years) |
|---|---|---|---|---|
| Perfluorobutylformate | HCOOCF2CF2CF2CF3 | 1,440 | 475 | 65.6 |
| 2,2,2-Trifluoroethylformate | HCOOCH2CF3 | 123 | 41 | 5.6 |
| 3,3,3-Trifluoropropylformate | HCOOCH2CH2CF3 | 64 | 21 | 2.9 |
| 1,2,2,2-Tetrafluoroethylformate | HCOOCHFCF3 | 1,720 | 569 | 78.6 |
| 1,1,1,3,3,3-Hexafluoropropan-2-ylformate | HCOOCH(CF3)2 | 1,220 | 403 | 55.7 |
| Perfluorobutylacetate | CH3COOCF2CF2CF2CF3 | 6 | 2 | 0.3 |
| Perfluoropropylacetate | CH3COOCF2CF2CF3 | 6 | 2 | 0.3 |
| Perfluoroethylacetate | CH3COOCF2CF3 | 8 | 3 | 0.3 |
| Trifluoromethylacetate | CH3COOCF3 | 8 | 3 | 0.3 |
| Methylcarbonofluoridate | FCOOCH3 | 350 | 116 | 15.9 |
| 1,1-Difluoroethylcarbonofluoridate | FCOOCF2CH3 | 99 | 33 | 4.5 |
| 1,1-Difluoroethyl2,2,2-trifluoroacetate | CF3COOCF2CH3 | 113 | 38 | 5.2 |
| Ethyl 2,2,2-trifluoroacetate | CF3COOCH2CH3 | 5 | 2 | 0.2 |
| 2,2,2-Trifluoroethyl2,2,2-trifluoroacetate | CF3COOCH2CF3 | 25 | 8 | 1.1 |
| Methyl 2,2,2-trifluoroacetate | CF3COOCH3 | 192 | 64 | 8.8 |
| Methyl 2,2-difluoroacetate | HCF2COOCH3 | 12 | 4 | 0.5 |
| Difluoromethyl 2,2,2-trifluoroacetate | CF3COOCHF2 | 99 | 33 | 4.5 |
| 2,2,3,3,4,4,4-Heptafluorobutan-1-ol | C3F7CH2OH | 124 | 41 | 5.7 |
| 1,1,2-Trifluoro-2-(trifluoromethoxy)-ethane | CHF2CHFOCF3 | 3,970 | 1,489 | 207.9 |
| 1-Ethoxy-1,1,2,3,3,3-hexafluoropropane | CF3CHFCF2OCH2CH3 | 86 | 28 | 3.9 |
| 1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane | CF3CF2CF2OCHFCF3 | 7,940 | 7,371 | 1,400.4 |
| 2,2,3,3-Tetrafluoro-1-propanol | CHF2CF2CH2OH | 48 | 16 | 2.2 |
| 2,2,3,4,4,4-Hexafluoro-1-butanol | CF3CHFCF2CH2OH | 63 | 21 | 2.8 |
| 2,2,3,3,4,4,4-Heptafluoro-1-butanol | CF3CF2CF2CH2OH | 60 | 20 | 2.7 |

| Name | Formula | Indivi-dualist (20 years) | Hierarch-ist (100 years) | Egalitarian (1,000 years) |
|---|---|---|---|---|
| 1,1,2,2-Tetrafluoro-3-methoxy-propane | CHF2CF2CH2OCH3 | 2 | 1 | 0.1 |
| perfluoro-2-methyl-3-pentanone | CF3CF2C(O)CF(CF3)2 | 0 | 0 | 0.0 |
| 3,3,3-Trifluoropropanal | CF3CH2CHO | 0 | 0 | 0.0 |
| 2-Fluoroethanol | CH2FCH2OH | 3 | 1 | 0.1 |
| 2,2-Difluoroethanol | CHF2CH2OH | 11 | 4 | 0.5 |
| 2,2,2-Trifluoroethanol | CF3CH2OH | 73 | 24 | 3.3 |
| 1,1'-Oxybis[2-(difluoromethoxy)-1,1,2,2-tetrafluoroethane | HCF2O(CF2CF2O)2CF2H | 9,910 | 5,741 | 840.5 |
| 1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12-hexadecafluoro-2,5,8,11-Tetraoxadodecane | HCF2O(CF2CF2O)3CF2H | 9,050 | 5,245 | 768.4 |
| 1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12,13,13,15,15-eicosafluoro-2,5,8,11,14-Pentaoxapentadecane | HCF2O(CF2CF2O)4CF2H | 7,320 | 4,240 | 621.6 |

## 2.4 From midpoint to endpoint

Endpoint characterization factors (CFe) for Climate Change (CC) for GHG x are calculated by

$$CFe_{x,c,a} = GWP_{x,c} \times F_{M\rightarrow,E,CC,c,a}$$

Whereby c denotes the cultural perspective, a denotes the area of protection (human health, terrestrial ecosystems or freshwater ecosystems) GWPx,c is the midpoint characterization factor and $F_{M\rightarrow,E,CC,c,a}$ is the midpoint to endpoint conversion factor for cultural perspective c and area of protection a. Table 1.3 provides the midpoint to endpoint factors for human health damage, terrestrial ecosystem damage and freshwater ecosystem damage, and the three cultural perspectives.
The first step from the midpoint to endpoint model is the step from time-integrated radiative forcing to time-integrated temperature increase. The metric that combines the AGWP ($yr \cdot W \cdot m^{-2} \cdot kg^{-1}$) and the temperature factor (TF in $°C \cdot m^2 \cdot W^{-1}$) is the time-integrated absolute global temperature potential (IAGTP). The IAGTPs for 1 kg $CO_2$ for, respectively, a 20, 100 and 1,000 year time horizon are $9.03 \cdot 10^{-15}$, $4.76 \cdot 10^{-14}$ and $4.23 \cdot 10^{-13}$ ($°C \cdot yr/kg\ CO_2$), as taken from Joos et al. (2013).

Concerning human health damage due to climate change, the increase in the risk of diseases (malnutrition, malaria and diarrhoea) and increased flood risk will lead to additional damage to human health in Disability-Adjusted Life Years (DALY). Not every region in the world is affected in equal measure by all of these effects. Therefore, in order to calculate the total effect on human health of an increase in temperature, summation over affected regions and health effects is performed (see De Schryver et al. 2009). This results in the following midpoint to endpoint factor for human health:

$$F_{M\rightarrow,E,CC,c,HH} = AGWP_{CO_2,c} \times TF_{CO_2,c} \sum_r \sum_h \Delta RR_{r,h,c} \times DALY_{r,h}$$
$$= IAGTP_{CO_2,c} \times \sum_r \sum_h \Delta RR_{r,h,c} \times DALY_{r,h}$$

Whereby IAGTP $CO_2$,c is the time-integrated absolute global temperature potential of 1 kg of $CO_2$ for perspective c (°C yr $kg^{-1}$), $\Delta RR_{r,h,c}$ ($C^{-1}$) is the increase in relative risk of health effect h in region r for perspective c due to an increase in global temperature, and $DALY_{r,h}$ is the yearly disability-adjusted life years lost in region r due to health effect h (DALY·$yr^{-1}$·°$C^{-1}$). For the egalitarian perspective, the damage factor (DALY·$yr^{-1}$·°$C^{-1}$) was taken directly from De Schryver et al. (2009). For the individualist and hierarchist perspectives, we adopted the relative risks from De Schryver et al. (2009), but maintained the DALYs without age-weighting and discounting to calculate the damage factor.
For terrestrial ecosystems, the midpoint to endpoint factor is calculated as follows:

$$F_{M\rightarrow,E,CC,c,TERR} = IAGTP_{CO_2,c} \times A_{terr} \times EF_{terr} \times SD_{terr}$$

Whereby A is the total surface of (semi-)natural terrestrial areas of the world, $1.08 \cdot 10^{14}$ $m^2$, $EF_{terr}$ is the effect factor, representing the increase in potentially disappeared fraction of species due to an increase in global temperature. The effect factor was taken from the review by Urban (2015), who reports a predicted extinction of 2.8% at current temperatures (0.8 °C above pre-industrial levels) and an extinction of 15.7% following a business-as-usual scenario (4.3 °C temperature increase above pre-industrial levels). Combining this data by using the differences between these two scenarios (i.e. 12.9%/3.5°C) yields an effect factor of 0.037 PDF·°$C^{-1}$; this factor is used for all perspectives. SDterr is the average species density for terrestrial ecosystems, which is approximated to be $1.48 \cdot 10^{-8}$ species.$m^{-2}$ (Goedkoop et al., 2008).
The midpoint to endpoint factor for freshwater ecosystems is calculated as follows:

$$F_{M\rightarrow,E,CC,c,fw} = IAGTP_{CO_2,c} \times SD_{fw} \sum_i EF_{fw,i} \times V_i$$

Whereby $EF_{fw,i}$ is the change in the potentially disappeared fraction of fish species in river basin i due to a change in temperature (PDF.°$C^{-1}$) and Vi is the total water volume of river basin i ($m^3$), both taken from Hanafiah et al. (2011). The influence of global temperature increase on river discharge and subsequent expected changes in fish species occurrences was modelled by Hanafiah et al. (2011), based on earlier work by Xenopoulos et al. (2005, 2006). SDfw is the freshwater species density, which approximates $7.89 \cdot 10^{-10}$ species.$m^{-3}$ (Goedkoop et al., 2008).

*Table 2.3. Midpoint to endpoint characterization factors for the different areas of protection and cultural perspectives.*

| **Area of protection** | **Unit** | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|---|
| Human health | DALY/kg $CO_2$eq | $8.12 \cdot 10^{-8}$ | $9.28 \cdot 10^{-7}$ | $1.25 \cdot 10^{-5}$ |
| Terrestrial ecosystems | Species.year/kg $CO_2$eq | $5.32 \cdot 10^{-10}$ | $2.80 \cdot 10^{-9}$ | $2.50 \cdot 10^{-8}$ |
| Aquatic ecosystems | Species.year/kg $CO_2$eq | $1.45 \cdot 10^{-14}$ | $7.65 \cdot 10^{-14}$ | $6.82 \cdot 10^{-13}$ |

# 3 Stratospheric ozone depletion

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This chapter is primarily based on the most recent report with updated Ozone Depletion Potentials (ODPs from the World Meteorological Organization (WMO, 2011)) Hayashi et al. (2006) and De Schryver et al. (2011). Changes introduced compared with the ReCiPe2008 chapter are:

- New semi-empirical ODPs were included with more specification between various chlorofluorocarbons (CFCs);
- A preliminary ODP for $N_2O$ was included;
- Three time horizons have now been consistently implemented: 20 years (Individualist), 100 years (Hierarchist) and infinite (Egalitarian);
- Midpoint to endpoint factors were recalculated, based on Hayashi et al. (2006).

## 3.1 Impact pathways and affected areas of protection

Emissions of Ozone Depleting Substances (ODSs) ultimately lead to damage to human health because of the resultant increase in UVB-radiation (Figure 3.1). Chemicals that deplete ozone are relatively persistent and have chlorine or bromine groups in their molecules that interact with ozone (mainly) in the stratosphere. After an emission of an ODS, the tropospheric concentrations of all ODSs increase and, after a time,, the stratospheric concentration of ODS also increases. This increase in ozone depleting potential leads to a decrease in the atmospheric ozone concentration, which in turn causes a larger portion of the UVB radiation to hit the earth. This increased radiation negatively affects human health, thus increasing the incidence of skin cancer and cataracts.

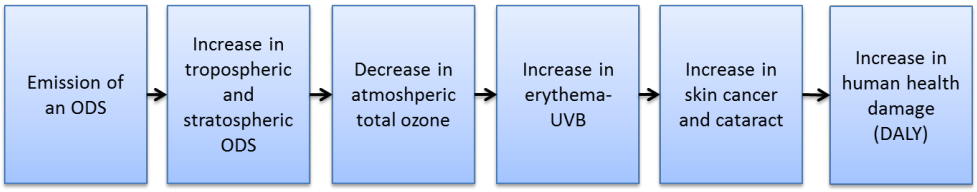


*Figure 3.1. Cause-and-effect chain for emissions of ozone depleting substances (ODS) resulting in damage to human health.*

## 3.2 Value choices

The choice of the time horizon and the resulting uncertainty of environmental pressure have been dealt with explicitly by using different cultural perspectives in the update of the characterization factors by De Schryver et al. (2011), as specified in Table 3.1. As the relationship between UVB and the development of cataract is rather uncertain (Struijs et al. 2009), cataract is only included in the Egalitarian perspective.

*Table 3.1. Value choices in the modelling of the effect of ozone depleting substances.*

| Choice category | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|
| Time horizon | 20 yr | 100 yr | Infinite |
| Included effects | Skin cancer | Skin cancer | Skin cancer<br>Cataract |

## 3.3 Characterization factors at midpoint level

The Ozone Depleting Potential (ODP), expressed in kg CFC-11 equivalents, is used as a characterization factor at the midpoint level. The ODP quantifies the amount of ozone a substance can deplete relative to CFC-11 for a specific time horizon and is therefore largely related to the molecular structure of the ODS and especially to the number of chlorine and bromine groups in the molecule, as well as the atmospheric lifetime of the chemical. ODPs are calculated by the World Meteorological Organization. The latest update was released in 2010 (WMO 2011). ODPs were calculated in a semi-empirical way by WMO (2011), whereby the fractional release of chlorine and bromine groups from the molecule of an ODS is based on observational data for air layers with different ages. The ozone destruction potency of bromine is 60 times higher than the destruction potency of chlorine (65 in arctic regions). By combining the fractional release and the number of bromine and chlorine groups in the molecule, the effect on the equivalent effective stratospheric chlorine (EESC) can be calculated for each ODS. From this change in EESC, the ODP can be calculated as follows:

$$ODP_{inf,x} = \frac{\Delta EESC_x}{\Delta EESC_{CFC-11}}$$

Whereby the $ODP_{inf,x}$ is the ODP for an infinite time horizon for ODS *x*, $\Delta EESC_x$ and $\Delta EESC_{cfc\text{-}11}$ are the changes in EESC caused by the emission of 1 kg of ODS *x* and 1 kg of CFC-11, respectively.
For the exact modelling procedure of the EESC, the reader is referred to the WMO report and underlying atmospheric models. The WMO provides ODPs for an infinite time horizon only. In order to provide ODPs for different time horizons as well, the atmospheric lifetimes of all ODSs compared to CFC-11 were taken into account. In order to calculate the fraction of damage at any time horizon, we followed De Schryver et al (2011):

$$F_t = 1 - e^{(-t-3)\cdot k}$$

Whereby Ft is the fraction of the total damage caused by an ODS during the first *t* years, *k* is the removal rate of the ODS ($yr^{-1}$), which is equivalent to the inverse of its atmospheric lifetime (provided by the WMO). The 3 in the formula indicates the time lag between emissions to the troposphere and transport to the stratosphere in years. The ODP for another time horizon was calculated by:

$$ODP_{t,x} = ODP_{inf,x} \cdot \frac{F_{t,x}}{F_{t,CFC-11}}$$

Whereby $ODP_{t,x}$ is the ODP at time horizon (*t*) for substance *x*, $ODP_{inf,x}$ is the infinite ODP of substance *x* as provided by the WMO, $F_{t,x}$ is the fraction of damage caused by substance *x* in time t and $F_{t,CFC-11}$ is the fraction of damage caused by CFC-11 at that same time *t*. We used this formula to calculate ODPs on a 20 year time horizon (Individualist) and a 100 year time horizon (Hierarchist). ODPs for an infinite time horizon were adopted from the WMO directly (Table 3.2).

*Table 3.2. Midpoint characterization factors (in kg CFC-11 equivalents/kg) for 21 ODSs for three perspectives.*

| Substance | Individualist (20 year) | Hierarchist (100 year) | Egalitarian (infinite) |
|---|---|---|---|
| **Annex A-I** | | | |
| CFC-11 | 1 | 1 | 1 |
| CFC-12 | 0.421 | 0.587 | 0.820 |
| CFC-113 | 0.504 | 0.664 | 0.850 |
| CFC-114 | 0.165 | 0.270 | 0.580 |
| CFC-115 | 0.032 | 0.061 | 0.570 |
| **Annex A-II** | | | |
| Halon-1301 | 11.841 | 14.066 | 15.900 |
| Halon-1211 | 15.053 | 8.777 | 7.900 |
| Halon-2402 | 22.200 | 14.383 | 13.000 |
| **Annex B-II** | | | |
| $CCl_4$ | 1.203 | 0.895 | 0.820 |
| **Annex B-III** | | | |
| $CH_3CCl_3$ | 0.396 | 0.178 | 0.160 |
| **Annex C-I** | | | |
| HCFC-22 | 0.085 | 0.045 | 0.040 |
| HCFC-123 | 0.025 | 0.011 | 0.010 |
| HCFC-124 | 0.049 | 0.022 | 0.020 |
| HCFC-141b | 0.275 | 0.134 | 0.120 |
| HCFC-142b | 0.111 | 0.067 | 0.060 |
| HCFC-225ca | 0.050 | 0.022 | 0.020 |
| HCFC-225cb | 0.073 | 0.033 | 0.030 |
| **Annex E** | | | |
| $CH_3Br$ | 1.649 | 0.734 | 0.660 |
| **Others** | | | |
| Halon-1202 | 4.247 | 1.892 | 1.700 |
| $CH_3Cl$ | 0.050 | 0.022 | 0.020 |
| $N_2O$* | 0.007 | 0.011 | 0.017 |

* ODPs for $N_2O$ should be considered preliminary, since the mode of action is different from the other ODSs and the ODP infinite is more uncertain.

## 3.4 From midpoint to endpoint

Endpoint characterization factors (CFe) for human health damage are calculated by:

$$CFe_{x,c} = ODP_{x,c} \times F_{M \to E,OD,c}$$

whereby $ODP_{x,c}$ is the ozone depletion potential of substance *x* (in CFC11-eq/kg) and $F_{M \to E,OD,c}$ is the midpoint to endpoint factor for ozone depletion (DALY/kg CFC11-eq) for cultural perspective *c*.

The human health effect of a change in stratospheric ozone was modelled by Hayashi et al. (2006) in two consecutive steps. The first step relates a change in ozone depleting substance to an increase in UV-B radiation and the second step couples this increase in UV-B radiation to an increase in the burden of disease.

The substances that deplete ozone are assumed to spread throughout the atmosphere and increase the potential for ozone depletion (expressed in EESC) in a spatially unspecific manner. To quantify the effect of EESC on the ozone layer thickness, observational data was used, i.e. the historical total amount of EESC has been coupled to the observed stratospheric ozone depletion from 1980 onwards. The year 1980 is used as a reference year because, before 1980, the effect of anthropogenic emissions on ozone depletion is considered to have been negligible. The effect of the EESC on the ozone concentration also differs per region, as well as per season. In the approach used by Hayashi et al. (2006), latitudinal zones with a width of 10 degrees are modelled for four different seasons. The amount of UVB radiation reaching the surface, however, depends on the optical thickness of the ozone layer rather than the actual total ozone amount. Furthermore, both direct UVB radiation and scattered radiation reaches the earth's surface. Therefore, Hayashi et al (2000) used a linear correlation between the theoretical optical thickness (in m) of the ozone layer and the apparent optical thickness (in m) to correct for this difference; different bandwidths of UVB radiation were modelled separately.

To calculate the damage to human health (in DALY), the increased incidence (cases/yr) of three types of skin cancer (malignant melanoma (MM), basal cell carcinoma (BCC) and squamous cell carcinoma (SCC)) due to UVB exposure (kJ/m2) was calculated. The impact of UVB radiation on the incidence of skin cancers is inversely related to the amount of skin pigment in humans. In order to take this into account, the percentage of people with each type of skin colour (black, yellow or white) was determined for each longitudinal zone. The increased incidence of cataract was included for the egalitarian perspective only because the relationship between cataract and UVB-radiation is still uncertain (Struijs et al. 2009). The DALY concept was applied to weight the different effects and sum them to a common unit. This procedure can be summarized as follows:

$$F_{M\rightarrow E,OD,c} = \Delta EESC_{CFC-11} \times \sum_{i}\sum_{q}\sum_{j} \Delta UVB_{i,q} \times EF_{i,q,j,c} \times DF_{j}$$

Whereby $\Delta UVB_{i,q}$ is the increase in UVB radiation (kJ/m$^2$) of bandwidth *q* in region *i*, $EF_{i,q,j,c}$ describes the extra incidence of disease *j* in region *i* caused by UVB radiation of bandwidth *q* for cultural perspective *c* and DF describes the damage to human health caused by the incidence of disease *j*. For more details about the damage and effect modelling, see Hayashi et al. (2006). Midpoint to endpoint factors (DALY/kg CFC-11 eq) are different for all three perspectives, due to the inclusion of different effects and the difference in time horizon per perspective (Table 3.3).

*Table 3.3. Midpoint to endpoint conversion factors (DALY/kg CFC-11eq).*

| **Midpoint to endpoint factor** | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|
| **Human health** | 2.37E-04 | 5.31E-04 | 1.34E-03 |

# 4 Ionizing radiation

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This chapter is primarily based on the work of Frischknecht et al. (2000) and De Schryver et al. (2011). Changes introduced compared with the ReCiPe2008 chapter are:

- Three time horizons have now been consistently implemented: 20 years (Individualist), 100 years (Hierarchist) and 100,000 years (Egalitarian);
- Dose and dose rate effectiveness factors (DDREFs) were specified per cultural perspective;
- Updated DALYs per fatal cancer incidence were applied.

## 4.1 Impact pathways and affected areas of protection

Starting from an anthropogenic emission of a radionuclide in the environment, the environmental cause and effect chain pathway can be divided into four consecutive steps (Figure 4.1):

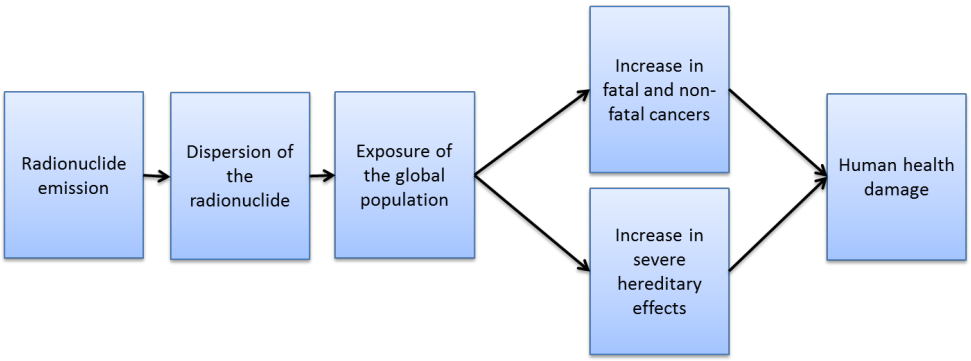


*Figure 4.1. Cause-and-effect chain, from an airborne or waterborne emission of a radionuclide to damage to human health.*

Anthropogenic emissions of radionuclides are generated in the nuclear fuel cycle (mining, processing and waste disposal), as well as during other human activities, such as the burning of coal and the extraction of phosphate rock. Firstly, the dispersion of the radionuclide throughout the environment is modelled. This step is followed by an exposure model in which the amount of radiation (effective collective dose) received by the entire population is determined. Exposure to the ionizing radiation caused by these radionuclides can lead to damaged DNA-molecules. During the effect analysis, the incidence of non-fatal cancers and the incidence of fatal cancers are distinguished from severe hereditary effects. As a final step, these are weighed in order to calculate the damage to human health in disability adjusted life years (DALY). There are currently no impact assessment methodologies to quantify the damage caused to ecosystems by ionizing radiation.

## 4.2 Value choices

Uncertainty due to choices is handled via different cultural perspectives. Most of these choices reflect different opinions on effect and damage

modelling. De Schryver et al. (2011) updated the original approach used by Frischknecht et al. (2000) in order to be more consistent with other impact categories. The value choices implemented in the ReCiPe update are (1) the time horizon of assessment, (2) the extrapolation from high dose exposure to low dose exposure, and (3) whether or not to include cancer types that might be caused by ionizing radiation (Table 4.1). From De Schryver et al. (2011), it is evident from these value choices that the choice of time horizon especially is of vital importance for long-lived radionuclides. Due to the longevity of some radionuclides, the fate models all use a long time horizon of 100,000 years. Note, however, that this time horizon is relatively short compared with the half-lives of the longest lived radionuclides, such as uranium-235 (half-life $7.1 \cdot 10^8$ years).

*Table 4.1. Value choices in the modelling of the effect of substances that emit ionizing radiation.*

| Choice category | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|
| Time horizon | 20 years | 100 years | 100,000 years |
| Dose and dose rate effectiveness factor (DDREF) | 10 | 6 | 2 |
| Included effects | -Thyroid, bone marrow, lung and breast cancer<br>-Hereditary disease | -Thyroid, bone marrow, lung, breast, bladder, colon, ovary, skin, liver, oesophagus and stomach cancer<br>-Hereditary disease | -Thyroid, bone marrow, lung, breast, bladder, colon, ovary, skin, liver, oesophagus, stomach, bone surface and remaining cancer<br>-Hereditary disease |

## 4.3 Characterization factors at midpoint level

During the fate analysis, the environmental fate of the emitted radionuclide is assessed for three different time horizons, following Frischknecht et al. (2000). The exposure analysis is used to estimate the collective exposure dose caused by the emission of a radionuclide. The collective dose is expressed in a unit called Man Sievert (man.Sv), which represents the total average exposure in Sievert (J/kg body weight) multiplied by the number of people in a population integrated over time. The number of people in the world was assumed to be stable at 10 billion for the next 100,000 years (Dreicer et al., 1995; Frischknecht et al., 2000). The collective dose caused by the emission of a radionuclide is also the point from which the characterization factor at mid-point level is derived. In this study, we present a midpoint characterization factor, called Ionizing Radiation Potential (IRP), relative to the emission of reference substance Cobalt-60 to air, yielding a midpoint factor in Co-60 to air equivalents according to the following equation:

$$IRP_{x,i} = \frac{CD_{x,i}}{CD_{Co-60,air}}$$

Whereby the $IRP_{x,i}$ is the Ionizing Radiation potential of 1kBq of substance *x* emitted to compartment *i*, $CD_{x,i}$ is the collective dose (in

Man.Sv) caused by the release of that substance to that compartment and $CD_{Co60-,air}$ is the collective dose caused by the release of a 1kBq of Co-60 to air. Separate midpoint factors are available for emissions to air, rivers and seas and for the three cultural perspectives, yielding up to nine emission factors for each radionuclide (Table 4.2).

*Table 4.2. Midpoint characterization factors (kBq Co-60 to air eq/kBq) per emission compartment.*

| Radionuclide | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|
| **Emissions to air** | | | |
| Am-241 | 5.45E+01 | 5.45E+01 | 5.55E+01 |
| C-14 | 6.14E-01 | 1.15E+00 | 1.29E+01 |
| Co-58 | 2.55E-02 | 2.55E-02 | 2.55E-02 |
| Co-60 | 1.00E+00 | 1.00E+00 | 1.00E+00 |
| Cs-134 | 7.18E-01 | 7.18E-01 | 7.18E-01 |
| Cs-137 | 1.27E+00 | 1.64E+00 | 1.64E+00 |
| H-3 | 8.55E-04 | 8.56E-04 | 8.56E-04 |
| I-129 | 8.32E+00 | 1.05E+01 | 2.07E+02 |
| I-131 | 9.09E-03 | 9.09E-03 | 9.09E-03 |
| I-133 | 5.64E-04 | 5.64E-04 | 5.64E-04 |
| Kr-85 | 6.03E-06 | 8.48E-06 | 8.48E-06 |
| Pb-210 | - | 9.09E-02 | 9.09E-02 |
| Po-210 | 9.09E-02 | 9.09E-02 | 9.09E-02 |
| Pu alpha[a] | - | - | 5.00E+00 |
| Pu-238 | - | - | 4.00E+00 |
| Pu-239 | 3.18E+01 | 3.18E+01 | 3.18E+01 |
| Ra-226 | - | - | 5.45E-02 |
| Rn-222 | 1.45E-03 | 1.45E-03 | 1.45E-03 |
| Ru-106 | 1.00E-01 | 1.00E-01 | 1.00E-01 |
| Sr-90 | 1.52E+00 | 2.45E+00 | 2.45E+00 |
| Tc-99 | 7.57E-01 | 1.18E+00 | 1.18E+00 |
| Th-230 | - | - | 2.73E+00 |
| U-234[a] | - | - | 5.82E+00 |
| U-235[a] | - | - | 1.27E+00 |
| U-238[a] | - | - | 4.91E-01 |
| Xe-133 | 8.55E-06 | 8.55E-06 | 8.55E-06 |
| **Emissions to fresh water (rivers and lakes)** | | | |
| Ag-110m | 3.00E-02 | 3.00E-02 | 3.00E-02 |
| Am-241 | 3.36E-03 | 3.45E-03 | 3.64E-03 |
| C-14 | 3.45E-03 | 6.09E-03 | 1.27E-02 |
| Co-58 | 2.45E-03 | 2.45E-03 | 2.45E-03 |
| Co-60 | 2.64E+00 | 2.64E+00 | 2.64E+00 |
| Cs-134 | 8.64E+00 | 8.64E+00 | 8.64E+00 |
| Cs-137 | 9.09E+00 | 1.00E+01 | 1.00E+01 |
| H-3 | 4.07E-05 | 4.12E-05 | 4.12E-05 |
| I-129 | 2.52E-01 | 2.87E-01 | 1.55E+02 |
| I-131 | 3.00E-02 | 3.00E-02 | 3.00E-02 |
| Mn-54 | 1.91E-02 | 1.91E-02 | 1.91E-02 |
| Pu-239 | 3.45E-04 | 3.73E-04 | 4.18E-04 |
| Ra-226[a] | - | - | 7.73E-03 |
| Ru-106 | 2.36E-04 | 2.36E-04 | 2.36E-04 |
| Sb-124 | 4.91E-02 | 4.91E-02 | 4.91E-02 |
| Sr-90 | 1.27E-02 | 2.45E-02 | 2.82E-02 |
| Tc-99 | 7.55E-03 | 3.09E-02 | 3.09E-02 |

| Radionuclide | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|
| U-234[a] | - | - | 1.45E-01 |
| U-235[a] | - | - | 1.36E-01 |
| U-238[a] | - | - | 1.36E-01 |
| **Emissions to the marine environment** | | | |
| Am-241 | 4.73E-02 | 4.82E-02 | 4.82E-02 |
| C-14 | 2.73E-02 | 2.73E-02 | 2.73E-02 |
| Cm alpha[a] | - | - | 3.45E+00 |
| Co-60 | 2.36E-02 | 2.36E-02 | 2.36E-02 |
| Cs-134 | 4.73E-03 | 4.73E-03 | 4.73E-03 |
| Cs-137 | 5.82E-03 | 5.82E-03 | 5.82E-03 |
| H-3 | 3.60E-06 | 4.05E-06 | 4.05E-06 |
| I-129 | 2.22E-02 | 3.00E-02 | 1.55E+02 |
| Pu alpha[a] | - | - | 4.45E+00 |
| Pu-239 | 5.27E-03 | 5.36E-03 | 5.73E-03 |
| Ru-106 | 1.09E-03 | 1.09E-03 | 1.09E-03 |
| Sb-125 | 8.91E-04 | 8.91E-04 | 8.91E-04 |
| Sr-90 | 4.55E-04 | 4.55E-04 | 4.55E-04 |
| Tc-99 | 7.82E-05 | 7.91E-05 | 1.09E-04 |
| U-234[a] | - | - | 1.36E-03 |
| U-235[a] | - | - | 2.03E-03 |
| U-238[a] | - | - | 8.33E-04 |

[a] Midpoint factors (Egalitarian perspective only) for Pu-alpha, Cm-alpha, Th-230 and the different uranium isotopes are taken from Frischknecht (2000) and converted to Co-60 to air equivalents.

## 4.4 From midpoint to endpoint

Endpoint characterization factors (CFe) for damage to human health are calculated by:

$$CFe_{x,i,c} = IRP_{x,i,c} \times F_{M\rightarrow,E,IR,c}$$

whereby $IRP_x$ is the ionizing radiation potential of substance *x* to emission compartment *i* (in Co-60 to air eq/kg) and $F_{M\rightarrow,E,IR,c}$ is the midpoint to endpoint factor for ionizing radiation (DALY/kg Co-60 to air eq.) for cultural perspective *c*.

The effect of receiving a collective dose of radiation was derived from studies conducted on occupational exposure and from long-term effect studies conducted on the citizens of Hiroshima and Nagasaki. In these cases, people were exposed to medium and high doses of radiation. The effect on the incidence of different cancer types was assessed by taking the fatal and non-fatal cancer incidence per cancer type from Frischknecht et al. (2000).
It is not certain that every cancer type can be caused by ionizing radiation, but it is certain that, in general, exposure to ionizing radiation causes an increased risk of cancer. The added risk of fatal cancers (all types combined) is 0.05 cases per man.Sv. For non-fatal cancers this is 0.12 cases per man.Sv. Because these effect values were based on medium to high exposure and the characterization factors applied in LCA refer to much lower doses, the question of how this effect data should be extrapolated to low doses is under discussion. Extrapolation is done by the so-called dose and dose-rate effectiveness factor (DDREF). This

value is used to correct the extra risk per man. Sv from high dose exposure to low dose exposure. A DDREF value of 2, for example, means that the additional risk from 1 man.Sv is twice as high at high doses, as at low doses this value is considered to be conservative and is therefore implemented for the Egalitarian perspective (Frischknecht et al. 2000). Values of 6 and 10 are used for the hierarchist and individualist perspectives, respectively. Severe hereditary effects are also taken into account. A dose of 1 man.Sv is estimated to cause 0.01 new cases of hereditary diseases.

The disability weight per cancer type was taken from De Schryver et al. (2011) for fatal cancer incidences and from Frischknecht et al. (2000) for the non-fatal incidence. No age weighting or discounting was taken into account. Frischknecht et al. (2000) expect approximately half of the severe hereditary effects to result in immediate death and the other half in a severe disease with a disability weight of 0.4, resulting in 57 DALYs per case of severe hereditary disease. The corresponding midpoint to endpoint factors (in DALY/kBq Co-60 to air equivalents) were derived for the three different cultural perspectives (Table 3.3) according to the following equation:

$$F_{M\rightarrow,E,IR,c} = CD_{Co-60,air} \times \sum_{j} EF_{j,c} \times DF_{j}$$

Whereby $EF_{j,c}$ is the modelled extra incidence per disease type *j* for perspective *c* and DF is the corresponding damage factor (DALY/incidence) for disease type *j*.

*Table 4.3. Midpoint to endpoint factors for the Individualist, Hierarchist and Egalitarian perspectives (DALY/kBq Co-60 emitted to air eq).*

| **Midpoint to endpoint** | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|
| **Human health** | 6.8E-09 | 8.5E-09 | 1.4E-08 |

# 5 Fine particulate matter formation

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This chapter is primarily based on Van Zelm et al. (2016), while the previous chapter in the ReCiPe report was mainly based on Van Zelm et al. (2008). Changes introduced compared with the ReCiPe2008 chapter are:

- The European factor has been replaced by a world average factor, based on region-specific factors.
- Lung cancer and cardiovascular mortality have been included, no morbidity.
- Value choices have been added.
- World-region specific characterization factors have been added.

## 5.1 Impact pathways and affected areas of protection

Air pollution that causes primary and secondary aerosols in the atmosphere can have a substantial negative impact on human health, ranging from respiratory symptoms to hospital admissions and death (WHO 2006, Friedrich et al. 2011, Burnett et al. 2014, Lelieveld et al. 2015). Fine Particulate Matter with a diameter of less than 2.5 µm (PM2.5) represents a complex mixture of organic and inorganic substances. PM2.5 causes human health problems as it reaches the upper part of the airways and lungs when inhaled. Secondary PM2.5 aerosols are formed in air from emissions of sulfur dioxide ($SO_2$), ammonia (NH3), and nitrogen oxides ($NO_x$), among other elements (WHO 2003).
WHO studies show that the mortality effects of chronic PM exposure are likely to be attributable to PM2.5 rather than to coarser particles of PM. Particles with a diameter of 2.5–10 µm (PM2.5–10) are related to respiratory morbidity (WHO 2006).

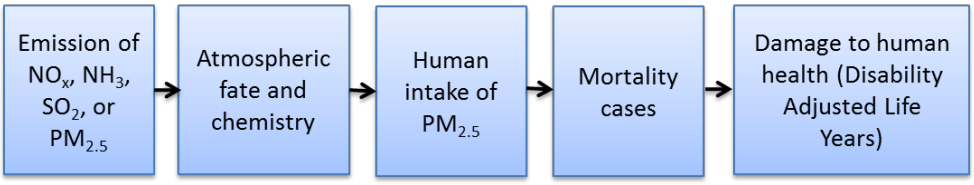


*Figure 5.1. Cause-and-effect chain, from fine dust formatting emissions to damage to human health.*

The modelling from emission to damage was divided into five consecutive steps, shown in Figure 5.1. 1) An emission of $NO_x$, $NH_3$, $SO_2$ or primary PM2.5 is followed by 2) atmospheric fate and chemistry in the air; $NO_x$, $NH_3$, and $SO_2$ are transformed in air to secondary aerosols. Subsequently, 3) PM2.5 can be inhaled by the human population, leading to 4) increased number of mortality cases in humans, and 5) final damage to human health. No thresholds for PM2.5 effects were assumed in the effect calculations. After thorough examination of all available evidence, a review by a WHO working group (WHO 2004) concluded that most epidemiological studies on large populations have been unable to identify a threshold concentration below which ambient

PM has no effect on mortality and morbidity. To express the life years affected by respiratory health damage due to exposure to PM2.5, Disability Adjusted Life Years (DALY) are used as a measure.

## 5.2 Value choices

For human health damage due to fine dust, the time horizon is not important as only short-living substances are involved. For the number of secondary substances included, we follow the choices of De Schryver et al. (2011). Inclusion or exclusion depends on the level of knowledge about the effects or exposure assumed for each perspective. The effects of secondary particulates from $SO_2$, $NH_3$ and $NO_x$ are all excluded for the individualist perspective, whereas the effects from $NH_3$ and $NO_x$ are excluded for the hierarchist perspective.

*Table 5.1. Value choices in modelling the effect of fine particulate matter formation.*

| Choice category | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|
| **Included effects** | Primary aerosols | Primary aerosols, secondary aerosols from $SO_2$ | Primary aerosols, secondary aerosols from $SO_2$, $NH_3$ and $NO_x$ |

## 5.3 Characterization factors at midpoint level

For the midpoint characterization factors of damage to human health due to PM2.5, the intake of a pollutant is important, as the effect and damage are precursor substance independent. The intake fraction (iF) of fine particulate matter due to emissions in region i is determined per precursor *x* ($iF_{x,i}$). Particulate matter formation potentials (PMFP) are expressed in primary PM2.5-equivalents by dividing $iF_{x,i}$ with the emission-weighted world average iF of PM2.5:

$$PMFP_{x,i} = \frac{iF_{x,i}}{iF_{PM2.5,world}}$$

The region-specific intake fraction was defined as the sum in the change in intake rate of PM2.5 in each receiving region j, due to a change in emission of a precursor substance in region *i* ($dM_{x,i}$). The intake rate can be calculated by multiplying the change in concentration of PM2.5 in each receptor region ($dC_{k,j}$) by the population ($N_j$) in the receptor region *i* and the average breathing rate per person (BR):

$$iF_{x,i} = \frac{\sum_j dC_j \cdot N_j \cdot BR}{dM_{x,i}}$$

The change in the ambient concentration of PM2.5 after the emission of a precursor is predicted with the emission – concentration sensitivity matrices for emitted precursors from the global source-receptor model TM5-FASST (FAst Scenario Screening Tool for Global Air Quality and Instantaneous Radiative Forcing), based on perturbation runs with TM5 (Van Dingenen et al. 2009, Krol et al. 2005). TM5 is a global chemical transport model hosted by the European Commission Joint Research Centre (JRC). TM5-FASST takes into account spatial features at the

emission site, as well as dispersion characteristics for the whole world. In this model, the world is divided into 56 source and an identical 56 receptor regions. The regions correspond to countries or a group of countries. The TM5 model output consists of the change in concentration for each receptor region, derived from gridded 1°×1° concentration results, following a change in emission, and is determined by lowering the year 2000 emissions (Lamarque et al. 2010) by 20% for each of the 56 source regions sequentially. The emission-normalized differences in a PM2.5 concentration between the unperturbed and perturbed cases, aggregated over each receptor region, are stored as the emission – concentration matrix elements. This procedure was performed for each source region and each precursor substance, i.e. $NH_3$, $NO_x$, $SO_2$, and primary PM2.5.

Table 5.2 shows the world average midpoint factors for PM2.5. Region-specific factors are given in the supporting information (Table S1.1).

*Table 5.2: World average particulate matter formation potentials of emitted substance x.*

| Pollutant | Emitted substance | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|---|
| Particulate Matter Formation Potential ($PM_{2.5}$-eq/kg) | | | | |
| $PM_{2.5}$ | $NH_3$ | - | - | 0.24 |
| | $NO_x$ | - | - | 0.11 |
| | $SO_2$ | - | 0.29 | 0.29 |
| | $PM_{2.5}$ | 1 | 1 | 1 |

To derive PMFPs for similar substances, conversion based on mole mass could be applied. E.g. for SO and $SO_3$ the CFs would become 0.39 and 0.23 respectively. For NO, $NO_2$, and $NO_3$ the factors would become 0.17, 0.11 and 0.08 respectively.

## 5.4 Characterization factors at endpoint level

World-average endpoint characterization factors ($CF_{e,x,i}$) for human health damage due to particulate matter formation of precursor *x* were calculated by:

$$CF_{e,x,world} = PMFP_{x,world} \times F_{M \to E,PM2.5}$$

whereby $F_{M \to E,PM2.5}$ is the midpoint to endpoint factor for the world average particulate matter formation characterization factors in (yr/kg PM2.5-eq). To keep a consistent midpoint to endpoint factor, this factor equals the world average endpoint characterization factor for particulate matter impacts due to primary PM2.5 emissions:

$$F_{M\rightarrow E,PM_{2.5}} = CF_{e,PM2.5,world} = \sum_i \left( \sum_j \left( \left( iF_{PM2.5,i\rightarrow j} \right) \cdot \sum_h \left( EF_{h,j} \cdot DF_{h,j} \right) \right) \cdot Em_{NOx,i} \right) / \sum_i Em_{PM2.5,i}$$

whereby $iF_{PM2.5,i\rightarrow j}$ is the dimensionless population intake fraction of particulate matter in receptor region *j* (in kg/year) following an emission change of primary PM2.5 in source region *i* (in kg/year), $EF_{h,j}$ is the cases of health effect h per kg of inhaled PM2.5, and $DF_h$ is the damage factor, which describes the disability adjusted life years per case of health effect *h*. Since all data for the effect factor are based on the population ≥ 30 years of age, only this part of the population was included for the effect factors, assuming no effects for younger people. Effect and damage factors were determined for cardiopulmonary and lung cancer mortality due to PM2.5 for two reasons: firstly, these contribute by far the most to overall disability adjusted life years (e.g. as shown in previous research (Van Zelm et al. 2008), and secondly, for these the most up-to-date and least uncertain data, related to relative risks and years of life lost are available (see e.g. Anenberg et al. 2010, Friedrich et al. 2011, Murray et al. 2012, WHO 2013). Midpoint to Endpoint conversion factors for PM2.5 emissions, related to human health effects, are shown in Table 5.3. Region-specific endpoint characterization factors, combining region-specific fate and effect factors following Van Zelm et al. (2016), are shown in the supporting information (Table S1.2).

*Table 5.3. Midpoint to endpoint conversion factors for human health damage (yr/kg PM2.5-eq).*

| **Pollutant** | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|
| $PM_{2.5}$ | 6.29 x$10^{-4}$ | 6.29 x$10^{-4}$ | **$10^{-4}$** |

# 6 Photochemical ozone formation

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This chapter is primarily based on Van Zelm et al. (2016), while the previous chapter was mainly based on Van Zelm et al. (2008). Changes introduced compared with the ReCiPe2008 chapter are:

- The European factor was replaced by a world average factor, based on region-specific factors;
- Respiratory mortality has been included;
- NOx equivalents instead of NMVOC equivalents, because NMVOC is a mixture of substances;
- To derive intake fractions for individual VOCs, the latest POCPs from Derwent et al. (2007b) were used;
- Damage to terrestrial ecosystems was included as well;
- World-region-specific characterization factors were added.

## 6.1 Impact pathways and affected areas of protection

Air pollution that causes primary and secondary aerosols in the atmosphere can have a substantial negative impact on human health, ranging from respiratory symptoms to hospital admissions and death (Bell et al. 2005, WHO 2006, Friedrich et al. 2011, Jerrett et al. 2009, Lelieveld et al. 2015). Ozone is not directly emitted into the atmosphere, but it is formed as a result of photochemical reactions of NOx 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 respiratory distress in humans, such as asthma and Chronic Obstructive Pulmonary Diseases (COPD). Additionally, ozone can have a negative impact on vegetation, including a reduction of growth and seed production, an acceleration of leaf senescence and a reduced ability to withstand stressors (see e.g. Ashmore 2005, Gerosa et al. 2015). Ozone formation is a non-linear process that depends on meteorological conditions and background concentrations of NOx and NMVOCs (European Environment Agency 2005).

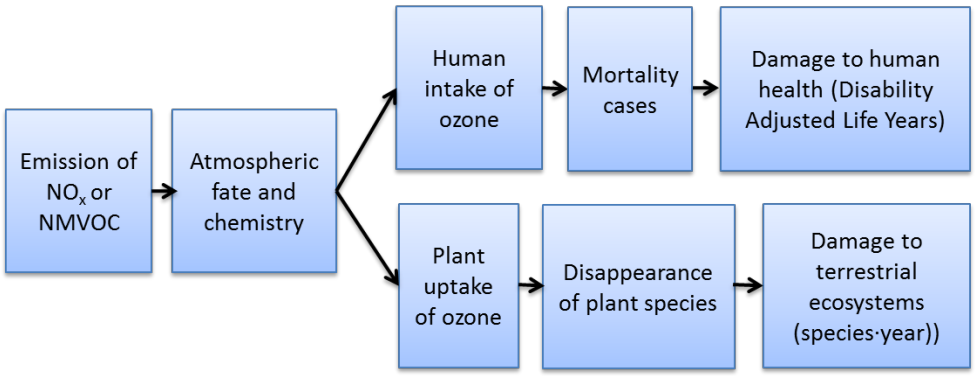


*Figure 6.1. Cause-and-effect chain, from ozone formatting emissions to damage to human health and ecosystems.*

The modelling from emission to damage was divided into five consecutive steps, shown in Figure 6.1. 1) An emission of $NO_x$ or NMVOC is followed by 2) atmospheric fate and chemistry in the air. $NO_x$ and NMVOCs are transformed in air to ozone. Subsequently, 3) ozone can be inhaled by the human population or taken up by plants, leading to 4) increased number of mortality cases among humans and detrimental effects on plant species, and 5) final damage to human health and ecosystems. No thresholds for ozone effects were assumed in the effect calculations. To express the life years affected by respiratory health damage due to exposure to ozone, Disability Adjusted Life Years (DALY) are used as a measure. To express the damage to terrestrial species affected due to exposure to ozone, species·yr is used as a measure.

## 6.2 Value choices

For damage due to ozone, the time horizon is not important as only short-living substances are involved. No other value choices were identified for this impact category.

## 6.3 Characterization factors at midpoint level

### *6.3.1 Human health damage*

For the midpoint characterization factors of damage to human health due to ozone, the intake of a pollutant is important, as the effect and damage is precursor substance independent. The intake fraction (iF) of ozone due to emissions in region i is determined per precursor *x* ($iF_{x,i}$). Human health Ozone formation potentials (HOFP) are expressed in $NO_x$-equivalents by dividing $iF_{x,i}$ by the emission-weighted world average iF of $NO_x$:

$$HOFP_{x,i} = \frac{iF_{x,i}}{iF_{NOx,world}}$$

The region-specific intake fraction was defined as the sum in the change in the ozone intake rate in each receiving region *j*, due to a change in emission of a precursor substance in region *i* ($dM_{x,i}$). The intake rate can be calculated by multiplying the change in concentration of ozone in each receptor region ($dC_{k,j}$) by the population ($N_j$) in the receptor region *i* and the average breathing rate per person (BR):

$$iF_{x,i} = \frac{\sum_j dC_j \cdot N_j \cdot BR}{dM_{x,i}}$$

The change in ambient concentration of ozone after the emission of a precursor is predicted with the emission – concentration sensitivity matrices for emitted precursors from the global source-receptor model TM5-FASST (FAst Scenario Screening Tool for Global Air Quality and Instantaneous Radiative Forcing), based on perturbation runs with TM5 (Van Dingenen et al. 2009, Krol et al. 2005). TM5 is a global chemical transport model hosted by the European Commission Joint Research Centre (JRC). TM5-FASST takes into account spatial features at the emission site, as well as dispersion characteristics for the whole world. In this model, the world is divided into 56 source and an identical 56 receptor regions. The regions correspond to countries or a group of countries. The TM5 model output consists of the change in concentration for each receptor region, derived from gridded 1°×1° concentration results, following a change in emission, and is determined by lowering the year 2000 emissions (Lamarque et al. 2010) by 20% for each of the 56 source regions sequentially. The emission-normalized differences in pollutant concentration between the unperturbed and perturbed cases, aggregated over each receptor region, are stored as the emission – concentration matrix elements. This procedure was performed for each source region and for $NO_x$, as well as NMVOC.

Table 6.1 shows the world average HOFPs. Region-specific factors are given in the supporting information (Table S2.1).

*Table 6.1. World average human health ozone formation potentials ($NO_x$-eq/kg) of emitted substance x.*

| Pollutant | Emitted substance | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|---|
| Ozone | $NO_x$ | 1 | 1 | 1 |
| | NMVOC | 0.18 | 0.18 | 0.18 |

To derive HOFPs for similar substances, conversion based on mole mass could be applied. E.g. for NO, $NO_2$, and $NO_3$ the factors would become 1.53, 1 and 0.74 respectively.

The midpoint factors of NMVOCs do not differentiate between ozone formation by single hydrocarbons. But reactivity among single hydrocarbons varies. 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 instances of relative reactivity, 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 derive intake fractions for individual VOCs, the latest POCPs from Derwent et al. (2007b) were used. The average POCP for NMVOCs was taken from Derwent et al. (2007a). The following equation was used to calculate the HOFP for a specific hydrocarbon:

$$HOFP_x = \frac{POCP_x}{POCP_{NMVOC}} \times HOFP_{NMVOC}$$

Table S2.2 in the supporting information shows midpoint factors for individual NMVOCs (equal for each perspective).

### 6.3.2 *Terrestrial ecosystem damage*

For the midpoint characterization factors of terrestrial ecosystem damage due to ozone forming emissions, the fate of a pollutant is important, as the effect is precursor substance independent. The fate factor (FF) for ozone formation due to emissions in region *i* is determined per precursor *x* ($FF_{x,i}$). The Ecosystem Ozone Formation Potential (EOFP), expressed in kg NOx equivalents, is calculated by dividing $FF_{x,i}$ by the emission-weighted world average FF of $NO_x$:

$$EOFP_{x,i} = \frac{FF_{x,i}}{FF_{NOx,world\ average}}$$

To determine the ecosystem fate factor, the AOT40 – i.e. the sum of the differences between the hourly mean ozone concentration and 40 ppb during daylight hours over the relevant growing season in ppm·h – was used as metric of the cumulative concentration change and derived with the TM5-FASST model. The fate factor then represents the sum in the change in AOT40 in each receiving grid *g*, due to a change in the emission of precursor x in region *i* (Van Goethem et al. 2013b):

$$\mathrm{FF_{x,i\rightarrow g}} = \sum_g \frac{\Delta AOT40_g}{\Delta M_{x,i}}$$

Monthly AOT40 concentrations per unit of emission of $NO_x$ and NMVOC were calculated on a 1°x1° grid resolution from hourly ozone concentrations resulting from the year 2000 reference run with TM5-CTM. To derive the AOT40, the longest growing season (i.e. for forests) was taken, which is from April to September for the Northern Hemisphere (Van Goethem et al. 2013b), and from October to March for the Southern Hemisphere (Van Zelm et al. 2016).
Table 6.2 shows the world average EOFPs. Region-specific factors are given in the supporting information (Table S2.1).

*Table 6.2. World average ecosystem damage ozone formation potentials ($NO_x$-eq/kg) of emitted substance x.*

| Pollutant | Emitted substance | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|---|
| Ozone | $NO_x$ | 1 | 1 | 1 |
| | NMVOC | 0.29 | 0.29 | 0.29 |

To derive EOFPs for similar substances, conversion based on mole mass could be applied. E.g. for NO, $NO_2$, and $NO_3$ the factors would become 1.53, 1 and 0.74 respectively.

The following equation was used to calculate the EOFP for a specific hydrocarbon:

$$EOFP_x = \frac{POCP_x}{POCP_{NMVOC}} \times EOFP_{NMVOC}$$

Table S2.4 in the supporting information shows midpoint factors for individual NMVOCs (equal for each perspective).

## 6.4 Characterization factors at endpoint level

### *6.4.1 Damage to human health*

World-average endpoint characterization factors ($CF_{e,x,i}$) for human health damage due to ozone formation of precursor x were calculated by:

$$CF_{e,x,world} = HOFP_{x,world} \times F_{M \to E,HO3}$$

whereby $F_{M \to E,HO3}$ is the midpoint to endpoint factor for the world average of damage to human health from ozone formation (yr/kg $NO_x$-eq). To keep a consistent midpoint to endpoint factor, this factor equals the emission-weighted world average endpoint characterization factor for ozone impacts due to $NO_x$:

$$F_{M \to E,NO_x} = CF_{e,NO_x,world} = \sum_i \left( \sum_j \left( \left( iF_{NOx,i \to j} \right) \cdot \sum_h \left( EF_{h,j} \cdot DF_{h,j} \right) \right) \cdot Em_{NOx,i} \right) / \sum_i Em_{NOx,i}$$

whereby $iF_{NOx,\ i \to}j$ is the dimensionless population intake fraction of ozone in receptor region *j* (in kg/year) following an emission change of $NO_x$ in source region *i* (in kg/year), $EF_{h,j}$ is the cases of health effect *h* per kg of inhaled ozone, $DF_h$ is the damage factor, which describes the years of life lost per case of health effect *h*, and $Em_{NOx,i}$ is the emission of $NO_x$ in region *i*. Since all data for the effect factor are based on the population ≥ 30 years of age, only this part of the population was included for the effect factors, assuming there were no effects for younger people. Effect and damage factors were determined for respiratory mortality due to ozone for two reasons: firstly, they contribute by far the most to overall disability adjusted life years, and secondly, the most up-to-date and least uncertain data related to relative risks and years of life lost are available for them (see e.g. Anenberg et al. 2010, Friedrich et al. 2011, Murray et al. 2012, WHO 2013).

Midpoint to Endpoint conversion factors for ozone emissions, related to human health effects, are shown in Table 6.5. Region-specific endpoint characterization factors, combining region-specific fate and effect factors following Van Zelm et al. (2016), are shown in the supporting information (Table S2.3).

*Table 6.5. Midpoint to endpoint conversion factors for damage to human health (yr/kg NOx-eq).*

| Pollutant | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|
| Ozone | $9.1 \times 10^{-7}$ | $9.1 \times 10^{-7}$ | $9.1 \times 10^{-7}$ |

### 6.4.2 *Terrestrial ecosystem damage*

Endpoint characterization factors (CFe) for terrestrial ecosystem damage are calculated by:

$$CF_{e,x,i} = EOFP_{x,i} \times F_{M \to E,O3}$$

whereby $F_{M \to E,O3}$ is the midpoint to endpoint factor for terrestrial ecosystem damage (species·year/kg $NO_x$-eq). This midpoint to endpoint factor equals the emission-weighted world average endpoint characterization factor for $NO_x$:

$$F_{M \to E,EO3} = CF_{e,NO_x,world} = SD_{terr} \cdot \sum_i \left( \sum_g \sum_n \left( FF_{NOx,i \to g} \cdot EF_{n,g} \right) \cdot Em_{NOx,i} \right) / \sum_i Em_{NOx,i}$$

whereby $EF_j$ is the effect factor in receiving grid *g*, $SD_{terr}$ the species density, and $Em_{NOx,i}$ is the emission of $NO_x$ in grid *i*. The average species density for terrestrial ecosystems approximates $1.48.10^{-8}$ species·$m^{-2}$ (Goedkoop et al. 2009).
The effect factor describes the change in the potentially disappeared fraction (PDF) of forest and grassland species due to the change in ground level ozone exposure over the forest and grassland areas. In the calculation of the effect factors, the growing season of forest and grassland species were taken into account. For the Northern Hemisphere, the growing season for grassland species was taken as May to July, and for the Southern Hemisphere from November to January. The effect factor was determined with data on AOT40 concentrations for which 50% reduction in productivity (EC50) was found for a number of forest or grassland species (Van Goethem et al. 2013a, b). The linear ecosystem effect factor was taken, assuming a linear change in PDF with changing AOT40, that represents the average effect between a PDF of 0.5 and 0 (Van Goethem et al. 2013b).

Table 5.6 shows the midpoint to endpoint conversion factors for ecosystem damage due to ozone formation. Region-specific endpoint characterization factors, combining region-specific fate and effect factors following Van Zelm et al. (2016), are shown in the supporting information (Table S2.3).

*Table 6.6. Midpoint to endpoint conversion factors for ecosystem damage due to ozone formation (species·yr/kg $NO_x$-eq).*

| | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|
| Midpoint to endpoint factor | $1.29 \cdot 10^{-7}$ | $1.29 \cdot 10^{-7}$ | $1.29 \cdot 10^{-7}$ |

# 7 Terrestrial acidification

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This chapter is primarily based on Roy et al. (2014). Changes introduced compared with the ReCiPe2008 chapter are:

- The European factor was replaced by a world average factor, based on grid-specific factors.
- Soil sensitivity was based on pH indicator H+ concentration instead of base saturation.
- Effects on all vascular plant species included, not only forest species.
- No value choices included.
- Country specific characterization factors have been provided as well.

## 7.1 Impact pathways and affected areas of protection

Atmospheric deposition of inorganic substances, such as sulphates, nitrates and phosphates, cause a change in acidity in the soil. For almost all plant species, there is a clearly defined optimum level of acidity. A serious deviation from this optimum level 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 a species occurrence (Goedkoop et al. 1999, Hayashi et al. 2004). Major acidifying emissions are $NO_x$, $NH_3$, or $SO_2$ (Van Zelm et al. 2015). This chapter describes the calculation of characterization factors for acidification for vascular plant species in biomes worldwide. Fate factors, accounting for the environmental persistence of an acidifying substance, can be calculated with an atmospheric deposition model, combined with a geochemical soil acidification model (Roy et al. 2012a,b, Van Zelm et al. 2007b). Effect factors, accounting for the ecosystem damage caused by an acidifying substance, can be calculated with dose-response curves of the potential occurrence of plant species, derived from logistic regression functions (Azevedo et al. 2013c). For acidification, we divided the endpoint modelling from emission to damage into six consecutive steps, shown in Figure 7.1. An emission of $NO_x$, $NH_3$ or $SO_2$ is followed by atmospheric fate before it is deposited on the soil. Subsequently, it will leach into the soil, changing the soil solution $H^+$ concentration. This change in acidity can affect the plant species living in the soil, causing them to disappear.

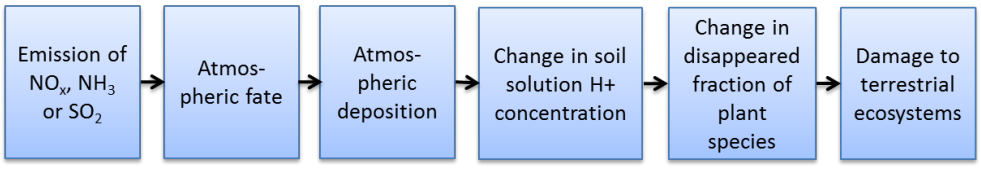


*Figure 7.1. Cause-and-effect chain, from acidifying emissions to relative species loss in terrestrial ecosystems.*

## 7.2 Value choices

No value choices were considered for acidification.

## 7.3 Characterization factors at midpoint level

For the midpoint characterization factors of terrestrial ecosystem damage due to acidifying emissions, the fate of a pollutant in the atmosphere and the soil is important, as the effect is precursor substance independent. The fate factor (FF) for acidification due to emissions in grid i is determined per precursor *x* ($FF_{x,i}$). The Acidification Potential (AP), expressed in kg $SO_2$ equivalents, is calculated by dividing $FF_{x,i}$ by the emission-weighted world average FF of $SO_2$:

$$AP_{x,i} = \frac{FF_{x,i}}{FF_{SO2,world\ average}}$$

The AP quantifies the soil acidity a substance emission can enhance relative to $SO_2$. The midpoint characterization factor was calculated in two steps. Firstly, grid-specific changes in acid deposition were calculated, following grid-specific changes in air emission (Roy et al. 2012b). These atmospheric fate factors [keq × $kgemitted^{-1}$]) represent the climatic conditions (e.g. wind speed and direction) and deposition mechanisms between the source and a receptor locations in a single fraction. Roy et al. (2012b) developed a simplified methodological approach to derive source-receptor matrices by considering the outcomes (i.e. weekly averaged emissions, depositions, mass fluxes in and out of air compartments) from an annual GEOS-Chem (Bey et al., 2001) simulation. GEOS-Chem is a 3D model of tropospheric chemistry, driven by assimilated meteorological observations from the Goddard Earth Observing System (GEOS) of the NASA Data Assimilation Office (Bey et al., 2001). The GEOS-Chem simulation, from which the atmospheric fate factors were derived, was on a 2° × 2.5° grid spatial resolution with meteorological data for 2005, which was representative of meteorology of the average from 1961 to 1990.
Secondly, soil sensitivity (mol $H^{+}\cdot L^{-1}\cdot m^{2}\cdot keq^{-1}\cdot yr$) was determined as the receptor change (if any) in soil properties over a certain area due to a certain deposition in a single fraction. For this, Roy et al. (2012a) used the geochemical steady-state model PROFILE (Warfvinge and Sverdrup, 1992) to calculate spatially explicit changes in soil H+ concentration due to a 10% change in deposition. PROFILE relies on mass balance calculations of different soil layers as a way to estimate several soil indicator values in the soil layer solution from given atmospheric deposition, weather characteristics (e.g. temperature, precipitation) and soil parameters (e.g. soil density, mineralogy, vegetation uptake). H+ concentration was chosen as soil indicator since it represented most accurately the most sensitive zones in the world, while also being less sensitive to parameter uncertainty (Roy et al. 2012a).
In equation, the fate factor reads:

$$FF_{x,i} = \sum_{j} FF_{air,x,i\rightarrow j} \times FF_{soil,x,j}$$

See Table 7.2 for the resulting world average APs. Country-specific factors are given in the supporting information (Table S3.1). Country-

specific and world-average factors are emission-weighted using grid-level data for base year 2005 from Roy et al. (2012b).

*Table 7.2. World average terrestrial acidification potential emissions of $NO_x$, $NH_3$ and $SO_2$ to air (in kg $SO_2$-equivalents/kg).*

| Substance | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|
| $NO_x$ | 0.36 | 0.36 | 0.36 |
| $NH_3$ | 1.96 | 1.96 | 1.96 |
| $SO_2$ | 1.00 | 1.00 | 1.00 |

To derive CFs for similar substances, conversion based on mole mass could be applied. E.g. for SO, SO3 and $H_2SO_4$ the CFs would become 1.33, 0.8, and 0.65 respectively. For NO, $NO_2$, and $NO_3$ the factors would become 0.55, 0.36 and 0.27 respectively.

## 7.4 From midpoint to endpoint

Endpoint characterization factors (CFe) for terrestrial ecosystem damage are calculated by:

$$CF_{e,x,i} = AP_{x,i} \times F_{M \to E,ACI}$$

whereby $F_{M \to E,ACI}$ is the midpoint to endpoint factor for terrestrial acidification (species·year/kg $SO_2$-eq).

To keep a consistent midpoint to endpoint conversion factor, this midpoint to endpoint factor for terrestrial acidification equals the emission-weighted world average endpoint characterization factor for $SO_2$:

$$F_{M \to E,ACI} = CF_{e,SO_2,world} = SD_{terr} \cdot \sum_i \left( \sum_j \left( FF_{air,SO2,i \to j} \cdot FF_{soil,SO2,j} \cdot EF_j \right) \cdot Em_{SO2,i} \right) / \sum_i Em_{SO2,i}$$

whereby $EF_j$ is the effect factor in receiving grid *j*, $SD_{terr}$ the species density, and $Em_{SO2,i}$ is the emission of $SO_2$ in grid *i*. The average species density for terrestrial ecosystems approximates $1.48.10^{-8}$ species·$m^{-2}$ (Goedkoop et al. 2009). The effect factor describes the $H^+$ concentration–species relationship by evaluating the absence of the species following pH declines. Biome-specific effect factors were determined as the marginal change in the Potentially Disappeared Fraction of vascular plant species (PDF) due to a marginal change in the H+ concentration (Roy et al. 2014). The soil $H^+$ concentration from the PROFILE model was used as the working point for the effect factor. Each soil j was allocated to its respective biome using the map by Olson et al. (2001). Biome-specific coefficients to determine the logistic regression of the concentration-response relationships are provided in Roy et al. (2014), following the method and data from Azevedo et al. (2013c).

Table 7.2 shows the midpoint to endpoint conversion factors for acidification. Country-specific endpoint characterization factors are in the supporting information (Table S3.2).

*Table 7.2. Midpoint to endpoint conversion factors for acidification (species·yr/kg $SO_2$-eq).*

| | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|
| Midpoint to endpoint factor | $2.12 \cdot 10^{-7}$ | $2.12 \cdot 10^{-7}$ | $2.12 \cdot 10^{-7}$ |

To derive CFs for similar substances, conversion based on mole mass could be applied. E.g. for SO and $SO_3$ the CFs would become 1.33 and 0.8 respectively.

# 8 Freshwater eutrophication

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This chapter is primarily based on Helmes et al. (2012), Azevedo et al. (2013a), Azevedo et al. (2013b), and Azevedo (2014). Changes introduced compared with the ReCiPe2008 report are:

- The European characterization factor was replaced by a world average factor, based on grid-specific factors.
- Fate factors were derived using a state-of-the-art global fate model for phosphorus instead of a European fate model.
- The effect factor was updated based on Azevedo et al. (2013b, 2014), including heterotrophic and autotrophic species.
- No marine eutrophication was included, because there is no endpoint model.

## 8.1 Impact pathways and affected areas of protection

Freshwater eutrophication occurs due to the discharge of nutrients into soil or into freshwater bodies and the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen. Environmental impacts related to freshwater eutrophication are numerous. They follow a sequence of ecological impacts offset by increasing nutrient emissions into fresh water, thereby increasing nutrient uptake by autotrophic organisms such as cyanobacteria and algae, and heterotrophic species such as fish and invertebrates. This ultimately leads to relative loss of species. In this work, emission impacts to fresh water are based on the transfer of phosphorus from the soil to freshwater bodies, its residence time in freshwater systems and on the potentially disappeared fraction (PDF) following an increase in phosphorus concentrations in fresh water (Figure 8.1).

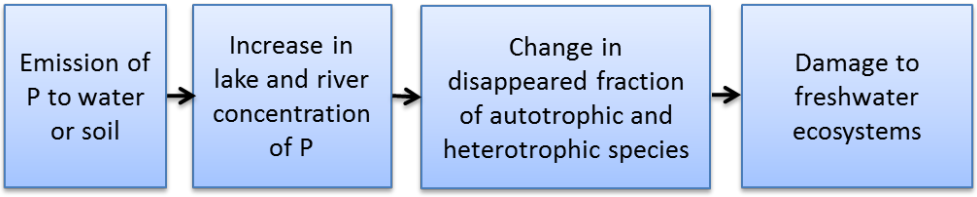


*Figure 8.1. Cause-and-effect chain for Phosphorus emissions causing loss of freshwater species richness.*

## 8.2 Value choices

There are no value choices considered in the modelling of fate and effects of P emissions.

## 8.3 Characterization factors at midpoint level

Helmes et al. (2012) derived fate factors (FFs) for phosphorus emissions to fresh water, based on a new global fate model on a half-degree grid resolution. The removal processes taken into account are grid-specific advection, phosphorus retention and water use. The FF represents the net residence time in the freshwater compartment (in years). The cumulative FF for an emission in a grid cell is the sum of the FFs for the individual cell of emission and of all downstream receptor grid cells j. Country and world aggregated fate factors were determined based on gridded population estimates, which served as a proxy for emission intensity of P in a grid. 0.5°×0.5° gridded population estimates of year 2000, taken from CIESIN et al. (2005), were used for this purpose.
With this method, we obtained a world average fate factor of P emissions to fresh water for 85 days (0.23 years). For emissions to agricultural soils, the FFs were multiplied by 0.1, as typically 10% of all P is transported from agricultural soil to surface waters (Bouwman et al. 2009). Emissions to seawater do not lead to freshwater eutrophication as there is no transport from seawater to fresh water. Here, we use the world average in the calculation of the freshwater eutrophication midpoint factors:

$$\mathrm{FEP}_{x,c,i} = \frac{\mathrm{FF}_{x,c,i}}{\mathrm{FF}_{P,fw,\text{world average}}}$$

whereby $FEP_{x,c,i}$ is the freshwater eutrophication potential of substance *x* for emission to compartment *c* in grid cell *i* (in kg P to freshwater equivalents /kg of substance *x* to compartment *c* in grid *i*), $FF_{x,c,i}$ is the fate factor of substance *x* emitted to compartment *c* in grid cell *i* (years) and $FF_{P,fw}$ is the world average fate factor of P emission to fresh water (85 days). To derive FEPs for phosphorus containing chemicals, conversion based on mole mass could be applied. E.g. the mole mass of $PO_4^{3-}$ is three times larger, so the FEPs are three times smaller. See Table 8.1 for the resulting world average FEPs. Applying the same method for phosphoric acid and phosphorus pentoxide leads to FEPs for emissions to freshwater of 0.32 and 0.22 kg P-eq. to freshwater/kg, respectively. Country-specific factors are given in the supporting information (Table S4.3).

*Table 8.1. Freshwater eutrophication potentials for phosphorus and phosphate to fresh water, agricultural soils and seawater (in kg P to freshwater-equivalents/kg), equal for all perspectives.*

| Substance | Emission compartment | FEP (kg P-eq to fresh water/kg) |
|---|---|---|
| Phosphorus (P) | fresh water | 1.00 |
| | agricultural soil | 0.10 |
| | seawater | 0 |
| Phosphate ($PO_4^{3-}$) | fresh water | 0.33 |
| | agricultural soil | 0.033 |
| | seawater | 0 |

## 8.4 From midpoint to endpoint

Endpoint characterization factors (CFe) for freshwater eutrophication ecosystem damage are calculated by:

$$CFe_{x,i} = FEP_{x,i} \times F_{M \to E,FE}$$

whereby $F_{M \to E,FE}$ is the midpoint to endpoint conversion factor for freshwater eutrophication (species·year/kg P to freshwater-eq).

To keep a consistent midpoint to endpoint conversion factor, this midpoint to endpoint factor for freshwater eutrophication equals the emission-weighted world average endpoint characterization factor for P emitted to fresh water:

$$\mathrm{F_{M \to E,FW}} = \mathrm{SD_{fw}} \times \sum_i \left( \sum_j \left( FF_{e,i,j} \cdot \overline{EF_j} \right) \cdot Em_{P,i} \right) / \sum_i Em_{P,i}$$

whereby $SD_{fw}$ the freshwater species density which approximates $7.89.10^{-10}$ species/$m^3$ (Goedkoop et al., 2009), $FF_{e,i,j}$ = the partial fate factor of P emitted to compartment *e* in grid cell *i* that travels to grid cell *j* (year), $EF_j$= the average effect factor of grid cell $_j$ (PDF/kg).
Note that we did not derive CFs if the emitting cell $_i$ was entirely deprived of water.
The average effect factor of grid cell *j* is averaged over the types of freshwater *w* (rivers or lakes), based on the fraction of their presence in that grid cell, and the two species groups (heterotrophs and autotrophs). The effect factor of species group *k* and water type *w* in grid cell *j* is described as:

$$EF_{w,k,j} = \frac{0.5}{10^{\alpha_{w,k,j}}}$$

whereby $\alpha_{w,k,j}$ = the total P level (log $m^3$/kg) in water type *w* (lakes or streams) of species group *k* (heterotrophs or autotrophs) in grid cell *j* at which the Potentially Disappeared Fraction of species (PDF) equals 50%. The effect factor was based on a probabilistic model of the cumulative Potentially Disappeared Fraction of species, as a logistic function of total P concentration (Azevedo et al. 2013a). Next to water and species type, the effect factor depends on the climate type (warm, temperate, xeric or cold). Only species disappearances with increasing P were included in the model. Possible new species occurrences with increasing P concentrations were excluded. The climate type per grid cell was identified based on the geographical location of each pixel and the respective effect factor was used. The effect factors and alphas for every climate-water, type-species group combination are given in the Supporting Information (Tables S4.1-S4.2).

The midpoint to endpoint conversion factor for freshwater eutrophication is given in Table 8.2. Emission-weighted country-specific endpoint characterization factors are given in the supporting information (Table S4.4).

*Table 8.2. Midpoint to endpoint conversion factor for freshwater eutrophication for all perspectives (species.yr/kg P-eq).*

| **Midpoint to endpoint factor** | **species.yr/kg P-eq** |
|---|---|
| Freshwater ecosystems | 6.1E-7 |

# 9 Toxicity

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This chapter is primarily based on the work conducted by Van Zelm et al. (2009, 2013). Changes introduced compared with the ReCiPe2008 chapter are:

- Separate midpoint factors for human cancer and non-cancer effects.
- Fate and exposure for dissociating organics were included.
- USEtox organic and inorganic database was implemented (3094 substances in total).
- Time horizon of 20 years were included for the Individualist perspective.
- Linear approach only for damage factor calculations.
- Effects on agricultural soil were excluded to prevent double counting with the land use impact category.

## 9.1 Impact pathways and affected areas of protection

The characterization factor of human toxicity and ecotoxicity accounts for the environmental persistence (fate), accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. Figure 9.1 shows the cause-effect pathway, from emission to the environment, via fate and exposure, to affected species and disease incidences, leading finally to damage to ecosystems and human health.

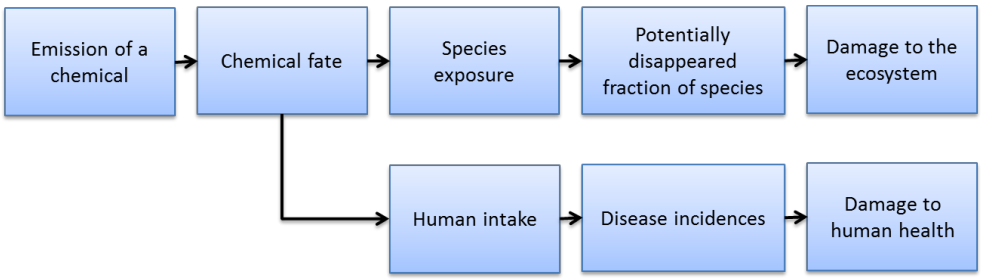


*Figure 9.1. Cause-and-effect chain, from emissions to damage to the ecosystem and damage to human health.*

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. We used the commonly applied multimedia fate, exposure and effects model, which is USES-LCA 2.0, the Uniform System for the Evaluation of Substances adapted for LCA (Van Zelm et al. 2009). USES-LCA 2.0 is a global multimedia fate, exposure and effects model. Environmental fate and exposure factors in multiple compartments and human intake fractions for inhalation and oral intake can be calculated for ten emission compartments. The fate part is time dependent; this is taken into account by USES-LCA 2.0 by allowing it to apply the model for various time horizons (20-100 years, and a steady-state option). The most recent updates of USES-LCA 2.0 are listed in the Supporting information (Section 5).

## 9.2 Value choices

Uncertainty due to value choices is handled via different cultural perspectives. Most of these choices reflect different opinions in effect and damage modelling. The choices associated with these three perspectives are summarized in Table 9.1.

### *9.2.1 Time horizon*

As shown by Huijbregts et al. (2001), the impact of metals largely depends on the time horizon of interest. We chose to define the egalitarian scenario with an infinite time horizon, while the hierarchic scenario uses a 100 year time horizon and individualist scenario takes a time horizon of 20 years.

### *9.2.2 Exposure routes*

The concept of bioconcentration, generally applicable for organic pollutants, might not hold for inorganics. For instance, Hendriks et al. (2001) showed that internal body concentrations of metals increase less than proportionally 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 occurs via all intake routes (air, drinking water, food). In contrast, the individualistic scenario assumes human exposure occurs via air and drinking water only.

### *9.2.3 Marine ecotoxicity*

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. The egalitarian and hierarchic scenarios include the sea and oceanic compartments in the calculation of the marine ecotoxicological impacts, while the individualistic scenario only includes the sea compartment in the calculations for essential metals. Essential metals are Cobalt, Copper, Manganese, Molybdenum and Zinc.

### *9.2.4 Carcinogenicity*

Concerning the carcinogenicity 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 World Health Organization (WHO), evaluated the carcinogenic risk of 844 substances (mixtures) to humans by assigning a carcinogenicity class to each substance (IARC 2004). The classes reflect the strength of the evidence for carcinogenicity derived from studies in humans and in experimental animals and from other relevant data. This information can be readily used to define two scenarios. The egalitarian and hierarchic scenarios include all 844 substances (IARC-category 1, 2A, 2B, 3 or no classification) and the individualistic scenario only includes the substances with strong evidence of carcinogenicity (IARC-category 1, 2A and 2B).

### 9.2.5 *Minimum number of tested species for ecotoxicity*

Uncertainty is relatively high for ecotoxicity effect factors in cases involving a low number of tested species, particularly lower than 4 species (Van Zelm et al. 2007a; Van Zelm et al. 2009). We have set the minimum number of tested species at 4 for the individualistic scenario, while no minimum requirements were set for the hierarchic and the egalitarian scenarios.

*Table 9.1. Value choices made in the three perspectives, adapted from De Schryver et al. (2011).*

| **Choice category** | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|
| Time horizon | 20 years | 100 years | Infinite |
| Exposure routes for human toxicity | Organics: all exposure routes. Metals: drinking water and air only | All exposure routes for all chemicals | All exposure routes for all chemicals |
| Environmental compartments for marine ecotoxicity | Sea + ocean for organics and non-essential metals. For essential metals, sea compartment included only, excluding oceanic compartments | Sea + ocean for all chemicals | Sea + ocean for all chemicals |
| Carcinogenicity | Only chemicals with TD50 classified as 1, 2A, 2B by IARC | All chemicals with reported TD50 | All chemicals with reported TD50 |
| Minimum number of tested species for ecotoxicity | 4 | 1 | 1 |

## 9.3 Characterization factors at midpoint level

The toxicity potential (TP), expressed in kg 1,4-dichlorobenzene-equivalents (1,4DCB-eq), is used as a characterization factor at the midpoint level for human toxicity, freshwater aquatic ecotoxicity, marine ecotoxicity and terrestrial ecotoxicity. The chemical 1,4-dichlorobenzene (1,4-DCB) is used as a reference substance in the midpoint calculations by dividing the calculated potential impact of the chemical by the potential impact of 1,4-DCB emitted to urban air for human toxicity, to fresh water for freshwater ecotoxicity, to seawater for marine ecotoxicity and to industrial soil for terrestrial ecotoxicity. Table 9.2 summarizes the

emission compartments, environments and human exposure routes that are included in the human TP calculations.

*Table 9.2. Emission compartments, environmental receptors and human exposure routes included.*

| Emission compartments | Environmental receptors | Human exposure routes |
|---|---|---|
| Urban air | Terrestrial environment (excl. agri land) | Inhalation |
| Rural air | Freshwater environment | Ingestion via root crops |
| Fresh water | Marine environment | Ingestion via leaf crops |
| Seawater | | Ingestion via meat products |
| Agricultural soil | | Ingestion via dairy products |
| Industrial soil | | Ingestion via eggs |
| | | Ingestion via freshwater fish |
| | | Ingestion via marine fish |
| | | Ingestion via drinking water |

The compartment-specific **ecotoxicological** midpoint characterization factor consists of a fate factor (FF), an effect factor (EF):

$$\mathrm{ETP}_{x,i,j,c} = \sum_{g} \frac{\mathrm{FF}_{x,i,j,g,c} \times \mathrm{EF}_{x,j,c}}{\mathrm{FF}_{\mathrm{DCB,ref},j,g,c} \times \mathrm{EF}_{\mathrm{DCB},j,c}}$$

- $\mathrm{ETP}_{j,i,x,c}$ is the ecological toxicity potential for receiving compartment *j* (fresh water, marine or terrestrial) of chemical *x* emitted to compartment i, transported to receiving compartment j, related to cultural perspective *c* (kg 1,4DCB-eq to fresh water for freshwater ecotoxicity, to sea (and ocean) water for marine ecotoxicity and to industrial soil for terrestrial ecotoxicity /kg).
- $\mathrm{FF}_{x,i,j,g,c}$ is the fate factor, defined as the marginal change in the steady state mass of substance *x* in an environmental compartment *j* at scale *g* due to a marginal emission in compartment *i* for cultural perspective *c* (years).
- $\mathrm{EF}_{x,j,c}$ is the effect factor ($m^3$/kg for marine and freshwater ecotoxicity, $m^2$/kg for terrestrial ecotoxicity), representing the change in Potentially Disappeared Fraction of species due to a change in the environmental concentration of substance *x* in receiving compartment *j* for cultural perspective *c*.

We included a linear concentration–response function with the average toxicity, based on acute data (EC50s), as a starting point. For the terrestrial environment, the effect factor was extrapolated from aquatic toxicity data with help of the equilibrium partitioning method (Golsteijn et al. 2013). With this method, it is assumed that chemical concentrations in pore water are the dominant exposure route for soil-dwelling organisms. When applying this method, it is assumed that the sensitivity of aquatic and terrestrial species is similar.

The **human toxicological** midpoint characterization factor consists of an intake fraction (iF), a combined effect and damage factor (EF) and

the characterization factor for 1,4-dichlorobenzene. This midpoint characterization factor (=toxicity potential) is specific for the compartment the substance has been emitted into, the intake route (oral or inhalation), scale (continental, moderate, tropic, arctic) and effect (carcinogenic, non-carcinogenic). All these toxicity potentials are aggregated to an overall human population characterization factor of substance x emitted to compartment i:

$$HTP_{i,x,c/nc,c} = \sum_{r}\sum_{g} \frac{iF_{x,i,r,g,c} \times EF_{x,r,c/\,nc,c}}{iF_{DCB,ua,r,g,c} \times EF_{DCB,r,c/nc,c}}$$

- $HTP_{i,x,c/\,nc,c}$ represents the human characterization factor at midpoint level for carcinogenic or non-carcinogenic effects of substances *x* to emission compartment *i* for cultural perspective *c* (kg 1,4DCB to urban air eq./kg).
- $iF_{x,i,r,g,c}$ is the human population intake fraction of substance *x* at geographical scale *g* via intake route *r* emitted to compartment *i* for cultural perspective *c* (Huijbregts et al. 2005).
- $EF_{x,r,c/nc,c}$ is the carcinogenic or non-carcinogenic effect factor of substance *x* for intake route *r* related to cultural perspective *c*, reflecting the change in lifetime disease incidence due to a change in intake of the substance and intake route of interest.

We work with a linear dose–response function for each disease endpoint and intake route. 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 cases in which chemical-specific information on absorption factors was lacking, complete oral and inhalational absorption was assumed.

As an example, Table 9.3 provides ETPs and HTPs of 1,4-DCB and Nickel for the three cultural perspectives and four emission compartments.

*Table 9.3. Midpoint characterisation factors (1,4-DCB eq/kg) for 1,4-DCB and Nickel.*

| Substance | Emission compart-ment | Individu-alist | Hierarchist | Egalita-rian |
|---|---|---|---|---|
| **Freshwater ecotoxicity** | | | | |
| 1,4-Dichlorobenzene | Urban air | 1.3E-03 | 1.3E-03 | 1.3E-03 |
| 1,4-Dichlorobenzene | Fresh water | **1** | **1** | **1** |
| 1,4-Dichlorobenzene | Seawater | 5.5E-04 | 5.4E-04 | 5.4E-04 |
| 1,4-Dichlorobenzene | Industrial soil | 3.2E-02 | 3.2E-02 | 3.2E-02 |
| Nickel | Urban air | 6.8E-01 | 2.2E+00 | 1.6E+01 |
| Nickel | Fresh water | 4.2E+01 | 4.6E+01 | 4.6E+01 |
| Nickel | Seawater | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Nickel | Industrial soil | 4.6E-01 | 3.2E+00 | 4.2E+01 |
| **Marine ecotoxicity** | | | | |

| Substance | Emission compart-ment | Individu-alist | Hierarchist | Egalita-rian |
|---|---|---|---|---|
| 1,4-Dichlorobenzene | Urban air | 1.5E-01 | 1.5E-01 | 1.5E-01 |
| 1,4-Dichlorobenzene | Fresh water | 1.8E-01 | 1.8E-01 | 1.8E-01 |
| 1,4-Dichlorobenzene | Seawater | **1** | **1** | **1** |
| 1,4-Dichlorobenzene | Industrial soil | 8.2E-02 | 8.2E-02 | 8.2E-02 |
| Nickel | Urban air | 3.1E+01 | 1.1E+02 | 5.5E+04 |
| Nickel | Fresh water | 1.3E+01 | 5.7E+01 | 2.5E+04 |
| Nickel | Seawater | 9.8E+01 | 3.2E+02 | 1.3E+05 |
| Nickel | Industrial soil | 9.4E-02 | 2.3E+00 | 2.3E+04 |
| **Terrestrial ecotoxicity** | | | | |
| 1,4-Dichlorobenzene | Urban air | 6.3E-03 | 6.3E-03 | 6.3E-03 |
| 1,4-Dichlorobenzene | Fresh water | 5.7E-03 | 5.7E-03 | 5.7E-03 |
| 1,4-Dichlorobenzene | Seawater | 2.7E-03 | 2.7E-03 | 2.7E-03 |
| 1,4-Dichlorobenzene | Industrial soil | **1** | **1** | **1** |
| Nickel | Urban air | 2.1E+01 | 5.4E+01 | 2.1E+02 |
| Nickel | Fresh water | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Nickel | Seawater | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Nickel | Industrial soil | 7.6E+00 | 3.7E+01 | 4.5E+02 |
| **Human toxicity (carcinogenic)** | | | | |
| 1,4-Dichlorobenzene | Urban air | **1** | **1** | **1** |
| 1,4-Dichlorobenzene | Fresh water | 6.9E-01 | 6.9E-01 | 6.9E-01 |
| 1,4-Dichlorobenzene | Seawater | 1.9E-01 | 1.9E-01 | 1.9E-01 |
| 1,4-Dichlorobenzene | Industrial soil | 2.3E-01 | 2.3E-01 | 2.3E-01 |
| Nickel | Urban air | 3.1E+01 | 3.7E+02 | 9.1E+02 |
| Nickel | Fresh water | 3.4E+00 | 2.3E+01 | 2.5E+02 |
| Nickel | Seawater | 0.0E+00 | 3.5E+00 | 1.2E+03 |
| Nickel | Industrial soil | 2.1E+00 | 1.2E+01 | 3.6E+02 |
| **Human toxicity (non-carcinogenic)** | | | | |
| 1,4-Dichlorobenzene | Urban air | **1** | **1** | **1** |
| 1,4-Dichlorobenzene | Fresh water | 1.7E+01 | 1.7E+01 | 1.7E+01 |
| 1,4-Dichlorobenzene | Seawater | 8.3E-01 | 8.2E-01 | 8.2E-01 |
| 1,4-Dichlorobenzene | Industrial soil | 1.1E+00 | 1.1E+00 | 1.1E+00 |
| Nickel | Urban air | 3.6E+01 | 2.3E+03 | 5.8E+03 |
| Nickel | Fresh water | 2.3E+01 | 1.5E+02 | 1.7E+03 |
| Nickel | Seawater | 0.0E+00 | 2.3E+01 | 7.9E+03 |
| Nickel | Industrial soil | 1.4E+01 | 8.1E+01 | 2.3E+03 |

## 9.4 From midpoint to endpoint

The ecotoxicological endpoints included are fresh water, marine and terrestrial ecotoxicity. Endpoint characterization factors (CFeco) for ecotoxicity are calculated:

$$\mathrm{CFeco}_{x,i,j,c} = \mathrm{ETP}_{x,i,j,c} \times \mathrm{F}_{M\rightarrow,E,ETOX,j,c}$$

Whereby $ETP_{x,i,j,c}$ is the ecotoxicity potential for environmental endpoint *j* (fresh water, marine, terrestrial) of substance *x* to emission compartment *i* related to cultural perspective *c* (in 1,4DCB-eq/kg) and $F_{M\rightarrow,E,ETOX,j,c}$ is the midpoint to endpoint factor for toxicity related to environmental endpoint *j* related to cultural perspective *c*. The midpoint to endpoint factors for ecotoxicity equals the endpoint characterization factors for 1,4DCB emitted to respectively fresh water (freshwater ecotoxicity), seawater (marine ecotoxicity) and industrial soil (terrestrial ecotoxicity), including species densities:

$$\mathrm{F}_{M\rightarrow,E,ETOX,j,c} = \sum_{g} \mathrm{SD}_{j} \times \mathrm{FF}_{DCB,ref,j,g,c} \times \mathrm{EF}_{DCB,j,c}$$

whereby $SD_j$ is the species density related to environmental endpoint *j* (terrestrial ecosystems: $1.48 \cdot 10^{-8}$ species/$m^2$, freshwater ecosystems: $7.89 \cdot 10^{-10}$ species/$m^3$ and marine ecosystems: $3.46 \cdot 10^{-12}$ species/$m^3$).

For damage to human health, carcinogenic and non-carcinogenic endpoint characterization factors (CFhum) are calculated:

$$\mathrm{CFhum}_{x,i,c/nc,c} = \mathrm{HTP}_{x,i,c/nc,c} \times \mathrm{F}_{M\rightarrow,E,HTOX,c/nc,c}$$

whereby $HTP_{x,i,nc/c,c}$ is the human toxicity potential for carcinogenic or non-carcinogenic effects of substance *x* to emission compartment *i* related to cultural perspective *c* (in 1,4DCB-eq/kg) and $F_{M\rightarrow,E,HTOX,c/nc,c}$ is the midpoint to endpoint factor for human carcinogenic or non-carcinogenic toxicity for cultural perspective *c*. The midpoint to endpoint factor for human carcinogenic or non-carcinogenic toxicity equals the endpoint characterization factor for 1,4DCB emitted to urban air:

$$\mathrm{F}_{M\rightarrow E,HTOX,c/nc,c} = \sum_{r} \sum_{g} \mathrm{iF}_{1,4-DCB,r,g,ua} \times \mathrm{EF}_{1,4-DCB,r,c/nc} \times \mathrm{DF}_{c/nc}$$

whereby $DF_{c/nc}$ is the damage factor for carcinogenic or non-carcinogenic effects, which equals, respectively, 11.5 disability adjusted life years (DALYs) per incidence case and 2.7 DALYs per incidence case.

Table 9.4 shows the midpoint to endpoint factors for each endpoint included. The values are the same for all the perspectives.

*Table 9.4. Midpoint to endpoint conversion factors for all endpoints and perspectives.*

| Midpoint to endpoint | Unit | Value |
|---|---|---|

| **conversion factor** | | |
|---|---|---|
| Freshwater ecotoxicity | species·yr/kg 1,4-DCB eq | 6.95E-10 |
| Marine ecotoxicity | species·yr/kg 1,4-DCB eq | 1.05E-10 |
| Terrestrial ecotoxicity | species*yr/kg 1,4-DCB eq | 5.39E-08 |
| Human toxicity (cancer) | DALY/kg 1,4-DCB eq | 3.32E-06 |
| Human toxicity (non-cancer) | DALY/kg 1,4-DCB eq | 6.65E-09 |

# 10 Water use

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Calculation of the midpoint characterization factors and the endpoint characterization factors for impacts on human health and terrestrial vegetation (ecosystem quality) are based on Pfister et al. (2009) and De Schryver et al. (2011), while Hanafiah et al. (2011) forms the basis for the impacts from water consumption on the endpoint aquatic ecosystems. Major changes made from the previous version are:

- Provide consumption/extraction ratios;
- The inclusion of characterization factors on an endpoint level for human health, terrestrial and aquatic ecosystems.

## 10.1 Impact pathways and affected areas of protection

The relevant impact pathways that are covered are shown in Figure 10.1. All water-related impacts used here are based on water consumption. Water consumption is the use of water in such a way that the water is evaporated, incorporated into products, transferred to other watersheds or disposed into the sea (Falkenmark et al. 2004). Water that has been consumed is thus not available anymore in the watershed of origin for humans nor for ecosystems.

The modelling steps start with the quantification of the reduction in freshwater availability. For humans, a reduction in freshwater availability leads to competition between different water uses. Too little irrigation will lead to reduced crop production and consequently to increased malnutrition among the local population. The vulnerability of the people to malnutrition is increasing, with lower human development indexes (HDI), while industrial countries (HDI>0.88) have enough means to buy food to prevent malnutrition and thus have no damage occurring to human health. Impacts on terrestrial ecosystems are modelled via a potential reduction in vegetation and plant diversity. The line of reasoning is that a reduction in blue water (water in lakes, rivers, aquifers and precipitation) will potentially also reduce the available green water (soil moisture) and thus lead to a reduction in plant species. The fractions of freshwater fish that disappear due to water consumption are estimated based on species-discharge relationships at river mouths.

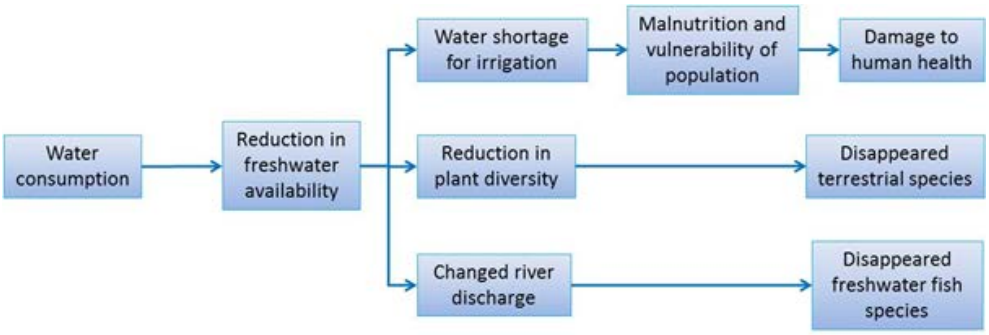


*Figure 10.1. Cause-and-effect chain of water consumption, leading to impacts on human health and ecosystem quality (both terrestrial and freshwater quality). The disappearance of freshwater fish species is based on Hanafiah et al. (2011), the other two are based on Pfister et al. (2009).*

## 10.2 Value choices

Value choices that are relevant to water consumption impacts on human health depend quite strongly on the management of the watersheds (resulting in changed variation factors, see next section) and the management of agricultural practices (reducing the amount of water required for producing a certain amount of food). The three cultural perspectives and the respective choices used are shown in Table 9.1 and have been adapted from De Schryver et al. (2011) (exclusion of age weighting and discounting).

*Table 10.1. Relevant value choices for modelling the impacts of water consumption.*

| Choice category | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|
| *Human health* | | | |
| Regulation of stream flow | High | Standard | Standard |
| Water requirement for food production | 1,000 $m^3$/yr·capita (efficient management) | 1,350 $m^3$/yr·capita (standard management) | 1,350 $m^3$/yr·capita (standard management) |
| *Terrestrial ecosystems* | *Zero (too uncertain)* | *Default value* | *Default value* |

For impacts on aquatic ecosystems, no value choices were identified. So, for aquatic ecosystems, the values for all three cultural perspectives are equal.
The factors for terrestrial ecosystems are considered very uncertain and are therefore not included in the individualistic perspective. The correlation between NPP and vascular plant species diversity is 0.6 on a global grid. Since all CFs from Pfister et al. (2009) are at watershed level, correlations were made between watershed averages of NPP and plant species richness. While high correlations could be found for watersheds with fewer than 2,000 species/10,000 $km^2$, no correlation could be found for watersheds with a higher species diversity. Because of this uncertainty, the individualist perspective will not take into account terrestrial ecosystems as endpoint. The endpoint CFs for the hierarchist and egalitarian perspectives are equal.

## 10.3 Characterization factors at midpoint level

The characterization factor (CF) at midpoint level is m3 of water consumed per $m^3$ of water extracted. Water *extraction* is the withdrawal of water from surface water bodies or the abstraction of groundwater from aquifer. It is the total amount of water withdrawn, irrespective of return flows to the water bodies or water use efficiencies. Water *consumption*, on the other hand is the amount of water that the watershed of origin is losing.

$$CF_{mid} = \begin{cases} 1 & if\ inventory\ in\ m^3\ consumed \\ water\ requirement\ ratio & if\ inventory\ in\ m^3\ withdrawn \end{cases}$$

Thus, for flows that are already given as consumptive water flows, the midpoint indicator coincides with the inventory. For water flows that are reported simply as withdrawal or as extracted water, a factor needs to be applied to account for the water-use efficiency. For agriculture, the consumptive part of the withdrawal can be estimated using water requirement ratios based on AQUASTAT (FAO 2012) and Döll and Siebert (2002) (see the Supporting Information of Verones et al. (2013)), as shown in Figure 10.2. The global average value is 0.44 (standard deviation 0.14). Values for individual countries can be found in the supporting information (Table S6.1). The higher the efficiency, the more of one $m^3$ of water withdrawn actually reaches the plants and is consumed; while more water needs to be withdrawn to reach the same result if the efficiency is lower; while a large part of the withdrawn water will not be consumed, but returned back to the environment. Thus, most industrial nations have high values, due to good irrigation infrastructure.

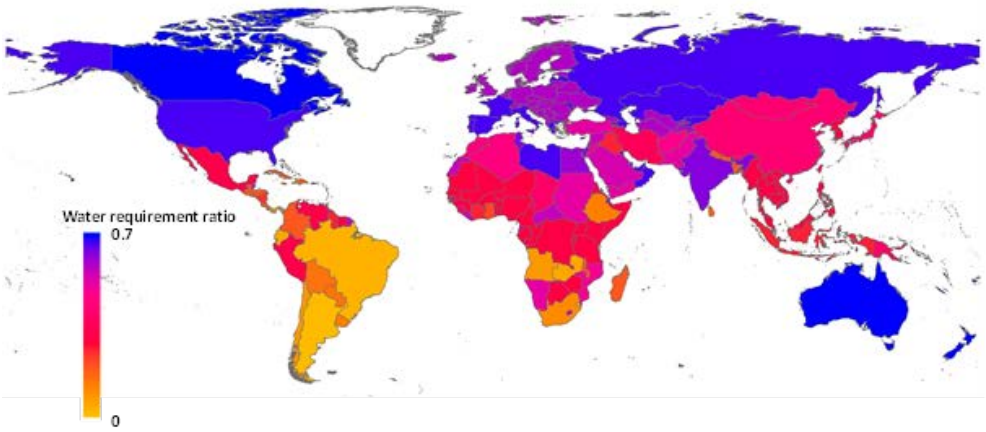


*Figure 10.2. Water requirement ratios for converting agricultural water extraction to agricultural water consumption based on AQUSTAT data (FAO 2012) and data from Döll and Siebert (2002).*

Water consumption in industry (generalized) and for domestic water use is much lower. It is assumed that, on a global level, 5 to 10% of industrial water use is consumptive (i.e. there is a return flow of 90-95% of withdrawn water) and 10% of domestic water use is consumptive (World Water Council nd, Hoekstra et al. 2012). Based on this information, we propose applying a water requirement ratio of 10% for both sectors.
It is important to note that, for groundwater abstractions, return flows from industrial and domestic water use should not be calculated, as

these will, in the vast majority of cases, return to surface water bodies instead of aquifers. Agricultural water may infiltrate and can thus return to aquifers, hence return flows can be applied for agricultural groundwater use. See Table 10.2 for a summary of the suggested water requirement ratios.

*Table 10.2. Water requirement ratios to convert water extraction to water consumption.*

| | **Surface water** | **Groundwater** |
|---|---|---|
| Agriculture | 0.44 | 0.44 |
| Industry | 0.1 | 1 |
| Domestic | 0.1 | 1 |

## 10.4 From midpoint to endpoint

### *10.4.1 Human health*

Endpoint characterization factors for the impacts of water consumption on human health use a water stress index (WSI) as part of their modelling scheme. The damage is calculated in disability adjusted life years (DALYs) for each watershed (or country) using the water stress index (WSI) that was developed by Pfister et al. (2009). The WSI is based on a ratio between the sum of freshwater withdrawals (not consumption) for different sectors *j* (WU) and hydrological availability in the watershed *i* (WA).

$$WTA_i = \frac{\sum_j WU_{ij}}{WA_i}$$

The WSI was calculated for each watershed and each country separately. It is a logistic function that scales the water stress between 0.01 and 1. The reason that it starts at 0.01 and not at 0 is that each water extraction leads at least to a marginal local impact according to Pfister et al. (2009).

$$WSI = \frac{1}{1 + e^{-6.4 \cdot WTA*} \cdot \left(\frac{1}{0.01} - 1\right)}$$

in which the WTA* is the modified WTA which takes into account that the ratio between withdrawals and the hydrological availability of water is not constant throughout the year and can lead, in periods of low water availability, to an increased stress. This stress is not completely compensated during times of low stress and therefore a correction for an increased effective water stress is required. The modified WTA* is calculated as:

$$WTA* = \begin{cases} \sqrt{VF} \cdot WTA & for\ SRF \\ VF \cdot WTA & for\ non-SRF \end{cases}$$

The variation factor (VF) is the necessary correction factor that allows the WTA to be differentiated between watersheds with strongly regulated flows (SRF) and those with no strongly regulated flows. SRFs lower the effect of variable precipitation in the watershed due to the available storage structures, but they potentially increase the evaporation. The VF

was calculated with the multiplicative standard deviations of monthly (s*month) and annual precipitation (s*year) for the climate normal period 1961-1990 and assuming a log-normal distribution.

$$VF = e^{\sqrt{ln(s^*_{month})^2 + ln(s^*_{year})^2}}$$

The grid-cell based VF (subscript k) was then aggregated to watershed level *i*, in order to calculate WTA* per watershed *i*.

$$VF_{i=} \frac{1}{\sum P_k} \sum_{k=1}^{n} VF_k \cdot P_k$$

in which Pk is the precipitation per grid cell. The global WSI values for the three different perspectives are shown in Table 9.3 and a map is shown in Figure 10.3. A list with country-based WSI for the three different perspectives from De Schryver et al. (2011) can be found in the supporting information (Table S6.2).

*Table 10.3. Global values for the WSI. The aggregation from country level to global values has been made based on total water consumption from 2010.*

| | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|
| WSI | 0.698 | 0.657 | 0.657 |

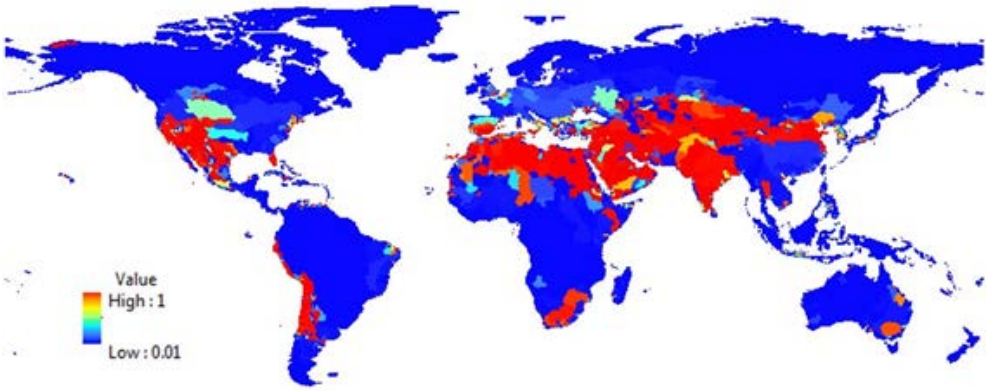


*Figure 10.3. Water Stress Index (WSI) on a watershed level, based on data from Pfister et al. (2009).*

The damage to human health is calculated based on malnutrition potentially caused by water consumption. Thus:

$$CF_{end} = \begin{cases} 1 \cdot CF_{malnutrition} & if\ inventory\ in\ m^3 consumed \\ water\ req.ratio \cdot CF_{malnutrition} & if\ inventory\ in\ m^3\ withdrawn \end{cases}$$

The damage to human health is calculated in disability adjusted life years (DALYs) due to water-scarcity-related malnutrition for each watershed (or country) *i* according to:

$$CF_{malnutrition,i} = \underbrace{WSI_i \cdot WU_{\%agriculture,i}}_{\text{Fate factor (Water deprivation factor)}} \cdot \underbrace{\frac{HDF_{malnutrition,i}}{WR_{malnutrition}}}_{\text{Effect factor}} \cdot \underbrace{DF_{malnutrition}}_{\text{Damage factor}}$$

The fate factor (water deprivation factor [$m^3$deprived/$m^3$consumed] of a watershed or a country *i* consists of the physical water stress (via WSI) and the fraction of water extracted for agriculture (WU%agriculture) in watershed *i*. Combined WSI and WU%agriculture inform on the fraction of water that will be missing in agriculture due to the consumed water in that region for the product or process under consideration in the LCA. The effect factor (EF [capita·yr/$m^3$deprived]) consists of a human development factor HDF [-] and per-capita water requirements to prevent malnutrition (WRmalnutrition [$m^3$/capita·yr], see also value choices) and indicates the number of people that are malnourished per year per water quantity that was deprived. The damage factor DFmalnutrition [DALY/yr·capita] indicates the damage caused by malnutrition. Both WR and DF are assumed to be independent of the spatial location. Pfister et al. (2009) set WRmalnutrition to 1,530 $m^3$/(yr·capita), as this is considered as the minimum dietary requirement for humans (Falkenmark et al. 2004). A global per-capita value for DFmalnutrition of $3.68.10^{-2}$ DALY/(yr.capita) was taken from De Schryver et al. (2011).
HDF is calculated according to:

$$HDF_{malnutrition} = \begin{cases} 1 & for\ HDI < 0.30 \\ 2.03 \cdot HDI^2 - 4.09 \cdot HDI + 2.04 & for\ 0.30 \leq HDI \leq 0.88 \\ 0 & for\ HDI > 0.88 \end{cases}$$

The HDF malnutrition values depend on the national human development index (HDI) and a polynomial fit of DALY values for malnutrition per 100,000 persons in 2001 (see Pfister et al. 2009). The global, average consumption-weighted human health CFs for the three different perspectives are listed in Table 10.4. Country values are given in the supporting information (Table S6.2).

*Table 10.4. Globally averaged endpoint characterization factors for impacts of water consumption on human health for the different perspectives.*

| | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|
| CF [DALY/$m^3$] | 3.10E-06 | 2.22E-06 | 2.22E-06 |

### *10.4.2 Terrestrial ecosystems*

Direct impacts of water consumption on terrestrial ecosystems are based on the damage for vascular plant species. The net primary productivity (NPP) is used as a proxy for the ecosystem well-being. In Pfister et al. (2009), the characterization factor is calculated as the sum of water-limited NPP in each pixel k of a watershed or a country i divided by the sum of grid-specific precipitation P as the weighting factor. The fraction of water-availability-limited NPP represents the vulnerability of an ecosystem to water shortages and therefore acts as a proxy for the potentially disappeared fraction (PDF). The unit of the water-limited NPP is

dimensionless (being a fraction), while the precipitation P is in m/year (equalling thus $m^3/m^2 \cdot yr$). The unit of the CF is thus $m^3/m^2 \cdot yr$, but can also be given as PDF· $m^3/m^2 \cdot yr$. In Pfister et al. (2009) the PDF is omitted as it is not a SI unit and merely indicates the presence of a fraction.

$$CF_i = \frac{\sum_{k=1}^{n} NPP_{water-limited,k}}{\sum_{k=1}^{n} P_k}$$

The water-limited NPP is calculated as shown here:

$$NPP_{water-limited} = ICC_{water} \cdot \left(1 - \frac{ICC_{temperature} + ICC_{radiation}}{2}\right)$$

There can be three climatic reasons for the limitation of net primary productivity, namely a lack of water ($ICC_{water}$), unsuitable temperatures ($ICC_{temperature}$) or solar radiation ($ICC_{radiation}$). Data for these climatic constraints for the growth of plants is provided by Nemani et al. (2003). The Indices for Individual Climatic Constraints (ICC) range between 0 and 1 after the simulation with climate models over the course of a year. Several of the constraints can inhibit plant growth at the same time. In order to prevent double counting, equal shares were attributed to the constraints if several of them were occurring at the same time (e.g. if two constraints are active, both get a share of 50%). The calculation of $NPP_{water-limited}$ then discounts the portion of plant growth that is not caused by a lack of water. On barren lands, $NPP_{water-limited}$ was set to zero.
To convert the results from potentially disappeared fractions to species·yr, the average terrestrial species density of $1.48 \cdot 10^{-8}$ species/$m^2$ (Goedkoop et al. 2009) is used. Values for countries are shown in the supporting information (Table S6.3); global values using an area-weighted approach are shown in Table 10.5.

*Table 10.5. Globally averaged endpoint characterization factors for impacts of water consumption on terrestrial ecosystems for the different perspectives.*

| | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|
| CF [species·yr/$m^3$] | 0 | 1.35E-08 | 1.35E-08 |

### *10.4.3 Aquatic ecosystems*

Impacts of water consumption on freshwater fish species have been calculated for river basins below. The reason for excluding river basins at higher latitudes is that the reported species discharge relationships are not representative for river basins above 42° latitude (Hanafiah et al. 2011). Characterization factors are estimated based on marginal changes in the river discharge at the mouth ($dQ_{mouth}$) of the river due to a marginal change in consumption (dWC) and the marginal change of species lost (dPDF) associated with that decrease in a discharge where V is the volume of the river basin.

$$CF = \frac{dQ_{mouth}}{dWC} \cdot \left(\frac{dPDF}{dQ_{mouth}} \cdot V\right) \quad \left[m^3 \cdot \frac{PDF \cdot yr}{m^3}\right]$$

The unit of the CF is PDF·$m^3$/(yr·$m^3$). The change in discharge was assumed to be equal to the change in water consumption, thus the first part of the former equation equals 1. The change in freshwater fish species richness is estimated according to Hanafiah et al. (2011):

$$\frac{dPDF}{dQ_{mouth}} = \frac{0.4}{Q_{mouth}} \left[\frac{PDF \cdot yr}{m^3}\right]$$

The characterization factors calculated by Hanafiah et al. (2011) do not contain value choices, because they are independent of time horizon, human water demands, discount rates and the like.
To convert the results from potentially disappeared fractions to species·yr, the average aquatic species density of $7.89 \cdot 10^{-10}$ species/m$^3$ (Goedkoop et al. 2009) is used. Values given for watersheds (Figure 10.4) and aggregated to countries are shown in the supporting information (Tables S6.3 and S6.4), the global median CF value based on watersheds is $6.04 \cdot 10^{-13}$ species·yr/m$^3$, the area-weighted country average is $1.74 \cdot 10^{-12}$ species·yr/m$^3$ (Table 10.6). The values for aquatic ecosystems are several orders of magnitude smaller than the values for the terrestrial ecosystems. This is because the CFs in PDF-units were larger for terrestrial ecosystems while the average species density is two orders of magnitude smaller for aquatic ecosystems.

*Table 10.6. Globally averaged values for impacts of water consumption on freshwater ecosystems in watersheds and area-weighted average on a country level.*

| | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|
| CF watershed median [species·yr/m$^3$] | 6.04E-13 | 6.04E-13 | 6.04E-13 |
| CF area-weighted country average [species·yr/m$^3$] | 1.74E-12 | 1.74E-12 | 1.74E-12 |

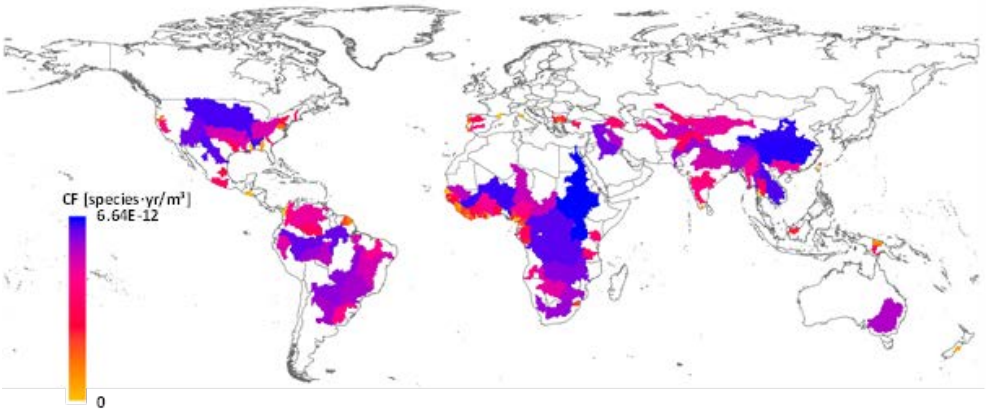


*Figure 10.4. Map with coverage of the watersheds, adapted from Hanafiah et al. (2011). Watersheds above 42° were excluded.*

# 11 Land use

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This chapter focuses on the relative species loss due to local land use, which covers the process of land transformation, land occupation and land relaxation (see below). Characterization factors (CFs) for these impact mechanisms are provided. CFs for the impact of land transformation and occupation are based on relative species losses calculated by De Baan et al. (2013) and Elshout et al. (2014). CFs for land relaxation are calculated based on the model from Köllner et al. (2007), using recovery times from Curran et al. (2014). Conceptually, this approach assumes that a natural situation would be present had no land use occurred. Therefore, the species richness of the current, anthropogenic land use is compared with the natural reference, not accounting for any other anthropogenic land uses that may have been in place before the current land use. It follows that the impact of land transformation from one anthropogenic land use to another is not covered in this chapter.
Major changes made from the previous version are:

- The CFs are now based on global scale data, whereas the previous versions focused on Europe.
- The local impact of land use is covered only, as we found the methods for regional impact too arbitrary to take into account.
- CFs specific to several species groups are now provided.
- In this document, we use the general term "land use" when referring to the complete cycle of land transformation, occupation and relaxation.

## 11.1 Impact pathways and affected areas of protection

The impact pathway of land use as included in this chapter is shown in Figure 11.1. This includes the direct, local impact of land use on terrestrial species via (1) change of land cover and (2) the actual use of the new land. Change of land cover directly affects the original habitat and the original species composition accordingly. The land use itself (i.e. agricultural and urban activities) further disqualifies the land as a suitable habitat for many species.

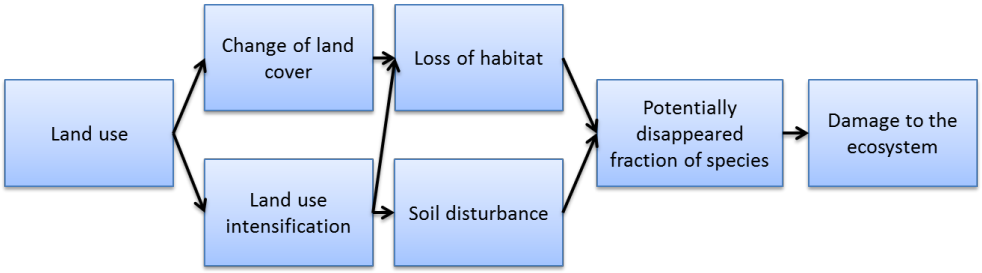


*Figure 11.1. Cause-and-effect chain of land use, leading to relative species loss in terrestrial ecosystems. Note that indirect pathways (e.g. the relative species loss due to land-use-induced climate change) are excluded.*

Three steps can be distinguished in the process of land use (Milà i Canals et al. 2007). Firstly, during the transformation phase, the land is made suitable for its new function, e.g. by removing the original vegetation. Secondly, during the occupation phase, the land is utilized for a certain period. These two steps are hereinafter covered in the CFs for land occupation, expressed in Potentially Disappeared Fraction of Species (PDF) per annual crop equivalent. Finally, after the land is no longer being used, there is a phase of relaxation, during which the land is allowed to return to a (semi-)natural state. It is assumed that during the period of relaxation, the land still has (some) negative impact on species richness, given that it is not immediately returned to primary habitat or will not return to the original habitat, but rather to a different state. CFs for land relaxation are provided separately, as they are expressed in a different unit: PDF · year per annual crop equivalent. Life Cycle Inventory (LCI) data on the area of land use and the duration of land relaxation are to be multiplied by the appropriate CFs and added to calculate the total damage to the ecosystem. Figure 11.2 provides an overview of the three phases of land use and the impact they have on land quality (including species richness).

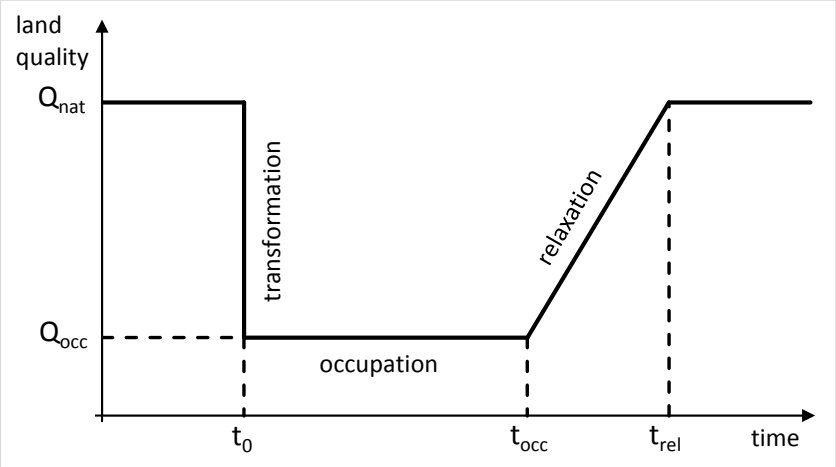


*Figure 11.2. Schematic overview of the three phases of land use and their impact on land quality (adapted from Milà i Canals et al. 2007). Land transformation and occupation occurs between $t_0$ and $t_{occ}$, and relaxation occurs between $t_{occ}$ and $t_{rel}$. Qnat shows the original, natural land quality and $Q_{occ}$ is the land quality after land transformation.*

Biodiversity may also be affected indirectly by land use, as a change of land cover and land use intensification may lead to increased emissions of greenhouse gases from biomass burning, fertilizer application and soil disturbance, and may therefore contribute to climate change. The impact of these greenhouse gas emissions on biodiversity can be calculated using the methodology provided in Chapter 2: Climate Change.

## 11.2 Value choices

No value choices were quantified in the calculations of the CFs for land use.

## 11.3 Characterization factors at midpoint level

### *11.3.1 Calculation*

Firstly, the midpoint characterization factor (in annual crop equivalents) for land transformation/occupation $CFm_{occ}$ is based on the relative species loss $S_{rel}$ caused by land use type *x*, proportionate to the relative species loss resulting from annual crop production:

$$CFm_{occ,x} = \frac{S_{rel,x}}{S_{rel,annualcrop}}$$

$S_{rel}$ is calculated by comparing field data on local species richness in specific types of natural and human-made land covers, using the linear relationship described by Köllner et al. (2007):

$$S_{rel,x} = 1 - \frac{S_{LU,x,i}}{S_{ref,i}}$$

whereby $S_{LU}$ and $S_{ref}$ are the observed species richness (number of species) under land use type *x* and the observed species richness of the reference land cover in region *i*, respectively. Equation 2 yields outcomes between -∞ and +1, whereby a negative value means a positive effect of land occupation (i.e. a larger species richness), and the maximum of one represents a hundred per cent loss of species richness. Secondly, the midpoint characterization factor for land relaxation to a (semi-)natural state $CFm_{relax}$ (in annual crop equivalent·yr) is directly related to $CFm_{occ}$, using the following equation from Köllner et al. (2007):

$$CFm_{relax,x} = CF_{occ,x} \times 0.5 \times t_{rel}$$

whereby $t_{rel}$ is the recovery time (years) for species richness. We assume a passive recovery towards a (semi-)natural, old-growth habitat based on average recovery times from Curran et al. (2014). They distinguish between forested and non-forested (open) ecosystems, as these natural vegetation types show different recovery rates. Across all taxa (mammals, birds, herpetofauna, invertebrates, and plants) and all regions (Palearctic, Neotropic, Nearctic, Indomalaya, Australasia and Afrotropic realms), they found that forested biomes require a median of 73.5 years (range 46.7-138.8) and open biomes require 7.5 years (range 4.7-14) before species richness is at a level comparable to the pre-transformation state. These recovery times are reported as independent of the type of land use that replaced the natural system. Based on the data from Curran et al. (2014) (see Table 1), a global average recovery time was calculated, weighted over the total areas of forest and open habitats in the world. Assuming that 40% of the global terrestrial area consists of forest biomes and 60% of grassland/shrubland biomes (based on Olson et al. 2001), the typical $t_{rel}$ is calculated to be 33.9 years.

$CFm_{occ}$ and $CFm_{relax}$ for the impact of different types of land use on total species richness are shown in Table 11.1. These can be used if detailed information is available on the transformation and occupation of various types of land use, and the focus of the assessment is on biodiversity in general. Alternatively, for assessments of the impact of land use on

specific species groups, additional midpoint CFs are provided in the Supporting Information (Table S7.1).
The procedure of applying the CFs presented here into the Ecoinvent v3 database is explained in the Supporting Information (Section 7).

*Table 11.1. Midpoint CFs for the impact of land transformation/occupation ($CFm_{occ}$) and land relaxation ($CFm_{relax}$) on total species richness. Each $CFm_{occ}$ is based on data taken from De Baan et al. (2013) on relative species loss related to different types of land use. The recovery time ($t_{rel}$) used in the calculation of $CFm_{relax}$ is the global average recovery time, as derived from Curran et al. (2014).*

| **Land use type** | **$CFm_{occ}$ (annual crop eq)** | **$CFm_{relax}$ (annual crop eq·yr)** |
|---|---|---|
| Used forest | 0.30 | 5.1 |
| Pasture and meadow | 0.55 | 9.3 |
| Annual crops | 1.00 | 17.0 |
| Permanent crops | 0.70 | 11.9 |
| Mosaic agriculture | 0.33 | 5.6 |
| Artificial areas[1] | 0.73 | 12.4 |

[1]urban areas, industrial areas, road and rail networks, dump sites.

### *11.3.2 Reference state*

The impact of land use on relative species richness is assessed here through a comparison of species richness in a certain land use situation with the situation in a reference state. Several reference states have been proposed for land use impact assessments, including the current mix of natural land covers within a biome/ecoregion or the current mix of all land uses (Koellner et al. 2013). In the present document, the reference state follows the concept of potential natural vegetation (PNV), which describes the expected state of mature vegetation that would develop if all human activities were to be stopped at once. The species richness of the PNV was approximated using monitoring data from current, (semi-)natural habitats, which were considered a valid reference if they were located within the same ecoregion (De Baan et al. 2013) or biome (Elshout et al. 2014) as the land use situation. The species richness in different types of natural vegetation can vary significantly (e.g. tropical rain forest vs. tundra) and CFs will vary accordingly. We refer to the original publications for biome-specific CFs for land occupation, which may be preferred over the global CFs provided here when assessing the impact of land use in a particular region. However, the coverage of the different biomes was too scarce to implement them in the current methodology. See Elshout et al. (2014) for further details.
Rather than selecting a reference habitat based on a specific ecoregion or biome, Curran et al. (2014) distinguished between two global types of natural reference vegetation in their calculation of the recovery times: forest and open vegetation. We propose the selection of the most likely type of reference based on the biome in which the land use takes place. Thus, the midpoint CFs for open vegetation should be used when assessing the impact of land use in grassland, savanna, shrubland, tundra or desert biomes, and those for forest vegetation should be used in the different forest and woodland biomes (see Olson et al. 2001).

Alternatively, the global average midpoint CFs (Table 1) can be used in assessments in which no distinction can be made between reference vegetation types due to a lack of information.

### *11.3.3 Taxonomic groups*

The midpoint CFs used here were derived using the species richness data for several taxonomic groups: plants, vertebrates (mammals and birds) and invertebrates (mainly arthropods) (De Baan et al. 2013, Elshout et al. 2014). These taxonomic groups react differently to land use, given that they generally have varying requirements for food, shelter and breeding or nesting (Elshout et al. 2014). Due to the variety of taxonomic groups included, the CFs are a proxy for the impact of land use on total species richness. However, one should keep in mind that well-studied species, such as plants and birds, are overrepresented in the dataset and that some taxonomic groups, such as reptiles and amphibians, are not included at all.

### *11.3.4 Active recovery*

Passive recovery times are assumed in calculating the midpoint CFs for land relaxation. When habitats are restored actively (including e.g. vegetation planning, animal reintroductions and replacement of top soil), the recovery of species richness accelerates by approximately 80% (Curran et al. 2014), thereby reducing the CFs for relaxation by the same percentage. Shorter recovery times from active recovery may be implemented in the calculations of the CFs for land relaxation, but only if the additional impact of the restoration activities is taken into account as well. For example, replacement of top soil would require the use of fossil-fuelled machinery, which increases the overall impact of the land use scenario on climate change. Hence, additional inventory data on the machinery used would be needed.

## 11.4 From midpoint to endpoint

The endpoint characterization factors for the transformation/occupation ($CFe_{occ}$) and relaxation ($CFe_{relax}$) of land use type *x* are calculated by:

$$CFe_{occ,x} = CFm_{occ,x} \times F_{M\rightarrow E,LU}$$
$$CFe_{relax,x} = CFm_{relax,x} \times F_{M\rightarrow E,LU}$$

whereby:

$$F_{M\rightarrow E,LU} = SD_{terr} \times S_{rel,annual\ crops}$$

$CFe_{occ,x}$ is the endpoint characterization factor for land occupation (species/m$^2$), $CFe_{relax,x}$ is the endpoint characterization factor for land relaxation (in species·yr/m$^2$). $CFm_{occ}$ is the midpoint characterization factor for land occupation (in annual crop eq) and $CFm_{relax}$ is the midpoint characterization factor for land relaxation (in annual crop eq·yr). FM->E,LU is the midpoint to endpoint conversion factor (species/m$^2$) (see Table 11.2). $SD_{terr}$ is the average species density for terrestrial ecosystems which is approximated to be $1.48 \cdot 10^{-8}$ species/m$^2$ (Goedkoop et al. 2009), and $S_{rel,annual}$ crop is the relative species loss for annual crops, which is 0.60 (annual crop eq$^{-1}$) (taken from De Baan et al. (2013), Table S7.2). See Table S7.3 for all endpoint characterization factors.

*Table 11.2. Midpoint to endpoint factors (species/$m^2$ annual crop eq) for land occupation and relaxation.*

| | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|
| Midpoint to endpoint factor | 8.88E-09 | 8.88E-09 | 8.88E-09 |

# 12 Mineral resource scarcity

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This chapter is based on Vieira et al. (2012), Vieira et al. (2016a) and Vieira et al. (2016b). The main changes made compared with the ReCiPe2008 report are:

- developing log-logistic regressions to determine cumulative grade-tonnage relationships and cumulative cost-tonnage relationships.
- use of mine-specific cost and production data.
- average modelling approach, considering all future production and without discounting.

## 12.1 Impact pathways and affected areas of protection

For the impact category of mineral resource scarcity, the damage modelling is subdivided into several steps (Figure 12.1). The primary extraction of a mineral resource (ME) will lead to an overall decrease in ore grade (OG), meaning the concentration of that resource in ores worldwide, which in turn will increase the ore produced per kilogram of mineral resource extracted (OP). This, when combined with the expected future extraction of that mineral resource, leads to an average surplus ore potential (SOP) which is the midpoint indicator for this impact category. An increase in surplus ore potential will then lead to a surplus cost potential. These two indicators follow the principle that mining sites with higher grades or with lower costs, for SOP and SCP, respectively, are the first to be explored. Here, we estimated the damage to natural resource scarcity.

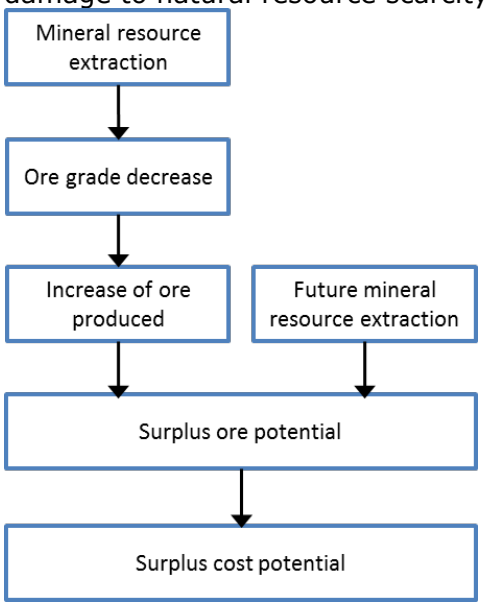


*Figure 12.1. Cause-and-effect chain, from mineral resource extraction to natural resource scarcity.*

## 12.2 Value choices

The value choice on the future extraction of mineral resources affects both the midpoint modelling and endpoint modelling of mineral resource scarcity (Vieira et al. 2016a,b). Two different reserve estimates were applied in the characterization factors' calculations. The first type of reserve estimate is the 'Reserves (R)', which is defined as that part of a resource "which could be economically extracted or produced at the time of determination", meaning at current prices and state of technology (U.S. Geological Survey 2014). This is the smallest reserve estimate available and, consequently, it can be considered for the shortest time frame. The 'Ultimate recoverable resource (URR)' refers to "the amount available in the upper crust of the earth that is ultimately recoverable". The definition of URR as used by UNEP (2011), called extractable geologic resource there, will be used here and is 0.01% of the total amount in the crust to a depth of 3 km. Extraction at this depth will be possible if new mining technologies are developed. However, it has been observed that, currently, open pit mining is preferred due to lower operational costs, even though underground mines often contain higher metal grades (Crowson, 2003). As open pit mines will most likely become depleted in the future, a shift towards underground mining is likely to occur. This is why URR is considered for the longest time frame and it represents the largest reserve estimate for which extraction is expected to be possible in the future.
There are various estimates for future mineral primary production, resulting in a range of characterization factors that depend on reserve estimates. The value choices are categorized by means of three cultural perspectives, as summarized in Table 12.1.

*Table 12.1. Value choices in the modelling of the effect of extracting mineral resources.*

| Choice category | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|
| Future production | Reserves | Ultimate recoverable resource | Ultimate recoverable resource |

## 12.3 Characterization factors at midpoint level

The midpoint characterization factor for mineral resource scarcity is Surplus Ore Potential (SOP). The SOP expresses the average extra amount of ore to be produced in the future due to the extraction of 1 kg of a mineral resource *x,* considering all future production (R) of that mineral resource relative to the average extra amount of ore produced in the future due to the extraction of 1 kg of copper (Cu), considering all future production of copper. The surplus ore potential, considering the extraction of a future amount of mineral resource, is called the Absolute Surplus Ore Potential (ASOP) and is expressed in the unit kg ore/kg x. The midpoint characterization factor of any mineral resource x and any reserve estimate ($R_x$) can then be calculated as follows:

$$\mathrm{SOP}_{x,\mathrm{R}} = \frac{\mathrm{ASOP}_{x,\mathrm{R}}}{\mathrm{ASOP}_{\mathrm{Cu,R}}}$$

which yields a future-production specific SOP with the unit kg Cu-eq/kg *x*.

The ASOP consists of two calculation steps (Vieira et al. 2016b). In the first step, a cumulative grade-tonnage relationship is derived (see example for copper in Figure 10.2). In the second step, the average cost increase resulting from all future extraction of mineral resource is calculated to arrive at the absolute surplus costs per unit of mineral resource extracted.
A cumulative grade-tonnage regression reflects the relationship between the cumulative extraction of a mineral resource and its ore grade. The ore grade of mineral resource *x* can be derived as (Vieira et al. 2012):

$$\mathrm{OG}_x = \exp(\alpha_x) \cdot \exp\left(\beta_x \cdot \ln\left(\frac{\mathrm{A}_x - \mathrm{CME}_x}{\mathrm{CME}_x}\right)\right)$$

whereby $OG_x$ is the ore grade of resource *x* (in kg x/kg ore), $A_x$ (in kg x) is the total amount of resource *x* extracted, $CME_x$ (in kg x) is the cumulative amount of mineral resource x extracted, and $\alpha_x$ and $\beta_x$ are, respectively, the scale and shape parameters of the log-logistic distribution of the cumulative grade-tonnage relationship for mineral resource *x*. In Table S8.1 in the Appendix, the parameters alpha and beta for each mineral resource covered can be found. The ore extracted per amount of resource *x* produced ($OP_x$ in kg ore/kg x) is equal to the inverse of the ore grade of the resource ($OG_x$ in fraction). To correct the mining data for co-production, the revenue-corrected ore grade, with allocation based on revenue, is applied.

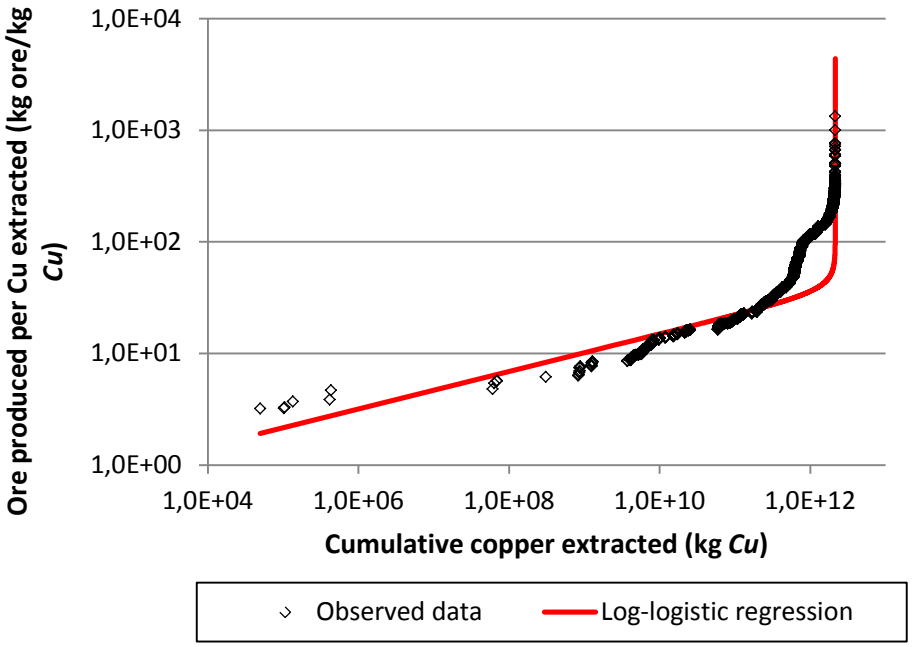


*Figure 12.2. Cumulative grade-tonnage relationship for existing copper mines (source: see supporting information section 8) plotted using a log-logistic regression (in logarithmic scale).*

The Absolute Surplus Ore Potential of mineral *x* $ASOP_x$ (kg ore/kg x) is defined as the extra amount of ore produced in the future per unit of mineral resource *x* extracted, which was calculated by Vieira et al. (2016b):

$$\mathrm{ASOP}_x = \frac{\int_{\mathrm{CME}_x}^{\mathrm{MME}_x} (\Delta \mathrm{OP}_x) d\mathrm{ME}_x}{\mathrm{R}_x}$$

whereby OP (kg ore) is the ore produced for a certain amount of mineral resource x extracted $ME_x$ (kg x), $R_x$ (kg x) is the actual reserve of the mineral resource *x*, $MME_x$ (kg x) is the maximum amount to be extracted of that mineral resource, and $CME_x$ is the current cumulative tonnage of mineral resource x extracted. The most important data sources used for deriving the midpoint characterization factors can be found in the Supporting information in Section 8).

There is sufficient information to derive ASOP-values for 18 mineral resources, namely aluminium, antimony, chromium, cobalt, copper, gold, iron, lead, lithium, manganese, molybdenum, nickel, niobium, phosphorus, silver, tin, uranium and zinc. For the minerals for which ASOP-values could not be derived on the basis of empirical cumulative grade-tonnage relationships, we used the price of a mineral resource to estimate its ASOP-value. Price data for 2013 was retrieved from Kelly and Matos (2013) in US dollars reference year 2013 (USD2013), except for the platinum group metals and uranium. For palladium, platinum and rhodium, average price data for 2013 was retrieved from Kitco Metals Inc. (2015). The ESA spot U3O8 data (a weighted average of triuranium octoxide prices paid by EU utilities for uranium delivered under spot contracts during the reference year) published by the Euratom Supply Agency (2015) was used to calculate the price for uranium. As shown in Figure 12.3, the price of a mineral can be considered as a good predictor for ASOP (explained variance of the regressions equals 90-91%).

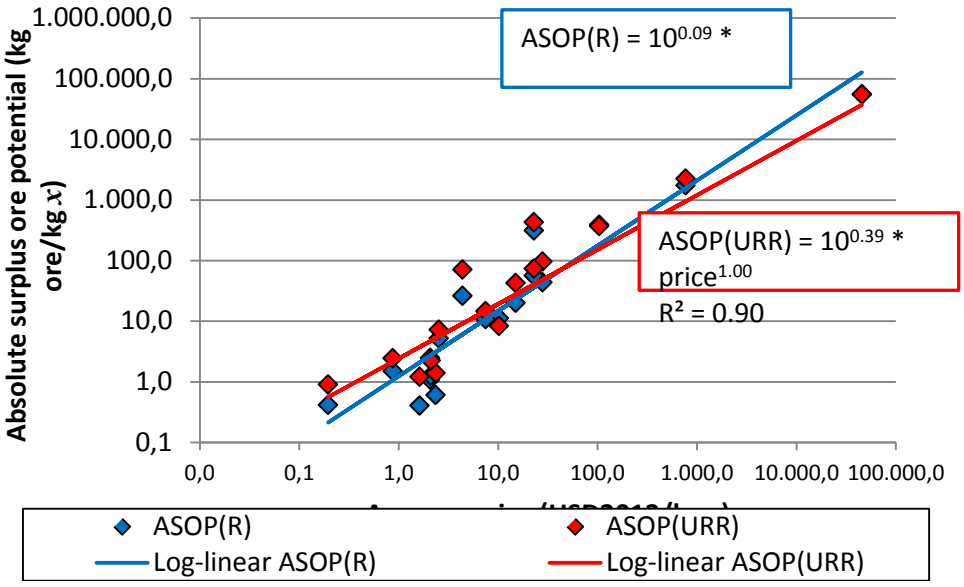


*Figure 12.3. Relationship between average price in 2013 (USD1998/kg x) and absolute surplus ore potential (kg ore/kg x).*

*Table 12.2. Midpoint characterization factors SOPs (in kg Cu-eq/kg) for 70 mineral resources and for the groups garnets, gemstones, platinum-group metals, rare-earth metals and zirconium minerals for three perspectives.*

| Mineral resource | Chemical element | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|---|
| Aluminium | Al | 1.01E-01 | 1.69E-01 | 1.69E-01 |
| Antimony | Sb | 1.03E+00 | 5.72E-01 | 5.72E-01 |
| Arsenic* | As | 8.89E-02 | 1.31E-01 | 1.31E-01 |
| Ball clay* | | 3.86E-03 | 7.09E-03 | 7.09E-03 |
| Barite* | | 1.36E-02 | 2.28E-02 | 2.28E-02 |
| Bauxite* | | 2.41E-03 | 4.58E-03 | 4.58E-03 |
| Bentonite clay* | | 6.07E-03 | 1.08E-02 | 1.08E-02 |
| Beryllium* | Be | 8.42E+01 | 7.67E+01 | 7.67E+01 |
| Bismuth* | Bi | 2.77E+00 | 3.20E+00 | 3.20E+00 |
| Boron* | B | 7.77E-02 | 1.16E-01 | 1.16E-01 |
| Cadmium* | Cd | 2.32E-01 | 3.20E-01 | 3.20E-01 |
| Caesium* | Ce | 1.90E+04 | 1.18E+04 | 1.18E+04 |
| Chromium | Cr | 5.57E-02 | 9.51E-02 | 9.51E-02 |
| Chrysotile* | | 2.21E-01 | 3.05E-01 | 3.05E-01 |
| Clay, unspecified* | | 5.85E-03 | 1.04E-02 | 1.04E-02 |
| Cobalt | Co | 4.01E+00 | 6.57E+00 | 6.57E+00 |
| Copper | Cu | 1.00E+00 | 1.00E+00 | 1.00E+00 |
| Diamond (industrial)* | C | 1.02E+02 | 9.15E+01 | 9.15E+01 |
| Diatomite* | | 3.07E-02 | 4.88E-02 | 4.88E-02 |
| Feldspar* | | 8.90E-03 | 1.54E-02 | 1.54E-02 |
| Fire clay* | | 1.95E-03 | 3.76E-03 | 3.76E-03 |
| Fuller's earth* | | 8.61E-03 | 1.50E-02 | 1.50E-02 |
| Gallium* | Ga | 9.28E+01 | 8.38E+01 | 8.38E+01 |
| Germanium* | Ge | 3.89E+02 | 3.17E+02 | 3.17E+02 |
| Gold | Au | 5.12E+03 | 3.73E+03 | 3.73E+03 |
| Graphite* | C | 1.34E-01 | 1.92E-01 | 1.92E-01 |
| Gypsum* | | 1.44E-03 | 2.83E-03 | 2.83E-03 |
| Hafnium* | Hf | 1.08E+02 | 9.67E+01 | 9.67E+01 |
| Ilmenite* | | 2.40E-02 | 3.88E-02 | 3.88E-02 |
| Indium* | In | 1.15E+02 | 1.03E+02 | 1.03E+02 |
| Iodine* | I | 6.51E+00 | 7.09E+00 | 7.09E+00 |
| Iron | Fe | 3.82E-02 | 6.19E-02 | 6.19E-02 |
| Iron ore* | | 1.02E-02 | 1.75E-02 | 1.75E-02 |
| Kaolin* | | 1.46E-02 | 2.45E-02 | 2.45E-02 |
| Kyanite* | | 3.15E-02 | 5.00E-02 | 5.00E-02 |
| Lead | Pb | 4.83E-01 | 4.91E-01 | 4.91E-01 |
| Lime* | | 1.19E-02 | 2.02E-02 | 2.02E-02 |
| Lithium | Li | 2.42E+00 | 4.86E+00 | 4.86E+00 |
| Magnesium* | Mg | 6.14E-01 | 7.90E-01 | 7.90E-01 |
| Manganese | Mn | 3.76E-02 | 8.23E-02 | 8.23E-02 |
| Mercury* | Hg | 8.37E+00 | 8.96E+00 | 8.96E+00 |
| Molybdenum | Mo | 2.90E+01 | 2.92E+01 | 2.92E+01 |
| Nickel | Ni | 1.85E+00 | 2.89E+00 | 2.89E+00 |
| Niobium | Nb | 4.46E+00 | 5.20E+00 | 5.20E+00 |
| Palladium* | Pd | 6.37E+03 | 4.28E+03 | 4.28E+03 |
| Perlite* | | 5.08E-03 | 9.16E-03 | 9.16E-03 |
| Phosphorus | P | 1.40E-01 | 1.67E-01 | 1.67E-01 |
| Platinum* | Pt | 1.38E+04 | 8.77E+03 | 8.77E+03 |

| Mineral resource | Chemical element | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|---|
| Potash* | | 6.93E-02 | 1.04E-01 | 1.04E-01 |
| Pumice and pumicite* | | 3.08E-03 | 5.76E-03 | 5.76E-03 |
| Rhodium* | Rh | 9.73E+03 | 6.34E+03 | 6.34E+03 |
| Rutile* | | 1.24E-01 | 1.79E-01 | 1.79E-01 |
| Selenium* | Se | 1.28E+01 | 1.33E+01 | 1.33E+01 |
| Silicon* | | 3.18E-01 | 4.28E-01 | 4.28E-01 |
| Silver | Ag | 1.61E+02 | 1.53E+02 | 1.53E+02 |
| Strontium* | Sr | 5.76E-02 | 8.75E-02 | 8.75E-02 |
| Talc* | | 2.34E-02 | 3.78E-02 | 3.78E-02 |
| Tantalum* | Ta | 5.66E+01 | 5.29E+01 | 5.29E+01 |
| Tellurium* | Te | 1.85E+01 | 1.87E+01 | 1.87E+01 |
| Thallium* | Tl | 1.63E+03 | 1.20E+03 | 1.20E+03 |
| Tin | Sn | 5.23E+00 | 5.03E+00 | 5.03E+00 |
| Titanium* | Ti | 6.89E-01 | 8.79E-01 | 8.79E-01 |
| Titanium dioxide* | | 3.88E-01 | 5.15E-01 | 5.15E-01 |
| Tripoli* | | 2.14E-02 | 3.48E-02 | 3.48E-02 |
| Tungsten* | W | 7.19E+00 | 7.78E+00 | 7.78E+00 |
| Uranium | U | 3.58E+01 | 2.52E+01 | 2.52E+01 |
| Vanadium* | V | 3.49E+00 | 3.97E+00 | 3.97E+00 |
| Wollastonite* | | 2.20E-02 | 3.58E-02 | 3.58E-02 |
| Zinc | Zn | 1.16E-01 | 1.53E-01 | 1.53E-01 |
| Garnets* | | 2.99E-02 | 4.76E-02 | 4.76E-02 |
| Gemstones* | | 1.25E+04 | 7.99E+03 | 7.99E+03 |
| Platinum-group metals* | | 5.55E+03 | 3.76E+03 | 3.76E+03 |
| Rare-earth metals* | | 2.75E+00 | 3.19E+00 | 3.19E+00 |
| Zirconium minerals* | | 1.21E-01 | 1.75E-01 | 1.75E-01 |

* For these mineral resources ASOPs are extrapolated from price information.

## 12.4 From midpoint to endpoint

Endpoint characterization factors (CFe) for the extraction of mineral resource *x* and the cultural perspective c are calculated by:

$$\mathrm{CF}e_{x,c} = \mathrm{SOP}_{x,c} \times \mathrm{F}_{\mathrm{M}\rightarrow\mathrm{E},c}$$

whereby c denotes the cultural perspective, SOPx,c is the midpoint characterization factor (in kg Cu-eq/kg x) and $\mathrm{F}_{\mathrm{M}\rightarrow\mathrm{E},c}$ is the midpoint to endpoint conversion factor for cultural perspective c (USD/kg Cu-eq).

The midpoint to endpoint factor for mineral resource scarcity equals the endpoint characterization factor for copper:

$$\mathrm{F}_{\mathrm{M}\rightarrow\mathrm{E},c} = \mathrm{ASOP}_{Cu,c} \times \frac{\mathrm{ASCP}_{x,c}}{\mathrm{ASOP}_{x,c}}$$

whereby $ASOP_{Cu}$ (10.8 and 14.6 kg ore/kg Cu for R and URR, respectively) is the Absolute Surplus Ore Potential of copper as calculated following Section 12.3 (Vieira et al., 2016b), $ASCP_x$ (USD2013/kg x) is the Absolute Surplus Cost Potential of the mineral resource *x*, and $ASOP_x$ (kg ore/kg x) is the Absolute Surplus Ore Potential of mineral resource *x* for each cultural perspective *c*. ASCP*x* was derived by Vieira et al. (2016a) similarly to $ASOP_x$, but with cumulative cost-tonnage relationships instead of cumulative grade-tonnage relationships (see Supporting information). The operating costs account for co-production and are allocated across all mine products in proportion to their revenue for the mine operator (World Mine Cost Data Exchange 2014).

Similarly to ASOP, the price of a mineral resource can also be considered as a good predictor for ASCP (explained variance of the regressions equals 92-99%). For this reason, the last part of the calculation of the midpoint to endpoint factor for mineral resource scarcity for each cultural perspective *c* can be calculated as follows:

$$\frac{\mathrm{ASCP}_{x,c}}{\mathrm{ASOP}_{x,c}} = \frac{10^{a_{\mathrm{ASCP},c}} \times price^{b_{\mathrm{ASCP},c}}}{10^{a_{\mathrm{ASOP},c}} \times price^{b_{\mathrm{ASOP},c}}} \approx \frac{10^{a_{\mathrm{ASCP},c}}}{10^{a_{\mathrm{ASOP},c}}}$$

whereby aASCP and bASCP are the intercept and the slope of the log-linear function between ASCP and the price of each mineral resource (Supporting information, Figure S8.2), and aASOP and bASOP are the intercept and the slope of the log-linear function between ASOP and the price of each mineral resource (Figure 12.3). The slopes b of all are approximately 1 (0.97-1.08), thus leading to a factor not larger than 4 if the price is excluded from the equation. Here, the average price of each mineral resource in 2013 was used.
Table 12.3 provides the midpoint to endpoint factors for mineral resource scarcity for the three cultural perspectives.

*Table 12.3. Midpoint to endpoint factors for mineral resources for each cultural perspective. The midpoint to endpoint factors equal the absolute surplus cost potential (in USD2013/kg Cu) derived for copper (Vieira et al. 2016a).*

| | Unit | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|---|
| **Midpoint to endpoint factor** | USD2013/kg *Cu* | 0.16 | 0.23 | 0.23 |

# 13 Fossil resource scarcity

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This chapter is based on Ponsioen et al. (2014) and Vieira and Huijbregts (in preparation). The main changes introduced compared with the ReCiPe2008 report are:

- use of more recent cost and future production data.
- use of log-linear cumulative cost-tonnage relationships.
- average modelling approach for endpoint indicator considering all future production and without discounting.

## 13.1 Impact pathways and affected areas of protection

For the impact category fossil resource scarcity, the damage modelling is subdivided into several steps (Figure 13.1). It is assumed in the endpoint modelling that fossil fuels with the lowest costs are extracted first. Consequently, the increase in fossil fuel extraction causes an increase in costs due either to a change in production technique or to sourcing from a costlier location. For example, when all conventional oil is depleted, alternative techniques, such as enhanced oil recovery, will be applied or oil will be produced in alternative geographical locations with higher costs, such as Arctic regions (Ponsioen et al. 2014). This, when combined with the expected future extraction of a fossil resource, leads to a surplus cost potential (SCP) which is the endpoint indicator for this impact category. Here, we estimated the damage to natural resource scarcity. The fossil fuel potential (higher heating value) was used as midpoint indicator.

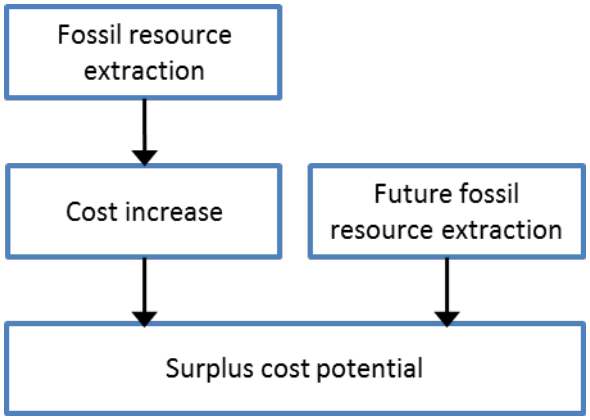


*Figure 13.1. Cause-and-effect chain, from fossil resource extraction to natural resource scarcity.*

## 13.2 Value choices

There were no value choices considered for fossil resources at midpoint or endpoint modelling.

## 13.3 Characterization factors at midpoint level

The midpoint indicator for fossil resource use, determined as the Fossil Fuel Potential of fossil resource *x* (kg oil-eq/unit of resource), is defined as the ratio between the energy content of fossil resource x and the energy content of crude oil, which is calculated by:

$$\mathrm{FFP}_x = \frac{\mathrm{HHV}_x}{\mathrm{HHV}_{oil}}$$

The fossil fuel potential (FFP) is based on the higher heating value (HHV) of each fossil resource and is provided for crude oil, natural gas, hard coal, brown coal and peat (see Table 13.1). We use the HHVs that were used in the Ecoinvent database (Jungbluth and Frischknecht 2010; Table S9.2).

*Table 13.1. Fossil fuel potentials (in kg oil-eq/unit of resource) for 5 fossil resources.*

| Fossil resource | Unit | Characterization factor |
|---|---|---|
| Crude oil | oil-eq/kg | 1 |
| Natural gas | oil-eq/$Nm^3$ | 0.84 |
| Hard coal | oil-eq/kg | 0.42 |
| Brown coal | oil-eq/kg | 0.22 |
| Peat | oil-eq/kg | 0.22 |

## 13.4 Characterization factors at endpoint level

Endpoint characterization factors (CFe) for the extraction of fossil resource *x*, expressed as Surplus Cost Potential (SCP), are calculated by Vieira and Huijbregts, *In preparation*.

$$\mathrm{CF}_e = \mathrm{SCP}_x = \frac{\int_{\mathrm{CFE}}^{\mathrm{MFE}} (\Delta \mathrm{C}_x)\, d\mathrm{FE}_x}{\mathrm{R}_x}$$

whereby $C_x$ (USD) is the cost determined via the log-linear cumulative cost-tonnage curve of fossil resource *x* (see crude oil in Figure 11.2) for an amount extracted of that resource *x* $FE_x$ (kg x for crude oil and hard coal and $m^3$ x for natural gas), $R_x$ (kg x) is the future production of the fossil resource *x*, $MFE_x$ is the maximum amount of that fossil resource to be extracted, and $CFE_x$ is the current cumulative tonnage of fossil resource *x* extracted.
A cumulative cost-tonnage regression reflects the relationship between the cumulative extraction of a fossil resource and its production costs. The cost of fossil resource *x* can be derived as (Vieira et al. 2016b):

$$\mathrm{C}_x = \frac{1}{a_x + b_x \cdot \ln(\mathrm{CFE}_x)}$$

whereby $C_x$ is the production cost of fossil resource *x* (in USD/kg or $Nm^3$ x), $CFE_x$ (in kg or $Nm^3$ x) is the cumulative amount of fossil resource *x* extracted, and $a_x$ and $b_x$ are, respectively, the intercept and slope of the log-linear distribution of the cumulative cost-tonnage relationship for fossil resource *x* (see crude oil in Figure 13.2).

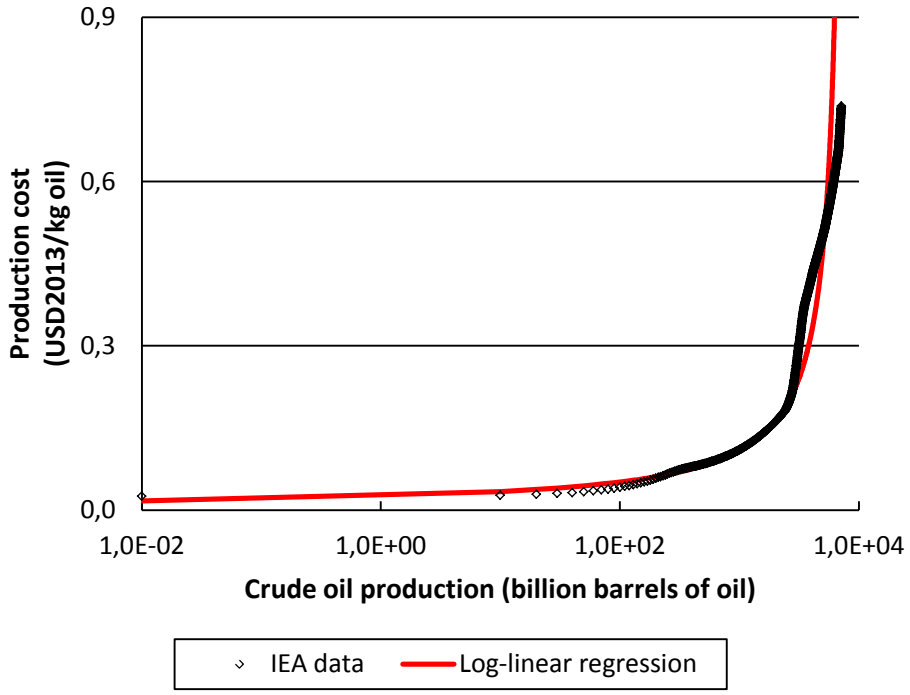


*Figure 13.2. Cumulative cost-tonnage relationship for crude oil plotted using a log-linear regression (x-axis in logarithmic scale).*

*Table 13.2. Endpoint characterization factors (in USD2013/unit of resource) for 5 fossil resources.*

| Fossil resource | Unit | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|---|
| **Crude oil** | USD2013/kg | 0.457 | 0.457 | 0.457 |
| **Hard coal** | USD2013/kg | 0.034 | 0.034 | 0.034 |
| **Natural gas** | USD2013/$Nm^3$ | 0.301 | 0.301 | 0.301 |
| **Brown coal*** | USD2013/kg | | | 0.034 |
| **Peat*** | USD2013/kg | | | 0.034 |

*No characterization factors were explicitly calculated for brown coal and peat due to lack of production and cost data. For the egalitarian perspective, from a precautionary point of view, the characterization factor of hard coal is adopted as a proxy.

# 14 Sum emissions

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## 14.1 Recommendations substance groups

For some applications, only a combined group of substances is known, instead of the individual ones. Databases already contain an inventory of these substance groups. To ensure maximum compatibility with the Ecoinvent 3.1 database, eight sum parameters were identified in that database. Characterization factors for various impact categories were derived by taking a weighted average of the substances within each substance group. The weighted averages are based on world emission data provided by Sleeswijk et al. (2008) for the year 2000. Weights are derived separately for each compartment (air, water, soil) based on the total emission of each substance to each compartment. See Table 14.1 for the included substances and their weights per substance group. If there are no emissions to a specific compartment, then no characterization factors are provided for that group and compartment.

Characterization factors for sub-compartments are based on the weights of their respective compartments, see Tables 14.2-14.4 for the weighted average factors per substance group and (sub)compartment for the Individualist, Hierarchist and Egalitarian perspectives, respectively. In total, there are 9 midpoint categories for which (some) of the substance groups have CFs. Note: Characterization factors for emissions to air are not derived specifically for urban or rural air for the midpoint categories Global Warming, Ozone Depletion, Ionizing Radiation and Photochemical Ozone Formation. The same factor, for unspecified air, is listed twice in Tables 14.2-14.4.

*Table 14.1. Total global emissions and derived weights per substance and emission compartment.*

| Substance | Emission air | Weight air | Emission water | Weight water | Emission soil | Weight soil |
|---|---|---|---|---|---|---|
| **Aldehydes, unspecified (kg)** | | | | | | |
| 2-Butenal | 2.32E+04 | 0.0002 | 3.46E+04 | 0.0019 | - | - |
| Acetalde-hyde | 2.73E+07 | 0.2741 | 7.22E+06 | 0.4021 | - | - |
| Benzalde-hyde | 5.64E+05 | 0.0057 | 1.65E+06 | 0.0919 | - | - |
| Formalde-hyde | 7.17E+07 | 0.7200 | 9.05E+06 | 0.5040 | - | - |
| **PAH, polycyclic aromatic hydrocarbons (kg)** | | | | | | |
| Anthracene | 3.77E+04 | 0.0084 | 9.55E+02 | 0.0196 | 1.85E+05 | 1 |
| Benzo(a)-pyrene | 1.10E+06 | 0.2459 | 4.28E+01 | 0.0009 | - | - |
| Fluoran-thene | 2.01E+05 | 0.0449 | 8.67E+01 | 0.0018 | - | - |
| Naphthalene | 2.41E+06 | 0.5388 | 4.67E+04 | 0.9561 | - | - |
| Phenan-threne | 5.56E+05 | 0.1243 | 1.02E+03 | 0.0209 | - | - |

| Substance | Emission air | Weight air | Emission water | Weight water | Emission soil | Weight soil |
|---|---|---|---|---|---|---|
| Pyrene | 1.68E+05 | 0.0376 | 3.98E+01 | 0.0008 | - | - |
| **Actinides, unspecified (kBq)** | | | | | | |
| Americium-241 | 1.40E+06 | 0.0290 | 9.35E+08 | 0.0091 | - | - |
| Uranium-234 | 1.94E+07 | 0.4020 | 9.22E+08 | 0.0090 | - | - |
| Uranium-235 | 8.42E+05 | 0.0174 | 4.05E+07 | 0.0004 | - | - |
| Uranium-238 | 1.82E+07 | 0.3771 | 1.16E+09 | 0.0113 | - | - |
| Plutonium-241 | 8.42E+06 | 0.1745 | 9.98E+10 | 0.9703 | - | - |
| **Carboxylic acids (kg)** | | | | | | |
| Formic acid | 7.24E+05 | 0.4254 | 2.62E+05 | 0.7973 | - | - |
| Acrylic acid | 9.78E+05 | 0.5746 | 6.66E+04 | 0.2027 | - | - |
| **Hydrocarbons, chlorinated (kg)** | | | | | | |
| Ethane, 1,1,1-trichloro-, HCFC-140 | 3.57E+05 | 3.70E-03 | 7.41E+04 | 4.10E-02 | - | - |
| Methane, tetrachloro-, CFC-10 | 4.17E+05 | 4.32E-03 | - | - | - | - |
| Ethane, 1,1,1,2-tetrachloro- | 4.80E+03 | 4.97E-05 | - | - | - | - |
| Ethane, 1,1,2,2-tetrachloro- | 4.59E+03 | 4.76E-05 | 1.22E+01 | 6.76E-06 | - | - |
| Ethane, 1,1,2-trichloro- | 5.75E+05 | 5.96E-03 | 2.40E+05 | 1.33E-01 | - | - |
| Benzene, 1,2,4-trichloro- | 1.49E+05 | 1.54E-03 | 1.12E+02 | 6.20E-05 | - | - |
| Ethane, 1,2-dichloro- | 2.43E+05 | 2.52E-03 | 5.91E+04 | 3.27E-02 | - | - |
| Ethene, 1,2-dichloro- | 9.33E+03 | 9.67E-05 | 1.52E+04 | 8.42E-03 | - | - |
| Propane, 1,2-dichloro- | 4.76E+06 | 4.93E-02 | 2.25E+03 | 1.25E-03 | - | - |
| Benzene, 1,3-dichloro- | 5.71E+03 | 5.92E-05 | 1.97E+02 | 1.09E-04 | - | - |
| Propene, 1,3-dichloro- | 1.73E+04 | 1.79E-04 | 2.77E+03 | 1.53E-03 | - | - |
| Allyl chloride | 5.83E+05 | 6.04E-03 | 1.21E+03 | 6.70E-04 | - | - |
| Benzotrichloride | 1.74E+03 | 1.80E-05 | - | - | - | - |
| Benzyl chloride | 1.95E+04 | 2.02E-04 | 3.88E+02 | 2.15E-04 | - | - |
| Benzene, chloro- | 1.72E+06 | 1.78E-02 | 6.66E+04 | 3.69E-02 | - | - |
| Ethane, chloro- | 5.30E+06 | 5.49E-02 | 9.42E+02 | 5.22E-04 | - | - |
| Chloroform | 4.20E+06 | 4.35E-02 | 5.56E+05 | 3.08E-01 | - | - |

| Substance | Emission air | Weight air | Emission water | Weight water | Emission soil | Weight soil |
|---|---|---|---|---|---|---|
| Propene, 1-chloro-1- | 9.16E+05 | 9.49E-03 | 0.00E+00 | 0.00E+00 | - | - |
| Methane, dichloro-, HCC-30 | 1.42E+07 | 1.47E-01 | 2.73E+05 | 1.51E-01 | - | - |
| Butadiene, hexachloro- | 4.00E+03 | 4.14E-05 | 0.00E+00 | 0.00E+00 | - | - |
| Benzene, hexachloro- | 2.60E+04 | 2.69E-04 | 2.17E+02 | 1.20E-04 | - | - |
| Cyclopenta-diene, hexachloro- | 1.23E+03 | 1.27E-05 | - | - | - | - |
| Ethane, hexachloro- | 3.12E+04 | 3.23E-04 | 4.70E+00 | 2.60E-06 | - | - |
| Methane, monochloro-, R-40 | 1.20E+07 | 1.24E-01 | 7.31E+03 | 4.05E-03 | - | - |
| Toluene, 2-chloro- | 4.76E+04 | 4.93E-04 | 8.27E+02 | 4.58E-04 | - | - |
| Benzene, 1,2-dichloro- | 4.31E+05 | 4.47E-03 | 1.05E+04 | 5.82E-03 | - | - |
| Benzene, 1,4-dichloro- | 2.08E+07 | 2.16E-01 | 2.78E+05 | 1.54E-01 | - | - |
| Benzene, pentachloro- | 1.53E+02 | 1.59E-06 | 1.64E+02 | 9.09E-05 | - | - |
| Ethane, pentachloro- | 1.29E+03 | 1.34E-05 | - | - | - | - |
| Ethene, tetrachloro- | 6.92E+06 | 7.17E-02 | 7.78E+04 | 4.31E-02 | - | - |
| Ethene, dichloro- (trans) | 4.12E+04 | 4.27E-04 | 2.07E+01 | 1.15E-05 | - | - |
| Butene, 1,4-dichloro-2- (trans) | 2.40E+02 | 2.49E-06 | - | - | - | - |
| Ethene, trichloro- | 2.03E+07 | 2.10E-01 | 1.06E+05 | 5.87E-02 | - | - |
| Ethene, chloro- | 2.43E+06 | 2.52E-02 | 3.24E+04 | 1.79E-02 | - | - |
| **Hydrocarbons, aliphatic, alkanes, cyclic** | | | | | | |
| Cyclohexane | 7.73E+06 | 0.9418 | 1.92E+04 | 0.5310 | - | - |
| Cyclohexa-nol | 1.38E+05 | 0.0168 | 4.68E+03 | 0.1294 | - | - |
| Cyclohexyla-mine | 5.70E+04 | 0.0069 | 3.76E+02 | 0.0104 | - | - |
| Dicyclo-pentadiene | 2.83E+05 | 0.0345 | 1.19E+04 | 0.3291 | - | - |
| **Hydrocarbons, aromatic** | | | | | | |
| Benzene, 1,2,4-trimethyl- | 8.52E+06 | 0.0136 | 7.88E+03 | 0.0127 | - | - |

| Substance | Emission air | Weight air | Emission water | Weight water | Emission soil | Weight soil |
|---|---|---|---|---|---|---|
| Benzene, 1,3,5-trimethyl- | 8.23E+06 | 0.0131 | 7.92E+02 | 0.0013 | - | - |
| Benzene | 1.48E+07 | 0.0236 | 8.53E+04 | 0.1371 | - | - |
| Benzene, ethyl- | 4.97E+07 | 0.0794 | 3.23E+04 | 0.0519 | - | - |
| Toluene | 5.45E+08 | 0.8703 | 4.96E+05 | 0.7971 | - | - |
| **Noble gases, radioactive** | | | | | | |
| Krypton-85 | 2.31E+15 | 0.9251 | - | - | - | - |
| Argon-41 | 1.87E+14 | 0.0749 | - | - | - | - |
| Radon-222 | 6.86E+10 | 0.0000 | - | - | - | - |

*Table 14.2. CFs per substance group, impact category and (sub)-compartment, Individualist perspective.*

| Substance group | (Sub)-compartment | Global warming | Ozone depletion | Ionizing radiation | Photochemical ozone (human) | Photochemical ozone (eco) | Freshwater ecotox | Marine ecotox | Terrestrial ecotox | Human tox (cancer) | Human tox (non-cancer) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg $CO_2$-eq | kg CFC11-eq | kg Co60to air-eq | kg $NO_x$-eq | kg $NO_x$-eq | kg 1,4DCB to freshwater-eq | kg 1,4DCB to saltwater-eq | kg 1,4DCB to ind soil-eq | kg 1,4DCB to urban air-eq | kg 1,4DCB to urban air-eq |
| Aldehydes, unspecified | Urban air | - | - | - | 1.74E-01 | 2.81E-01 | 2.28E-02 | 1.96E-02 | 1.37E-02 | 4.14E+01 | 1.44E+01 |
| | Rural air | - | - | - | 1.74E-01 | 2.81E-01 | 1.03E-02 | 2.91E-02 | 9.21E-03 | 1.35E+00 | 2.14E+01 |
| | Fresh water | - | - | - | - | - | 5.85E-01 | 1.94E-02 | 5.43E-04 | 8.16E-02 | 1.26E+01 |
| | Seawater | - | - | - | - | - | 9.66E-05 | 1.03E-01 | 5.87E-05 | 4.46E-03 | 1.57E-01 |
| PAH, polycyclic aromatic hydro-carbons | Urban air | - | - | - | - | - | 2.03E-01 | 8.53E+00 | 7.98E-02 | 3.25E+01 | 1.03E+00 |
| | Rural air | - | - | - | - | - | 3.44E-01 | 1.56E+01 | 5.16E-02 | 3.14E+01 | 2.01E+00 |
| | Fresh water | - | - | - | - | - | 1.30E+01 | 1.07E+00 | 2.85E-03 | 3.20E-02 | 2.53E+01 |
| | Seawater | - | - | - | - | - | 4.86E-03 | 1.10E+01 | 1.21E-03 | 2.30E-03 | 1.10E+00 |
| | Industrial soil* | - | - | - | - | - | 6.02E+00 | 5.43E+00 | 1.46E+01 | - | 4.57E-01 |
| | Agricultural soil* | - | - | - | - | - | 8.59E-01 | 5.05E+00 | 1.48E+01 | - | 1.26E-01 |
| Actinides, unspecified | Air | - | - | 1.58E+00 | - | - | - | - | - | - | - |
| | Fresh water | - | - | 3.05E-05 | - | - | - | - | - | - | - |
| | Seawater | - | - | 4.30E-04 | - | - | - | - | - | - | - |
| Carboxylic acids | Urban air | - | - | - | 4.63E-03 | 7.46E-03 | 2.19E-02 | 3.21E-03 | 6.90E-02 | - | 2.64E+00 |
| | Rural air | - | - | - | 4.63E-03 | 7.46E-03 | 6.39E-03 | 4.49E-03 | 6.59E-02 | - | 3.79E+00 |
| | Fresh water | - | - | - | - | - | 9.48E-02 | 1.33E-03 | 1.28E-06 | - | 5.13E-01 |
| | Seawater | - | - | - | - | - | 6.32E-10 | 9.40E-03 | 6.48E-09 | - | 6.88E-05 |
| Hydro- | Urban air | 3.02E | 1.29E- | - | 2.66E-02 | 4.29E-02 | 3.60E-04 | 5.17E-02 | 2.53E-03 | 1.87E+00 | 4.87E+01 |

| Substance group | (Sub)-compartment | Global warming | Ozone depletion | Ionizing radiation | Photochemical ozone (human) | Photochemical ozone (eco) | Freshwater ecotox | Marine ecotox | Terrestrial ecotox | Human tox (cancer) | Human tox (non-cancer) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg $CO_2$-eq | kg CFC11-eq | kg Co60to air-eq | kg $NO_x$-eq | kg $NO_x$-eq | kg 1,4DCB to freshwater-eq | kg 1,4DCB to saltwater-eq | kg 1,4DCB to ind soil-eq | kg 1,4DCB to urban air-eq | kg 1,4DCB to urban air-eq |
| carbons, chlorinated | Rural air | +01 3.02E +01 | 02 1.29E-02 | - | 2.66E-02 | 4.29E-02 | 3.63E-04 | 5.21E-02 | 2.49E-03 | 1.26E+00 | 4.94E+01 |
| | Fresh water | - | - | - | - | - | 3.35E-01 | 6.33E-02 | 2.93E-03 | 6.72E-01 | 5.22E+01 |
| | Seawater | - | - | - | - | - | 1.65E-04 | 3.45E-01 | 1.44E-03 | 2.18E-01 | 1.13E+01 |
| Hydro-carbons, | Urban air | - | - | - | 9.84E-02 | 1.59E-01 | 6.16E-04 | 2.46E-04 | 7.30E-04 | - | 8.68E-02 |
| aliphatic, | Rural air | - | - | - | 9.84E-02 | 1.59E-01 | 2.58E-04 | 3.04E-04 | 6.64E-04 | - | 6.24E-02 |
| alkanes, | Fresh water | - | - | - | - | - | 3.02E-01 | 5.52E-03 | 7.32E-05 | - | 7.49E-01 |
| cyclic | Seawater | - | - | - | - | - | 1.50E-06 | 1.71E-01 | 6.22E-06 | - | 1.47E-02 |
| Hydro-carbons, | Urban air | - | - | - | 1.63E-01 | 2.63E-01 | 1.52E-05 | 3.81E-04 | 4.43E-05 | 1.60E-01 | 1.24E-01 |
| aromatic | Rural air | - | - | - | 1.63E-01 | 2.63E-01 | 1.81E-05 | 4.56E-04 | 3.79E-05 | 1.62E-02 | 1.05E-01 |
| | Fresh water | - | - | - | - | - | 1.39E-01 | 2.05E-02 | 4.80E-05 | 5.35E-02 | 8.72E-01 |
| | Seawater | - | - | - | - | - | 6.47E-06 | 9.01E-02 | 1.94E-05 | 2.31E-02 | 8.60E-02 |
| Noble gases, radioactive, unspecified | Air | - | - | 5.62E-06 | - | - | - | - | - | - | - |

* CF based on Anthracene only

*Table 14.3. CFs per substance group, impact category and (sub)-compartment, Hierarchist perspective*

| Substance group | (Sub)-compartment | Global warming | Ozone depletion | Ionizing radiation | Photochemical ozone (human) | Photochemical ozone (eco) | Freshwater ecotox | Marine ecotox | Terrestrial ecotox | Human tox (cancer) | Human tox (non-cancer) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg $CO_2$-eq | kg CFC11-eq | kg Co60toair-eq | kg $NO_x$-eq | kg $NO_x$-eq | kg 1,4DCB to freshwater-eq | kg 1,4DCB to saltwater-eq | kg 1,4DCB to ind soil-eq | kg 1,4DCB to urban air-eq | kg 1,4DCB to urban air-eq |
| Aldehydes, unspecified | Urban air | - | - | - | 1.74E-01 | 2.81E-01 | 2.28E-02 | 1.95E-02 | 1.37E-02 | 4.14E+01 | 1.44E+01 |
| | Rural air | - | - | - | 1.74E-01 | 2.81E-01 | 1.03E-02 | 2.91E-02 | 9.22E-03 | 1.35E+00 | 2.14E+01 |
| | Fresh water | - | - | - | - | - | 5.85E-01 | 1.94E-02 | 5.44E-04 | 8.26E-02 | 1.26E+01 |
| | Seawater | - | - | - | - | - | 9.66E-05 | 1.03E-01 | 5.86E-05 | 4.50E-03 | 1.57E-01 |
| PAH, polycyclic aromatic hydrocarbons | Urban air | - | - | - | - | - | 2.03E-01 | 8.56E+00 | 7.96E-02 | 3.38E+01 | 1.03E+00 |
| | Rural air | - | - | - | - | - | 3.45E-01 | 1.56E+01 | 5.17E-02 | 3.14E+01 | 2.01E+00 |
| | Fresh water | - | - | - | - | - | 1.30E+01 | 1.06E+00 | 2.84E-03 | 8.95E-01 | 2.53E+01 |
| | Seawater | - | - | - | - | - | 4.85E-03 | 1.10E+01 | 1.21E-03 | 6.84E-02 | 1.10E+00 |
| | Industrial soil* | - | - | - | - | - | 6.00E+00 | 5.40E+00 | 1.45E+01 | - | 4.55E-01 |
| | Agricultural soil* | - | - | - | - | - | 8.57E-01 | 5.03E+00 | 1.48E+01 | - | 1.26E-01 |
| Actinides, unspecified | Air | - | - | 1.58E+00 | - | - | - | - | - | - | - |
| | Fresh water | - | - | 3.14E-05 | - | - | - | - | - | - | - |

| Substance group | (Sub)-compartment | Global warming | Ozone depletion | Ionizing radiation | Photochemical ozone (human) | Photochemical ozone (eco) | Freshwater ecotox | Marine ecotox | Terrestrial ecotox | Human tox (cancer) | Human tox (non-cancer) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg $CO_2$-eq | kg CFC11-eq | kg Co60toair-eq | kg $NO_x$-eq | kg $NO_x$-eq | kg 1,4DCB to freshwater-eq | kg 1,4DCB to saltwater-eq | kg 1,4DCB to ind soil-eq | kg 1,4DCB to urban air-eq | kg 1,4DCB to urban air-eq |
| | Seawater | - | - | 4.38E-04 | - | - | - | - | - | - | - |
| Carboxylic acids | Urban air | - | - | - | 4.63E-03 | 7.46E-03 | 2.19E-02 | 3.21E-03 | 6.90E-02 | - | 2.64E+00 |
| | Rural air | - | - | - | 4.63E-03 | 7.46E-03 | 6.39E-03 | 4.49E-03 | 6.59E-02 | - | 3.79E+00 |
| | Fresh water | - | - | - | - | - | 9.48E-02 | 1.33E-03 | 1.28E-06 | - | 5.13E-01 |
| | Seawater | - | - | - | - | - | 6.33E-10 | 9.41E-03 | 6.49E-09 | - | 6.89E-05 |
| Hydrocarbons, chlorinated | Urban air | 1.38E+01 | 7.26E-03 | - | 2.66E-02 | 4.29E-02 | 3.62E-04 | 5.27E-02 | 2.61E-03 | 2.27E+00 | 5.00E+01 |
| | Rural air | 1.38E+01 | 7.26E-03 | - | 2.66E-02 | 4.29E-02 | 3.65E-04 | 5.33E-02 | 2.57E-03 | 1.39E+00 | 5.07E+01 |
| | Fresh water | - | - | - | - | - | 3.35E-01 | 6.34E-02 | 2.94E-03 | 9.59E-01 | 5.22E+01 |
| | Seawater | - | - | - | - | - | 1.65E-04 | 3.46E-01 | 1.44E-03 | 3.41E-01 | 1.13E+01 |
| Hydrocarbons, aliphatic, alkanes, cyclic | Urban air | - | - | - | 9.84E-02 | 1.59E-01 | 6.16E-04 | 2.45E-04 | 7.30E-04 | - | 8.68E-02 |
| | Rural air | - | - | - | 9.84E-02 | 1.59E-01 | 2.58E-04 | 3.03E-04 | 6.64E-04 | - | 6.24E-02 |
| | Fresh water | - | - | - | - | - | 3.02E-01 | 5.53E-03 | 7.33E-05 | - | 7.49E-01 |
| | Seawater | - | - | - | - | - | 1.50E-06 | 1.71E-01 | 6.22E-06 | - | 1.47E-02 |

| Substance group | (Sub)-compartment | Global warming | Ozone depletion | Ionizing radiation | Photochemical ozone (human) | Photochemical ozone (eco) | Freshwater ecotox | Marine ecotox | Terrestrial ecotox | Human tox (cancer) | Human tox (non-cancer) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg $CO_2$-eq | kg CFC11-eq | kg Co60toair-eq | kg $NO_x$-eq | kg $NO_x$-eq | kg 1,4DCB to freshwater-eq | kg 1,4DCB to saltwater-eq | kg 1,4DCB to ind soil-eq | kg 1,4DCB to urban air-eq | kg 1,4DCB to urban air-eq |
| Hydrocarbons, aromatic | Urban air | - | - | - | 1.63E-01 | 2.63E-01 | 1.54E-05 | 3.88E-04 | 4.54E-05 | 1.72E-01 | 1.24E-01 |
| | Rural air | - | - | - | 1.63E-01 | 2.63E-01 | 1.86E-05 | 4.72E-04 | 3.85E-05 | 1.73E-02 | 1.05E-01 |
| | Fresh water | - | - | - | - | - | 1.55E-01 | 3.70E-03 | 4.86E-05 | 5.53E-02 | 8.72E-01 |
| | Seawater | - | - | - | - | - | 6.68E-06 | 1.06E-01 | 1.96E-05 | 2.34E-02 | 8.59E-02 |
| Noble gases, radioactive, unspecified | Air | - | - | 7.88E-06 | - | - | - | - | - | - | - |

* CF based on Anthracene only

*Table 14.4. CFs per substance group, impact category and (sub)-compartment, Egalitarian perspective*

| **Substance group** | **(Sub)-compart-ment** | **Global warm-ing** | **Ozone deple-tion** | **Ionizing radiation** | **Photo-chemical ozone (human)** | **Photo-chemical ozone (eco)** | **Fresh-water ecotox** | **Marine ecotox** | **Terres-trial ecotox** | **Human tox (cancer)** | **Human tox (non-cancer)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg $CO_2$-eq | kg CFC11-eq | kg Co60toair-eq | kg $NO_x$-eq | kg $NO_x$-eq | kg 1,4DCB to freshwater-eq | kg 1,4DCB to saltwater-eq | kg 1,4DCB to ind soil-eq | kg 1,4DCB to urban air-eq | kg 1,4DCB to urban air-eq |
| Alde-hydes, unspeci-fied | Urban air | - | - | - | 1.74E-01 | 2.81E-01 | 2.28E-02 | 1.95E-02 | 1.37E-02 | 4.14E+01 | 1.44E+01 |
| | Rural air | - | - | - | 1.74E-01 | 2.81E-01 | 1.03E-02 | 2.91E-02 | 9.22E-03 | 1.35E+00 | 2.14E+01 |
| | Fresh water | - | - | - | - | - | 5.85E-01 | 1.94E-02 | 5.44E-04 | 8.26E-02 | 1.26E+01 |
| | Seawater | - | - | - | - | - | 9.66E-05 | 1.03E-01 | 5.86E-05 | 4.50E-03 | 1.57E-01 |
| PAH, polycyclic aromatic hydro-carbons | Urban air | - | - | - | - | - | 2.03E-01 | 8.56E+00 | 7.96E-02 | 3.38E+01 | 1.03E+00 |
| | Rural air | - | - | - | - | - | 3.45E-01 | 1.56E+01 | 5.17E-02 | 3.14E+01 | 2.01E+00 |
| | Fresh water | - | - | - | - | - | 1.30E+01 | 1.06E+00 | 2.84E-03 | 8.95E-01 | 2.53E+01 |
| | Seawater | - | - | - | - | - | 4.85E-03 | 1.10E+01 | 1.21E-03 | 6.84E-02 | 1.10E+00 |
| | Industrial soil* | - | - | - | - | - | 6.00E+00 | 5.40E+00 | 1.45E+01 | - | 4.55E-01 |
| | Agricultural soil* | - | - | - | - | - | 8.57E-01 | 5.03E+00 | 1.48E+01 | - | 1.26E-01 |
| Actinides, unspeci-fied | Air | - | - | 4.16E+00 | - | - | - | - | - | - | - |
| | Fresh water | - | - | 2.92E-03 | - | - | - | - | - | - | - |
| | Seawater | - | - | 4.61E-04 | - | - | - | - | - | - | - |
| Carboxylic acids | Urban air | - | - | - | 4.63E-03 | 7.46E-03 | 2.19E-02 | 3.21E-03 | 6.90E-02 | - | 2.64E+00 |
| | Rural air | - | - | - | 4.63E-03 | 7.46E-03 | 6.39E-03 | 4.49E-03 | 6.59E-02 | - | 3.79E+00 |
| | Fresh water | - | - | - | - | - | 9.48E-02 | 1.33E-03 | 1.28E-06 | - | 5.13E-01 |
| | Seawater | - | - | - | - | - | 6.33E-10 | 9.41E-03 | 6.49E-09 | - | 6.89E-05 |

| Substance group | (Sub)-compart-ment | Global warm-ing | Ozone deple-tion | Ionizing radiation | Photo-chemical ozone (human) | Photo-chemical ozone (eco) | Fresh-water ecotox | Marine ecotox | Terres-trial ecotox | Human tox (cancer) | Human tox (non-cancer) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg $CO_2$-eq | kg CFC11-eq | kg Co60toair-eq | kg $NO_x$-eq | kg $NO_x$-eq | kg 1,4DCB to freshwater-eq | kg 1,4DCB to saltwater-eq | kg 1,4DCB to ind soil-eq | kg 1,4DCB to urban air-eq | kg 1,4DCB to urban air-eq |
| Hydro-carbons, chlori-nated | Urban air | 1.97E+00 | 6.62E-03 | - | 2.66E-02 | 4.29E-02 | 3.62E-04 | 5.27E-02 | 2.61E-03 | 2.27E+00 | 5.00E+01 |
| | Rural air | 1.97E+00 | 6.62E-03 | - | 2.66E-02 | 4.29E-02 | 3.65E-04 | 5.33E-02 | 2.57E-03 | 1.39E+00 | 5.07E+01 |
| | Fresh water | - | - | - | - | - | 3.35E-01 | 6.34E-02 | 2.94E-03 | 9.59E-01 | 5.22E+01 |
| | Seawater | - | - | - | - | - | 1.65E-04 | 3.46E-01 | 1.44E-03 | 3.41E-01 | 1.13E+01 |
| Hydro-carbons, aliphatic, alkanes, cyclic | Urban air | - | - | - | 9.84E-02 | 1.59E-01 | 6.16E-04 | 2.45E-04 | 7.30E-04 | - | 8.68E-02 |
| | Rural air | - | - | - | 9.84E-02 | 1.59E-01 | 2.58E-04 | 3.03E-04 | 6.64E-04 | - | 6.24E-02 |
| | Fresh water | - | - | - | - | - | 3.02E-01 | 5.53E-03 | 7.33E-05 | - | 7.49E-01 |
| | Seawater | - | - | - | - | - | 1.50E-06 | 1.71E-01 | 6.22E-06 | - | 1.47E-02 |
| Hydro-carbons, aromatic | Urban air | - | - | - | 1.63E-01 | 2.63E-01 | 1.54E-05 | 3.88E-04 | 4.54E-05 | 1.72E-01 | 1.24E-01 |
| | Rural air | - | - | - | 1.63E-01 | 2.63E-01 | 1.86E-05 | 4.72E-04 | 3.85E-05 | 1.73E-02 | 1.05E-01 |
| | Fresh water | - | - | - | - | - | 1.55E-01 | 3.70E-03 | 4.86E-05 | 5.53E-02 | 8.72E-01 |
| | Seawater | - | - | - | - | - | 6.68E-06 | 1.06E-01 | 1.96E-05 | 2.34E-02 | 8.59E-02 |
| Noble gases, radio-active, unspeci-fied | Air | - | - | 7.88E-06 | - | - | - | - | - | - | - |

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# SUPPORTING INFORMATION

# 16 S1. Supporting Information on fine dust formation

## 16.1 Country-specific characterization factors

*Table S1.1. Midpoint characterization factors for human health damage due to fine dust formation (kg primary PM2.5-equivalents/kg).*

| | | **PM2.5** | **$NH_3$** | **$NO_x$** | **$SO_2$** |
|---|---|---|---|---|---|
| *World Weighted Average* | ***World*** | ***1*** | ***0.24*** | ***0.11*** | ***0.29*** |
| Austria, Slovenia, Liechtenstein | Europe | 1.47 | 0.89 | 0.18 | 0.21 |
| Switzerland, Liechtenstein | Europe | 1.92 | 1.70 | 0.29 | 0.27 |
| Belgium, Luxemburg, Netherlands | Europe | 1.95 | 1.04 | 0.19 | 0.19 |
| Spain, Portugal | Europe | 0.94 | 0.16 | 0.10 | 0.23 |
| Finland | Europe | 0.24 | 0.23 | 0.03 | 0.05 |
| France, Andorra | Europe | 1.50 | 0.32 | 0.16 | 0.22 |
| Great Britain, Ireland | Europe | 1.67 | 0.54 | 0.09 | 0.14 |
| Greece, Cyprus | Europe | 0.83 | 0.19 | 0.16 | 0.27 |
| Italy, Malta, San Marino, Monaco | Europe | 2.02 | 0.65 | 0.22 | 0.28 |
| Germany | Europe | 1.74 | 0.62 | 0.22 | 0.21 |
| Sweden, Denmark | Europe | 0.38 | 0.13 | 0.11 | 0.08 |
| Turkey | Europe | 1.00 | 0.27 | 0.17 | 0.30 |
| Norway, Iceland, Svalbard | Europe | 0.34 | 0.05 | 0.06 | 0.05 |
| Bulgaria | Europe | 0.94 | 0.28 | 0.16 | 0.19 |
| Hungary | Europe | 1.19 | 0.51 | 0.12 | 0.16 |
| Poland, Baltic states | Europe | 0.79 | 0.46 | 0.08 | 0.13 |
| Serbia and Montenegro, Macedonia, Albania, Croatia | Europe | 0.91 | 0.32 | 0.15 | 0.17 |
| Czech Republic, Slovakia | Europe | 1.23 | 0.68 | 0.15 | 0.15 |
| Romania | Europe | 1.30 | 0.34 | 0.21 | 0.21 |
| Near East: Israel, Jordan, Lebanon, Palestine Terr, Syria | Europe | 1.79 | 0.45 | 0.06 | 0.35 |
| Morocco, Tunisia, Libya, Algeria | Africa | 1.07 | 0.11 | 0.05 | 0.25 |
| Egypt | Africa | 4.55 | 1.55 | 0.04 | 0.33 |
| Gulf states | Asia | 1.22 | 0.32 | 0.09 | 0.36 |
| West Africa | Africa | 0.48 | 0.03 | 0.01 | 0.18 |
| Eastern Africa | Africa | 0.28 | 0.01 | 0.00 | 0.21 |
| Southern Africa (excl. RSA) | Africa | 0.13 | 0.01 | 0.00 | 0.09 |
| Republic of South Africa, Swaziland Lesotho | Africa | 0.50 | 0.09 | 0.00 | 0.08 |
| Kazakhstan | Europe | 0.19 | 0.09 | 0.06 | 0.06 |
| Rest of former Soviet Union | Europe | 1.59 | 0.50 | 0.06 | 0.22 |

| | | PM2.5 | $NH_3$ | $NO_x$ | $SO_2$ |
|---|---|---|---|---|---|
| *World Weighted Average* | ***World*** | ***1*** | ***0.24*** | ***0.11*** | ***0.29*** |
| Russia, Armenia, Georgia, Azerbaijan | Europe | 0.81 | 0.23 | 0.05 | 0.11 |
| Eastern part of Russia | Asia | 0.13 | 0.04 | 0.08 | 0.06 |
| Ukraine, Belarus, Moldavia | Europe | 0.84 | 0.25 | 0.12 | 0.14 |
| South Korea | Asia | 2.15 | 1.59 | 0.06 | 0.32 |
| Japan | Asia | 2.65 | 0.74 | 0.06 | 0.27 |
| Australia | Oceania | 0.04 | 0.01 | 0.00 | 0.02 |
| New Zealand | Oceania | 0.02 | 0.09 | 0.00 | 0.15 |
| Pacific Islands, Papua New Guinea | Oceania | 0.02 | 0.01 | 0.00 | 0.15 |
| Mongolia, North Korea | Asia | 1.13 | 0.14 | 0.16 | 0.26 |
| China, Hong Kong, Macao | Asia | 2.90 | 0.71 | 0.38 | 0.46 |
| Taiwan | Asia | 0.75 | 0.44 | 0.02 | 0.25 |
| Rest of South Asia | Asia | 6.95 | 0.19 | 0.59 | 1.51 |
| India, Maldives, Sri Lanka | Asia | 4.99 | 0.26 | 0.47 | 1.26 |
| Indonesia, Papua New Guinea, East Timor | Asia | 0.28 | 0.01 | 0.02 | 0.14 |
| Thailand | Asia | 0.95 | 0.03 | 0.02 | 0.24 |
| Malaysia, Singapore, Brunei | Asia | 0.27 | 0.03 | 0.01 | 0.13 |
| Philippines | Asia | 0.83 | 0.12 | 0.03 | 0.07 |
| Vietnam | Asia | 1.83 | 0.12 | 0.02 | 0.40 |
| Cambodia, Laos, Myanmar | Asia | 0.54 | 0.04 | 0.05 | 0.28 |
| Canada, Greenland | North America | 0.10 | 0.10 | 0.03 | 0.04 |
| United States | North America | 0.68 | 0.23 | 0.02 | 0.08 |
| Brazil | South America | 0.23 | 0.02 | 0.00 | 0.14 |
| Mexico | North America | 0.85 | 0.15 | 0.03 | 0.17 |
| Central America, Caribbean | North America | 0.40 | 0.06 | 0.02 | 0.11 |
| Chile | South America | 1.92 | 0.58 | 0.01 | 0.08 |
| Argentina, Falklands, Uruguay | South America | 0.36 | 0.01 | 0.00 | 0.10 |
| Rest South America | South America | 0.19 | 0.04 | 0.01 | 0.16 |

*Table S1.2. Region-specific endpoint characterization factors for human health damage due to fine dust formation (yr·kton$^{-1}$) (Van Zelm et al. 2016).*

| **Source region** | **Continent** | **Emitted substance** | | | |
|---|---|---|---|---|---|
| | | **$PM_{2.5}$** | **$NH_3$** | **$NO_x$** | **$SO_2$** |
| *World Weighted Average* | *World* | *629.2* | *149.2* | *70.1* | *183.2* |
| Austria, Slovenia, Liechtenstein | Europe | 1.2E+03 | 7.4E+02 | 1.6E+02 | 1.7E+02 |
| Switzerland, Liechtenstein | Europe | 1.5E+03 | 1.3E+03 | 2.3E+02 | 2.1E+02 |
| Belgium, Luxemburg, Netherlands | Europe | 1.3E+03 | 7.0E+02 | 1.4E+02 | 1.4E+02 |
| Spain, Portugal | Europe | 6.1E+02 | 1.1E+02 | 6.3E+01 | 1.5E+02 |
| Finland | Europe | 2.4E+02 | 2.4E+02 | 4.2E+01 | 5.3E+01 |
| France, Andorra | Europe | 8.2E+02 | 1.9E+02 | 1.0E+02 | 1.5E+02 |
| Great Britain, Ireland | Europe | 1.3E+03 | 4.0E+02 | 6.3E+01 | 1.1E+02 |
| Greece, Cyprus | Europe | 6.5E+02 | 1.6E+02 | 1.4E+02 | 1.7E+02 |
| Italy, Malta, San Marino, Monaco | Europe | 1.6E+03 | 5.2E+02 | 1.8E+02 | 2.2E+02 |
| Germany | Europe | 1.3E+03 | 4.8E+02 | 1.7E+02 | 1.7E+02 |
| Sweden, Denmark | Europe | 3.1E+02 | 1.1E+02 | 9.1E+01 | 7.0E+01 |
| Turkey | Europe | 8.1E+02 | 2.3E+02 | 1.4E+02 | 2.0E+02 |
| Norway, Iceland, Svalbard | Europe | 2.5E+02 | 3.9E+01 | 4.8E+01 | 4.8E+01 |
| Bulgaria | Europe | 1.2E+03 | 3.5E+02 | 2.0E+02 | 1.7E+02 |
| Hungary | Europe | 1.4E+03 | 5.7E+02 | 1.3E+02 | 1.6E+02 |
| Poland, Baltic states | Europe | 8.1E+02 | 4.8E+02 | 8.9E+01 | 1.3E+02 |
| Serbia and Montenegro, Macedonia, Albania, Croatia | Europe | 9.6E+02 | 3.6E+02 | 1.6E+02 | 1.5E+02 |
| Czech Republic, Slovakia | Europe | 1.2E+03 | 6.5E+02 | 1.4E+02 | 1.4E+02 |
| Romania | Europe | 1.7E+03 | 4.5E+02 | 2.7E+02 | 2.1E+02 |
| Near East: Israel, Jordan, Lebanon, Palestine Terr., Syria | Europe | 7.6E+02 | 2.0E+02 | 3.2E+01 | 1.8E+02 |
| Morocco, Tunisia, Libya, Algeria | Africa | 6.6E+02 | 6.4E+01 | 3.4E+01 | 1.6E+02 |
| Egypt | Africa | 2.2E+03 | 7.6E+02 | 2.1E+01 | 1.7E+02 |
| Gulf states | Asia | 5.6E+02 | 1.4E+02 | 4.7E+01 | 2.1E+02 |
| West Africa | Africa | 2.4E+02 | 1.5E+01 | 3.2E+00 | 9.3E+01 |
| Eastern Africa | Africa | 1.4E+02 | 7.9E+00 | 2.7E+00 | 1.1E+02 |
| Southern Africa (excl RSA) | Africa | 6.3E+01 | 4.1E+00 | 8.5E-01 | 4.6E+01 |
| Republic of South Africa, Swaziland Lesotho | Africa | 3.2E+02 | 5.5E+01 | 2.1E+00 | 4.6E+01 |
| Kazakhstan | Europe | 2.4E+02 | 1.2E+02 | 6.3E+01 | 5.7E+01 |
| Rest of former Soviet Union | Europe | 1.1E+03 | 3.6E+02 | 4.2E+01 | 1.5E+02 |
| Russia, Armenia, Georgia, Azerbaijan | Europe | 1.4E+03 | 3.8E+02 | 8.0E+01 | 1.3E+02 |
| Eastern part of Russia | Asia | 1.3E+02 | 4.1E+01 | 6.2E+01 | 5.3E+01 |
| Ukraine, Belarus, | Europe | 1.3E+03 | 3.9E+02 | 1.8E+02 | 1.7E+02 |

| Source region | Continent | Emitted substance | | | |
|---|---|---|---|---|---|
| | | $PM_{2.5}$ | $NH_3$ | $NO_x$ | $SO_2$ |
| *World Weighted Average* | *World* | *629.2* | *149.2* | *70.1* | *183.2* |
| Moldavia | | | | | |
| South Korea | Asia | 7.0E+02 | 5.2E+02 | 2.7E+01 | 1.4E+02 |
| Japan | Asia | 1.5E+03 | 4.1E+02 | 3.7E+01 | 1.5E+02 |
| Australia | Oceania | 2.0E+01 | 3.3E+00 | 6.9E-01 | 1.4E+01 |
| New Zealand | Oceania | 9.4E+00 | 5.8E+01 | 9.5E-01 | 1.1E+02 |
| Pacific Islands, Papua New Guinea | Oceania | 1.1E+01 | 6.9E+00 | 2.5E+00 | 1.0E+02 |
| Mongolia, North Korea | Asia | 7.2E+02 | 8.2E+01 | 8.8E+01 | 1.5E+02 |
| China, Hong Kong, Macao | Asia | 1.7E+03 | 4.2E+02 | 2.3E+02 | 2.7E+02 |
| Taiwan | Asia | 3.5E+02 | 2.3E+02 | 9.0E+00 | 1.3E+02 |
| Rest of South Asia | Asia | 4.0E+03 | 1.1E+02 | 3.7E+02 | 9.5E+02 |
| India, Maldives, Sri Lanka | Asia | 3.4E+03 | 1.7E+02 | 3.2E+02 | 8.3E+02 |
| Indonesia, Papua New Guinea, East Timor | Asia | 1.9E+02 | 6.4E+00 | 1.1E+01 | 9.4E+01 |
| Thailand | Asia | 2.3E+02 | 1.1E+01 | 9.9E+00 | 8.8E+01 |
| Malaysia, Singapore, Brunei | Asia | 9.7E+01 | 1.5E+01 | 6.5E+00 | 6.0E+01 |
| Philippines | Asia | 5.6E+02 | 8.0E+01 | 1.7E+01 | 4.5E+01 |
| Vietnam | Asia | 9.6E+02 | 7.2E+01 | 1.4E+01 | 2.1E+02 |
| Cambodia, Laos, Myanmar | Asia | 3.4E+02 | 2.3E+01 | 2.9E+01 | 1.6E+02 |
| Canada, Greenland | North America | 8.8E+01 | 8.1E+01 | 1.9E+01 | 2.9E+01 |
| United States | North America | 4.5E+02 | 1.5E+02 | 1.4E+01 | 5.3E+01 |
| Brazil | South America | 9.7E+01 | 1.1E+01 | 4.9E-01 | 6.4E+01 |
| Mexico | North America | 2.2E+02 | 4.2E+01 | 9.4E+00 | 5.3E+01 |
| Central America, Caribbean | North America | 1.6E+02 | 2.5E+01 | 6.9E+00 | 4.7E+01 |
| Chile | South America | 6.6E+02 | 2.4E+02 | 3.2E+00 | 3.2E+01 |
| Argentina, Falklands, Uruguay | South America | 2.1E+02 | 6.4E+00 | 4.4E-01 | 6.3E+01 |
| Rest South America | South America | 7.1E+01 | 2.0E+01 | 3.5E+00 | 6.5E+01 |

# 17 S2. Supporting Information on ozone formation

## 17.1 Country-specific characterization factors

*Table S2.1. Region-specific ozone formation potentials for human health damage (HOFP in kg $NO_x$-eq·$kg^{-1}$) and ecosystem damage (EOFP in kg $NO_x$-equivalents/kg).*

| | | **HOFP (kg NOx-eq·$kg^{-1}$)** | | **EOFP (kg NOx-eq·$kg^{-1}$)** | |
|---|---|---|---|---|---|
| | | **Emitted substance** | | | |
| | | **$NO_x$** | **NMVOC** | **$NO_x$** | **NMVOC** |
| *World Weighted Average* | *World* | *1* | *0.18* | *1* | *0.29* |
| Austria, Slovenia, Liechtenstein | Europe | 0.78 | 0.39 | 1.61 | 0.90 |
| Switzerland, Liechtenstein | Europe | 1.04 | 0.43 | 1.56 | 0.76 |
| Belgium, Luxemburg, Netherlands | Europe | -0.48 | 0.69 | 0.16 | 1.10 |
| Spain, Portugal | Europe | 1.18 | 0.37 | 3.41 | 1.12 |
| Finland | Europe | 0.21 | 0.24 | 0.53 | 0.59 |
| France, Andorra | Europe | 0.77 | 0.49 | 1.81 | 1.06 |
| Great Britain, Ireland | Europe | -0.20 | 0.60 | 0.44 | 1.15 |
| Greece, Cyprus | Europe | 0.95 | 0.42 | 3.27 | 1.39 |
| Italy, Malta, San Marino, Monaco | Europe | 1.13 | 0.57 | 2.60 | 1.41 |
| Germany | Europe | 0.13 | 0.52 | 1.78 | 0.90 |
| Sweden, Denmark | Europe | 0.47 | 0.27 | 1.28 | 0.68 |
| Turkey | Europe | 1.21 | 0.31 | 3.24 | 0.97 |
| Norway, Iceland, Svalbard | Europe | 1.03 | 0.20 | 3.24 | 0.51 |
| Bulgaria | Europe | 0.88 | 0.27 | 2.12 | 0.79 |
| Hungary | Europe | 0.63 | 0.32 | 1.28 | 0.79 |
| Poland, Baltic states | Europe | 0.41 | 0.36 | 1.00 | 0.78 |
| Serbia and Montenegro, Macedonia, Albania, Croatia | Europe | 1.11 | 0.23 | 2.69 | 0.69 |
| Czech Republic, Slovakia | Europe | 0.34 | 0.38 | 0.79 | 0.78 |
| Romania | Europe | 0.90 | 0.30 | 1.79 | 0.77 |
| Near East: Israel, Jordan, Lebanon, Palestine Terr, Syria | Europe | 0.90 | 0.27 | 2.29 | 0.78 |
| Morocco, Tunisia, Libya, Algeria | Africa | 1.17 | 0.21 | 4.28 | 0.66 |
| Egypt | Africa | 1.17 | 0.43 | 2.05 | 0.86 |
| Gulf states | Asia | 1.17 | 0.16 | 3.04 | 0.30 |
| West Africa | Africa | 1.39 | 0.08 | 0.69 | 0.09 |
| Eastern Africa | Africa | 0.70 | 0.04 | 0.38 | 0.07 |
| Southern Africa (excl RSA) | Africa | 0.43 | 0.02 | 0.51 | 0.08 |
| Republic of South Africa, Swaziland Lesotho | Africa | 0.27 | 0.08 | 1.00 | 0.08 |

| | | HOFP (kg NOx-eq·kg$^{-1}$) | | EOFP (kg NOx-eq·kg$^{-1}$) | |
|---|---|---|---|---|---|
| | | Emitted substance | | | |
| | | $NO_x$ | NMVOC | $NO_x$ | NMVOC |
| *World Weighted Average* | *World* | *1* | *0.18* | *1* | *0.29* |
| Kazakhstan | Europe | 0.66 | 0.15 | 2.84 | 0.37 |
| Rest of former Soviet Union | Europe | 1.04 | 0.19 | 3.32 | 0.42 |
| Russia, Armenia, Georgia, Azerbaijan | Europe | 0.55 | 0.24 | 1.78 | 0.64 |
| Eastern part of Russia | Asia | 0.74 | 0.11 | 2.80 | 0.20 |
| Ukraine, Belarus, Moldavia | Europe | 0.75 | 0.29 | 1.85 | 0.78 |
| South Korea | Asia | 0.05 | 0.84 | 1.40 | 1.28 |
| Japan | Asia | -0.12 | 0.50 | 0.80 | 0.71 |
| Australia | Oceania | 0.27 | 0.02 | 0.08 | 0.02 |
| New Zealand | Oceania | 0.09 | 0.01 | 0.03 | 0.00 |
| Pacific Islands, Papua New Guinea | Oceania | 0.40 | 0.01 | 0.20 | 0.02 |
| Mongolia, North Korea | Asia | 0.83 | 0.08 | 2.42 | -0.47 |
| China, Hong Kong, Macao | Asia | 2.07 | 0.37 | 0.07 | 0.33 |
| Taiwan | Asia | 1.27 | 0.30 | 1.28 | 0.40 |
| Rest of South Asia | Asia | 4.82 | 0.31 | 1.82 | 0.13 |
| India, Maldives, Sri Lanka | Asia | 4.04 | 0.33 | 0.35 | 0.15 |
| Indonesia, Papua New Guinea, East Timor | Asia | 0.97 | 0.02 | 0.65 | 0.02 |
| Thailand | Asia | 1.76 | 0.06 | 0.55 | 0.10 |
| Malaysia, Singapore, Brunei | Asia | 1.10 | 0.03 | 1.12 | 0.03 |
| Philippines | Asia | 0.49 | 0.08 | 0.36 | 0.10 |
| Vietnam | Asia | 1.46 | 0.05 | 0.68 | 0.11 |
| Cambodia, Laos, Myanmar | Asia | 1.91 | 0.05 | 0.62 | 0.12 |
| Canada, Greenland | North America | 0.41 | 0.18 | 2.55 | 0.45 |
| United States | North America | 0.35 | 0.34 | 0.35 | 0.84 |
| Brazil | South America | 0.83 | 0.03 | 0.27 | 0.02 |
| Mexico | North America | 1.26 | 0.12 | 2.64 | 0.26 |
| Central America, Caribbean | North America | 1.16 | 0.08 | 1.44 | 0.18 |
| Chile | South America | 0.35 | 0.18 | 0.64 | 0.08 |
| Argentina, Falklands, Uruguay | South America | 0.46 | 0.04 | 0.20 | 0.01 |
| Rest South America | South America | 0.94 | 0.02 | 0.28 | 0.03 |

*Table S2.2. Midpoint characterisation factors for individual NMVOCs expressed as Human health Ozone Formation Potentials (HOFP in $NO_x$-equivalents/kg) for tropospheric ozone formation.*

| CAS nr | Substance name | HOFP ($NO_x$- |
|---|---|---|
| 000074-84-0 | Ethane | 0.03 |
| 000074-98-6 | Propane | 0.05 |
| 000106-97-8 | Butane | 0.11 |
| 000075-28-5 | i-Butane | 0.10 |
| 000109-66-0 | Pentane | 0.15 |
| 000078-78-4 | i-Pentane | 0.12 |
| 000463-82-1 | Neopentane | 0.07 |
| 000110-54-3 | Hexane | 0.15 |
| 000107-83-5 | 2-Methylpentane | 0.15 |
| 000096-14-0 | 3-Methylpentane | 0.16 |
| 000075-83-2 | 2,2-Dimethylbutane | 0.08 |
| 000079-29-8 | 2,3-Dimethylbutane | 0.18 |
| 000142-82-5 | Heptane | 0.13 |
| 000591-76-4 | 2-Methylhexane | 0.12 |
| 000589-34-4 | 3-Methylhexane | 0.15 |
| 000111-65-9 | Octane | 0.12 |
| 000592-27-8 | 2-Methylheptane | 0.12 |
| 000589-81-1 | 3-Methylheptane | 0.13 |
| 000111-84-2 | Nonane | 0.12 |
| 003221-61-2 | 2-Methyloctane | 0.12 |
| 002216-33-3 | 3-Methyloctane | 0.12 |
| 002216-34-4 | 4-Methyloctane | 0.13 |
| 000922-28-1 | 3,4-Dimethylheptane | 0.13 |
| 000124-18-5 | Decane | 0.13 |
| 000871-93-0 | 2-Methylnonane | 0.13 |
| 005911-04-6 | 3-Methylnonane | 0.14 |
| 017301-94-9 | 4-Methylnonane | 0.13 |
| 015869-89-3 | 2,5-Dimethyloctane | 0.14 |
| 002051-30-1 | 2,6-Dimethyloctane | 0.13 |
| 014676-29-0 | 2-Methyl-3-ethylheptane | 0.12 |
| 013475-81-5 | 2,2-Dimethyl-3,3-dimethylhexane | 0.07 |
| 001120-21-4 | Undecane | 0.13 |
| 006975-98-0 | 2-Methyldecane | 0.12 |
| 013151-34-3 | 3-Methyldecane | 0.13 |
| 002847-72-5 | 4-Methyldecane | 0.13 |
| 013151-35-4 | 5-Methyldecane | 0.13 |
| 000112-40-3 | Dodecane | 0.12 |
| 000629-50-5 | Tridecane | 0.15 |
| 000629-59-4 | Tetradecane | 0.17 |

| CAS nr | Substance name | HOFP ($NO_x$- |
|---|---|---|
| 000096-37-7 | Methylcyclopentane | 0.18 |
| 000110-82-7 | Cyclohexane | 0.10 |
| 000108-87-2 | Methylcyclohexane | 0.24 |
| 001678-91-7 | Ethylcyclohexane | 0.23 |
| 001678-92-8 | Propylcyclohexane | 0.22 |
| 001678-97-3 | 1,2,3-Trimethylcyclohexane | 0.21 |
| 000696-29-7 | i-Propylcyclohexane | 0.22 |
| 001678-93-9 | Butylcyclohexane | 0.21 |
| 001678-98-4 | i-Butylcyclohexane | 0.21 |
| 004291-80-9 | 1-Methyl-3-propylcyclohexane | 0.22 |
| 004291-81-0 | 1-Methyl-4-propylcyclohexane | 0.20 |
| 004292-92-6 | Pentylcyclohexane | 0.20 |
| 004292-75-5 | Hexylcyclohexane | 0.20 |
| 000074-85-1 | Ethylene | 0.36 |
| 000115-07-1 | Propylene | 0.42 |
| 000106-98-9 | But-1-ene | 0.38 |
| 000590-18-1 | Cis-but-2-ene | 0.41 |
| 000624-64-6 | Trans-but-2-ene | 0.42 |
| 000106-98-9 | Butylene | 0.23 |
| 000106-99-0 | 1,3-Butadiene | 0.32 |
| 000627-20-3 | Cis-pent-2-ene | 0.40 |
| 000646-04-8 | Trans-pent-2-ene | 0.40 |
| 000109-67-1 | 1-Pentene | 0.34 |
| 000563-46-2 | 2-Methylbut-1-ene | 0.27 |
| 000563-45-1 | 3-Methylbut-1-ene | 0.26 |
| 000513-35-9 | 2-Methylbut-2-ene | 0.30 |
| 000078-79-5 | Isoprene | 0.41 |
| 000592-41-6 | Hex-1-ene | 0.32 |
| 007688-21-3 | Cis-hex-2-ene | 0.38 |
| 009016-80-2 | Trans-hex-2-ene | 0.37 |
| 000080-56-8 | Alpha-pinene | 0.25 |
| 000127-91-3 | Beta-pinene | 0.12 |
| 000138-86-3 | Limonene | 0.26 |
| 004516-90-9 | 2-Methyl-3-butenol | -0.01 |
| 000071-43-2 | Benzene | 0.04 |
| 000108-88-3 | Toluene | 0.16 |
| 000095-47-6 | o-Xylene | 0.28 |
| 000108-38-3 | m-Xylene | 0.31 |
| 000106-42-3 | p-Xylene | 0.26 |
| 000100-41-4 | Ethylbenzene | 0.17 |
| 000103-65-1 | Propylbenzene | 0.14 |
| 000098-82-8 | i-Propylbenzene | 0.12 |

| CAS nr | Substance name | HOFP ($NO_x$- |
|---|---|---|
| 000526-73-8 | 1,2,3-Trimethylbenzene | 0.38 |
| 000095-63-6 | 1,2,4-Trimethylbenzene | 0.40 |
| 000108-67-8 | 1,3,5-Trimethylbenzene | 0.39 |
| 000611-14-3 | o-Ethyltoluene | 0.26 |
| 000620-14-4 | m-Ethyltoluene | 0.28 |
| 000622-96-8 | p-Ethyltoluene | 0.23 |
| 029224-55-3 | 3,5-Dimethylethylbenzene | 0.38 |
| 025550-13-4 | 3,5-Diethyltoluene | 0.36 |
| 000527-53-7 | 1,2,3,5-Tetramethylbenzene | 0.38 |
| 000095-93-2 | 1,2,4,5-Tetramethylbenzene | 0.36 |
| 000099-87-6 | 1-Methyl-4-i-propylbenzene | 0.27 |
| 000535-77-3 | 1-Methyl-3-i-propylbenzene | 0.32 |
| 000100-42-5 | Styrene | 0.02 |
| 000050-00-0 | Formaldehyde | 0.17 |
| 000075-07-0 | Acetaldehyde | 0.20 |
| 000123-38-6 | Propionaldehyde | 0.26 |
| | i-Propionaldehyde | 0.18 |
| 000123-72-8 | Butyraldehyde | 0.25 |
| 000100-62-3 | Pentanal | 0.26 |
| 000590-86-3 | 3-Methylbutanal | 0.15 |
| 000100-52-7 | Benzaldehyde | -0.07 |
| 000529-20-4 | 2-Methylbenzaldehyde | -0.10 |
| 000620-23-5 | 3-Methylbenzaldehyde | -0.07 |
| 000104-87-0 | 4-Methylbenzaldehyde | 0.02 |
| 000067-56-1 | Methanol | 0.05 |
| 000064-17-5 | Ethanol | 0.12 |
| 000071-23-8 | Propanol | 0.17 |
| 000067-63-0 | i-Propanol | 0.07 |
| 000071-36-3 | Butanol | 0.19 |
| 000078-83-1 | i-Butanol | 0.13 |
| 000078-92-2 | sec-butanol | 0.15 |
| 000075-65-0 | t-Butanol | 0.01 |
| 000123-51-3 | 3-Methyl-1-butanol | 0.16 |
| 000108-95-2 | Phenol | -0.02 |
| 000095-48-7 | o-Cresol | 0.07 |
| 000095-87-4 | 2,5-Xylenol | 0.20 |
| 000105-67-9 | 2,4-Xylenol | 0.20 |
| 000526-75-0 | 2,3-Xylenol | 0.12 |
| 000108-93-0 | Cyclohexanol | 0.16 |
| 000123-42-2 | Diacetone alcohol | 0.11 |
| 000067-64-1 | Acetone | 0.02 |
| 000078-93-3 | Methylethylketone | 0.12 |

| CAS nr | Substance name | HOFP ($NO_x$- |
|---|---|---|
| 000108-10-1 | Methyl-i-butylketone | 0.19 |
| 000108-94-1 | Cyclohexanone | 0.11 |
| 000107-87-9 | Methylpropylketone | 0.00 |
| 000107-31-3 | Methyl formate | 0.01 |
| 000079-20-9 | Methyl acetate | 0.03 |
| 000141-78-6 | Ethyl acetate | 0.07 |
| 000108-21-4 | i-Propyl acetate | 0.08 |
| 000123-86-4 | Butyl acetate | 0.09 |
| 000109-60-4 | n-Propyl acetate | 0.09 |
| 000064-18-6 | Formic acid | 0.01 |
| 000064-19-7 | Acetic acid | 0.03 |
| 000079-09-4 | Propanoic acid | 0.05 |
| 000115-10-6 | Dimethylether | 0.07 |
| 000060-29-7 | Diethylether | 0.17 |
| 000108-20-3 | Di-i-propylether | 0.16 |
| 000107-21-1 | Ethylene glycol | 0.12 |
| 000057-55-6 | Propylene glycol | 0.14 |
| 000111-76-2 | 2-Butoxyethanol | 0.16 |
| 000107-98-2 | 1-Methoxy-2-propanol | 0.12 |
| 000109-86-4 | 2-Methoxyethanol | 0.11 |
| 000110-80-5 | 2-Ethoxyethanol | 0.13 |
| 000107-02-8 | Acrolein | 0.20 |
| 000078-85-3 | Methacrolein | 0.33 |
| 000107-22-2 | Glyoxal | 0.08 |
| 000078-98-8 | Methylglyoxal | 0.37 |
| 000074-86-2 | Acetylene | 0.03 |
| 000074-99-7 | Propyne | 0.26 |
| 000075-09-2 | Methylene dichloride | 0.01 |
| 000075-00-3 | Ethyl chloride | 0.04 |
| 000127-18-4 | Tetrachloroethylene | 0.00 |
| 000079-01-6 | Trichloroethylene | 0.11 |
| 000075-34-3 | Ethylidene dichloride | 0.20 |
| 000071-55-6 | Methyl chloroform | 0.00 |
| 000074-87-3 | Methyl chloride | 0.00 |
| 000156-59-2 | Cis-dichloroethylene | 0.00 |
| 000156-60-5 | Trans-dichloroethylene | 0.00 |
| 000067-66-3 | Chloroform | 0.00 |

*Table S2.3. Region-specific endpoint characterization factors for human health damage (Van Zelm et al. 2016) and ecosystem damage due to ozone formation.*

| **Source region** | **Continent** | **Human health damage (yr·kton$^{-1}$)** | | **Ecosystem damage (species·yr/kg)** | |
|---|---|---|---|---|---|
| | | **Emitted substance** | | | |
| | | **NOx** | **NMVOC** | **NOx** | **NMVOC** |
| *World Weighted Average* | ***World*** | ***9.1·10$^{-1}$*** | ***1.6·10$^{-1}$*** | ***1.29·10$^{-7}$*** | ***3.68·10$^{-8}$*** |
| Austria, Slovenia, Liechtenstein | Europe | 3.3E-01 | 1.9E-01 | 1.62E-07 | 9.73E-08 |
| Switzerland, Liechtenstein | Europe | 4.2E-01 | 2.0E-01 | 2.09E-07 | 9.11E-08 |
| Belgium, Luxemburg, Netherlands | Europe | -2.2E-01 | 3.3E-01 | 2.95E-08 | 1.13E-07 |
| Spain, Portugal | Europe | 6.2E-01 | 2.2E-01 | 3.64E-07 | 1.13E-07 |
| Finland | Europe | 1.1E-01 | 1.3E-01 | 5.11E-08 | 7.14E-08 |
| France, Andorra | Europe | 3.2E-01 | 2.4E-01 | 2.08E-07 | 1.12E-07 |
| Great Britain, Ireland | Europe | -1.6E-01 | 3.2E-01 | 4.83E-08 | 1.13E-07 |
| Greece, Cyprus | Europe | 4.4E-01 | 2.3E-01 | 2.71E-07 | 1.07E-07 |
| Italy, Malta, San Marino, Monaco | Europe | 4.6E-01 | 2.7E-01 | 2.12E-07 | 1.35E-07 |
| Germany | Europe | 6.9E-02 | 2.5E-01 | 1.46E-07 | 1.00E-07 |
| Sweden, Denmark | Europe | 1.9E-01 | 1.5E-01 | 1.42E-07 | 7.18E-08 |
| Turkey | Europe | 6.2E-01 | 1.9E-01 | 4.35E-07 | 1.00E-07 |
| Norway, Iceland, Svalbard | Europe | 4.5E-01 | 1.2E-01 | 3.37E-07 | 5.01E-08 |
| Bulgaria | Europe | 3.9E-01 | 1.5E-01 | 2.01E-07 | 7.70E-08 |
| Hungary | Europe | 2.8E-01 | 1.7E-01 | 1.46E-07 | 8.47E-08 |
| Poland, Baltic states | Europe | 1.8E-01 | 1.8E-01 | 1.25E-07 | 8.95E-08 |
| Serbia and Montenegro, Macedonia, Albania, Croatia | Europe | 4.9E-01 | 1.4E-01 | 2.63E-07 | 6.85E-08 |
| Czech Republic, Slovakia | Europe | 1.6E-01 | 1.9E-01 | 8.67E-08 | 8.96E-08 |
| Romania | Europe | 3.8E-01 | 1.6E-01 | 1.99E-07 | 8.17E-08 |
| Near East: Israel, Jordan, Lebanon, Palestine Terr, Syria | Europe | 4.9E-01 | 1.8E-01 | 1.84E-07 | 7.23E-08 |
| Morocco, Tunisia, Libya, Algeria | Africa | 9.9E-01 | 1.7E-01 | 4.54E-07 | 7.41E-08 |
| Egypt | Africa | 6.0E-01 | 2.5E-01 | 1.08E-07 | 5.41E-08 |
| Gulf states | Asia | 9.7E-01 | 1.6E-01 | 2.64E-07 | 3.02E-08 |
| West Africa | Africa | 2.4E+00 | 1.1E-01 | 1.71E-07 | 1.52E-08 |
| Eastern Africa | Africa | 9.7E-01 | 4.3E-02 | 9.47E-08 | 1.13E-08 |
| Southern Africa (excl RSA) | Africa | 5.8E-01 | 2.3E-02 | 7.70E-08 | 7.31E-09 |
| Republic of South | Africa | 4.0E-01 | 1.1E-01 | 1.49E-07 | 2.13E-08 |

| Source region | Continent | Human health damage (yr·kton$^{-1}$) | | Ecosystem damage (species·yr/kg) | |
|---|---|---|---|---|---|
| | | Emitted substance | | | |
| | | NOx | NMVOC | NOx | NMVOC |
| *World Weighted Average* | ***World*** | ***9.1·10$^{-1}$*** | ***1.6·10$^{-1}$*** | ***1.29·10$^{-7}$*** | ***3.68·10$^{-8}$*** |
| Africa, Swaziland Lesotho | | | | | |
| Kazakhstan | Europe | 4.0E-01 | 1.0E-01 | 4.39E-07 | 4.83E-08 |
| Rest of former Soviet Union | Europe | 7.0E-01 | 1.5E-01 | 5.34E-07 | 6.18E-08 |
| Russia, Armenia, Georgia, Azerbaijan | Europe | 3.0E-01 | 1.4E-01 | 2.51E-07 | 8.25E-08 |
| Eastern part of Russia | Asia | 4.7E-01 | 7.7E-02 | 2.67E-07 | 2.92E-08 |
| Ukraine, Belarus, Moldavia | Europe | 3.4E-01 | 1.6E-01 | 2.27E-07 | 8.85E-08 |
| South Korea | Asia | 4.1E-01 | 5.0E-01 | 9.58E-08 | 1.12E-07 |
| Japan | Asia | 2.3E-03 | 2.7E-01 | 5.43E-08 | 6.47E-08 |
| Australia | Oceania | 2.8E-01 | 1.8E-02 | 6.84E-09 | 1.94E-09 |
| New Zealand | Oceania | 6.2E-02 | 8.8E-03 | 1.16E-10 | 2.64E-10 |
| Pacific Islands, Papua New Guinea | Oceania | 4.5E-01 | 1.0E-02 | 2.02E-08 | 2.04E-09 |
| Mongolia, North Korea | Asia | 5.8E-01 | 5.0E-02 | 2.14E-07 | -7.06E-08 |
| China, Hong Kong, Macao | Asia | 1.6E+00 | 2.9E-01 | 5.88E-09 | 4.19E-08 |
| Taiwan | Asia | 1.0E+00 | 2.0E-01 | 9.16E-08 | 4.87E-08 |
| Rest of South Asia | Asia | 5.7E+00 | 3.7E-01 | 3.30E-07 | 1.70E-08 |
| India, Maldives, Sri Lanka | Asia | 5.2E+00 | 4.1E-01 | 6.43E-08 | 2.09E-08 |
| Indonesia, Papua New Guinea, East Timor | Asia | 1.0E+00 | 1.8E-02 | 5.78E-08 | 2.71E-09 |
| Thailand | Asia | 1.2E+00 | 5.3E-02 | 7.49E-08 | 1.39E-08 |
| Malaysia, Singapore, Brunei | Asia | 7.0E-01 | 3.0E-02 | 1.25E-07 | 5.28E-09 |
| Philippines | Asia | 4.8E-01 | 7.2E-02 | 3.45E-08 | 1.27E-08 |
| Vietnam | Asia | 1.1E+00 | 4.3E-02 | 9.56E-08 | 1.40E-08 |
| Cambodia, Laos, Myanmar | Asia | 1.8E+00 | 4.4E-02 | 5.52E-08 | 1.22E-08 |
| Canada, Greenland | North America | 2.0E-01 | 1.1E-01 | 3.42E-07 | 5.98E-08 |
| United States | North America | 1.9E-01 | 1.9E-01 | 4.65E-08 | 1.42E-07 |
| Brazil | South America | 4.5E-01 | 1.8E-02 | 4.08E-08 | 1.73E-09 |
| Mexico | North America | 5.8E-01 | 8.4E-02 | 8.06E-07 | 4.06E-08 |
| Central America, Caribbean | North America | 6.7E-01 | 5.9E-02 | 2.36E-07 | 2.58E-08 |

| Source region | Continent | Human health damage (yr·kton$^{-1}$) | | Ecosystem damage (species·yr/kg) | |
|---|---|---|---|---|---|
| | | Emitted substance | | | |
| | | NOx | NMVOC | NOx | NMVOC |
| *World Weighted Average* | ***World*** | ***$9.1 \cdot 10^{-1}$*** | ***$1.6 \cdot 10^{-1}$*** | ***$1.29 \cdot 10^{-7}$*** | ***$3.68 \cdot 10^{-8}$*** |
| Chile | South America | 1.8E-01 | 7.6E-02 | 1.20E-07 | 9.87E-09 |
| Argentina, Falklands, Uruguay | South America | 3.3E-01 | 3.0E-02 | 3.75E-08 | 4.09E-10 |
| Rest South America | South America | 5.1E-01 | 1.6E-02 | 6.36E-08 | 4.28E-09 |

*Table S2.4. Midpoint characterisation factors for individual NMVOCs expressed as Ecosystem Ozone Formation Potentials (EOFP in $NO_x$-equivalents/kg) for tropospheric ozone formation*.

| CAS nr | Substance name | EOFP ($NO_x$- |
|---|---|---|
| 000074-84-0 | Ethane | 0.05 |
| 000074-98-6 | Propane | 0.08 |
| 000106-97-8 | Butane | 0.18 |
| 000075-28-5 | i-Butane | 0.16 |
| 000109-66-0 | Pentane | 0.23 |
| 000078-78-4 | i-Pentane | 0.20 |
| 000463-82-1 | Neopentane | 0.11 |
| 000110-54-3 | Hexane | 0.23 |
| 000107-83-5 | 2-Methylpentane | 0.24 |
| 000096-14-0 | 3-Methylpentane | 0.25 |
| 000075-83-2 | 2,2-Dimethylbutane | 0.13 |
| 000079-29-8 | 2,3-Dimethylbutane | 0.29 |
| 000142-82-5 | Heptane | 0.20 |
| 000591-76-4 | 2-Methylhexane | 0.19 |
| 000589-34-4 | 3-Methylhexane | 0.25 |
| 000111-65-9 | Octane | 0.20 |
| 000592-27-8 | 2-Methylheptane | 0.20 |
| 000589-81-1 | 3-Methylheptane | 0.22 |
| 000111-84-2 | Nonane | 0.20 |
| 003221-61-2 | 2-Methyloctane | 0.20 |
| 002216-33-3 | 3-Methyloctane | 0.20 |
| 002216-34-4 | 4-Methyloctane | 0.22 |
| 000922-28-1 | 3,4-Dimethylheptane | 0.21 |
| 000124-18-5 | Decane | 0.21 |
| 000871-93-0 | 2-Methylnonane | 0.20 |
| 005911-04-6 | 3-Methylnonane | 0.23 |
| 017301-94-9 | 4-Methylnonane | 0.20 |
| 015869-89-3 | 2,5-Dimethyloctane | 0.22 |
| 002051-30-1 | 2,6-Dimethyloctane | 0.21 |

| CAS nr | Substance name | EOFP ($NO_x$- |
|---|---|---|
| 014676-29-0 | 2-Methyl-3-ethylheptane | 0.20 |
| 013475-81-5 | 2,2-Dimethyl-3,3- | 0.11 |
| 001120-21-4 | Undecane | 0.21 |
| 006975-98-0 | 2-Methyldecane | 0.20 |
| 013151-34-3 | 3-Methyldecane | 0.21 |
| 002847-72-5 | 4-Methyldecane | 0.21 |
| 013151-35-4 | 5-Methyldecane | 0.20 |
| 000112-40-3 | Dodecane | 0.19 |
| 000629-50-5 | Tridecane | 0.25 |
| 000629-59-4 | Tetradecane | 0.27 |
| 000096-37-7 | Methylcyclopentane | 0.29 |
| 000110-82-7 | Cyclohexane | 0.16 |
| 000108-87-2 | Methylcyclohexane | 0.38 |
| 001678-91-7 | Ethylcyclohexane | 0.37 |
| 001678-92-8 | Propylcyclohexane | 0.35 |
| 001678-97-3 | 1,2,3-Trimethylcyclohexane | 0.33 |
| 000696-29-7 | i-Propylcyclohexane | 0.35 |
| 001678-93-9 | Butylcyclohexane | 0.34 |
| 001678-98-4 | i-Butylcyclohexane | 0.34 |
| 004291-80-9 | 1-Methyl-3-propylcyclohexane | 0.35 |
| 004291-81-0 | 1-Methyl-4-propylcyclohexane | 0.33 |
| 004292-92-6 | Pentylcyclohexane | 0.33 |
| 004292-75-5 | Hexylcyclohexane | 0.33 |
| 000074-85-1 | Ethylene | 0.58 |
| 000115-07-1 | Propylene | 0.68 |
| 000106-98-9 | But-1-ene | 0.61 |
| 000590-18-1 | Cis-but-2-ene | 0.66 |
| 000624-64-6 | Trans-but-2-ene | 0.68 |
| 000106-98-9 | Butylene | 0.37 |
| 000106-99-0 | 1,3-Butadiene | 0.52 |
| 000627-20-3 | Cis-pent-2-ene | 0.64 |
| 000646-04-8 | Trans-pent-2-ene | 0.65 |
| 000109-67-1 | 1-Pentene | 0.56 |
| 000563-46-2 | 2-Methylbut-1-ene | 0.44 |
| 000563-45-1 | 3-Methylbut-1-ene | 0.43 |
| 000513-35-9 | 2-Methylbut-2-ene | 0.48 |
| 000078-79-5 | Isoprene | 0.67 |
| 000592-41-6 | Hex-1-ene | 0.51 |
| 007688-21-3 | Cis-hex-2-ene | 0.61 |
| 009016-80-2 | Trans-hex-2-ene | 0.60 |
| 000080-56-8 | Alpha-pinene | 0.40 |
| 000127-91-3 | Beta-pinene | 0.19 |

| CAS nr | Substance name | EOFP ($NO_x$- |
|---|---|---|
| 000138-86-3 | Limonene | 0.41 |
| 004516-90-9 | 2-Methyl-3-butenol | -0.01 |
| 000071-43-2 | Benzene | 0.06 |
| 000108-88-3 | Toluene | 0.26 |
| 000095-47-6 | o-Xylene | 0.46 |
| 000108-38-3 | m-Xylene | 0.50 |
| 000106-42-3 | p-Xylene | 0.42 |
| 000100-41-4 | Ethylbenzene | 0.27 |
| 000103-65-1 | Propylbenzene | 0.22 |
| 000098-82-8 | i-Propylbenzene | 0.19 |
| 000526-73-8 | 1,2,3-Trimethylbenzene | 0.61 |
| 000095-63-6 | 1,2,4-Trimethylbenzene | 0.64 |
| 000108-67-8 | 1,3,5-Trimethylbenzene | 0.63 |
| 000611-14-3 | o-Ethyltoluene | 0.43 |
| 000620-14-4 | m-Ethyltoluene | 0.46 |
| 000622-96-8 | p-Ethyltoluene | 0.37 |
| 029224-55-3 | 3,5-Dimethylethylbenzene | 0.61 |
| 025550-13-4 | 3,5-Diethyltoluene | 0.57 |
| 000527-53-7 | 1,2,3,5-Tetramethylbenzene | 0.61 |
| 000095-93-2 | 1,2,4,5-Tetramethylbenzene | 0.58 |
| 000099-87-6 | 1-Methyl-4-i-propylbenzene | 0.44 |
| 000535-77-3 | 1-Methyl-3-i-propylbenzene | 0.51 |
| 000100-42-5 | Styrene | 0.03 |
| 000050-00-0 | Formaldehyde | 0.27 |
| 000075-07-0 | Acetaldehyde | 0.32 |
| 000123-38-6 | Propionaldehyde | 0.42 |
| | i-Propionaldehyde | 0.29 |
| 000123-72-8 | Butyraldehyde | 0.41 |
| 000100-62-3 | Pentanal | 0.41 |
| 000590-86-3 | 3-Methylbutanal | 0.24 |
| 000100-52-7 | Benzaldehyde | -0.11 |
| 000529-20-4 | 2-Methylbenzaldehyde | -0.16 |
| 000620-23-5 | 3-Methylbenzaldehyde | -0.11 |
| 000104-87-0 | 4-Methylbenzaldehyde | 0.03 |
| 000067-56-1 | Methanol | 0.08 |
| 000064-17-5 | Ethanol | 0.20 |
| 000071-23-8 | Propanol | 0.28 |
| 000067-63-0 | i-Propanol | 0.11 |
| 000071-36-3 | Butanol | 0.30 |
| 000078-83-1 | i-Butanol | 0.21 |
| 000078-92-2 | sec-butanol | 0.23 |
| 000075-65-0 | t-Butanol | 0.01 |

| CAS nr | Substance name | EOFP ($NO_x$- |
|---|---|---|
| 000123-51-3 | 3-Methyl-1-butanol | 0.26 |
| 000108-95-2 | Phenol | -0.03 |
| 000095-48-7 | o-Cresol | 0.11 |
| 000095-87-4 | 2,5-Xylenol | 0.32 |
| 000105-67-9 | 2,4-Xylenol | 0.32 |
| 000526-75-0 | 2,3-Xylenol | 0.20 |
| 000108-93-0 | Cyclohexanol | 0.26 |
| 000123-42-2 | Diacetone alcohol | 0.17 |
| 000067-64-1 | Acetone | 0.04 |
| 000078-93-3 | Methylethylketone | 0.19 |
| 000108-10-1 | Methyl-i-butylketone | 0.30 |
| 000108-94-1 | Cyclohexanone | 0.17 |
| 000107-87-9 | Methylpropylketone | -0.01 |
| 000107-31-3 | Methyl formate | 0.02 |
| 000079-20-9 | Methyl acetate | 0.04 |
| 000141-78-6 | Ethyl acetate | 0.11 |
| 000108-21-4 | i-Propyl acetate | 0.12 |
| 000123-86-4 | Butyl acetate | 0.15 |
| 000109-60-4 | n-Propyl acetate | 0.14 |
| 000064-18-6 | Formic acid | 0.02 |
| 000064-19-7 | Acetic acid | 0.05 |
| 000079-09-4 | Propanoic acid | 0.08 |
| 000115-10-6 | Dimethylether | 0.11 |
| 000060-29-7 | Diethylether | 0.27 |
| 000108-20-3 | Di-i-propylether | 0.26 |
| 000107-21-1 | Ethylene glycol | 0.19 |
| 000057-55-6 | Propylene glycol | 0.23 |
| 000111-76-2 | 2-Butoxyethanol | 0.26 |
| 000107-98-2 | 1-Methoxy-2-propanol | 0.20 |
| 000109-86-4 | 2-Methoxyethanol | 0.17 |
| 000110-80-5 | 2-Ethoxyethanol | 0.22 |
| 000107-02-8 | Acrolein | 0.32 |
| 000078-85-3 | Methacrolein | 0.54 |
| 000107-22-2 | Glyoxal | 0.13 |
| 000078-98-8 | Methylglyoxal | 0.59 |
| 000074-86-2 | Acetylene | 0.04 |
| 000074-99-7 | Propyne | 0.43 |
| 000075-09-2 | Methylene dichloride | 0.02 |
| 000075-00-3 | Ethyl chloride | 0.06 |
| 000127-18-4 | Tetrachloroethylene | 0.01 |
| 000079-01-6 | Trichloroethylene | 0.17 |
| 000075-34-3 | Ethylidene dichloride | 0.32 |

| CAS nr | Substance name | EOFP ($NO_x$- |
|---|---|---|
| 000071-55-6 | Methyl chloroform | -0.01 |
| 000074-87-3 | Methyl chloride | 0.01 |
| 000156-59-2 | Cis-dichloroethylene | 0.00 |
| 000156-60-5 | Trans-dichloroethylene | -0.01 |
| 000067-66-3 | Chloroform | 0.00 |

# 18 S3. Supporting Information on acidification

## 18.1 Country-specific characterization factors

*Table S3.1. Country-specific terrestrial acidification potentials for terrestrial ecosystem damage due to acidifying emissions (kg $SO_2$-equivalents/kg).*

| | **$NO_x$** | **$NH_3$** | **$SO_2$** |
|---|---|---|---|
| *World Weighted Average* | ***0.36*** | ***1.96*** | ***1*** |
| Afghanistan | 0.88 | 3.21 | 2.17 |
| Albania | 0.52 | 2.39 | 1.28 |
| Algeria | 0.23 | 0.93 | 0.46 |
| American Samoa | 0.01 | 0.01 | 0.01 |
| Andorra | 0.55 | 3.12 | 1.44 |
| Angola | 0.29 | 1.05 | 1.14 |
| Anguilla | 0.06 | 0.58 | 0.17 |
| Antarctica | 0.06 | 0.03 | 0.03 |
| Antigua & Barbuda | 0.06 | 0.59 | 0.18 |
| Argentina | 0.14 | 0.67 | 0.99 |
| Armenia | 0.71 | 3.12 | 1.87 |
| Aruba | 0.09 | 0.62 | 0.17 |
| Australia | 0.14 | 0.43 | 0.28 |
| Austria | 0.92 | 6.39 | 2.54 |
| Azerbaijan | 0.66 | 2.55 | 1.49 |
| Bahamas | 0.15 | 1.36 | 0.40 |
| Bahrain | 0.66 | 1.87 | 1.18 |
| Bangladesh | 0.32 | 0.65 | 0.59 |
| Barbados | 0.07 | 0.58 | 0.18 |
| Belarus | 0.60 | 2.38 | 2.04 |
| Belgium | 0.74 | 4.56 | 2.01 |
| Belize | 0.10 | 0.78 | 0.33 |
| Benin | 0.13 | 0.56 | 0.67 |
| Bhutan | 0.48 | 2.29 | 1.34 |
| Bolivia | 0.23 | 1.23 | 2.08 |
| Bosnia Herzegovina | 0.71 | 4.21 | 1.94 |
| Botswana | 0.33 | 1.23 | 1.11 |
| Bouvet Island | - | 0.01 | 0.03 |
| Brazil | 0.29 | 1.67 | 1.26 |
| British Indian Ocean Territory | 0.04 | 0.12 | 0.07 |
| British Virgin Is | 0.06 | 0.58 | 0.17 |
| Brunei | 0.12 | 0.32 | 0.28 |
| Bulgaria | 0.54 | 1.90 | 1.09 |
| Burkina Faso | 0.14 | 0.73 | 0.71 |
| Burundi | 0.24 | 1.25 | 1.33 |
| Cambodia | 0.18 | 0.45 | 0.40 |
| Cameroon | 0.24 | 1.11 | 1.09 |
| Canada | 0.85 | 6.39 | 3.17 |
| Cape Verde | 0.05 | 0.50 | 0.22 |
| Central African Republic | 0.52 | 1.96 | 1.87 |
| Chad | 0.32 | 1.35 | 1.42 |
| Chile | 0.31 | 2.41 | 1.42 |

| | $NO_x$ | $NH_3$ | $SO_2$ |
|---|---|---|---|
| *World Weighted Average* | ***0.36*** | ***1.96*** | ***1*** |
| China | 0.63 | 2.29 | 1.55 |
| Christmas Island | 0.06 | 0.17 | 0.16 |
| Colombia | 0.17 | 1.29 | 0.48 |
| Congo | 0.26 | 1.92 | 1.63 |
| Congo DRC | 0.27 | 1.10 | 1.90 |
| Comoros | 0.14 | 0.42 | 0.39 |
| Cook Islands | 0.01 | 0.00 | 0.00 |
| Costa Rica | 0.15 | 1.50 | 0.74 |
| Cote d'Ivoire | 0.11 | 0.75 | 0.61 |
| Croatia | 0.75 | 4.13 | 1.75 |
| Cuba | 0.11 | 0.92 | 0.31 |
| Cyprus | 0.41 | 0.94 | 0.57 |
| Czech Republic | 0.97 | 6.71 | 2.77 |
| Denmark | 0.80 | 5.00 | 2.44 |
| Djibouti | 0.22 | 0.71 | 0.50 |
| Dominican Republic | 0.07 | 0.58 | 0.16 |
| Ecuador | 0.24 | 1.77 | 0.90 |
| Egypt | 0.71 | 1.50 | 2.06 |
| El Salvador | 0.11 | 0.85 | 0.37 |
| Equatorial Guinea | 0.22 | 1.77 | 1.00 |
| Eritrea | 0.26 | 0.87 | 0.60 |
| Estonia | 0.65 | 2.26 | 2.52 |
| Ethiopia | 0.25 | 0.73 | 0.67 |
| Faroe Islands | 0.32 | 0.76 | 0.85 |
| Falkland Islands | 0.08 | 0.11 | 0.94 |
| Fiji | 0.01 | 0.02 | 0.02 |
| Finland | 0.63 | 2.57 | 3.61 |
| France | 0.66 | 3.62 | 1.71 |
| French Guiana | 0.15 | 1.00 | 0.57 |
| French Polynesia | 0.01 | 0.00 | 0.00 |
| French Southern Antarctic Lands | 0.06 | 0.00 | 0.03 |
| Gabon | 0.21 | 1.73 | 1.19 |
| Gambia | 0.14 | 0.92 | 0.69 |
| Gaza Strip | 0.70 | 1.82 | 1.33 |
| Georgia | 0.74 | 4.05 | 2.04 |
| Germany | 0.86 | 4.96 | 2.43 |
| Ghana | 0.11 | 0.56 | 0.62 |
| Greece | 0.42 | 1.50 | 0.78 |
| Greenland | 0.11 | 0.48 | 1.17 |
| Grenada | 0.09 | 0.60 | 0.20 |
| Guadeloupe | 0.05 | 0.58 | 0.18 |
| Guam | 0.05 | 0.21 | 0.11 |
| Guatemala | 0.12 | 0.95 | 0.41 |
| Guinea | 0.14 | 1.07 | 0.53 |
| Guinea-Bissau | 0.12 | 0.97 | 0.36 |
| Guyana | 0.24 | 1.91 | 0.82 |
| Haiti | 0.08 | 0.61 | 0.18 |
| Honduras | 0.10 | 0.69 | 0.33 |
| Hungary | 0.78 | 3.93 | 1.83 |

| | $NO_x$ | $NH_3$ | $SO_2$ |
|---|---|---|---|
| *World Weighted Average* | ***0.36*** | ***1.96*** | ***1*** |
| Iceland | 0.19 | 1.80 | 1.10 |
| India | 0.35 | 0.84 | 0.66 |
| Indonesia | 0.14 | 0.49 | 0.45 |
| Iran | 0.51 | 1.63 | 1.08 |
| Iraq | 0.53 | 1.22 | 1.02 |
| Ireland | 0.35 | 1.28 | 1.22 |
| Isle of Man | 0.44 | 2.06 | 1.39 |
| Israel | 0.95 | 2.47 | 1.88 |
| Italy | 0.70 | 4.76 | 1.25 |
| Jamaica | 0.08 | 0.66 | 0.20 |
| Jan Mayen | 0.18 | 0.21 | 0.32 |
| Japan | 0.29 | 1.62 | 0.82 |
| Jersey | 0.51 | 2.23 | 1.29 |
| Jordan | 0.63 | 1.52 | 1.59 |
| Kazakhstan | 0.75 | 2.33 | 1.70 |
| Kenya | 0.27 | 0.98 | 0.92 |
| Kiribati | 0.01 | 0.00 | 0.01 |
| Kuwait | 0.74 | 2.03 | 1.73 |
| Kyrgyzstan | 1.34 | 6.39 | 2.84 |
| Laos | 0.25 | 0.69 | 0.54 |
| Latvia | 0.64 | 2.38 | 2.12 |
| Lebanon | 0.46 | 1.08 | 0.71 |
| Lesotho | 0.26 | 0.55 | 0.52 |
| Liberia | 0.15 | 2.38 | 0.73 |
| Libya | 0.26 | 0.91 | 0.58 |
| Liechtenstein | 0.83 | 4.72 | 2.18 |
| Lithuania | 0.66 | 2.63 | 2.11 |
| Luxembourg | 0.83 | 5.63 | 2.43 |
| Macedonia | 0.67 | 3.28 | 1.81 |
| Madagascar | 0.21 | 0.88 | 0.61 |
| Malawi | 0.33 | 1.28 | 1.35 |
| Malaysia | 0.14 | 0.35 | 0.41 |
| Mali | 0.18 | 1.37 | 0.66 |
| Malta | 0.31 | 1.04 | 0.68 |
| Martinique | 0.06 | 0.59 | 0.18 |
| Mauritania | 0.33 | 3.62 | 1.13 |
| Mauritius | 0.08 | 0.19 | 0.12 |
| Mayotte | 0.14 | 0.38 | 0.33 |
| Mexico | 0.20 | 1.70 | 0.74 |
| Moldova | 0.51 | 1.53 | 1.18 |
| Micronesia | 0.01 | 0.04 | 0.05 |
| Mongolia | 0.67 | 1.75 | 1.79 |
| Montserrat | 0.05 | 0.58 | 0.18 |
| Morocco | 0.18 | 0.80 | 0.34 |
| Mozambique | 0.25 | 0.73 | 0.97 |
| Myanmar | 0.28 | 0.85 | 0.82 |
| Namibia | 0.36 | 1.67 | 0.56 |
| Nepal | 0.46 | 1.37 | 0.86 |
| Netherlands | 0.73 | 4.05 | 1.98 |

| | $NO_x$ | $NH_3$ | $SO_2$ |
|---|---|---|---|
| *World Weighted Average* | ***0.36*** | ***1.96*** | ***1*** |
| Netherlands Antilles | 0.09 | 0.62 | 0.17 |
| New Caledonia | 0.02 | 0.06 | 0.10 |
| New Zealand | 0.19 | 0.70 | 0.86 |
| Nicaragua | 0.10 | 0.66 | 0.36 |
| Niger | 0.23 | 1.29 | 2.00 |
| Nigeria | 0.18 | 0.72 | 0.81 |
| Niue | 0.01 | 0.01 | 0.01 |
| North Korea | 0.77 | 4.88 | 1.66 |
| Norway | 0.73 | 5.52 | 2.28 |
| Oman | 0.33 | 1.04 | 0.67 |
| Palau | 0.07 | 0.23 | 0.14 |
| Pakistan | 0.94 | 3.62 | 2.49 |
| Panama | 0.11 | 0.86 | 0.55 |
| Papua New Guinea | 0.04 | 0.22 | 0.22 |
| Paraguay | 0.15 | 0.82 | 0.98 |
| Peru | 0.33 | 2.58 | 2.75 |
| Philippines | 0.14 | 0.40 | 0.33 |
| Pitcairn island | 0.01 | 0.01 | 0.02 |
| Poland | 0.90 | 5.75 | 2.60 |
| Portugal | 0.35 | 2.68 | 0.88 |
| Puerto Rico | 0.07 | 0.58 | 0.16 |
| Qatar | 0.67 | 2.02 | 1.25 |
| Reunion | 0.10 | 0.22 | 0.28 |
| Romania | 0.66 | 4.05 | 1.83 |
| Russia | 0.65 | 2.54 | 2.30 |
| Rwanda | 0.23 | 1.79 | 1.62 |
| Samoa | 0.01 | 0.01 | 0.01 |
| Sao Tome & Principe | 0.06 | 0.48 | 0.69 |
| Saudi Arabia | 0.83 | 2.51 | 2.73 |
| Senegal | 0.19 | 1.29 | 0.77 |
| Serbia & Montenegro | 0.70 | 3.38 | 1.86 |
| Seychelles | 0.15 | 0.32 | 0.30 |
| Sierra Leone | 0.16 | 2.12 | 0.72 |
| Slovakia | 0.88 | 5.48 | 2.48 |
| Slovenia | 0.86 | 6.11 | 2.27 |
| Solomon Is | 0.01 | 0.03 | 0.07 |
| Somalia | 0.26 | 1.12 | 0.49 |
| South Africa | 0.30 | 0.98 | 0.63 |
| South Georgia & the South Sandwich Islands | 0.09 | 0.03 | 0.02 |
| South Korea | 0.44 | 1.66 | 0.91 |
| Spain | 0.40 | 2.27 | 1.10 |
| Sri Lanka | 0.11 | 0.20 | 0.14 |
| St Helena | 0.08 | 0.16 | 0.09 |
| St Lucia | 0.06 | 0.59 | 0.18 |
| St Kitts & Nevis | 0.06 | 0.58 | 0.17 |
| Sudan | 0.38 | 1.37 | 1.38 |
| Suriname | 0.18 | 1.33 | 0.60 |
| Svalbard | 0.26 | 0.14 | 0.15 |
| Swaziland | 0.24 | 0.52 | 0.56 |

| | $NO_x$ | $NH_3$ | $SO_2$ |
|---|---|---|---|
| *World Weighted Average* | ***0.36*** | ***1.96*** | ***1*** |
| Sweden | 0.84 | 7.86 | 3.07 |
| Switzerland | 0.83 | 5.52 | 2.21 |
| Syria | 0.44 | 1.03 | 0.74 |
| Tajikistan | 1.12 | 3.55 | 2.43 |
| Tanzania | 0.24 | 0.80 | 1.04 |
| Thailand | 0.21 | 0.51 | 0.45 |
| Timor, East | 0.07 | 0.19 | 0.18 |
| Togo | 0.12 | 0.52 | 0.63 |
| Tonga | 0.01 | 0.01 | 0.01 |
| Trinidad Tobago | 0.12 | 0.61 | 0.23 |
| Tunisia | 0.29 | 0.91 | 0.56 |
| Turkey | 0.45 | 1.44 | 0.87 |
| Turkmenistan | 0.85 | 2.98 | 1.92 |
| Turks & Caicos Islands | 0.08 | 0.74 | 0.22 |
| Uganda | 0.33 | 1.61 | 1.58 |
| Ukraine | 0.49 | 1.73 | 1.18 |
| United Arab Emirates | 0.51 | 2.10 | 1.12 |
| United Kingdom | 0.52 | 2.76 | 1.56 |
| USA | 0.60 | 5.36 | 1.91 |
| Uruguay | 0.11 | 0.43 | 0.40 |
| Uzbekistan | 0.98 | 2.72 | 2.44 |
| Vanuatu | 0.01 | 0.03 | 0.03 |
| Venezuela | 0.15 | 1.13 | 0.32 |
| Vietnam | 0.25 | 0.69 | 0.65 |
| Virgin Is | 0.06 | 0.58 | 0.17 |
| Wallis & Futuna | 0.01 | 0.01 | 0.01 |
| West Bank | 0.58 | 1.26 | 1.16 |
| Western Sahara | 0.14 | 0.80 | 0.40 |
| Yemen | 0.31 | 1.26 | 0.73 |
| Zambia | 0.30 | 0.91 | 2.10 |
| Zimbabwe | 0.27 | 0.66 | 1.05 |

*Table S3.2. Country-specific endpoint characterization factors for terrestrial ecosystem damage due to acidifying emissions (species·yr/kg) (Roy et al. 2014).*

| | $NO_x$ | $NH_3$ | $SO_2$ |
|---|---|---|---|
| *World Weighted Average* | $\boldsymbol{7.70 \cdot 10^{-8}}$ | $\boldsymbol{4.14 \cdot 10^{-7}}$ | $\boldsymbol{2.12 \cdot 10^{-7}}$ |
| Afghanistan | 1.54E-07 | 5.56E-07 | 5.59E-07 |
| Albania | 1.17E-07 | 4.81E-07 | 3.05E-07 |
| Algeria | 1.01E-07 | 4.69E-07 | 4.34E-07 |
| American Samoa | 1.64E-09 | 1.30E-09 | 2.65E-09 |
| Andorra | 1.21E-07 | 6.90E-07 | 3.55E-07 |
| Angola | 1.72E-07 | 6.39E-07 | 7.55E-07 |
| Anguilla | 1.64E-08 | 1.21E-07 | 4.13E-08 |
| Antarctica | 1.39E-08 | 6.99E-09 | 7.50E-09 |
| Antigua & Barbuda | 1.42E-08 | 1.22E-07 | 4.31E-08 |
| Argentina | 2.65E-08 | 1.26E-07 | 1.25E-07 |
| Armenia | 1.43E-07 | 5.73E-07 | 4.22E-07 |
| Aruba | 3.02E-08 | 1.69E-07 | 4.78E-08 |
| Australia | 4.06E-08 | 1.37E-07 | 1.17E-07 |

| | $NO_x$ | $NH_3$ | $SO_2$ |
|---|---|---|---|
| *World Weighted Average* | ***7.70·10$^{-8}$*** | ***4.14·10$^{-7}$*** | ***2.12·10$^{-7}$*** |
| Austria | 1.48E-07 | 8.13E-07 | 4.08E-07 |
| Azerbaijan | 1.36E-07 | 5.05E-07 | 3.95E-07 |
| Bahamas | 2.00E-08 | 1.64E-07 | 5.42E-08 |
| Bahrain | 8.13E-08 | 3.20E-07 | 1.94E-07 |
| Bangladesh | 8.36E-08 | 1.67E-07 | 1.60E-07 |
| Barbados | 2.04E-08 | 1.40E-07 | 4.87E-08 |
| Belarus | 1.54E-07 | 7.12E-07 | 5.19E-07 |
| Belgium | 1.28E-07 | 7.99E-07 | 3.46E-07 |
| Belize | 2.34E-08 | 1.60E-07 | 6.35E-08 |
| Benin | 4.57E-08 | 1.82E-07 | 3.14E-07 |
| Bhutan | 1.20E-07 | 4.01E-07 | 2.96E-07 |
| Bolivia | 6.56E-08 | 3.51E-07 | 2.53E-07 |
| Bosnia Herzegovina | 1.40E-07 | 7.73E-07 | 3.85E-07 |
| Botswana | 8.52E-08 | 3.36E-07 | 4.32E-07 |
| Brazil | - | 1.69E-09 | 8.36E-09 |
| British Indian Ocean Territory | 0.00E+00 | 5.70E-07 | 3.11E-07 |
| British Virgin Islands | 1.04E-07 | 2.86E-08 | 1.95E-08 |
| Brunei | 8.78E-09 | 1.21E-07 | 4.13E-08 |
| Bulgaria | 1.64E-08 | 8.70E-08 | 8.57E-08 |
| Burkina Faso | 2.86E-08 | 4.78E-07 | 3.36E-07 |
| Burundi | 1.29E-07 | 2.53E-07 | 4.74E-07 |
| Cambodia | 4.82E-08 | 4.19E-07 | 6.78E-07 |
| Cameroon | 9.38E-08 | 2.41E-07 | 1.79E-07 |
| Canada | 5.86E-08 | 3.58E-07 | 3.40E-07 |
| Cape Verde | 9.55E-08 | 8.36E-07 | 4.28E-07 |
| Central African Republic | 1.10E-07 | 1.15E-07 | 5.99E-08 |
| Chad | 1.06E-08 | 1.05E-06 | 9.31E-07 |
| Chile | 2.83E-07 | 3.85E-07 | 5.08E-07 |
| China | 1.46E-07 | 2.69E-07 | 1.40E-07 |
| Christmas Island | 4.19E-08 | 4.40E-07 | 3.30E-07 |
| Colombia | 1.31E-07 | 4.20E-08 | 3.80E-08 |
| Congo | 6.41E-08 | 5.46E-07 | 1.10E-07 |
| Congo DRC | 9.35E-08 | 5.73E-07 | 6.41E-07 |
| Comoros | 1.14E-07 | 4.07E-07 | 1.30E-06 |
| Cook Islands | 5.24E-08 | 1.32E-07 | 1.79E-07 |
| Costa Rica | 1.97E-09 | 3.91E-10 | 9.01E-10 |
| Cote d'Ivoire | 2.55E-08 | 1.57E-07 | 5.21E-08 |
| Croatia | 3.42E-08 | 2.28E-07 | 2.90E-07 |
| Cuba | 1.37E-07 | 6.94E-07 | 3.48E-07 |
| Cyprus | 2.12E-08 | 1.76E-07 | 6.50E-08 |
| Czech Republic | 9.87E-08 | 3.21E-07 | 2.10E-07 |
| Denmark | 1.69E-07 | 1.17E-06 | 5.03E-07 |
| Djibouti | 1.25E-07 | 6.91E-07 | 3.52E-07 |
| Dominican Republic | 7.02E-08 | 2.35E-07 | 1.67E-07 |
| Ecuador | 1.76E-08 | 1.28E-07 | 4.01E-08 |
| Egypt | 6.53E-08 | 4.44E-07 | 2.04E-07 |
| El Salvador | 1.22E-07 | 3.61E-07 | 3.11E-07 |
| Equatorial Guinea | 2.69E-08 | 1.79E-07 | 6.62E-08 |
| Eritrea | 5.33E-08 | 3.02E-07 | 2.90E-07 |

| | $NO_x$ | $NH_3$ | $SO_2$ |
|---|---|---|---|
| *World Weighted Average* | ***7.70·10$^{-8}$*** | ***4.14·10$^{-7}$*** | ***2.12·10$^{-7}$*** |
| Estonia | 7.96E-08 | 2.21E-07 | 2.03E-07 |
| Ethiopia | 1.49E-07 | 6.05E-07 | 5.65E-07 |
| Faroe Is | 9.31E-08 | 2.59E-07 | 2.63E-07 |
| Falkland Islands | 7.12E-08 | 1.02E-07 | 1.30E-07 |
| Fiji | 1.63E-08 | 2.26E-08 | 5.85E-08 |
| Finland | 2.26E-09 | 4.25E-09 | 1.12E-08 |
| France | 1.30E-07 | 4.13E-07 | 5.80E-07 |
| French Guiana | 1.17E-07 | 5.95E-07 | 3.03E-07 |
| French Polynesia | 4.77E-08 | 3.08E-07 | 1.64E-07 |
| French Southern Antarctic Lands | 1.34E-09 | 3.09E-10 | 5.02E-10 |
| Gabon | 1.42E-08 | 7.55E-10 | 9.72E-09 |
| Gambia | 6.25E-08 | 2.28E-07 | 1.64E-07 |
| Gaza Strip | 7.10E-08 | 6.08E-07 | 4.44E-07 |
| Georgia | 9.49E-08 | 2.99E-07 | 2.35E-07 |
| Germany | 1.55E-07 | 7.70E-07 | 4.77E-07 |
| Ghana | 1.43E-07 | 7.74E-07 | 4.11E-07 |
| Greece | 3.83E-08 | 1.94E-07 | 3.09E-07 |
| Greenland | 1.07E-07 | 3.95E-07 | 2.58E-07 |
| Grenada | 2.78E-08 | 2.71E-07 | 6.79E-07 |
| Guadeloupe | 3.34E-08 | 1.67E-07 | 5.79E-08 |
| Guam | 1.44E-08 | 1.32E-07 | 4.44E-08 |
| Guatemala | 8.76E-09 | 3.67E-08 | 2.15E-08 |
| Guinea | 2.66E-08 | 2.00E-07 | 5.68E-08 |
| Guinea-Bissau | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Guyana | 3.69E-08 | 3.32E-07 | 2.09E-07 |
| Haiti | 2.38E-08 | 1.66E-07 | 1.05E-07 |
| Honduras | 7.61E-08 | 5.43E-07 | 2.31E-07 |
| Hungary | 1.79E-08 | 1.37E-07 | 4.77E-08 |
| Iceland | 2.90E-08 | 2.13E-07 | 8.01E-08 |
| India | 1.45E-07 | 7.12E-07 | 3.69E-07 |
| Indonesia | 3.80E-08 | 3.20E-07 | 2.68E-07 |
| Iran | 7.84E-08 | 1.79E-07 | 1.54E-07 |
| Iraq | 2.78E-08 | 9.47E-08 | 8.44E-08 |
| Ireland | 1.02E-07 | 3.63E-07 | 2.66E-07 |
| Isle of Man | 1.02E-07 | 2.87E-07 | 2.40E-07 |
| Israel | 5.45E-08 | 1.21E-07 | 1.21E-07 |
| Italy | 6.53E-08 | 2.31E-07 | 1.72E-07 |
| Jamaica | 9.81E-08 | 3.14E-07 | 2.50E-07 |
| Jan Mayen | 1.23E-07 | 5.92E-07 | 3.00E-07 |
| Japan | 1.79E-08 | 1.21E-07 | 3.89E-08 |
| Jersey | 3.83E-08 | 3.42E-08 | 8.10E-08 |
| Jordan | 7.87E-08 | 2.21E-07 | 1.49E-07 |
| Kazakhstan | 9.49E-08 | 3.05E-07 | 2.49E-07 |
| Kenya | 1.98E-07 | 7.62E-07 | 5.93E-07 |
| Kiribati | 8.91E-08 | 2.35E-07 | 2.90E-07 |
| Kuwait | 2.07E-09 | 7.71E-10 | 2.19E-09 |
| Kyrgyzstan | 9.98E-08 | 3.95E-07 | 1.91E-07 |
| Laos | 2.44E-07 | 1.18E-06 | 5.55E-07 |
| Latvia | 7.34E-08 | 2.63E-07 | 1.79E-07 |

| | $NO_x$ | $NH_3$ | $SO_2$ |
|---|---|---|---|
| *World Weighted Average* | ***7.70·10$^{-8}$*** | ***4.14·10$^{-7}$*** | ***2.12·10$^{-7}$*** |
| Lebanon | 1.51E-07 | 7.39E-07 | 5.28E-07 |
| Lesotho | 9.38E-08 | 2.99E-07 | 2.01E-07 |
| Liberia | 4.87E-08 | 8.94E-08 | 1.26E-07 |
| Libya | 3.23E-08 | 4.44E-07 | 2.26E-07 |
| Liechtenstein | 9.61E-08 | 3.03E-07 | 4.43E-07 |
| Lithuania | 1.40E-07 | 7.76E-07 | 3.92E-07 |
| Luxembourg | 1.52E-07 | 7.37E-07 | 5.18E-07 |
| Macedonia | 1.46E-07 | 1.05E-06 | 4.57E-07 |
| Madagascar | 1.37E-07 | 5.79E-07 | 3.71E-07 |
| Malawi | 5.62E-08 | 2.10E-07 | 1.88E-07 |
| Malaysia | 1.45E-07 | 4.77E-07 | 7.77E-07 |
| Mali | 3.08E-08 | 8.76E-08 | 8.98E-08 |
| Malta | 5.37E-08 | 5.68E-07 | 3.60E-07 |
| Martinique | 8.17E-08 | 2.46E-07 | 2.13E-07 |
| Mauritania | 1.84E-08 | 1.45E-07 | 4.91E-08 |
| Mauritius | 4.87E-08 | 3.61E-07 | 2.40E-07 |
| Mayotte | 2.32E-08 | 5.18E-08 | 4.71E-08 |
| Mexico | 4.90E-08 | 1.14E-07 | 1.38E-07 |
| Moldova | 4.10E-08 | 3.33E-07 | 9.31E-08 |
| Micronesia | 1.30E-07 | 5.22E-07 | 3.67E-07 |
| Mongolia | 2.16E-09 | 8.41E-09 | 1.30E-08 |
| Montserrat | 1.72E-07 | 7.68E-07 | 6.32E-07 |
| Morocco | 1.44E-08 | 1.32E-07 | 4.44E-08 |
| Mozambique | 7.22E-08 | 2.93E-07 | 1.75E-07 |
| Myanmar | 8.50E-08 | 2.32E-07 | 2.95E-07 |
| Namibia | 7.61E-08 | 2.41E-07 | 2.31E-07 |
| Nepal | 7.10E-08 | 1.73E-07 | 2.28E-07 |
| Netherlands | 1.23E-07 | 3.32E-07 | 2.50E-07 |
| Netherlands Antilles | 1.15E-07 | 4.78E-07 | 2.71E-07 |
| New Caledonia | 3.02E-08 | 1.69E-07 | 4.78E-08 |
| New Zealand | 3.36E-09 | 1.01E-08 | 1.63E-08 |
| Nicaragua | 4.07E-08 | 2.28E-07 | 1.22E-07 |
| Niger | 2.80E-08 | 2.26E-07 | 7.15E-08 |
| Nigeria | 7.62E-08 | 3.03E-07 | 4.91E-07 |
| Niue | 6.85E-08 | 2.34E-07 | 2.68E-07 |
| North Korea | 1.86E-09 | 1.27E-09 | 2.29E-09 |
| Norway | 1.28E-07 | 6.66E-07 | 3.11E-07 |
| Oman | 1.15E-07 | 7.02E-07 | 3.54E-07 |
| Palau | 8.87E-08 | 2.84E-07 | 2.32E-07 |
| Pakistan | 1.49E-08 | 4.22E-08 | 3.21E-08 |
| Panama | 1.19E-07 | 4.19E-07 | 3.26E-07 |
| Papua New Guinea | 2.78E-08 | 1.69E-07 | 5.36E-08 |
| Paraguay | 1.46E-08 | 8.24E-08 | 8.66E-08 |
| Peru | 3.54E-08 | 2.06E-07 | 1.94E-07 |
| Philippines | 5.03E-08 | 3.71E-07 | 2.10E-07 |
| Pitcairn Islands | 3.14E-08 | 9.89E-08 | 8.23E-08 |
| Poland | 2.47E-09 | 1.10E-09 | 2.53E-09 |
| Portugal | 1.51E-07 | 7.78E-07 | 4.23E-07 |
| Puerto Rico | 6.02E-08 | 2.93E-07 | 1.30E-07 |

| | $NO_x$ | $NH_3$ | $SO_2$ |
|---|---|---|---|
| *World Weighted Average* | ***7.70·10$^{-8}$*** | ***4.14·10$^{-7}$*** | ***2.12·10$^{-7}$*** |
| Qatar | 1.72E-08 | 1.32E-07 | 4.28E-08 |
| Reunion | 8.61E-08 | 3.85E-07 | 2.15E-07 |
| Romania | 2.69E-08 | 6.04E-08 | 1.27E-07 |
| Russia | 1.37E-07 | 6.75E-07 | 3.77E-07 |
| Rwanda | 1.89E-07 | 8.14E-07 | 7.56E-07 |
| Samoa | 8.07E-08 | 5.00E-07 | 6.99E-07 |
| Sao Tome & Principe | 1.64E-09 | 1.34E-09 | 2.72E-09 |
| Saudi Arabia | 1.75E-08 | 1.46E-07 | 2.53E-07 |
| Senegal | 1.04E-07 | 3.76E-07 | 2.68E-07 |
| Serbia & Montenegro | 2.81E-08 | 1.81E-07 | 1.34E-07 |
| Seychelles | 1.42E-07 | 6.63E-07 | 3.89E-07 |
| Sierra Leone | 5.14E-08 | 9.03E-08 | 1.12E-07 |
| Slovakia | 3.60E-08 | 4.43E-07 | 2.34E-07 |
| Slovenia | 1.52E-07 | 8.44E-07 | 4.13E-07 |
| Solomon Islands | 1.42E-07 | 8.13E-07 | 3.79E-07 |
| Somalia | 2.35E-09 | 9.47E-09 | 2.99E-08 |
| South Africa | 7.13E-08 | 2.09E-07 | 1.29E-07 |
| South Georgia & the South Sandwich Islands | 6.17E-08 | 1.54E-07 | 1.61E-07 |
| South Korea | 2.16E-08 | 8.58E-09 | 8.21E-09 |
| Spain | 8.72E-08 | 3.70E-07 | 2.13E-07 |
| Sri Lanka | 7.98E-08 | 3.88E-07 | 1.82E-07 |
| St Helena | 2.55E-08 | 5.27E-08 | 3.83E-08 |
| St Lucia | 2.25E-08 | 4.37E-08 | 2.71E-08 |
| St Kitts & Nevis | 1.84E-08 | 1.45E-07 | 4.91E-08 |
| Sudan | 1.64E-08 | 1.21E-07 | 4.13E-08 |
| Suriname | 1.84E-07 | 6.22E-07 | 6.28E-07 |
| Svalbard | 5.48E-08 | 3.70E-07 | 1.66E-07 |
| Swaziland | 7.12E-08 | 2.95E-08 | 3.32E-08 |
| Sweden | 8.29E-08 | 3.05E-07 | 2.53E-07 |
| Switzerland | 1.33E-07 | 9.43E-07 | 4.40E-07 |
| Syria | 1.33E-07 | 6.87E-07 | 3.63E-07 |
| Tajikistan | 9.55E-08 | 2.68E-07 | 2.07E-07 |
| Tanzania | 2.03E-07 | 6.69E-07 | 5.25E-07 |
| Thailand | 9.55E-08 | 2.69E-07 | 5.30E-07 |
| Timor, East | 2.43E-08 | 1.72E-07 | 1.05E-07 |
| Togo | 2.03E-08 | 6.30E-08 | 6.14E-08 |
| Tonga | 4.14E-08 | 1.69E-07 | 3.05E-07 |
| Trinidad Tobago | 2.01E-09 | 2.46E-09 | 4.00E-09 |
| Tunisia | 4.88E-08 | 2.06E-07 | 7.96E-08 |
| Turkey | 9.12E-08 | 3.14E-07 | 3.14E-07 |
| Turkmenistan | 1.13E-07 | 3.86E-07 | 2.69E-07 |
| Turks & Caicos Islands | 1.51E-07 | 5.39E-07 | 5.18E-07 |
| Uganda | 1.55E-08 | 1.19E-07 | 4.44E-08 |
| Ukraine | 1.03E-07 | 3.08E-07 | 4.20E-07 |
| United Arab Emirates | 1.36E-07 | 5.59E-07 | 4.00E-07 |
| United Kingdom | 1.04E-07 | 3.98E-07 | 3.54E-07 |
| USA | 7.55E-08 | 2.43E-07 | 1.76E-07 |
| Uruguay | 7.71E-08 | 6.94E-07 | 2.37E-07 |

| | $NO_x$ | $NH_3$ | $SO_2$ |
|---|---|---|---|
| *World Weighted Average* | ***7.70·10$^{-8}$*** | ***4.14·10$^{-7}$*** | ***2.12·10$^{-7}$*** |
| Uzbekistan | 2.09E-08 | 8.10E-08 | 7.16E-08 |
| Vanuatu | 1.92E-07 | 6.36E-07 | 5.88E-07 |
| Venezuela | 2.28E-09 | 7.02E-09 | 1.15E-08 |
| Vietnam | 5.61E-08 | 4.07E-07 | 1.05E-07 |
| Virgin Islands | 6.78E-08 | 2.18E-07 | 1.85E-07 |
| Wallis & Futuna | 1.64E-08 | 1.21E-07 | 4.13E-08 |
| West Bank | 1.76E-09 | 2.59E-09 | 4.87E-09 |
| Western Sahara | 9.56E-08 | 3.14E-07 | 2.43E-07 |
| Yemen | 6.11E-08 | 7.33E-07 | 2.43E-07 |
| Zambia | 7.36E-08 | 2.35E-07 | 1.89E-07 |
| Zimbabwe | 1.40E-07 | 4.40E-07 | 1.69E-06 |

# 19 S4. Supporting Information on eutrophication

## 19.1 Effect factor calculations

The logistic function parameter α was derived for four biogeographic regions, i.e. cold, temperate, (sub)tropical and xeric, as well as for lakes and streams, and for heterotrophic and autotrophic species separately. For heterotrophic species in xeric lakes as well as for both species groups in cold and xeric streams, the α coefficient could not be determined. In those cases, the α parameters of (sub)tropical lakes and streams were employed as the α for xeric lakes and streams, respectively, and the α for temperate streams was employed as the α for cold streams. Factors were recalculated from Azevedo et al. (2013).

*Table S4.1. Linear effect factors for streams and lakes for the different climate zones.*

| | **Heterotrophic species** | | **Autotrophic species** | | **Combined** | |
|---|---|---|---|---|---|---|
| | Lake [PDF·m$^3$/kg] | Stream [PDF·m$^3$/kg] | Lake [PDF·m$^3$/kg] | Stream [PDF·m$^3$/kg] | Lake [PDF·m$^3$/kg] | Stream [PDF·m$^3$/kg] |
| tropical | 13,458 | 778 | 813 | 2,323 | 7,135 | 1,550 |
| sub-tropical | 13,458 | 778 | 813 | 2,323 | 7,135 | 1,550 |
| temperate | 1,253 | 674 | 5,754 | 766 | 3,504 | 720 |
| cold | 18,280 | 674 | 8,530 | 766 | 13,405 | 720 |
| xeric | 13,458 | 778 | 2,594 | 2,323 | 8,026 | 1,550 |

*Table S4.2. Alfa for streams and lakes for the different climate zones.*

| | **Heterotrophs** | | **Autotrophs** | |
|---|---|---|---|---|
| | Lake [PDF·L/mg] | Stream [PDF· L /mg] | Lake [PDF· L /mg] | Stream [PDF· L /mg] |
| (sub)tropical | -1.430 | -0.192 | -0.211 | -0.667 |
| temperate | -0.399 | -0.130 | -1.061 | -0.185 |
| cold | -1.563 | na | -1.232 | na |
| xeric | na | na | -0.715 | na |

## 19.2 Country-specific characterization factors

*Table S4.3: Country-specific freshwater eutrophication potentials for freshwater ecosystem damage (kg P-equivalents/kg).*

| | **Emitted to fresh water** | | **Emitted to soil** | |
|---|---|---|---|---|
| **Country** | **P** | **$PO_4^{3-}$** | **P** | **$PO_4^{3-}$** |
| Afghanistan | 8.55E-01 | 2.79E-01 | 8.55E-02 | 2.79E-02 |
| Albania | 1.22E-01 | 3.97E-02 | 1.22E-02 | 3.97E-03 |
| Algeria | 2.93E-01 | 9.55E-02 | 2.93E-02 | 9.55E-03 |
| Angola | 2.41E-01 | 7.86E-02 | 2.41E-02 | 7.86E-03 |
| Argentina | 3.75E-01 | 1.22E-01 | 3.75E-02 | 1.22E-02 |
| Armenia | 1.91E-01 | 6.22E-02 | 1.91E-02 | 6.22E-03 |
| Australia | 5.71E-01 | 1.86E-01 | 5.71E-02 | 1.86E-02 |
| Austria | 5.35E-01 | 1.74E-01 | 5.35E-02 | 1.74E-02 |

| | Emitted to fresh water | | Emitted to soil | |
|---|---|---|---|---|
| **Country** | **P** | **$PO_4^{3-}$** | **P** | **$PO_4^{3-}$** |
| Azerbaijan | 1.03E+00 | 3.35E-01 | 1.03E-01 | 3.35E-02 |
| Bangladesh | 9.83E-02 | 3.21E-02 | 9.83E-03 | 3.21E-03 |
| Belarus | 5.18E-01 | 1.69E-01 | 5.18E-02 | 1.69E-02 |
| Belgium | 3.86E-01 | 1.26E-01 | 3.86E-02 | 1.26E-02 |
| Belize | 2.72E-01 | 8.88E-02 | 2.72E-02 | 8.88E-03 |
| Benin | 3.77E-01 | 1.23E-01 | 3.77E-02 | 1.23E-02 |
| Bhutan | 1.45E-01 | 4.72E-02 | 1.45E-02 | 4.72E-03 |
| Bolivia | 4.30E+00 | 1.40E+00 | 4.30E-01 | 1.40E-01 |
| Bosnia and Herzegovina | 3.25E-01 | 1.06E-01 | 3.25E-02 | 1.06E-02 |
| Botswana | 3.43E-02 | 1.12E-02 | 3.43E-03 | 1.12E-03 |
| Brazil | 1.21E+00 | 3.96E-01 | 1.21E-01 | 3.96E-02 |
| Brunei Darussalam | 2.09E-02 | 6.83E-03 | 2.09E-03 | 6.83E-04 |
| Bulgaria | 4.09E-01 | 1.33E-01 | 4.09E-02 | 1.33E-02 |
| Burkina Faso | 3.32E-01 | 1.08E-01 | 3.32E-02 | 1.08E-02 |
| Burundi | 2.08E+01 | 6.79E+00 | 2.08E+00 | 6.79E-01 |
| Cambodia | 7.64E-01 | 2.49E-01 | 7.64E-02 | 2.49E-02 |
| Cameroon | 3.79E-01 | 1.23E-01 | 3.79E-02 | 1.23E-02 |
| Canada | 7.59E+00 | 2.48E+00 | 7.59E-01 | 2.48E-01 |
| Central African Republic | 3.47E-01 | 1.13E-01 | 3.47E-02 | 1.13E-02 |
| Chad | 6.01E-01 | 1.96E-01 | 6.01E-02 | 1.96E-02 |
| Chile | 1.96E-01 | 6.39E-02 | 1.96E-02 | 6.39E-03 |
| China | 4.68E-01 | 1.53E-01 | 4.68E-02 | 1.53E-02 |
| Colombia | 2.67E-01 | 8.70E-02 | 2.67E-02 | 8.70E-03 |
| Congo | 2.30E-01 | 7.52E-02 | 2.30E-02 | 7.52E-03 |
| Congo DRC | 1.73E+00 | 5.64E-01 | 1.73E-01 | 5.64E-02 |
| Costa Rica | 1.16E-01 | 3.77E-02 | 1.16E-02 | 3.77E-03 |
| Côte d'Ivoire | 3.24E-01 | 1.06E-01 | 3.24E-02 | 1.06E-02 |
| Croatia | 2.93E-01 | 9.56E-02 | 2.93E-02 | 9.56E-03 |
| Cuba | 4.94E-01 | 1.61E-01 | 4.94E-02 | 1.61E-02 |
| Cyprus | 3.77E-01 | 1.23E-01 | 3.77E-02 | 1.23E-02 |
| Czech Republic | 6.74E-01 | 2.20E-01 | 6.74E-02 | 2.20E-02 |
| Denmark | 6.29E-01 | 2.05E-01 | 6.29E-02 | 2.05E-02 |
| Djibouti | 7.93E-01 | 2.59E-01 | 7.93E-02 | 2.59E-02 |
| Dominican Republic | 1.15E-01 | 3.76E-02 | 1.15E-02 | 3.76E-03 |
| Ecuador | 9.81E-02 | 3.20E-02 | 9.81E-03 | 3.20E-03 |
| Egypt | 1.00E-01 | 3.26E-02 | 1.00E-02 | 3.26E-03 |
| El Salvador | 3.15E-01 | 1.03E-01 | 3.15E-02 | 1.03E-02 |
| Equatorial Guinea | 1.07E-01 | 3.49E-02 | 1.07E-02 | 3.49E-03 |

| | Emitted to fresh water | | Emitted to soil | |
|---|---|---|---|---|
| **Country** | **P** | **$PO_4^{3-}$** | **P** | **$PO_4^{3-}$** |
| Eritrea | 1.54E-01 | 5.02E-02 | 1.54E-02 | 5.02E-03 |
| Estonia | 4.01E-01 | 1.31E-01 | 4.01E-02 | 1.31E-02 |
| Ethiopia | 2.24E+00 | 7.31E-01 | 2.24E-01 | 7.31E-02 |
| Falkland Islands | 2.11E-01 | 6.90E-02 | 2.11E-02 | 6.90E-03 |
| Fiji | 2.08E-02 | 6.79E-03 | 2.08E-03 | 6.79E-04 |
| Finland | 1.91E+00 | 6.21E-01 | 1.91E-01 | 6.21E-02 |
| France | 1.65E-01 | 5.39E-02 | 1.65E-02 | 5.39E-03 |
| French Guiana | 4.25E-02 | 1.39E-02 | 4.25E-03 | 1.39E-03 |
| Gabon | 2.20E-01 | 7.17E-02 | 2.20E-02 | 7.17E-03 |
| Gambia | 1.34E-01 | 4.38E-02 | 1.34E-02 | 4.38E-03 |
| Georgia | 1.28E+00 | 4.17E-01 | 1.28E-01 | 4.17E-02 |
| Germany | 4.69E-01 | 1.53E-01 | 4.69E-02 | 1.53E-02 |
| Ghana | 2.53E-01 | 8.24E-02 | 2.53E-02 | 8.24E-03 |
| Greece | 5.00E-01 | 1.63E-01 | 5.00E-02 | 1.63E-02 |
| Guatemala | 5.05E-01 | 1.65E-01 | 5.05E-02 | 1.65E-02 |
| Guinea | 3.39E-01 | 1.10E-01 | 3.39E-02 | 1.10E-02 |
| Guinea-Bissau | 2.25E-01 | 7.33E-02 | 2.25E-02 | 7.33E-03 |
| Guyana | 5.43E-02 | 1.77E-02 | 5.43E-03 | 1.77E-03 |
| Haiti | 8.27E-02 | 2.70E-02 | 8.27E-03 | 2.70E-03 |
| Honduras | 8.67E-02 | 2.83E-02 | 8.67E-03 | 2.83E-03 |
| Hungary | 5.14E-01 | 1.68E-01 | 5.14E-02 | 1.68E-02 |
| Iceland | 1.96E-01 | 6.39E-02 | 1.96E-02 | 6.39E-03 |
| India | 2.10E-01 | 6.85E-02 | 2.10E-02 | 6.85E-03 |
| Indonesia | 1.01E-01 | 3.28E-02 | 1.01E-02 | 3.28E-03 |
| Iran | 2.63E+00 | 8.57E-01 | 2.63E-01 | 8.57E-02 |
| Iraq | 7.25E-01 | 2.36E-01 | 7.25E-02 | 2.36E-02 |
| Ireland | 6.99E-01 | 2.28E-01 | 6.99E-02 | 2.28E-02 |
| Israel | 2.51E-01 | 8.20E-02 | 2.51E-02 | 8.20E-03 |
| Italy | 4.61E-01 | 1.50E-01 | 4.61E-02 | 1.50E-02 |
| Japan | 1.73E-01 | 5.66E-02 | 1.73E-02 | 5.66E-03 |
| Jordan | 8.82E+00 | 2.88E+00 | 8.82E-01 | 2.88E-01 |
| Kazakhstan | 1.11E+00 | 3.62E-01 | 1.11E-01 | 3.62E-02 |
| Kenya | 5.74E+00 | 1.87E+00 | 5.74E-01 | 1.87E-01 |
| Kyrgyzstan | 1.34E+00 | 4.38E-01 | 1.34E-01 | 4.38E-02 |
| Laos | 2.41E-01 | 7.87E-02 | 2.41E-02 | 7.87E-03 |
| Latvia | 9.64E-02 | 3.14E-02 | 9.64E-03 | 3.14E-03 |
| Lebanon | 3.84E-01 | 1.25E-01 | 3.84E-02 | 1.25E-02 |
| Lesotho | 4.11E-01 | 1.34E-01 | 4.11E-02 | 1.34E-02 |

| | Emitted to fresh water | | Emitted to soil | |
|---|---|---|---|---|
| **Country** | **P** | **$PO_4^{3-}$** | **P** | **$PO_4^{3-}$** |
| Liberia | 1.19E-01 | 3.87E-02 | 1.19E-02 | 3.87E-03 |
| Libya | 1.95E+00 | 6.34E-01 | 1.95E-01 | 6.34E-02 |
| Lithuania | 3.24E-01 | 1.06E-01 | 3.24E-02 | 1.06E-02 |
| Luxembourg | 1.53E-01 | 4.99E-02 | 1.53E-02 | 4.99E-03 |
| Madagascar | 1.94E-01 | 6.31E-02 | 1.94E-02 | 6.31E-03 |
| Malawi | 2.21E+01 | 7.22E+00 | 2.21E+00 | 7.22E-01 |
| Malaysia | 5.51E-02 | 1.80E-02 | 5.51E-03 | 1.80E-03 |
| Mali | 8.18E-01 | 2.67E-01 | 8.18E-02 | 2.67E-02 |
| Mauritania | 4.33E-01 | 1.41E-01 | 4.33E-02 | 1.41E-02 |
| Mexico | 5.58E-01 | 1.82E-01 | 5.58E-02 | 1.82E-02 |
| Moldova | 6.89E-01 | 2.25E-01 | 6.89E-02 | 2.25E-02 |
| Mongolia | 5.23E+00 | 1.70E+00 | 5.23E-01 | 1.70E-01 |
| Montenegro | 2.97E-01 | 9.68E-02 | 2.97E-02 | 9.68E-03 |
| Morocco | 1.08E-01 | 3.51E-02 | 1.08E-02 | 3.51E-03 |
| Mozambique | 8.08E-01 | 2.64E-01 | 8.08E-02 | 2.64E-02 |
| Myanmar | 1.12E-01 | 3.67E-02 | 1.12E-02 | 3.67E-03 |
| Namibia | 1.00E-01 | 3.27E-02 | 1.00E-02 | 3.27E-03 |
| Nepal | 2.31E-01 | 7.53E-02 | 2.31E-02 | 7.53E-03 |
| Netherlands | 2.90E-01 | 9.44E-02 | 2.90E-02 | 9.44E-03 |
| New Caledonia | 1.54E+00 | 5.03E-01 | 1.54E-01 | 5.03E-02 |
| New Zealand | 2.91E-01 | 9.50E-02 | 2.91E-02 | 9.50E-03 |
| Nicaragua | 1.24E+00 | 4.04E-01 | 1.24E-01 | 4.04E-02 |
| Niger | 4.15E-01 | 1.35E-01 | 4.15E-02 | 1.35E-02 |
| Nigeria | 3.12E-01 | 1.02E-01 | 3.12E-02 | 1.02E-02 |
| North Korea | 2.03E-01 | 6.61E-02 | 2.03E-02 | 6.61E-03 |
| Norway | 6.00E-01 | 1.96E-01 | 6.00E-02 | 1.96E-02 |
| Pakistan | 2.02E-01 | 6.60E-02 | 2.02E-02 | 6.60E-03 |
| Palestinian Territory | 1.18E+01 | 3.86E+00 | 1.18E+00 | 3.86E-01 |
| Panama | 3.91E-02 | 1.27E-02 | 3.91E-03 | 1.27E-03 |
| Papua New Guinea | 8.33E-02 | 2.72E-02 | 8.33E-03 | 2.72E-03 |
| Paraguay | 3.36E-01 | 1.10E-01 | 3.36E-02 | 1.10E-02 |
| Peru | 2.24E+00 | 7.29E-01 | 2.24E-01 | 7.29E-02 |
| Philippines | 1.67E-01 | 5.45E-02 | 1.67E-02 | 5.45E-03 |
| Poland | 3.94E-01 | 1.28E-01 | 3.94E-02 | 1.28E-02 |
| Portugal | 6.72E-02 | 2.19E-02 | 6.72E-03 | 2.19E-03 |
| Romania | 2.55E-01 | 8.33E-02 | 2.55E-02 | 8.33E-03 |
| Russian Federation | 7.11E-01 | 2.32E-01 | 7.11E-02 | 2.32E-02 |
| Rwanda | 1.03E+01 | 3.35E+00 | 1.03E+00 | 3.35E-01 |

| | Emitted to fresh water | | Emitted to soil | |
|---|---|---|---|---|
| **Country** | **P** | **$PO_4^{3-}$** | **P** | **$PO_4^{3-}$** |
| Senegal | 2.20E-01 | 7.18E-02 | 2.20E-02 | 7.18E-03 |
| Serbia | 3.75E-01 | 1.22E-01 | 3.75E-02 | 1.22E-02 |
| Sierra Leone | 8.51E-02 | 2.77E-02 | 8.51E-03 | 2.77E-03 |
| Slovakia | 6.30E-01 | 2.05E-01 | 6.30E-02 | 2.05E-02 |
| Slovenia | 3.02E-01 | 9.84E-02 | 3.02E-02 | 9.84E-03 |
| Somalia | 3.87E-01 | 1.26E-01 | 3.87E-02 | 1.26E-02 |
| South Africa | 3.13E-01 | 1.02E-01 | 3.13E-02 | 1.02E-02 |
| South Korea | 8.99E-02 | 2.93E-02 | 8.99E-03 | 2.93E-03 |
| South Sudan | 8.13E-01 | 2.65E-01 | 8.13E-02 | 2.65E-02 |
| Spain | 6.20E-02 | 2.02E-02 | 6.20E-03 | 2.02E-03 |
| Sri Lanka | 1.52E-01 | 4.95E-02 | 1.52E-02 | 4.95E-03 |
| Sudan | 6.44E-01 | 2.10E-01 | 6.44E-02 | 2.10E-02 |
| Suriname | 2.49E-01 | 8.11E-02 | 2.49E-02 | 8.11E-03 |
| Swaziland | 8.35E-01 | 2.72E-01 | 8.35E-02 | 2.72E-02 |
| Sweden | 1.45E+00 | 4.72E-01 | 1.45E-01 | 4.72E-02 |
| Switzerland | 2.95E+00 | 9.64E-01 | 2.95E-01 | 9.64E-02 |
| Syria | 7.53E-01 | 2.46E-01 | 7.53E-02 | 2.46E-02 |
| Tajikistan | 3.44E-01 | 1.12E-01 | 3.44E-02 | 1.12E-02 |
| Tanzania | 1.77E+01 | 5.76E+00 | 1.77E+00 | 5.76E-01 |
| Thailand | 2.16E-01 | 7.04E-02 | 2.16E-02 | 7.04E-03 |
| The Former Yugoslav Republic of Macedonia | 1.73E-01 | 5.64E-02 | 1.73E-02 | 5.64E-03 |
| Togo | 4.63E-01 | 1.51E-01 | 4.63E-02 | 1.51E-02 |
| Tunisia | 8.08E-01 | 2.63E-01 | 8.08E-02 | 2.63E-02 |
| Turkey | 1.23E+00 | 4.01E-01 | 1.23E-01 | 4.01E-02 |
| Turkmenistan | 6.09E-01 | 1.99E-01 | 6.09E-02 | 1.99E-02 |
| Uganda | 7.61E+00 | 2.48E+00 | 7.61E-01 | 2.48E-01 |
| Ukraine | 4.26E-01 | 1.39E-01 | 4.26E-02 | 1.39E-02 |
| United Kingdom | 9.57E-02 | 3.12E-02 | 9.57E-03 | 3.12E-03 |
| United States | 4.47E+00 | 1.46E+00 | 4.47E-01 | 1.46E-01 |
| Uruguay | 7.95E-01 | 2.59E-01 | 7.95E-02 | 2.59E-02 |
| Uzbekistan | 2.45E-01 | 7.99E-02 | 2.45E-02 | 7.99E-03 |
| Venezuela | 1.91E-01 | 6.21E-02 | 1.91E-02 | 6.21E-03 |
| Vietnam | 6.61E-02 | 2.16E-02 | 6.61E-03 | 2.16E-03 |
| Zambia | 3.13E+00 | 1.02E+00 | 3.13E-01 | 1.02E-01 |
| Zimbabwe | 3.80E-01 | 1.24E-01 | 3.80E-02 | 1.24E-02 |

*Table S4.4: Country-specific endpoint characterization factors for freshwater eutrophication damage (species·yr/kg).*

| | Emitted to fresh water | | Emitted to soil | |
|---|---|---|---|---|
| **Country** | **P** | **$PO_4^{3-}$** | **P** | **$PO_4^{3-}$** |
| Afghanistan | 3.17E-07 | 1.03E-07 | 3.17E-08 | 1.03E-08 |
| Albania | 5.04E-08 | 1.64E-08 | 5.04E-09 | 1.64E-09 |
| Algeria | 1.69E-07 | 5.51E-08 | 1.69E-08 | 5.51E-09 |
| Angola | 1.23E-07 | 4.01E-08 | 1.23E-08 | 4.01E-09 |
| Argentina | 1.96E-07 | 6.39E-08 | 1.96E-08 | 6.39E-09 |
| Armenia | 3.99E-07 | 1.30E-07 | 3.99E-08 | 1.30E-08 |
| Australia | 4.85E-07 | 1.58E-07 | 4.85E-08 | 1.58E-08 |
| Austria | 1.81E-07 | 5.90E-08 | 1.81E-08 | 5.90E-09 |
| Azerbaijan | 1.73E-06 | 5.64E-07 | 1.73E-07 | 5.64E-08 |
| Bangladesh | 8.52E-08 | 2.78E-08 | 8.52E-09 | 2.78E-09 |
| Belarus | 2.13E-07 | 6.95E-08 | 2.13E-08 | 6.95E-09 |
| Belgium | 8.83E-08 | 2.88E-08 | 8.83E-09 | 2.88E-09 |
| Belize | 2.99E-07 | 9.75E-08 | 2.99E-08 | 9.75E-09 |
| Benin | 1.56E-07 | 5.09E-08 | 1.56E-08 | 5.09E-09 |
| Bhutan | 4.42E-08 | 1.44E-08 | 4.42E-09 | 1.44E-09 |
| Bolivia | 5.25E-06 | 1.71E-06 | 5.25E-07 | 1.71E-07 |
| Bosnia and Herzegovina | 9.08E-08 | 2.96E-08 | 9.08E-09 | 2.96E-09 |
| Botswana | 1.04E-08 | 3.39E-09 | 1.04E-09 | 3.39E-10 |
| Brazil | 1.37E-06 | 4.47E-07 | 1.37E-07 | 4.47E-08 |
| Brunei Darussalam | 5.94E-09 | 1.94E-09 | 5.94E-10 | 1.94E-10 |
| Bulgaria | 1.65E-07 | 5.38E-08 | 1.65E-08 | 5.38E-09 |
| Burkina Faso | 1.35E-07 | 4.40E-08 | 1.35E-08 | 4.40E-09 |
| Burundi | 1.86E-05 | 6.07E-06 | 1.86E-06 | 6.07E-07 |
| Cambodia | 6.67E-07 | 2.18E-07 | 6.67E-08 | 2.18E-08 |
| Cameroon | 2.55E-07 | 8.32E-08 | 2.55E-08 | 8.32E-09 |
| Canada | 2.27E-06 | 7.40E-07 | 2.27E-07 | 7.40E-08 |
| Central African Republic | 1.15E-07 | 3.75E-08 | 1.15E-08 | 3.75E-09 |
| Chad | 5.97E-07 | 1.95E-07 | 5.97E-08 | 1.95E-08 |
| Chile | 1.06E-07 | 3.46E-08 | 1.06E-08 | 3.46E-09 |
| China | 2.46E-07 | 8.02E-08 | 2.46E-08 | 8.02E-09 |
| Colombia | 1.69E-07 | 5.51E-08 | 1.69E-08 | 5.51E-09 |
| Congo | 7.46E-08 | 2.43E-08 | 7.46E-09 | 2.43E-09 |
| Congo DRC | 1.90E-06 | 6.20E-07 | 1.90E-07 | 6.20E-08 |
| Costa Rica | 1.21E-07 | 3.95E-08 | 1.21E-08 | 3.95E-09 |
| Côte d'Ivoire | 1.62E-07 | 5.28E-08 | 1.62E-08 | 5.28E-09 |
| Croatia | 8.93E-08 | 2.91E-08 | 8.93E-09 | 2.91E-09 |
| Cuba | 6.17E-07 | 2.01E-07 | 6.17E-08 | 2.01E-08 |
| Cyprus | 2.35E-07 | 7.66E-08 | 2.35E-08 | 7.66E-09 |

| | Emitted to fresh water | | Emitted to soil | |
|---|---|---|---|---|
| **Country** | **P** | **$PO_4^{3-}$** | **P** | **$PO_4^{3-}$** |
| Czech Republic | 3.72E-07 | 1.21E-07 | 3.72E-08 | 1.21E-08 |
| Denmark | 4.76E-07 | 1.55E-07 | 4.76E-08 | 1.55E-08 |
| Djibouti | 1.15E-06 | 3.75E-07 | 1.15E-07 | 3.75E-08 |
| Dominican Republic | 1.32E-07 | 4.30E-08 | 1.32E-08 | 4.30E-09 |
| Ecuador | 5.81E-08 | 1.89E-08 | 5.81E-09 | 1.89E-09 |
| Egypt | 2.94E-08 | 9.59E-09 | 2.94E-09 | 9.59E-10 |
| El Salvador | 3.88E-07 | 1.27E-07 | 3.88E-08 | 1.27E-08 |
| Equatorial Guinea | 3.03E-08 | 9.88E-09 | 3.03E-09 | 9.88E-10 |
| Eritrea | 1.65E-07 | 5.38E-08 | 1.65E-08 | 5.38E-09 |
| Estonia | 2.31E-07 | 7.53E-08 | 2.31E-08 | 7.53E-09 |
| Ethiopia | 2.23E-06 | 7.27E-07 | 2.23E-07 | 7.27E-08 |
| Falkland Islands | 1.28E-07 | 4.17E-08 | 1.28E-08 | 4.17E-09 |
| Fiji | 5.91E-09 | 1.93E-09 | 5.91E-10 | 1.93E-10 |
| Finland | 4.45E-06 | 1.45E-06 | 4.45E-07 | 1.45E-07 |
| France | 4.33E-08 | 1.41E-08 | 4.33E-09 | 1.41E-09 |
| French Guiana | 1.38E-08 | 4.50E-09 | 1.38E-09 | 4.50E-10 |
| Gabon | 9.79E-08 | 3.19E-08 | 9.79E-09 | 3.19E-09 |
| Gambia | 8.67E-08 | 2.83E-08 | 8.67E-09 | 2.83E-09 |
| Georgia | 9.62E-07 | 3.14E-07 | 9.62E-08 | 3.14E-08 |
| Germany | 2.46E-07 | 8.02E-08 | 2.46E-08 | 8.02E-09 |
| Ghana | 8.65E-08 | 2.82E-08 | 8.65E-09 | 2.82E-09 |
| Greece | 2.96E-07 | 9.65E-08 | 2.96E-08 | 9.65E-09 |
| Guatemala | 3.32E-07 | 1.08E-07 | 3.32E-08 | 1.08E-08 |
| Guinea | 1.29E-07 | 4.21E-08 | 1.29E-08 | 4.21E-09 |
| Guinea-Bissau | 1.43E-07 | 4.66E-08 | 1.43E-08 | 4.66E-09 |
| Guyana | 2.19E-08 | 7.14E-09 | 2.19E-09 | 7.14E-10 |
| Haiti | 2.81E-08 | 9.16E-09 | 2.81E-09 | 9.16E-10 |
| Honduras | 5.51E-08 | 1.80E-08 | 5.51E-09 | 1.80E-09 |
| Hungary | 1.35E-07 | 4.40E-08 | 1.35E-08 | 4.40E-09 |
| Iceland | 4.50E-07 | 1.47E-07 | 4.50E-08 | 1.47E-08 |
| India | 1.78E-07 | 5.80E-08 | 1.78E-08 | 5.80E-09 |
| Indonesia | 7.65E-08 | 2.49E-08 | 7.65E-09 | 2.49E-09 |
| Iran | 2.38E-06 | 7.76E-07 | 2.38E-07 | 7.76E-08 |
| Iraq | 2.56E-07 | 8.35E-08 | 2.56E-08 | 8.35E-09 |
| Ireland | 4.24E-07 | 1.38E-07 | 4.24E-08 | 1.38E-08 |
| Israel | 3.46E-07 | 1.13E-07 | 3.46E-08 | 1.13E-08 |
| Italy | 2.01E-07 | 6.55E-08 | 2.01E-08 | 6.55E-09 |
| Japan | 9.51E-08 | 3.10E-08 | 9.51E-09 | 3.10E-09 |

| | Emitted to fresh water | | Emitted to soil | |
|---|---|---|---|---|
| **Country** | **P** | **$PO_4^{3-}$** | **P** | **$PO_4^{3-}$** |
| Jordan | 1.11E-05 | 3.62E-06 | 1.11E-06 | 3.62E-07 |
| Kazakhstan | 1.59E-06 | 5.19E-07 | 1.59E-07 | 5.19E-08 |
| Kenya | 2.71E-06 | 8.84E-07 | 2.71E-07 | 8.84E-08 |
| Kyrgyzstan | 8.00E-07 | 2.61E-07 | 8.00E-08 | 2.61E-08 |
| Laos | 8.24E-08 | 2.69E-08 | 8.24E-09 | 2.69E-09 |
| Latvia | 5.11E-08 | 1.67E-08 | 5.11E-09 | 1.67E-09 |
| Lebanon | 5.06E-08 | 1.65E-08 | 5.06E-09 | 1.65E-09 |
| Lesotho | 5.42E-08 | 1.77E-08 | 5.42E-09 | 1.77E-09 |
| Liberia | 6.29E-08 | 2.05E-08 | 6.29E-09 | 2.05E-09 |
| Libya | 2.86E-06 | 9.33E-07 | 2.86E-07 | 9.33E-08 |
| Lithuania | 1.77E-07 | 5.77E-08 | 1.77E-08 | 5.77E-09 |
| Luxembourg | 2.02E-08 | 6.59E-09 | 2.02E-09 | 6.59E-10 |
| Madagascar | 2.03E-07 | 6.62E-08 | 2.03E-08 | 6.62E-09 |
| Malawi | 8.32E-06 | 2.71E-06 | 8.32E-07 | 2.71E-07 |
| Malaysia | 3.42E-08 | 1.12E-08 | 3.42E-09 | 1.12E-09 |
| Mali | 4.26E-07 | 1.39E-07 | 4.26E-08 | 1.39E-08 |
| Mauritania | 2.40E-07 | 7.83E-08 | 2.40E-08 | 7.83E-09 |
| Mexico | 7.12E-07 | 2.32E-07 | 7.12E-08 | 2.32E-08 |
| Moldova | 3.43E-07 | 1.12E-07 | 3.43E-08 | 1.12E-08 |
| Mongolia | 1.59E-06 | 5.19E-07 | 1.59E-07 | 5.19E-08 |
| Montenegro | 1.24E-07 | 4.04E-08 | 1.24E-08 | 4.04E-09 |
| Morocco | 4.04E-08 | 1.32E-08 | 4.04E-09 | 1.32E-09 |
| Mozambique | 8.91E-07 | 2.91E-07 | 8.91E-08 | 2.91E-08 |
| Myanmar | 5.81E-08 | 1.89E-08 | 5.81E-09 | 1.89E-09 |
| Namibia | 2.85E-08 | 9.29E-09 | 2.85E-09 | 9.29E-10 |
| Nepal | 1.26E-07 | 4.11E-08 | 1.26E-08 | 4.11E-09 |
| Netherlands | 1.70E-07 | 5.54E-08 | 1.70E-08 | 5.54E-09 |
| New Caledonia | 2.01E-06 | 6.55E-07 | 2.01E-07 | 6.55E-08 |
| New Zealand | 1.65E-07 | 5.38E-08 | 1.65E-08 | 5.38E-09 |
| Nicaragua | 1.52E-06 | 4.96E-07 | 1.52E-07 | 4.96E-08 |
| Niger | 1.35E-07 | 4.40E-08 | 1.35E-08 | 4.40E-09 |
| Nigeria | 2.28E-07 | 7.44E-08 | 2.28E-08 | 7.44E-09 |
| North Korea | 1.09E-07 | 3.55E-08 | 1.09E-08 | 3.55E-09 |
| Norway | 1.42E-06 | 4.63E-07 | 1.42E-07 | 4.63E-08 |
| Pakistan | 1.38E-07 | 4.50E-08 | 1.38E-08 | 4.50E-09 |
| Palestinian Territory | 1.73E-05 | 5.64E-06 | 1.73E-06 | 5.64E-07 |
| Panama | 2.91E-08 | 9.49E-09 | 2.91E-09 | 9.49E-10 |
| Papua New Guinea | 4.16E-08 | 1.36E-08 | 4.16E-09 | 1.36E-09 |

| | Emitted to fresh water | | Emitted to soil | |
|---|---|---|---|---|
| **Country** | **P** | **$PO_4^{3-}$** | **P** | **$PO_4^{3-}$** |
| Paraguay | 1.85E-07 | 6.03E-08 | 1.85E-08 | 6.03E-09 |
| Peru | 2.59E-06 | 8.45E-07 | 2.59E-07 | 8.45E-08 |
| Philippines | 1.84E-07 | 6.00E-08 | 1.84E-08 | 6.00E-09 |
| Poland | 1.99E-07 | 6.49E-08 | 1.99E-08 | 6.49E-09 |
| Portugal | 2.29E-08 | 7.47E-09 | 2.29E-09 | 7.47E-10 |
| Romania | 5.21E-08 | 1.70E-08 | 5.21E-09 | 1.70E-09 |
| Russian Federation | 3.06E-07 | 9.98E-08 | 3.06E-08 | 9.98E-09 |
| Rwanda | 5.88E-06 | 1.92E-06 | 5.88E-07 | 1.92E-07 |
| Senegal | 1.02E-07 | 3.33E-08 | 1.02E-08 | 3.33E-09 |
| Serbia | 1.17E-07 | 3.82E-08 | 1.17E-08 | 3.82E-09 |
| Sierra Leone | 4.42E-08 | 1.44E-08 | 4.42E-09 | 1.44E-09 |
| Slovakia | 2.93E-07 | 9.55E-08 | 2.93E-08 | 9.55E-09 |
| Slovenia | 9.15E-08 | 2.98E-08 | 9.15E-09 | 2.98E-09 |
| Somalia | 1.87E-07 | 6.10E-08 | 1.87E-08 | 6.10E-09 |
| South Africa | 2.16E-07 | 7.04E-08 | 2.16E-08 | 7.04E-09 |
| South Korea | 4.12E-08 | 1.34E-08 | 4.12E-09 | 1.34E-09 |
| South Sudan | 3.64E-07 | 1.19E-07 | 3.64E-08 | 1.19E-08 |
| Spain | 2.52E-08 | 8.22E-09 | 2.52E-09 | 8.22E-10 |
| Sri Lanka | 1.53E-07 | 4.99E-08 | 1.53E-08 | 4.99E-09 |
| Sudan | 2.73E-07 | 8.90E-08 | 2.73E-08 | 8.90E-09 |
| Suriname | 2.86E-07 | 9.33E-08 | 2.86E-08 | 9.33E-09 |
| Swaziland | 2.35E-07 | 7.66E-08 | 2.35E-08 | 7.66E-09 |
| Sweden | 3.25E-06 | 1.06E-06 | 3.25E-07 | 1.06E-07 |
| Switzerland | 1.84E-06 | 6.00E-07 | 1.84E-07 | 6.00E-08 |
| Syria | 6.27E-07 | 2.04E-07 | 6.27E-08 | 2.04E-08 |
| Tajikistan | 1.93E-07 | 6.29E-08 | 1.93E-08 | 6.29E-09 |
| Tanzania | 7.93E-06 | 2.59E-06 | 7.93E-07 | 2.59E-07 |
| Thailand | 1.64E-07 | 5.35E-08 | 1.64E-08 | 5.35E-09 |
| The Former Yugoslav Republic of Macedonia | 3.57E-08 | 1.16E-08 | 3.57E-09 | 1.16E-09 |
| Togo | 2.47E-07 | 8.05E-08 | 2.47E-08 | 8.05E-09 |
| Tunisia | 4.77E-07 | 1.56E-07 | 4.77E-08 | 1.56E-08 |
| Turkey | 1.05E-06 | 3.42E-07 | 1.05E-07 | 3.42E-08 |
| Turkmenistan | 1.95E-07 | 6.36E-08 | 1.95E-08 | 6.36E-09 |
| Uganda | 9.24E-06 | 3.01E-06 | 9.24E-07 | 3.01E-07 |
| Ukraine | 1.72E-07 | 5.61E-08 | 1.72E-08 | 5.61E-09 |
| United Kingdom | 4.54E-08 | 1.48E-08 | 4.54E-09 | 1.48E-09 |
| United States | 1.49E-06 | 4.86E-07 | 1.49E-07 | 4.86E-08 |

| | Emitted to fresh water | | Emitted to soil | |
|---|---|---|---|---|
| **Country** | **P** | **$PO_4^{3-}$** | **P** | **$PO_4^{3-}$** |
| Uruguay | 2.52E-07 | 8.22E-08 | 2.52E-08 | 8.22E-09 |
| Uzbekistan | 9.21E-08 | 3.00E-08 | 9.21E-09 | 3.00E-09 |
| Venezuela | 1.45E-07 | 4.73E-08 | 1.45E-08 | 4.73E-09 |
| Vietnam | 4.19E-08 | 1.37E-08 | 4.19E-09 | 1.37E-09 |
| Zambia | 1.92E-06 | 6.26E-07 | 1.92E-07 | 6.26E-08 |
| Zimbabwe | 2.81E-07 | 9.16E-08 | 2.81E-08 | 9.16E-09 |

# 20 S5. Supporting information on toxicity

## 20.1 Model adaptations in USES-LCA 2.0

### *20.1.1 Dissociating chemicals*

Acids and bases exist in neutral or ionized forms. The ratio between these ionic and neutral forms depends on the pKa of the chemical and the pH of the environment (Henderson 1908). Ionic species have different physical–chemical properties than their neutral equivalents, which results in changed behaviour regarding transport and removal processes (Kah et al. 2007; Franco et al. 2008; Franco et al. 2010). Transport processes within and between and removal processes from each environmental compartment can be affected since ionization takes place in water, which is present in all environmental compartments. Appropriate regressions to determine the Koc for monovalent acids and bases that more accurately describe the partitioning behaviour for this group of chemicals were established by Franco et al. (2008). Recommendations from Franco et al. (2010) are followed regarding the choice of regressions, as described for USES-LCA 2.0 by Van Zelm et al. 2013.

Accumulation of chemicals from the environmental compartment into plants and organisms is a key component of chemical risk assessment. Dissociating chemicals behave differently with respect to these transport processes. For this reason, the most recent modelling advances for dissociating organics have been included in USES-LCA 2.0:

- $BCF_{fish}$: Calculation routines for dissociating chemicals replace the original USEtox estimates. When no experimental values are available, the $BCF_{fish}$ for dissociating organics is calculated using the regressions of Fu et al. (2009).
- $BAF_{milk}$: When no experimental values are available, the $BAF_{milk}$ is determined using the regressions of Hendriks et al. (2007) for both neutral and dissociating organics.
- $BAF_{meat}$: When no experimental values are available, the $BAF_{meat}$ is determined using the regressions of Hendriks et al. (2007) for both neutral and dissociating organics.
- RCF: When no experimental data are available, values for both dissociation and non-dissociating organics are calculated using the plant uptake model originally described in Trapp (2009) but expanded and available at http://homepage.env.dtu.dk/stt/PhD%20course%202013website/index.htm
- TSCF: When no experimental data are available, values for both dissociation and non-dissociating organics are calculated using the plant uptake model originally described in Trapp (2009), but expanded and available at http://homepage.env.dtu.dk/stt/PhD%20course%202013website/index.htm

### *20.1.2 USEtox substance database*

To calculate freshwater fate and exposure factors, the substance database of the USEtox model (Rosenbaum et al. 2008) is included in USES–LCA 2.0. The USEtox substance database contains 3,073 organic chemicals and 20 (essential) metals. Physico-chemical properties in the

USEtox database are gathered from the EPISuite 4.0 software package (USEPA 2009). EPISuite provides experimental data when available and, additionally, EPISuite can be used to estimate chemical parameters when experimental data are not available. The USEtox database replaces the original USES-LCA 2.0. Improvements (specific for dissociating chemicals) and additions to the USEtox database are summarized in Table S5.1.

*Table S5.1. Additions to USEtox organic and inorganic database.*

| **Name** | **Unit** | **Source** |
|---|---|---|
| Dimensionless plant/air partition coefficient vegetation | $m^3/m^3$ | Extracted from the original USES-LCA 2.0 substance database for organics |
| OVERALL MASS TRANSFER COEFFICIENT air/plant interface | m/s | Extracted from the original USES-LCA 2.0 substance database for organics |
| Root/soil PARTITION COEFFICIENT | kg(wwt)/kg(wwt) | Extracted from the original USES-LCA 2.0 substance database for organics |
| Leaf/soil PARTITION COEFFICIENT | kg(wwt)/kg(wwt) | Extracted from the original USES-LCA 2.0 substance database for organics |
| Transpiration Stream Concentration Factor | - | Extracted from the original USES-LCA 2.0 substance database for organics. Additionally, the plant uptake model of Trapp (2009) is included. |
| Root Concentration Factor | l/kg wwt | Extracted from the original USES-LCA 2.0 substance database for organics. Additionally, the plant uptake model of Trapp (2009) is included. |
| Bioaccumulation factor for meat | d/kg(food) | Calculated (for both neutral and dissociating organics) using the regressions of Hendriks et al. (2007) |
| Bioaccumulation factor for milk | d/kg(food) | Calculated (for both neutral and dissociating organics) using the regressions of Hendriks et al. (2007) |
| Fish/water PARTITION COEFFICIENT | l/kg | Calculated for dissociating organics using the regressions of Fu et al. (2009) |
| Bioavailability for oral uptake | - | Extracted from the original USES-LCA 2.0 substance database for both organics and metals |

| Name | Unit | Source |
|---|---|---|
| Bioavailability for inhalation | - | Extracted from the original USES-LCA 2.0 substance database for both organics and metals |
| IARC classification | - | (IARC 2004) |
| FRACTION in gas phase air (METAL/INORGANIC) | - | Extracted from the original USES-LCA 2.0 substance database for metals |
| Gas WASHOUT (METAL/INORGANIC) | $m.s^{-1}$ | Extracted from the original USES-LCA 2.0 substance database for metals |
| Aerosol COLLECTION EFFICIENCY | - | Extracted from the original USES-LCA 2.0 substance database for metals |

# 21 S6. Supporting information on water stress

## 21.1 Water requirement ratios per country

The list of water requirements per country (Table S6.1) is based on data from Döll and Siebert (2002) and AQUASTAT (FAO 2012) (see also Supporting Information of Verones et al. (2013)).

*Table S6.1. Water requirements for agriculture per country.*

| Country | Water requirement ratio | Country | Water requirement ratio |
|---|---|---|---|
| Afghanistan | 0.38 | Libya | 0.6 |
| Albania | 0.5 | Liechtenstein | 0.5 |
| Algeria | 0.37 | Lithuania | 0.5 |
| American Samoa | 0.7 | Luxembourg | 0.5 |
| Andorra | 0.5 | Macau | 0.36 |
| Angola | 0.2 | Macedonia | 0.5 |
| Anguilla | 0.45 | Madagascar | 0.25 |
| Antigua and Barbuda | 0.45 | Malawi | 0.25 |
| Argentina | 0.16 | Malaysia | 0.3 |
| Armenia | 0.5 | Maldives | 0.35 |
| Aruba | 0.45 | Mali | 0.3 |
| Australia | 0.7 | Malta | 0.6 |
| Austria | 0.5 | Man, Isle of | 0.5 |
| Azerbaijan | 0.6 | Marshall Islands | 0.7 |
| Bahamas, The | 0.45 | Martinique | 0.45 |
| Bahrain | 0.6 | Mauritania | 0.29 |
| Baker Island | 0.7 | Mauritius | 0.45 |
| Bangladesh | 0.25 | Mayotte | 0.45 |
| Barbados | 0.45 | Mexico | 0.31 |
| Belgium | 0.5 | Midway Islands | 0.7 |
| Belize | 0.45 | Moldova | 0.6 |
| Benin | 0.3 | Monaco | 0.5 |
| Bermuda | 0.6 | Mongolia | 0.36 |
| Bhutan | 0.35 | Montenegro | 0.5 |
| Bolivia | 0.23 | Montserrat | 0.45 |
| Bosnia and Herzegovina | 0.5 | Morocco | 0.37 |
| Botswana | 0.3 | Mozambique | 0.39 |
| Bouvet Island | 0.55 | Myanmar (Burma) | 0.3 |
| Brazil | 0.17 | Namibia | 0.4 |
| British Indian Ocean Territory | 0.4 | Nauru | 0.7 |
| British Virgin Islands | 0.45 | Nepal | 0.25 |
| Brunei | 0.4 | Netherlands | 0.5 |
| Bulgaria | 0.5 | Netherlands Antilles | 0.5 |
| Burkina Faso | 0.3 | New Caledonia | 0.7 |
| Burundi | 0.3 | New Zealand | 0.7 |
| Byelarus | 0.5 | Nicaragua | 0.27 |
| Cambodia | 0.3 | Niger | 0.3 |
| Cameroon | 0.3 | Nigeria | 0.3 |

| Country | Water requirement ratio | Country | Water requirement ratio |
|---|---|---|---|
| Canada | 0.7 | Niue | 0.7 |
| Cape Verde | 0.45 | Norfolk Island | 0.7 |
| Cayman Islands | 0.45 | North Korea | 0.3 |
| Central African Republic | 0.45 | Northern Mariana Islands | 0.35 |
| Chad | 0.35 | Norway | 0.5 |
| Chile | 0.2 | Oman | 0.6 |
| China | 0.36 | Pacific Islands (Palau) | 0.7 |
| Christmas Island | 0.7 | Pakistan | 0.4 |
| Cocos (Keeling) Islands | 0.7 | Panama | 0.2 |
| Colombia | 0.25 | Papua New Guinea | 0.35 |
| Comoros | 0.55 | Paracel Islands | 0.35 |
| Congo | 0.3 | Paraguay | 0.23 |
| Cook Islands | 0.45 | Peru | 0.31 |
| Costa Rica | 0.25 | Philippines | 0.3 |
| Croatia | 0.5 | Pitcairn Islands | 0.7 |
| Cuba | 0.25 | Poland | 0.5 |
| Cyprus | 0.6 | Portugal | 0.6 |
| Czech Republic | 0.5 | Puerto Rico | 0.45 |
| Denmark | 0.5 | Qatar | 0.6 |
| Djibouti | 0.55 | Reunion | 0.45 |
| Dominica | 0.45 | Romania | 0.5 |
| Dominican Republic | 0.25 | Russia | 0.6 |
| Ecuador | 0.19 | Rwanda | 0.3 |
| Egypt | 0.53 | San Marino | 0.5 |
| El Salvador | 0.25 | Sao Tome and Principe | 0.45 |
| Equatorial Guinea | 0.45 | Saudi Arabia | 0.43 |
| Eritrea | 0.32 | Senegal | 0.3 |
| Estonia | 0.5 | Serbia | 0.5 |
| Ethiopia | 0.22 | Seychelles | 0.45 |
| Falkland Islands (Islas Malvinas) | 0.45 | Sierra Leone | 0.33 |
| Faroe Islands | 0.5 | Singapore | 0.35 |
| Federated States of Micronesia | 0.7 | Slovakia | 0.5 |
| Fiji | 0.7 | Slovenia | 0.5 |
| Finland | 0.5 | Solomon Islands | 0.4 |
| France | 0.6 | Somalia | 0.3 |
| French Guiana | 0.45 | South Africa | 0.21 |
| French Polynesia | 0.45 | South Georgia and the South Sandwich Islands | 0.45 |
| French Southern & Antarctic Lands | 0.45 | South Korea | 0.3 |
| Gabon | 0.3 | Spain | 0.6 |
| Gambia, The | 0.3 | Spratly Islands | 0.4 |
| Gaza Strip | 0.6 | Sri Lanka | 0.24 |
| Georgia | 0.5 | St. Helena | 0.45 |
| Germany | 0.5 | St. Kitts and Nevis | 0.45 |
| Ghana | 0.26 | St. Lucia | 0.45 |
| Gibraltar | 0.6 | St. Pierre and Miquelon | 0.7 |

| Country | Water requirement ratio | Country | Water requirement ratio |
|---|---|---|---|
| Glorioso Islands | 0.45 | St. Vincent and the Grenadines | 0.45 |
| Greece | 0.6 | Sudan | 0.4 |
| Grenada | 0.45 | Suriname | 0.3 |
| Guadeloupe | 0.45 | Svalbard | 0.5 |
| Guam | 0.4 | Swaziland | 0.16 |
| Guatemala | 0.25 | Sweden | 0.5 |
| Guernsey | 0.5 | Switzerland | 0.5 |
| Guinea | 0.3 | Syria | 0.45 |
| Guinea-Bissau | 0.3 | Taiwan | 0.35 |
| Guyana | 0.28 | Tajikistan | 0.5 |
| Haiti | 0.2 | Tanzania, United Republic of | 0.3 |
| Heard Island & McDonald Islands | 0.45 | Thailand | 0.3 |
| Honduras | 0.25 | Togo | 0.3 |
| Howland Island | 0.45 | Tokelau | 0.7 |
| Hungary | 0.5 | Tonga | 0.7 |
| Iceland | 0.5 | Trinidad and Tobago | 0.45 |
| India | 0.54 | Tunisia | 0.54 |
| Indonesia | 0.28 | Turkey | 0.4 |
| Iran | 0.32 | Turkmenistan | 0.5 |
| Iraq | 0.28 | Turks and Caicos Islands | 0.45 |
| Ireland | 0.5 | Tuvalu | 0.7 |
| Israel | 0.6 | Uganda | 0.3 |
| Italy | 0.6 | Ukraine | 0.5 |
| Ivory Coast | 0.28 | United Arab Emirates | 0.6 |
| Jamaica | 0.25 | United Kingdom | 0.5 |
| Jan Mayen | 0.5 | United States | 0.6 |
| Japan | 0.35 | Uruguay | 0.22 |
| Jarvis Island | 0.7 | Uzbekistan | 0.5 |
| Jersey | 0.5 | Vanuatu | 0.7 |
| Johnston Atoll | 0.45 | Venezuela | 0.31 |
| Jordan | 0.39 | Vietnam | 0.31 |
| Juan De Nova Island | 0.6 | Virgin Islands | 0.45 |
| Kazakhstan | 0.6 | Wake Island | 0.7 |
| Kenya | 0.3 | Wallis and Futuna | 0.7 |
| Kiribati | 0.45 | West Bank | 0.6 |
| Kuwait | 0.6 | Western Sahara | 0.45 |
| Kyrgyzstan | 0.6 | Western Samoa | 0.7 |
| Laos | 0.3 | Yemen | 0.4 |
| Latvia | 0.6 | Zaire | 0.3 |
| Lebanon | 0.4 | Zambia | 0.19 |
| Lesotho | 0.45 | Zimbabwe | 0.3 |
| Liberia | 0.45 | | |

## 21.2 Results on country level for WSI and human health

The results in Table S6.2 are based on De Schryver et al. (2011) and Pfister et al. (2009).

*Table S6.2. Country averages for the Water Stress Index (WSI), as well as characterization factors (CFs) for Human health (HH) for three different cultural perspectives.*

| Country | WSI egalitarian [-] | WSI Hierarchist [-] | WSI individualist [-] | CF Egalitarian [DALY/m$^3$] | CF Hierarchist [DALY/m$^3$] | CF Individualist [DALY/m$^3$] |
|---|---|---|---|---|---|---|
| Afghanistan | 8.92E-01 | 8.92E-01 | 9.41E-01 | 3.10E-06 | 3.10E-06 | 4.36E-06 |
| Albania | 1.59E-01 | 1.59E-01 | 2.87E-01 | 1.32E-07 | 1.32E-07 | 3.25E-07 |
| Algeria | 8.09E-01 | 8.09E-01 | 8.53E-01 | 1.55E-06 | 1.55E-06 | 2.21E-06 |
| Andorra | 7.25E-02 | 7.25E-02 | 1.91E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Angola | 3.51E-02 | 3.51E-02 | 5.92E-02 | 2.92E-07 | 2.92E-07 | 6.24E-07 |
| Argentina | 3.71E-01 | 3.71E-01 | 3.96E-01 | 6.72E-08 | 6.72E-08 | 9.62E-08 |
| Armenia | 8.76E-01 | 8.76E-01 | 9.53E-01 | 1.20E-06 | 1.20E-06 | 1.75E-06 |
| Australia | 4.57E-01 | 4.57E-01 | 6.02E-01 | 5.76E-18 | 5.76E-18 | 6.69E-16 |
| Austria | 6.04E-02 | 6.04E-02 | 1.44E-01 | 6.38E-09 | 6.38E-09 | 2.04E-08 |
| Azerbaijan | 9.09E-01 | 9.09E-01 | 9.87E-01 | 1.30E-06 | 1.30E-06 | 1.89E-06 |
| Bahamas | 1.32E-01 | 1.32E-01 | 4.82E-01 | 1.09E-09 | 1.09E-09 | 5.38E-09 |
| Bangladesh | 2.63E-01 | 2.63E-01 | 2.80E-01 | 1.95E-06 | 1.95E-06 | 2.69E-06 |
| Belarus | 4.39E-02 | 4.39E-02 | 9.52E-02 | 6.98E-09 | 6.98E-09 | 2.17E-08 |
| Belgium | 6.86E-01 | 6.86E-01 | 9.00E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Belize | 1.03E-02 | 1.03E-02 | 1.03E-02 | 8.80E-09 | 8.80E-09 | 1.20E-08 |
| Benin | 1.67E-02 | 1.67E-02 | 2.09E-02 | 1.33E-07 | 1.33E-07 | 2.24E-07 |
| Bhutan | 1.73E-02 | 1.73E-02 | 2.41E-02 | 8.35E-08 | 8.35E-08 | 1.57E-07 |
| Bolivia | 2.18E-01 | 2.18E-01 | 2.18E-01 | 5.41E-07 | 5.41E-07 | 7.30E-07 |
| Bosnia and Herzegovina | 4.66E-02 | 4.66E-02 | 1.06E-01 | 5.12E-09 | 5.12E-09 | 1.62E-08 |
| Botswana | 3.30E-01 | 3.30E-01 | 4.94E-01 | 1.97E-06 | 1.97E-06 | 3.99E-06 |
| Brazil | 5.35E-02 | 5.35E-02 | 6.99E-02 | 3.73E-08 | 3.73E-08 | 6.96E-08 |
| Brunei Darussalam | 1.01E-02 | 1.01E-02 | 1.01E-02 | 4.38E-11 | 4.38E-11 | 5.95E-11 |
| Bulgaria | 2.81E-01 | 2.81E-01 | 4.81E-01 | 1.26E-07 | 1.26E-07 | 2.68E-07 |
| Burkina Faso | 1.34E-02 | 1.34E-02 | 1.48E-02 | 8.42E-08 | 8.42E-08 | 1.27E-07 |
| Burundi | 1.36E-02 | 1.36E-02 | 1.53E-02 | 8.86E-08 | 8.86E-08 | 1.31E-07 |
| Cambodia | 2.67E-02 | 2.67E-02 | 3.61E-02 | 5.09E-08 | 5.09E-08 | 9.45E-08 |
| Cameroon | 1.12E-02 | 1.12E-02 | 1.17E-02 | 3.42E-08 | 3.42E-08 | 4.80E-08 |
| Canada | 1.09E-01 | 1.09E-01 | 1.81E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Canarias | 1.54E-01 | 1.54E-01 | 1.71E-01 | 7.44E-07 | 7.44E-07 | 1.07E-06 |
| Central African Republic | 1.14E-02 | 1.14E-02 | 1.20E-02 | 1.33E-08 | 1.33E-08 | 1.90E-08 |
| Chad | 1.13E-01 | 1.13E-01 | 1.97E-01 | 8.98E-07 | 8.98E-07 | 2.08E-06 |
| Chile | 7.73E-01 | 7.73E-01 | 7.98E-01 | 2.93E-07 | 2.93E-07 | 4.08E-07 |
| China | 5.39E-01 | 5.39E-01 | 5.66E-01 | 7.58E-07 | 7.58E-07 | 1.07E-06 |
| Colombia | 2.93E-02 | 2.93E-02 | 3.09E-02 | 2.15E-08 | 2.15E-08 | 3.16E-08 |
| Congo | 1.00E-02 | 1.00E-02 | 1.01E-02 | 2.86E-08 | 2.86E-08 | 3.87E-08 |
| Congo DRC | 1.09E-02 | 1.09E-02 | 1.13E-02 | 3.53E-08 | 3.53E-08 | 5.03E-08 |
| Costa Rica | 2.82E-02 | 2.82E-02 | 7.99E-02 | 2.72E-08 | 2.72E-08 | 8.90E-08 |
| Côte d'Ivoire | 1.22E-02 | 1.22E-02 | 1.32E-02 | 5.78E-08 | 5.78E-08 | 8.57E-08 |
| Croatia | 5.11E-02 | 5.11E-02 | 1.18E-01 | 5.94E-09 | 5.94E-09 | 1.87E-08 |

| Country | WSI egalitarian [-] | WSI Hierarchist [-] | WSI individualist [-] | CF Egalitarian [DALY/m$^3$] | CF Hierarchist [DALY/m$^3$] | CF Individualist [DALY/m$^3$] |
|---|---|---|---|---|---|---|
| Cuba | 2.47E-01 | 2.47E-01 | 2.96E-01 | 2.00E-07 | 2.00E-07 | 3.24E-07 |
| Cyprus | 7.40E-01 | 7.40E-01 | 9.67E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Czech Republic | 8.07E-02 | 8.07E-02 | 2.14E-01 | 2.21E-09 | 2.21E-09 | 6.82E-09 |
| Denmark | 5.69E-02 | 5.69E-02 | 1.24E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Djibouti | 5.20E-02 | 5.20E-02 | 6.08E-02 | 5.12E-07 | 5.12E-07 | 7.55E-07 |
| Dominican Republic | 7.02E-02 | 7.02E-02 | 9.77E-02 | 1.52E-07 | 1.52E-07 | 2.86E-07 |
| Ecuador | 2.20E-01 | 2.20E-01 | 2.24E-01 | 4.65E-07 | 4.65E-07 | 6.38E-07 |
| Egypt | 7.65E-01 | 7.65E-01 | 7.70E-01 | 2.58E-06 | 2.58E-06 | 3.51E-06 |
| El Salvador | 7.97E-02 | 7.97E-02 | 2.47E-01 | 2.36E-08 | 2.36E-08 | 4.47E-08 |
| Equatorial Guinea | 1.03E-02 | 1.03E-02 | 1.04E-02 | 7.94E-10 | 7.94E-10 | 1.08E-09 |
| Eritrea | 5.72E-01 | 5.72E-01 | 6.29E-01 | 1.09E-06 | 1.09E-06 | 1.80E-06 |
| Estonia | 2.52E-02 | 2.52E-02 | 3.73E-02 | 1.24E-09 | 1.24E-09 | 2.22E-09 |
| Ethiopia | 2.23E-01 | 2.23E-01 | 2.38E-01 | 2.14E-06 | 2.14E-06 | 3.08E-06 |
| Fiji | 4.64E-03 | 4.64E-03 | 4.66E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Finland | 8.75E-01 | 8.75E-01 | 8.76E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| France | 3.85E-01 | 3.85E-01 | 3.85E-01 | 9.49E-08 | 9.49E-08 | 1.32E-07 |
| French Guiana | 6.60E+01 | 6.60E+01 | 7.90E+01 | 5.77E-07 | 5.77E-07 | 1.13E-06 |
| Gabon | 4.49E+01 | 4.49E+01 | 5.08E+01 | 1.20E-08 | 1.20E-08 | 1.62E-08 |
| Gambia | 2.26E-04 | 2.26E-04 | 2.28E-04 | 1.18E-10 | 1.18E-10 | 1.85E-10 |
| Georgia | 1.67E-02 | 1.67E-02 | 1.97E-02 | 1.63E-09 | 1.63E-09 | 2.21E-09 |
| Germany | 3.47E+01 | 3.47E+01 | 3.77E+01 | 7.17E-08 | 7.17E-08 | 1.15E-07 |
| Ghana | 1.01E+00 | 1.01E+00 | 2.59E+00 | 9.28E-07 | 9.28E-07 | 1.36E-06 |
| Greece | 4.51E-04 | 4.51E-04 | 7.15E-04 | 9.23E-10 | 9.23E-10 | 2.94E-09 |
| Guatemala | 4.57E+01 | 4.57E+01 | 5.48E+01 | 1.60E-07 | 1.60E-07 | 3.53E-07 |
| Guinea | 1.18E-03 | 1.18E-03 | 2.03E-03 | 4.88E-08 | 4.88E-08 | 1.25E-07 |
| Guinea-Bissau | 1.13E+01 | 1.13E+01 | 1.37E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Guyana | 2.82E-03 | 2.82E-03 | 3.32E-03 | 4.80E-08 | 4.80E-08 | 9.92E-08 |
| Haiti | 9.73E-03 | 9.73E-03 | 1.01E-02 | 1.45E-07 | 1.45E-07 | 2.25E-07 |
| Honduras | 1.89E-01 | 1.89E-01 | 3.29E-01 | 1.49E-07 | 1.49E-07 | 2.31E-07 |
| Hungary | 2.46E-02 | 2.46E-02 | 3.12E-02 | 1.55E-08 | 1.55E-08 | 2.18E-08 |
| Iceland | 3.94E-01 | 3.94E-01 | 9.32E-01 | 4.18E-07 | 4.18E-07 | 9.69E-07 |
| India | 1.08E-03 | 1.08E-03 | 1.09E-03 | 5.00E-08 | 5.00E-08 | 8.53E-08 |
| Indonesia | 6.88E+02 | 6.88E+02 | 6.99E+02 | 6.87E-09 | 6.87E-09 | 2.20E-08 |
| Iran | 1.51E+02 | 1.51E+02 | 2.01E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Iraq | 8.02E-02 | 8.02E-02 | 8.15E-02 | 4.51E-06 | 4.51E-06 | 6.15E-06 |
| Ireland | 1.69E+00 | 1.69E+00 | 1.70E+00 | 7.61E-07 | 7.61E-07 | 1.37E-06 |
| Israel | 2.12E-04 | 2.12E-04 | 3.30E-04 | 9.27E-07 | 9.27E-07 | 1.26E-06 |
| Italy | 7.43E-02 | 7.43E-02 | 7.53E-02 | 2.10E-06 | 2.10E-06 | 2.83E-06 |
| Jamaica | 1.16E+01 | 1.16E+01 | 1.45E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Japan | 8.53E-04 | 8.53E-04 | 1.07E-03 | 5.55E-07 | 5.55E-07 | 7.72E-07 |
| Jordan | 2.73E-01 | 2.73E-01 | 3.02E-01 | 7.89E-13 | 7.89E-13 | 2.52E-12 |
| Kazakhstan | 1.33E+01 | 1.33E+01 | 1.34E+01 | 1.32E-08 | 1.32E-08 | 1.93E-08 |
| Kenya | 9.69E-01 | 9.69E-01 | 1.11E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Kuwait | 1.70E-02 | 1.70E-02 | 2.14E-02 | 7.01E-07 | 7.01E-07 | 9.46E-07 |
| Kyrgyzstan | 3.99E-03 | 3.99E-03 | 3.99E-03 | 6.43E-07 | 6.43E-07 | 9.17E-07 |
| Laos | 2.72E+01 | 2.72E+01 | 2.73E+01 | 1.16E-07 | 1.16E-07 | 1.98E-07 |

| Country | WSI egalitarian [-] | WSI Hierarchist [-] | WSI individualist [-] | CF Egalitarian [DALY/m$^3$] | CF Hierarchist [DALY/m$^3$] | CF Individualist [DALY/m$^3$] |
|---|---|---|---|---|---|---|
| Latvia | 1.55E-01 | 1.55E-01 | 2.17E-01 | 1.43E-08 | 1.43E-08 | 1.94E-08 |
| Lebanon | 1.28E-04 | 1.28E-04 | 1.68E-04 | 1.35E-06 | 1.35E-06 | 1.82E-06 |
| Lesotho | 1.52E+00 | 1.52E+00 | 1.59E+00 | 3.87E-08 | 3.87E-08 | 7.26E-08 |
| Liberia | 2.37E-01 | 2.37E-01 | 2.82E-01 | 7.28E-10 | 7.28E-10 | 1.39E-09 |
| Libya | 1.20E-04 | 1.20E-04 | 1.20E-04 | 1.47E-06 | 1.47E-06 | 2.03E-06 |
| Liechtenstein | 1.20E+02 | 1.20E+02 | 1.42E+02 | 3.03E-06 | 3.03E-06 | 4.85E-06 |
| Lithuania | 7.11E-02 | 7.11E-02 | 1.79E-01 | 1.20E-07 | 1.20E-07 | 1.64E-07 |
| Luxembourg | 7.46E-04 | 7.46E-04 | 1.24E-03 | 6.12E-07 | 6.12E-07 | 9.10E-07 |
| Madagascar | 5.23E-01 | 5.23E-01 | 1.31E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Madeira | 3.02E-02 | 3.02E-02 | 5.82E-02 | 1.27E-06 | 1.27E-06 | 1.76E-06 |
| Malawi | 9.57E-01 | 9.57E-01 | 1.46E+00 | 1.03E-09 | 1.03E-09 | 2.33E-09 |
| Malaysia | 1.90E-02 | 1.90E-02 | 2.09E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Mali | 1.57E-02 | 1.57E-02 | 3.10E-02 | 3.56E-07 | 3.56E-07 | 8.05E-07 |
| Mauritania | 3.36E+00 | 3.36E+00 | 3.47E+00 | 1.27E-07 | 1.27E-07 | 1.92E-07 |
| Mexico | 5.84E-02 | 5.84E-02 | 6.62E-02 | 1.38E-08 | 1.38E-08 | 3.29E-08 |
| Moldova | 1.27E+01 | 1.27E+01 | 1.33E+01 | 2.14E-06 | 2.14E-06 | 2.97E-06 |
| Mongolia | 2.41E-01 | 2.41E-01 | 4.80E-01 | 1.69E-07 | 1.69E-07 | 3.20E-07 |
| Montenegro | 8.16E-04 | 8.16E-04 | 1.02E-03 | 2.61E-07 | 2.61E-07 | 3.78E-07 |
| Morocco | 2.71E-03 | 2.71E-03 | 4.87E-03 | 7.05E-08 | 7.05E-08 | 1.74E-07 |
| Mozambique | 3.48E+01 | 3.48E+01 | 3.64E+01 | 4.90E-08 | 4.90E-08 | 7.80E-08 |
| Myanmar | 6.43E-01 | 6.43E-01 | 8.56E-01 | 6.28E-09 | 6.28E-09 | 1.31E-08 |
| Namibia | 4.11E-03 | 4.11E-03 | 8.10E-03 | 4.05E-06 | 4.05E-06 | 5.70E-06 |
| Nepal | 2.96E-02 | 2.96E-02 | 5.20E-02 | 1.39E-06 | 1.39E-06 | 2.39E-06 |
| Netherlands | 9.94E-01 | 9.94E-01 | 9.94E-01 | 3.10E-08 | 3.10E-08 | 7.88E-08 |
| New Zealand | 9.57E+00 | 9.57E+00 | 1.99E+01 | 2.87E-07 | 2.87E-07 | 7.19E-07 |
| Nicaragua | 7.41E-03 | 7.41E-03 | 1.02E-02 | 5.81E-06 | 5.81E-06 | 7.85E-06 |
| Niger | 8.78E-04 | 8.78E-04 | 1.26E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Nigeria | 3.72E-02 | 3.72E-02 | 3.99E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| North Korea | 4.38E+00 | 4.38E+00 | 4.51E+00 | 5.46E-08 | 5.46E-08 | 1.05E-07 |
| Norway | 1.03E+00 | 1.03E+00 | 1.36E+00 | 1.08E-06 | 1.08E-06 | 1.57E-06 |
| Oman | 8.02E-02 | 8.02E-02 | 1.38E-01 | 3.16E-06 | 3.16E-06 | 4.39E-06 |
| Pakistan | 2.57E-01 | 2.57E-01 | 2.60E-01 | 1.20E-06 | 1.20E-06 | 2.08E-06 |
| Palestinian Territory | 1.54E+02 | 1.54E+02 | 1.78E+02 | 6.60E-15 | 6.60E-15 | 8.94E-15 |
| Panama | 4.81E-01 | 4.81E-01 | 4.82E-01 | 4.70E-07 | 4.70E-07 | 6.35E-07 |
| Papua New Guinea | 1.96E-05 | 1.96E-05 | 3.74E-05 | 3.86E-06 | 3.86E-06 | 5.76E-06 |
| Paraguay | 4.99E-04 | 4.99E-04 | 4.99E-04 | 6.42E-07 | 6.42E-07 | 8.67E-07 |
| Peru | 3.62E-02 | 3.62E-02 | 3.87E-02 | 1.04E-08 | 1.04E-08 | 1.95E-08 |
| Philippines | 2.04E+02 | 2.04E+02 | 2.09E+02 | 1.14E-09 | 1.14E-09 | 1.55E-09 |
| Poland | 2.58E+00 | 2.58E+00 | 3.60E+00 | 7.61E-09 | 7.61E-09 | 1.10E-08 |
| Portugal | 9.52E-05 | 9.52E-05 | 1.84E-04 | 1.78E-07 | 1.78E-07 | 4.22E-07 |
| Puerto Rico | 3.83E+02 | 3.83E+02 | 7.04E+02 | 6.49E-07 | 6.49E-07 | 1.19E-06 |
| Qatar | 1.28E+00 | 1.28E+00 | 2.05E+00 | 3.11E-09 | 3.11E-09 | 8.00E-09 |
| Romania | 7.68E+00 | 7.68E+00 | 8.04E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Russian Federation | 2.45E-02 | 2.45E-02 | 4.88E-02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Rwanda | 3.22E+01 | 3.22E+01 | 6.38E+01 | 6.43E-08 | 6.43E-08 | 8.73E-08 |
| San Marino | 2.78E-04 | 2.78E-04 | 3.35E-04 | 2.16E-08 | 2.16E-08 | 4.16E-08 |
| Sao Tome and Principe | 1.98E-06 | 1.98E-06 | 4.10E-06 | 1.42E-07 | 1.42E-07 | 3.66E-07 |

| Country | WSI egalitarian [-] | WSI Hierarchist [-] | WSI individualist [-] | CF Egalitarian [DALY/m$^3$] | CF Hierarchist [DALY/m$^3$] | CF Individualist [DALY/m$^3$] |
|---|---|---|---|---|---|---|
| Saudi Arabia | 7.04E-04 | 7.04E-04 | 7.05E-04 | 7.20E-08 | 7.20E-08 | 1.15E-07 |
| Senegal | 7.28E+04 | 7.28E+04 | 7.32E+04 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Serbia | 9.08E+01 | 9.08E+01 | 9.47E+01 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Sierra Leone | 1.94E+01 | 1.94E+01 | 4.21E+01 | 6.13E-10 | 6.13E-10 | 8.30E-10 |
| Slovakia | 2.80E-05 | 2.80E-05 | 2.91E-05 | 5.42E-07 | 5.42E-07 | 7.34E-07 |
| Slovenia | 1.23E-01 | 1.23E-01 | 2.89E-01 | 1.27E-07 | 1.27E-07 | 2.24E-07 |
| Somalia | 1.19E-02 | 1.19E-02 | 2.83E-02 | 3.55E-08 | 3.55E-08 | 9.82E-08 |
| South Africa | 5.61E+00 | 5.61E+00 | 5.76E+00 | 1.91E-07 | 1.91E-07 | 2.69E-07 |
| South Korea | 4.32E+00 | 4.32E+00 | 5.32E+00 | 6.79E-09 | 6.79E-09 | 2.16E-08 |
| South Sudan | 5.42E-04 | 5.42E-04 | 7.05E-04 | 2.07E-07 | 2.07E-07 | 3.23E-07 |
| Spain | 1.38E-03 | 1.38E-03 | 1.59E-03 | 2.51E-06 | 2.51E-06 | 3.53E-06 |
| Sri Lanka | 1.25E+01 | 1.25E+01 | 1.58E+01 | 6.05E-09 | 6.05E-09 | 1.93E-08 |
| Sudan | 8.33E+01 | 8.33E+01 | 1.22E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Suriname | 5.83E+03 | 5.83E+03 | 6.49E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Swaziland | 2.62E-03 | 2.62E-03 | 2.82E-03 | 4.07E-06 | 4.07E-06 | 5.53E-06 |
| Sweden | 7.79E-04 | 7.79E-04 | 1.02E-03 | 2.40E-06 | 2.40E-06 | 4.02E-06 |
| Switzerland | 2.60E-02 | 2.60E-02 | 4.32E-02 | 9.80E-10 | 9.80E-10 | 2.69E-09 |
| Syria | 4.01E-02 | 4.01E-02 | 9.94E-02 | 1.19E-06 | 1.19E-06 | 1.78E-06 |
| Tajikistan | 1.34E+02 | 1.34E+02 | 1.35E+02 | 1.02E-08 | 1.02E-08 | 1.52E-08 |
| Tanzania | 6.68E+01 | 6.68E+01 | 6.69E+01 | 3.22E-07 | 3.22E-07 | 5.66E-07 |
| Thailand | 6.41E-03 | 6.41E-03 | 7.23E-03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| The Former Yugoslav Republic of Macedonia | 5.82E+00 | 5.82E+00 | 9.15E+00 | 1.10E-11 | 1.10E-11 | 3.50E-11 |
| Togo | 8.01E-03 | 8.01E-03 | 1.62E-02 | 1.86E-06 | 1.86E-06 | 2.52E-06 |
| Trinidad and Tobago | 4.97E-06 | 4.97E-06 | 5.32E-06 | 2.45E-06 | 2.45E-06 | 3.31E-06 |
| Tunisia | 8.23E-04 | 8.23E-04 | 9.42E-04 | 1.33E-07 | 1.33E-07 | 1.98E-07 |
| Turkey | 2.81E-06 | 2.81E-06 | 4.02E-06 | 3.44E-07 | 3.44E-07 | 7.33E-07 |
| Turkmenistan | 1.11E+01 | 1.11E+01 | 1.15E+01 | 3.01E-07 | 3.01E-07 | 8.23E-07 |
| Uganda | 1.32E+03 | 1.32E+03 | 1.47E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Ukraine | 1.04E+03 | 1.04E+03 | 1.05E+03 | 6.63E-08 | 6.63E-08 | 1.03E-07 |
| United Arab Emirates | 4.47E+01 | 4.47E+01 | 5.49E+01 | 1.90E-07 | 1.90E-07 | 4.38E-07 |
| United Kingdom | 3.56E-01 | 3.56E-01 | 5.28E-01 | 1.71E-06 | 1.71E-06 | 2.40E-06 |
| United States | 8.20E-07 | 8.20E-07 | 8.50E-07 | 9.80E-07 | 9.80E-07 | 1.62E-06 |
| Uruguay | 2.16E-02 | 2.16E-02 | 2.29E-02 | 1.05E-06 | 1.05E-06 | 1.50E-06 |
| Uzbekistan | 5.72E-02 | 5.72E-02 | 7.71E-02 | 1.73E-06 | 1.73E-06 | 2.34E-06 |
| Venezuela | 3.87E-02 | 3.87E-02 | 4.12E-02 | 6.49E-08 | 6.49E-08 | 1.08E-07 |
| Vietnam | 6.23E+00 | 6.23E+00 | 6.24E+00 | 2.16E-07 | 2.16E-07 | 3.87E-07 |
| Yemen | 4.63E-01 | 4.63E-01 | 5.49E-01 | 8.38E-08 | 8.38E-08 | 1.14E-07 |
| Zambia | 1.80E+00 | 1.80E+00 | 1.93E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Zimbabwe | 4.51E+00 | 4.51E+00 | 5.14E+00 | 3.37E-09 | 3.37E-09 | 4.83E-09 |

## 21.3 Results on country level for terrestrial and aquatic ecosystems

The results in Table S6.3 are based on Pfister et al. (2009) and Hanafiah et al. (2011). For aquatic ecosystems we excluded minor islands and report the average values of the primary land of each country.

*Table S6.3. Country averages for terrestrial and aquatic ecosystem quality (EQ) for three different cultural perspectives.*

| Country | CF terrestrial EQ [species-eq·yr/m$^3$] | | | CF aquatic EQ [species-eq·yr/m$^3$] |
|---|---|---|---|---|
| | Individualist | Hierarchist | Egalitarian | all perspectives |
| Afghanistan | 0 | 1.41E-08 | 1.41E-08 | 1.72E-12 |
| Albania | 0 | 2.18E-09 | 2.18E-09 | 0 |
| Algeria | 0 | 1.05E-08 | 1.05E-08 | 2.21E-12 |
| Andorra | 0 | 0 | 0 | 0 |
| Angola | 0 | 5.41E-09 | 5.41E-09 | 2.78E-12 |
| Argentina | 0 | 9.73E-09 | 9.73E-09 | 2.47E-12 |
| Armenia | 0 | 6.64E-09 | 6.64E-09 | 1.02E-12 |
| Australia | 0 | 3.30E-08 | 3.30E-08 | 2.42E-12 |
| Austria | 0 | 6.43E-10 | 6.43E-10 | 0 |
| Azerbaijan | 0 | 6.94E-09 | 6.94E-09 | 1.02E-12 |
| Bangladesh | 0 | 2.16E-09 | 2.16E-09 | 2.49E-12 |
| Belarus | 0 | 1.94E-09 | 1.94E-09 | 0 |
| Belgium | 0 | 2.14E-09 | 2.14E-09 | 0 |
| Belize | 0 | 1.01E-09 | 1.01E-09 | 0 |
| Benin | 0 | 4.60E-09 | 4.60E-09 | 2.31E-12 |
| Bhutan | 0 | 3.73E-09 | 3.73E-09 | 2.52E-12 |
| Bolivia | 0 | 1.52E-09 | 1.52E-09 | 2.74E-12 |
| Bosnia and Herzegovina | 0 | 1.25E-09 | 1.25E-09 | 0 |
| Botswana | 0 | 1.83E-08 | 1.83E-08 | 2.16E-12 |
| Brazil | 0 | 2.07E-09 | 2.07E-09 | 2.39E-12 |
| Brunei Darussalam | 0 | 6.83E-10 | 6.83E-10 | 0 |
| Bulgaria | 0 | 4.88E-09 | 4.88E-09 | 5.59E-13 |
| Burkina Faso | 0 | 1.01E-08 | 1.01E-08 | 2.47E-12 |
| Burundi | 0 | 1.97E-09 | 1.97E-09 | 5.24E-12 |
| Cambodia | 0 | 1.06E-09 | 1.06E-09 | 3.75E-12 |
| Cameroon | 0 | 1.68E-09 | 1.68E-09 | 1.61E-12 |
| Canada | 0 | 1.27E-09 | 1.27E-09 | 0 |
| Central African Republic | 0 | 2.76E-09 | 2.76E-09 | 3.15E-12 |
| Chad | 0 | 1.14E-07 | 1.14E-07 | 2.15E-12 |
| Chile | 0 | 4.28E-09 | 4.28E-09 | 0 |
| China | 0 | 4.58E-09 | 4.58E-09 | 3.91E-12 |
| Columbia | 0 | 8.01E-10 | 8.01E-10 | 1.48E-12 |
| Congo | 0 | 1.10E-09 | 1.10E-09 | 2.82E-12 |
| Congo DRC (Zaire) | 0 | 1.25E-09 | 1.25E-09 | 3.65E-12 |
| Costa Rica | 0 | 1.47E-09 | 1.47E-09 | 0 |
| Cote D'ivoire (Ivory Coast) | 0 | 1.86E-09 | 1.86E-09 | 1.1E-12 |
| Croatia | 0 | 1.80E-09 | 1.80E-09 | 0 |
| Cuba | 0 | 2.64E-09 | 2.64E-09 | 0 |
| Cyprus | 0 | 2.88E-09 | 2.88E-09 | 0 |

| Country | CF terrestrial EQ [species-eq·yr/m$^3$] | | | CF aquatic EQ [species-eq·yr/m$^3$] |
|---|---|---|---|---|
| | Individualist | Hierarchist | Egalitarian | all perspectives |
| Czech Republic | 0 | 1.63E-09 | 1.63E-09 | 0 |
| Denmark | 0 | 1.56E-09 | 1.56E-09 | 0 |
| Djibouti | 0 | 5.86E-08 | 5.86E-08 | 0 |
| Dominican Republic | 0 | 9.57E-10 | 9.57E-10 | 0 |
| Ecuador | 0 | 3.51E-09 | 3.51E-09 | 2.55E-12 |
| Egypt | 0 | 1.27E-07 | 1.27E-07 | 6.64E-12 |
| El Salvador | 0 | 3.97E-09 | 3.97E-09 | 9.5E-14 |
| Equatorial Guinea | 0 | 9.15E-10 | 9.15E-10 | 6.55E-13 |
| Eritrea | 0 | 5.43E-08 | 5.43E-08 | 6.64E-12 |
| Estonia | 0 | 3.32E-09 | 3.32E-09 | 0 |
| Ethiopia | 0 | 1.28E-08 | 1.28E-08 | 6.64E-12 |
| Falkland Islands (Malvinas) | 0 | 0 | 0 | 0 |
| Fiji | 0 | 6.27E-10 | 6.27E-10 | 0 |
| Finland | 0 | 1.79E-09 | 1.79E-09 | 0 |
| France, Metropolitan | 0 | 2.43E-09 | 2.43E-09 | 1.4E-13 |
| French Guiana | 0 | 5.09E-10 | 5.09E-10 | 4.22E-13 |
| Gabon | 0 | 1.12E-09 | 1.12E-09 | 8.58E-13 |
| Gambia | 0 | 2.95E-09 | 2.95E-09 | 1.04E-12 |
| Georgia | 0 | 1.84E-09 | 1.84E-09 | 1.02E-12 |
| Germany | 0 | 1.89E-09 | 1.89E-09 | 0 |
| Ghana | 0 | 2.25E-09 | 2.25E-09 | 1.3E-12 |
| Greece | 0 | 2.73E-09 | 2.73E-09 | 5.05E-13 |
| Guatemala | 0 | 8.54E-09 | 8.54E-09 | 1.83E-13 |
| Guinea | 0 | 1.92E-09 | 1.92E-09 | 2.39E-12 |
| Guinea Bissau | 0 | 2.66E-09 | 2.66E-09 | 5.71E-13 |
| Guyana | 0 | 7.37E-10 | 7.37E-10 | 2.73E-12 |
| Haiti | 0 | 2.33E-09 | 2.33E-09 | 0 |
| Honduras | 0 | 9.92E-10 | 9.92E-10 | 5.8E-14 |
| Hungary | 0 | 3.14E-09 | 3.14E-09 | 0 |
| Iceland | 0 | 8.24E-10 | 8.24E-10 | 0 |
| India | 0 | 5.83E-09 | 5.83E-09 | 1.78E-12 |
| Indonesia | 0 | 9.74E-10 | 9.74E-10 | 5.91E-13 |
| Iran | 0 | 1.80E-08 | 1.80E-08 | 1.82E-12 |
| Iraq | 0 | 2.05E-08 | 2.05E-08 | 2.75E-12 |
| Ireland | 0 | 1.56E-09 | 1.56E-09 | 0 |
| Israel | 0 | 8.04E-09 | 8.04E-09 | 0 |
| Italy | 0 | 2.78E-09 | 2.78E-09 | 2.19E-13 |
| Jamaica | 0 | 3.06E-09 | 3.06E-09 | 0 |
| Japan | 0 | 1.50E-09 | 1.50E-09 | 0 |
| Jordan | 0 | 2.66E-08 | 2.66E-08 | 2.96E-12 |
| Kazakhstan | 0 | 1.87E-08 | 1.87E-08 | 1.07E-12 |
| Kenya | 0 | 1.57E-08 | 1.57E-08 | 2.36E-12 |
| Korea, Democratic People's Republic of | 0 | 1.45E-09 | 1.45E-09 | 0 |
| Korea, Republic of | 0 | 2.05E-10 | 2.05E-10 | 0 |
| Kuwait | 0 | 2.95E-08 | 2.95E-08 | 0 |
| Kyrgyzstan | 0 | 8.95E-09 | 8.95E-09 | 1.33E-12 |
| Laos, Peoples Democratic Republic | 0 | 2.64E-09 | 2.64E-09 | 3.7E-12 |

| Country | CF terrestrial EQ [species-eq·yr/m$^3$] | | | CF aquatic EQ [species-eq·yr/m$^3$] |
|---|---|---|---|---|
| | Individualist | Hierarchist | Egalitarian | all perspectives |
| of | | | | |
| Latvia | 0 | 2.97E-09 | 2.97E-09 | 0 |
| Lebanon | 0 | 7.95E-09 | 7.95E-09 | 0 |
| Lesotho | 0 | 5.91E-09 | 5.91E-09 | 2.6E-12 |
| Liberia | 0 | 7.15E-10 | 7.15E-10 | 4.82E-13 |
| Libyan Arab Jamahiriya | 0 | 1.22E-08 | 1.22E-08 | 0 |
| Lithuania | 0 | 2.16E-09 | 2.16E-09 | 0 |
| Luxembourg | 0 | 2.15E-09 | 2.15E-09 | 0 |
| Macedonia, The Former Republic of Yugoslavia | 0 | 3.62E-09 | 3.62E-09 | 6.04E-13 |
| Madagascar | 0 | 8.15E-09 | 8.15E-09 | 0 |
| Malawi | 0 | 6.71E-09 | 6.71E-09 | 2.89E-12 |
| Malaysia | 0 | 3.02E-09 | 3.02E-09 | 5.87E-13 |
| Mali | 0 | 1.59E-09 | 1.59E-09 | 3.94E-12 |
| Mauritania | 0 | 4.74E-08 | 4.74E-08 | 2.34E-12 |
| Mexico | 0 | 9.66E-09 | 9.66E-09 | 2.01E-12 |
| Moldova, Republic of | 0 | 4.73E-09 | 4.73E-09 | 0 |
| Mongolia | 0 | 3.94E-08 | 3.94E-08 | 0 |
| Morocco | 0 | 1.86E-08 | 1.86E-08 | 0 |
| Mozambique | 0 | 1.16E-08 | 1.16E-08 | 2.69E-12 |
| Myanmar | 0 | 2.43E-09 | 2.43E-09 | 2.01E-12 |
| Namibia | 0 | 1.77E-07 | 1.77E-07 | 2.25E-12 |
| Nepal | 0 | 3.63E-09 | 3.63E-09 | 2.12E-12 |
| Netherlands | 0 | 3.08E-09 | 3.08E-09 | 0 |
| New Caledonia | 0 | 0 | 0 | 0 |
| New Zealand | 0 | 1.10E-09 | 1.10E-09 | 2.25E-13 |
| Nicaragua | 0 | 1.00E-09 | 1.00E-09 | 0 |
| Niger | 0 | 6.75E-08 | 6.75E-08 | 3.09E-12 |
| Nigeria | 0 | 3.06E-09 | 3.06E-09 | 2.71E-12 |
| Norway | 0 | 6.73E-10 | 6.73E-10 | 0 |
| Oman | 0 | 2.41E-08 | 2.41E-08 | 0 |
| Pakistan | 0 | 2.23E-08 | 2.23E-08 | 1.71E-12 |
| Panama | 0 | 3.20E-09 | 3.20E-09 | 3.4E-14 |
| Papua New Guinea | 0 | 0 | 0 | 5.02E-13 |
| Paraguay | 0 | 2.27E-09 | 2.27E-09 | 2.74E-12 |
| Peru | 0 | 2.17E-09 | 2.17E-09 | 2.51E-12 |
| Philippines | 0 | 8.19E-10 | 8.19E-10 | 0 |
| Poland | 0 | 2.97E-09 | 2.97E-09 | 0 |
| Portugal | 0 | 2.23E-09 | 2.23E-09 | 6.17E-13 |
| Puerto Rico | 0 | 1.94E-09 | 1.94E-09 | 0 |
| Qatar | 0 | 6.19E-08 | 6.19E-08 | 0 |
| Reunion | 0 | 0 | 0 | 0 |
| Romania | 0 | 3.70E-09 | 3.70E-09 | 0 |
| Russian Federation | 0 | 2.18E-09 | 2.18E-09 | 0 |
| Rwanda | 0 | 1.13E-09 | 1.13E-09 | 5.93E-12 |
| Saudi Arabia | 0 | 2.28E-08 | 2.28E-08 | 2.96E-12 |
| Senegal | 0 | 4.06E-08 | 4.06E-08 | 1.32E-12 |
| Sierra Leone | 0 | 8.58E-10 | 8.58E-10 | 3.52E-13 |

| Country | CF terrestrial EQ [species-eq·yr/m$^3$] | | | CF aquatic EQ [species-eq·yr/m$^3$] |
|---|---|---|---|---|
| | Individualist | Hierarchist | Egalitarian | all perspectives |
| Slovakia | 0 | 1.54E-09 | 1.54E-09 | 0 |
| Slovenia | 0 | 5.57E-10 | 5.57E-10 | 0 |
| Somalia | 0 | 1.61E-07 | 1.61E-07 | 0 |
| South Africa | 0 | 1.82E-08 | 1.82E-08 | 2.53E-12 |
| South Sudan | 0 | 3.41E-08 | 3.41E-08 | 6.6E-12 |
| Spain | 0 | 4.56E-09 | 4.56E-09 | 8.07E-13 |
| Sri Lanka | 0 | 1.35E-09 | 1.35E-09 | 5.19E-13 |
| Sudan | 0 | 3.41E-08 | 3.41E-08 | 6.32E-12 |
| Suriname | 0 | 4.77E-10 | 4.77E-10 | 5.89E-13 |
| Swaziland | 0 | 9.22E-09 | 9.22E-09 | 5.2E-13 |
| Sweden | 0 | 3.34E-09 | 3.34E-09 | 0 |
| Switzerland | 0 | 7.76E-10 | 7.76E-10 | 0 |
| Syrian Arab Republic | 0 | 1.52E-08 | 1.52E-08 | 2.95E-12 |
| Tajikistan | 0 | 1.07E-08 | 1.07E-08 | 2.19E-12 |
| Tanzania, United Republic of | 0 | 6.51E-09 | 6.51E-09 | 3.36E-12 |
| Thailand | 0 | 1.11E-09 | 1.11E-09 | 2.23E-12 |
| Togo | 0 | 2.67E-09 | 2.67E-09 | 1.01E-12 |
| Trinidad & Tobago | 0 | 0 | 0 | 0 |
| Tunisia | 0 | 1.32E-08 | 1.32E-08 | 0 |
| Turkey | 0 | 8.58E-09 | 8.58E-09 | 2.13E-12 |
| Turkmenistan | 0 | 1.46E-08 | 1.46E-08 | 1.52E-12 |
| Uganda | 0 | 9.15E-10 | 9.15E-10 | 6.62E-12 |
| Ukraine | 0 | 4.92E-09 | 4.92E-09 | 0 |
| United Arab Emirates | 0 | 5.06E-08 | 5.06E-08 | 0 |
| United Kingdom | 0 | 1.74E-09 | 1.74E-09 | 0 |
| United States | 0 | 5.20E-09 | 5.20E-09 | 2.9E-12 |
| Uruguay | 0 | 5.60E-10 | 5.60E-10 | 1.46E-12 |
| Uzbekistan | 0 | 1.49E-08 | 1.49E-08 | 2E-12 |
| Venezuela | 0 | 1.21E-09 | 1.21E-09 | 1.62E-12 |
| Vietnam | 0 | 2.00E-09 | 2.00E-09 | 3.39E-12 |
| Western Sahara | 0 | 1.07E-07 | 1.07E-07 | 0 |
| Yemen | 0 | 6.71E-08 | 6.71E-08 | 0 |
| Zambia | 0 | 5.67E-09 | 5.67E-09 | 3.06E-12 |
| Zimbabwe | 0 | 1.87E-08 | 1.87E-08 | 2.76E-12 |

## 21.4 Endpoints on watershed level for aquatic ecosystems

The characterization factors for aquatic ecosystems based on Hanafiah et al. (2011) are given for several major watersheds and sub-watersheds. We excluded watersheds above 42° latitude from the list (Table S6.4). The values are valid for all three cultural perspectives.

*Table S6.4. Endpoint CFs for impacts of water consumption on aquatic ecosystems, modified from Hanafiah et al (2011).*

| Watershed | CF [species·yr/$m^3$] | Watershed | CF [species·yr/$m^3$] |
|---|---|---|---|
| Agly (France) | 1.40E-13 | Mono (Togo) | 6.38E-13 |
| Agnébi (RCI) | 4.45E-13 | Mungo (Cameroun) | 1.84E-14 |
| Allegheny river (a. Ohio) | 7.21E-13 | Murgab ou Murghab ou Mourbab (fSU-Afghanistan) Endo | 1.35E-12 |
| Altamaha (USA) | 6.04E-13 | Murray-Darling (Australia) | 2.42E-12 |
| Amazon (Br. Mère Maranon) (Peru-Brazil) | 3.08E-12 | Muskingum River (s.a. Ohio) (a. Allegheny) | 2.17E-13 |
| Apalachicola (USA) | 2.28E-13 | Naryn (a. Syr Darya) (fSU) | 1.07E-12 |
| Approuague | 3.72E-13 | Nasia (a. White Volta) (Ghana) | 3.08E-13 |
| Araguaia (Araguaya, Central Brazil) | 2.70E-12 | Nesta-Nestos (Greece-Bulgaria) | 3.79E-13 |
| Arkansas River (USA) | 2.17E-12 | Niandan (Guinea) (a. Niger) | 4.47E-13 |
| Athi-Galana-Sabaki River Drainage System (Kenya, from Nairobi eastward to Mombasa) | 1.47E-12 | Niari-Kouilou (Congo) | 5.99E-13 |
| Balsas (Mexico) | 8.92E-13 | Niger (Afr. Int.) | 4.41E-12 |
| Bandama (RCI) | 8.76E-13 | Nil (Af., int.) | 6.64E-12 |
| Bear Creek | 7.97E-14 | Nilwala Ganga (Sri Lanka) | 1.09E-13 |
| Bénoué (Nigeria-Cameroun) (a. Niger) | 1.59E-12 | Nipoué (Cess, Liberia-RCI) | 4.36E-13 |
| Bia (RCI-Ghana) | 3.94E-13 | Ntem (Cameroon-Gabon-Guinea Equatorial) | 4.62E-13 |
| Big Darby Creek (s. a. Ohio) (a. Scioto) | 2.07E-13 | Nyong (Cameroon) | 5.14E-13 |
| Black Volta (Burkina-Ghana) (a. Volta) | 1.92E-12 | N'Zi (a. Bandama) (RCI) | 6.81E-13 |
| Boubo (RCI) | 2.07E-13 | N'Zo (a. Sassandra) (RCI) | 3.80E-13 |
| Brahmaputra (Dyardanes, Oedanes, Tsangpo, Zangbo, Tibet, China, NE India and Bangladesh) | 2.52E-12 | Ogôoué (Gabon) | 8.52E-13 |
| Canadian (s. a. Mississippi) (USA) | 1.84E-12 | Ogun (Nigeria) | 6.01E-13 |

| Watershed | CF [species·yr/$m^3$] | Watershed | CF [species·yr/$m^3$] |
|---|---|---|---|
| Casamance (West Africa) | 4.95E-13 | Ohio Brush Creek (a. Ohio) | 1.14E-13 |
| Cauvery (Karnataka, India) | 8.92E-13 | Ohio river (a. Mississipi) | 2.10E-12 |
| Cavado (Portugal) | 2.11E-13 | Okavango (Southwest central Africa) | 2.03E-12 |
| Cavally (Liberia-RCI) | 4.77E-13 | Olentangy River (a. Little Scioto) | 1.62E-13 |
| Chao Phrya (Menam) (Thailand) | 8.84E-13 | Ombrone (Tuscany, Western Italy) | 2.19E-13 |
| Chari (Lac Tchad) | 2.19E-12 | Orange (South Africa) | 2.60E-12 |
| Chittar (Tamil Nadu, India) | 2.61E-13 | Orinoco (Venezuela-Colombia) | 1.68E-12 |
| Chobe River (Southwest Africa/Namibia) | 1.83E-12 | Ouémé (Benin) | 6.99E-13 |
| Colorado (USA-Mexico) | 2.99E-12 | Oyapock (Guiana-Brazil) | 3.50E-13 |
| Comoé (RCI-Burkina) | 1.10E-12 | Paint Creek (a. Scioto river) | 2.19E-13 |
| Connecticut river (USA) | 6.50E-13 | Panuco (Mexico) | 6.43E-13 |
| Cross (Nigeria-Cameroon) | 5.53E-13 | Paraguay (Brazil-Arg.-Paraguay) (a. Parana) | 2.34E-12 |
| Cumberland river (a. Ohio) | 1.22E-12 | Parana (Brazil-Paraguay-Argentina) | 2.49E-12 |
| Cunene ou Kunene (Namibia-Angola) | 1.17E-12 | Pará-Tocantins (Brazil) | 2.13E-12 |
| Daka (a. Volta) (Ghana) | 1.36E-13 | Parnaiba (Brazil) | 1.49E-12 |
| Dibamba (Cameroon) | 1.95E-13 | Paz (San Salvador) | 2.02E-13 |
| Dodo (aka Déo) (RCI) | 1.15E-13 | Pecos (a. Rio Grande) | 2.16E-12 |
| Douro (Portugal-Spain) | 7.06E-13 | Pilcomayo (South central South America) | 2.78E-12 |
| Elk river (s. a. Ohio) (a. Kanawha) | 3.86E-13 | Pongolo ou Maputo (RCA-Mozambique) | 5.20E-13 |
| Embarras River (a. Wabash) | 4.03E-13 | Potomac (USA) | 4.08E-13 |
| Erhjen River (Southern River) | 5.44E-14 | Pra River (West Africa) | 3.52E-13 |
| Euphrates (Firat Nehri, Al-Furat, Southwest Asia) | 2.96E-12 | Purus (Northwest central South America) | 2.60E-12 |
| Evros-Maritsa (Greece-Turkey-Bulgaria) | 5.70E-13 | Rakaïa river (New-Zealand) | 2.25E-13 |
| Fatala (West Africa) | 2.77E-13 | Red River (USA) | 2.01E-12 |
| Fly (Nlle-Guinée) | 7.18E-13 | Rio Grande (USA-Mexico) | 3.15E-12 |
| Gambia (Guinea-Gambia) | 1.07E-12 | Rio Negro (a. Amazon) (Colomb.-Venez.-Brazil) | 8.28E-13 |

| Watershed | CF [species·yr/m$^3$] | Watershed | CF [species·yr/m$^3$] |
|---|---|---|---|
| Gandaki river (a. Gange) (Nepal) | 5.33E-13 | Rokel River (Seli River, West Africa) | 5.21E-13 |
| Ganges (India) | 2.11E-12 | Ruaha (a. Rufiji) (Tanzania) | 5.87E-13 |
| Géba (Guinea Bissau, West Africa) | 8.36E-13 | Rufiji (Tanzania) | 1.00E-12 |
| Gila (a. Colorado) | 1.91E-12 | Sabine (USA) | 7.62E-13 |
| Gin Ganga (Sri Lanka) | 1.87E-13 | Sacramento (USA) | 1.12E-12 |
| Godavari (Central India) | 1.03E-12 | Sado (Portugal) | 3.01E-13 |
| Green River (a. Ohio) | 1.26E-12 | Saint John (West Africa) | 7.77E-13 |
| Guadiana (Portugal-Esp.) | 1.09E-12 | Sakaria (Turkey) | 7.20E-13 |
| Hocking River (a. Ohio) | 1.81E-13 | Saloum (West Africa) | 1.97E-13 |
| Indus (Tibet-India-Pakistan) | 2.55E-12 | Salween (Tibet-China-Myanmar-Thailand) | 2.82E-12 |
| Irrawaddy River (Irawadi, Central Myanmar Burma) | 1.63E-12 | San Francisco (a. Gila) (USA) | 5.40E-12 |
| Jong (Sierra Leone) | 3.25E-13 | San Juan (a. Colorado) (USA) | 4.96E-13 |
| Kabul (a. Indus) (Afghanistan-India) | 7.78E-13 | San Pédro (RCI) | 3.08E-13 |
| Kafue (a. Zambèze) (Zambia) | 1.25E-12 | San Tiguel (ou Miguel) San Salvador) | 2.49E-13 |
| Kalu Ganga (Sri Lanka) | 1.97E-13 | Sanaga (Cameroun) | 9.23E-13 |
| Kan (s.a. Bandama) (RCI) | 7.97E-13 | Sassandra (RCI) | 7.03E-13 |
| Kanawha river (a. Ohio) | 1.78E-13 | Savannah (USA) | 6.26E-13 |
| Kaoping River (Southern Taiwan) | 2.59E-13 | Scioto Brush Creek (a. Scioto) | 6.45E-11 |
| Kapuas (Bornéo) | 5.87E-13 | Scioto River (a. Ohio) | 4.14E-13 |
| Kasaï (a. Zaïre) (Zaïre-Angola) | 1.96E-12 | Senegal (Guinée-Sénégal) | 2.34E-12 |
| Kelani Ganga(Sri Lanka) | 2.22E-13 | Sepik-Ramu (Nlle-Guinée) | 3.12E-13 |
| Kinniconick River (a. Ohio) | 1.77E-10 | Sewa (Sierra Leone) | 3.14E-13 |
| Klamath (USA) | 4.11E-13 | Shire (a. Zambezi) (Malawi-Mozambique) | 1.29E-12 |
| Kogon (Guinea, West Africa) | 3.57E-13 | Sinnamary (Guyane) | 3.40E-13 |
| Kolenté (Guinée, Great Scarcies) | 2.99E-13 | Sokoto (a. Niger) (Nigeria) | 3.42E-13 |
| Konkouré (Guinea) | 4.09E-13 | St Joseph River (s.a. Wabash) | 2.52E-13 |
| Kourou (Guiana) | 1.62E-13 | St Paul (Liberia) | 4.97E-13 |
| Kribi ou Kienké (Cameroon) | 1.56E-13 | Strymon-Strouma (Greece-Bulgaria) | 6.04E-13 |
| Krishna (Karnataka, India) | 1.18E-12 | Sucio (a. Lempa) (San Salvador) | 3.36E-14 |

| Watershed | CF [species·yr/m$^3$] | Watershed | CF [species·yr/m$^3$] |
|---|---|---|---|
| Kura (Russia and Turkey) | 1.02E-12 | Surkhandarya ou Surchandarya (fSU) | 2.04E-13 |
| Kwando River (Southwest Africa/Namibia) | 8.92E-13 | Susquehanna (USA) | 6.30E-13 |
| Licking River (a. Ohio) | 7.15E-14 | Symmes River (a. Ohio) | 1.10E-13 |
| Lima (Portugal) | 1.68E-13 | Tana (Kenya) | 9.63E-13 |
| Limpopo (Botswana-Mozamb.-Rhodesia-RSA) | 2.52E-12 | Tano (West Africa) | 6.02E-13 |
| Little Miami River (a. Ohio) | 1.87E-13 | Tanshui (Northern Taiwan) | 5.25E-13 |
| Little Scarcies (West Africa) | 3.72E-13 | Tarim (China) | 1.99E-12 |
| Little Scioto river (a. Ohio) | 1.03E-13 | Tennessee River (a. Ohio) | 1.05E-12 |
| Little Wabash River (a. Wabash) | 3.36E-13 | Tibagi (Brazil) | 7.52E-13 |
| Lobé (Cameroon) | 1.25E-13 | Tigris (Southeast Turkey and Iraq) | 2.38E-12 |
| Loffa (Guinea-Liberia) | 4.62E-13 | Tominé ou Rio Corubal (Guinea-Guinea Bissau) | 6.05E-13 |
| Lokoundjé (Cameroon) | 2.90E-13 | Tsengwen River (Southwestern Taiwan) | 2.22E-13 |
| Madeira (a. Amazon) (Brazil-Bolivia) | 2.36E-12 | Tygart Creek (a. Ohio) | 4.08E-13 |
| Mae Khlong (Thailand) | 1.86E-13 | Ubangi (a. Zaïre) (Congo-RCA) | 2.37E-12 |
| Magdalena (Colombia) | 1.28E-12 | Uruguay (Brazil-Arg.-Uruguay) | 1.46E-12 |
| Mahaweli Ganga (Sri Lanka) | 5.19E-13 | Vakhsh ou Vachs (fSU) (a. Amu Darya) | 2.31E-12 |
| Mano (Liberia) | 3.80E-13 | Volta (Ghana-Burkina) | 1.59E-12 |
| Marahoué (a. Bandama) (RCI) | 3.37E-13 | Vouga (Portugal) | 2.47E-13 |
| Marañon (Peru) | 2.09E-12 | Wabash River (a. Ohio) | 8.05E-13 |
| Maroni (Guyana-Surinam) | 5.15E-13 | Wouri (Cameroon) | 2.08E-13 |
| Mekong (Asia Southeast, Int.) | 3.75E-12 | Xi Jiang River (Pearl River, Chu Chiang, Zhu, Southeast China) | 1.67E-12 |
| Minho (Portugal-Spain) | 4.80E-13 | Yangzi Jiang (Tibet-China) | 5.52E-12 |
| Mira (Portugal) | 2.86E-13 | Yani (s.a. Bandama) (RCI) | 2.11E-13 |
| Mississipi (USA) | 3.85E-12 | Yellow (Huang He, Huang Ho, China) | 4.84E-12 |
| Missouri (USA) | 3.85E-12 | Zaïre (Afr., Int.) | 3.62E-12 |
| Moa (Guinea-Sierra Leone) | 5.33E-13 | Zambezi (Mozambique-Zambia-Angola) | 2.89E-12 |

| Watershed | CF [species·yr/m$^3$] | Watershed | CF [species·yr/m$^3$] |
|---|---|---|---|
| Mobile (USA) | 8.28E-14 | Zeravshan (a. Syr Darya) (fSU) | 1.86E-12 |
| Mondego (Portugal) | 3.71E-13 | Zuni (s. a. Colorado) (a. Little Colorado) | 1.93E-13 |

# 22 S7. Supporting information on land use

*Table S7.1. Midpoint CFs for the impact of land transformation/occupation ($CF_{occ}$; based on data from De Baan et al. 2013), and land relaxation ($CFm_{relax}$) on specific species groups. The recovery times ($t_{rel}$) used in the calculation of $CFm_{relax}$ are collected from Curran et al. (2014).*

| | **$CFm_{occ}$ (annual crop eq)** | | | | **$t_{rel}$ (year)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *mammals* | | *birds* | | *insects* | | *invertebrates* | | *plants* | | *trees* | |
| *Land use type* | *mammals* | *birds* | *arthropods* | *vascular plants* | *forest* | *open* | *forest* | *Open* | *forest* | *open* | *forest* | *open* | *forest* | *open* | *forest* | *open* |
| Pasture and meadow | 0.55 | 0.33 | 0.42 | 0.18 | 69.4 | 7.2 | 68.6 | 6.3 | 69.2 | 7.0 | 79.5 | 8.0 | 73.5 | 7.3 | 102.2 | 10.4 |
| Annual crops | 0.75 | 0.88 | 1.08 | 0.70 | 69.4 | 7.2 | 68.6 | 6.3 | 69.2 | 7.0 | 79.5 | 8.0 | 73.5 | 7.3 | 102.2 | 10.4 |
| Permanent crops | 0.45 | 1.03 | 0.93 | 0.47 | 69.4 | 7.2 | 68.6 | 6.3 | 69.2 | 7.0 | 79.5 | 8.0 | 73.5 | 7.3 | 102.2 | 10.4 |
| Mosaic agriculture | -0.23 | 0.37 | 0.07 | 0.62 | 69.4 | 7.2 | 68.6 | 6.3 | 69.2 | 7.0 | 79.5 | 8.0 | 73.5 | 7.3 | 102.2 | 10.4 |
| Artificial areas | - | - | - | -0.70 | 69.4 | 7.2 | 68.6 | 6.3 | 69.2 | 7.0 | 79.5 | 8.0 | 73.5 | 7.3 | 102.2 | 10.4 |

| | ***CFm*$_{relax}$ (annual crop eq·yr)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *mammals* | | *birds* | | *insects* | | *invertebrates* | | *plants* | | *trees* | |
| *Land use type* | *forest* | *open* | *forest* | *open* | *forest* | *open* | *forest* | *open* | *forest* | *open* | *forest* | *open* |
| Pasture and meadow | 19.1 | 2.0 | 11.4 | 1.1 | 14.4 | 1.5 | 16.6 | 1.7 | 6.7 | 0.7 | 9.4 | 1.0 |
| Annual crops | 26.0 | 2.7 | 30.3 | 2.8 | 37.5 | 3.8 | 43.1 | 4.3 | 25.7 | 2.5 | 35.8 | 3.6 |
| Permanent crops | 15.6 | 1.6 | 35.5 | 3.3 | 32.3 | 3.3 | 37.1 | 3.7 | 17.2 | 1.7 | 23.8 | 2.4 |
| Mosaic agriculture | -8.1 | -0.8 | 12.6 | 1.2 | 2.3 | 0.2 | 2.7 | 0.3 | 22.7 | 2.2 | 31.5 | 3.2 |
| Artificial areas | - | - | - | - | - | - | - | - | -25.7 | 2.5 | -35.8 | -3.6 |

*Table S7.2. Relative species losses (Srel) due to land transformation/occupation provided by De Baan et al. (2013). Numbers presented here are total world averages. Biome or species group-specific Srel can be found in the original publication.*

| ***Land use type*** | $S_{rel}$ |
|---|---|
| Pasture and meadow | 0.33 |
| Annual crops | 0.60 |
| Permanent crops | 0.42 |
| Mosaic agriculture | 0.2 |
| Artificial areas | 0.44 |

*Table S7.3. Endpoint CFs for the impact of land occupation (CFeocc) and land relaxation (CFerelax) on total species richness.*

| ***Land use type*** | **$CFe_{occ}$ species·/$m^2$** | **$CFe_{relax}$ species·yr/$m^2$** |
|---|---|---|
| Used forest | 2.66E-09 | 4.52E-08 |
| Pasture and meadow | 4.88E-09 | 1.51E-07 |
| Annual crops | 8.88E-09 | 8.28E-08 |
| Permanent crops | 6.22E-09 | 1.05E-07 |
| Mosaic agriculture | 2.93E-09 | 4.97E-08 |
| Artificial areas | 6.48E-09 | 1.10E-07 |

## 22.1 Implementation of land use in Ecoinvent v3.

We recommend a procedure different from the one in the main text when using data from Ecoinvent.
Net transformation of natural land to anthropogenically used land constitutes one of the major drivers of species' extinctions. Newly transformed natural land constitutes an additional impact that should be taken into account in addition to the effects of land occupation, which cover the effect of not allowing land to return to a natural state for an extended period of time. Only natural land transformation is included here, land that is transformed from one type of anthropogenic use to another is not taken into account. Five types of natural land were identified in the Ecoinvent database (see Table S7.3). Transformation from this type of natural land constitutes an impact on the ecosystem while transformation to one of these land types has a benefit for the ecosystem (i.e. negative CFs). Note that transformation to primary forest is not possible. Characterization factors are derived as follows (equation 1):

$$CF_{trans,i} = 0.5 * CF_{occ,max} * T_{rec,i}$$

Whereby the CF of transformation of land type (in annual crop equivalents) i is calculated as a function of the maximum occupation CF (1 annual crop equivalent) and Trec,i is the recovery time of land type i (73.5 years for forest and 7.5 years for open land). The equation constitutes the area under the curve resulting from a linear transformation of anthropogenic land occupation back to a natural state. Transformation to any of the land types is calculated as the negative

equivalent of the CF for transformation to ensure that only the effects of net natural land transformation are included.

*Table S7.4. Midpoint CFs for transformation of natural land.*

| Name | Midpoint CF (annual crop equivalents·yr) |
|---|---|
| Transformation, from grassland, natural (non-use) | 3.75 |
| Transformation, from forest, primary (non-use) | 36.75 |
| Transformation, from forest, secondary (non-use) | 36.75 |
| Transformation, from shrub land, sclerophyllous | 3.75 |
| Transformation, from wetland, inland (non-use) | 3.75 |
| Transformation, to shrub land, sclerophyllous | -3.75 |
| Transformation, to forest, secondary (non-use) | -36.75 |
| Transformation, to wetland, inland (non-use) | -3.75 |
| Transformation, to grassland, natural (non-use) | -3.75 |

Because the midpoint indicators are expressed in the same units as the midpoints for land occupation, one can calculate the endpoint impact by multiplying by the same midpoint to endpoint factor.
Additionally, Ecoinvent distinguishes between 30 categories of land occupation in its inventory. We suggest that these different categories are matched to the CFs from ReCiPe as follows:

*Table S7.5. Matching of land occupation categories in Ecoinvent with ReCiPe.*

| Name in Ecoinvent | Name in ReCiPe |
|---|---|
| Occupation, pasture, man-made, intensive | pasture |
| Occupation, permanent crop, non-irrigated, intensive | permanent crops |
| Occupation, mineral extraction site | artificial area |
| Occupation, annual crop, greenhouse | artificial area |
| Occupation, permanent crop, irrigated, intensive | permanent crops |
| Occupation, industrial area | artificial area |
| Occupation, construction site | artificial area |
| Occupation, annual crop, non-irrigated, intensive | annual crops |
| Occupation, traffic area, road network | artificial area |
| Occupation, annual crop, irrigated, intensive | annual crops |
| Occupation, dump site | artificial area |
| Occupation, river, artificial | - |
| Occupation, annual crop | annual crops |
| Occupation, lake, artificial | - |
| Occupation, annual crop, non-irrigated, extensive | annual crops |
| Occupation, traffic area, rail/road embankment | artificial area |
| Occupation, pasture, man-made, extensive | pasture |
| Occupation, forest, extensive | managed forest |
| Occupation, forest, intensive | managed forest |
| Occupation, permanent crop | permanent crops |
| Occupation, traffic area, rail network | artificial area |
| Occupation, seabed, infrastructure | - |
| Occupation, seabed, drilling and mining | - |
| Occupation, annual crop, non-irrigated | annual crops |
| Occupation, shrub land, sclerophyllous | managed forest |
| Occupation, annual crop, irrigated | annual crops |
| Occupation, urban, discontinuously built | artificial area |
| Occupation, pasture, man-made | pasture |
| Occupation, grassland, natural (non-use) | - |
| Occupation, urban/industrial fallow (non-use) | artificial area |

# 23 S8. Supporting information on mineral resource scarcity

## 23.1 Data used to derive ASOPs

We used the data from Singer et al. (1993) on ore grades and ore produced for 50 different types of mineral deposits containing a total of 3,310 mines as the main basis to derive cumulative grade-tonnage relationships. If more recent datasets for specific mineral deposits were available, these were used instead of Singer et al. (1993). This was the case for carbonatite (Berger et al. 2009), for Ni-Co laterite (Berger et al. 2011), for porphyry copper (Singer et al. 2005), for sediment-hosted copper (Cox et al. 2007), for sediment-hosted zinc-lead (Singer et al. 2009), and for volcanogenic massive sulfide (Mosier et al. 2009). Mosier et al. 2009 replaced the data from Singer et al. (1993) for the deposit types besshi, cyprus massive sulphide and kuroko. For coverage of antimony and lithium, Berger (1993) for gold-antimony deposits and Rogers (1996) for lithium pegmatite deposits were used, respectively. The cumulative resource extracted up to now (CME) is calculated as the total production from Kelly and Matos (2014), which contains world mine production tonnage since 1900 for every resource under study, except for uranium. For uranium, data was retrieved from NEA-IAEA (2014).

Reserves were set equal to the global resource reserves as specified by the U.S. Geological Survey (2014), except for uranium and phosphorus. For uranium, the global reserves, following the same definition, were taken from Hall and Coleman (2012). For phosphorus, the same type of reserves estimate was retrieved from Van Vuuren et al. (2010). Schneider et al. (2015) estimated the ultimate recoverable resource (URR) for 20 metals, 12 of which are relevant for our study. URR data, following the same definition for the remaining metals covered in this study (gold, niobium, silver, tin, uranium), was taken from UNEP (2011). For phosphorus, the URR estimate used was 43.6 gigatons of phosphorus pentoxide (P2O5), which was the medium estimate reported by Van Vuuren et al. (2010).
See Table S8.1 for more details concerning the data used for deriving the SOPs.

*Table S8.1. Data used for deriving the SOPs (Vieira et al. 2016b).*

| | **Cumulative grade-tonnage regression parameters** | | | **Cumulative mineral resource extracted (CME in kg *x*)** | **Reserves (R in kg *x*)** | **Ultimate recoverable resource (URR in kg *x*)** |
|---|---|---|---|---|---|---|
| **Mineral resource** | **Scale $\alpha$** | **Shape β** | **$R^2$** | | | |
| Aluminium | -1.35 | 0.10 | 0.91 | 1.04E+12 | 1.48E+13 | 1.34E+16 |
| Antimony | -2.06 | 0.42 | 0.85 | 6.79E+09 | 1.80E+09 | 6.61E+10 |
| Chromium | -1.15 | 0.12 | 0.87 | 2.06E+11 | 1.48E+11 | 1.52E+13 |
| Cobalt | -4.86 | 0.17 | 0.95 | 2.28E+09 | 7.20E+09 | 2.86E+12 |
| Copper | -3.61 | 0.17 | 0.79 | 5.92E+11 | 6.90E+11 | 4.36E+12 |
| Gold | -11.9 | 0.20 | 0.86 | 1.44E+08 | 5.40E+07 | 7.20E+07 |
| Iron | -0.57 | 0.13 | 0.93 | 3.41E+13 | 8.10E+13 | 6.46E+15 |
| Lead | -2.61 | 0.21 | 0.85 | 2.35E+11 | 8.90E+10 | 2.81E+12 |
| Lithium | -4.95 | 0.11 | 0.72 | 9.81E+09 | 1.30E+10 | 3.47E+12 |
| Manganese | -1.19 | 0.08 | 0.77 | 5.80E+11 | 5.70E+11 | 1.27E+14 |
| Molybdenum | -6.34 | 0.27 | 0.94 | 6.62E+09 | 1.10E+10 | 1.82E+11 |
| Nickel | -4.26 | 0.16 | 0.93 | 5.53E+10 | 7.40E+10 | 7.76E+12 |
| Niobium | -4.39 | 0.27 | 0.70 | 1.07E+09 | 4.30E+09 | 4.80E+11 |
| Phosphorus | -2.14 | 0.10 | 0.93 | 9.78E+11 | 2.18E+12 | 1.90E+13 |
| Silver | -8.08 | 0.26 | 0.73 | 1.13E+09 | 5.20E+08 | 2.00E+10 |
| Tin | -4.95 | 0.21 | 0.79 | 2.00E+10 | 4.70E+09 | 2.20E+11 |
| Uranium | -5.54 | 0.50 | 0.86 | 2.71E+09 | 2.52E+09 | 4.30E+11 |
| Zinc | -1.62 | 0.15 | 0.70 | 4.58E+11 | 2.50E+11 | 1.11E+13 |

## 23.2 Data used to derive midpoint to endpoint factors

The Absolute Surplus Cost Potential (ASCP) of mineral resource x was calculated in Vieira et al. (2016a) by:

$$\mathrm{ASCP}_x = \frac{\int_{\mathrm{CME}_x}^{\mathrm{MME}_x} (\Delta \mathrm{C}_x)\, d\mathrm{ME}_x}{\mathrm{R}_x}$$

whereby $C_x$ (USD) is the operating cost determined via the log-logistic cumulative cost-tonnage curve of mineral resource *x* for an amount extracted of that mineral resource $ME_x$ (kg x), $R_x$ (kg x) is the reserve of mineral resource *x*, defined as the difference between the current cumulative tonnage of mineral resource x extracted ($CME_x$) and the maximum tonnage of mineral resource *x* extracted ($MME_x$).
The cumulative cost-tonnage curve for mineral resource x was derived following the principle that mining sites with lower costs are the first to be explored, copper mines producing a certain mineral resource were sorted by increasing order of costs per mineral resource extracted. A log-logistic distribution was fitted on the inverse of operating costs per mineral resource extracted and the cumulative mineral resource extracted to account for the skewness in the data points by Vieira et al. (2016a):

$$\frac{1}{\mathrm{C}_x} = \exp(\alpha_x) \cdot \exp\left(\beta_x \cdot \ln\left(\frac{\mathrm{MME}_x - \mathrm{CME}_x}{\mathrm{CME}_x}\right)\right)$$

whereby α_x is the location parameter and β_x is the scale parameter of the log-logistic cost distribution for mineral resource *x*. See example of cumulative cost-tonnage curve for copper in Figure S8.1.

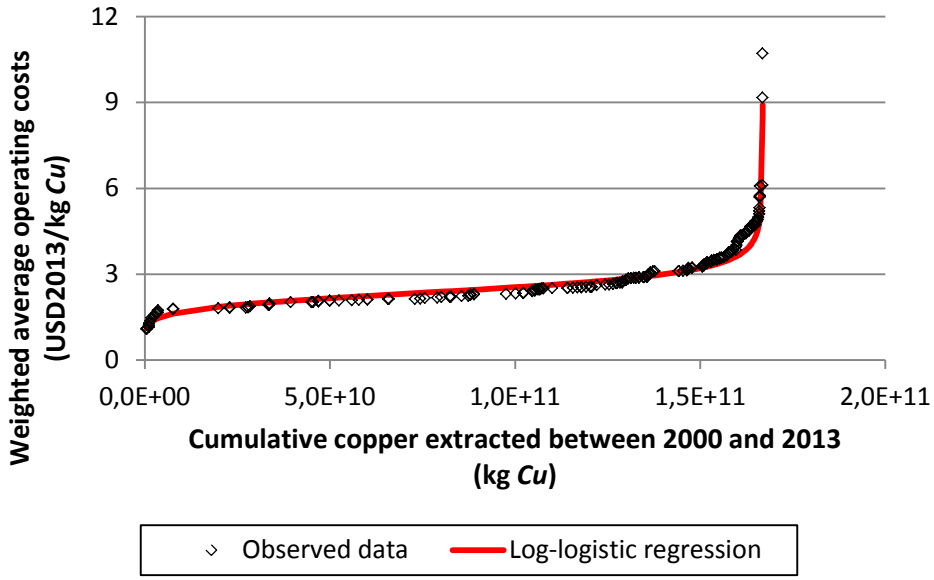


*Figure S8.1. Cumulative cost-tonnage relationship for copper plotted using a log-logistic regression (in logarithmic scale).*

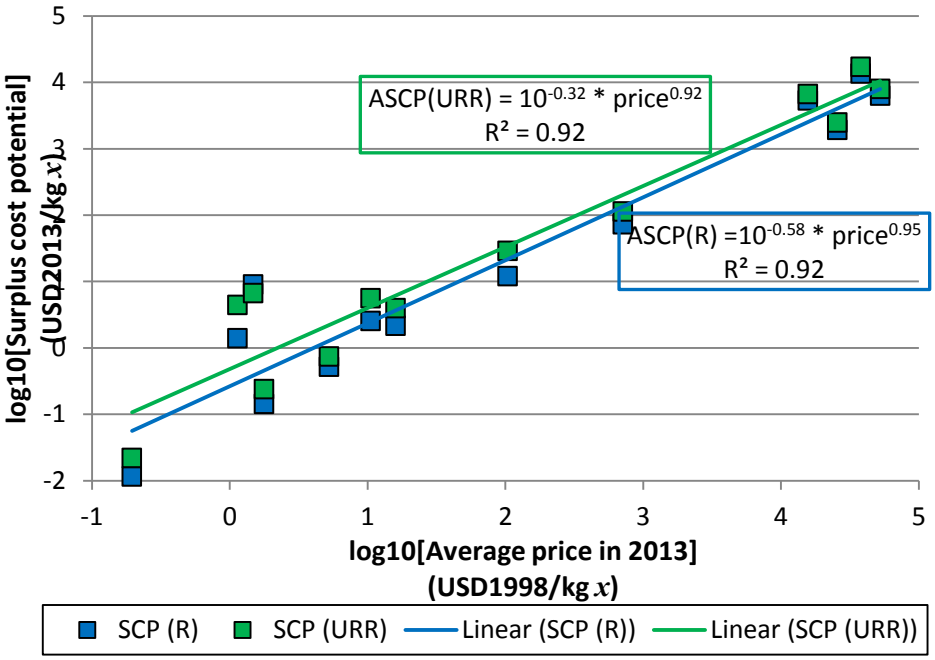


*Figure S8.2. Relationship between average price in 2013 (USD1998/kg x) and absolute surplus cost potential (USD2013/kg x).*

# 24 S9. Supporting information on fossil resource extraction

## 24.1 Data used to derive FFPs

*Table S9.1. Data used for deriving the FFPs (Jungbluth and Frischknecht 2010).*

| Name | Unit | Higher heating value (HHV) |
|---|---|---|
| Brown coal | MJ-eq/kg | 9.9 |
| Crude oil | MJ-eq/kg | 45.8 |
| Hard coal | MJ-eq/kg | 19.1 |
| Natural gas | MJ-eq/$Nm^3$ | 38.3 |
| Peat | MJ-eq/kg | 9.9 |

## 24.2 Data used to derive SCPs

The data used to derive the cost-cumulative production relationships for crude oil, natural gas and hard coal were retrieved from the International Energy Agency (2013). For crude oil and natural gas, the data include the costs and quantity of resources already produced, as well as estimates of the future quantity and the production costs per production technique, e.g. conventional oil or oil in ultra-deep water. For hard coal, a production-cost curve is provided for global hard coal reserves up to 2011 and for export-oriented thermal coal on a free-on-board (FOB) basis (International Energy Agency, 2013). The future production value used is the largest future production value reported in International Energy Agency (2013). In Table S9.2 the cumulative cost-tonnage equation parameters a and b for each fossil resource and the reserves can be found.

*Table S9.2. Data used for deriving the SCPs (Vieira and Huijbregts, in prep.)*

| | **Cumulative cost-tonnage regression parameters** | | **Surplus cost potential** | | |
|---|---|---|---|---|---|
| **Fossil resource** | **Intercept *a*** | **Slope *b*** | **Cum. fossil extracted (CFE in kg or $Nm^3$ *x*)** | **Current cost (C in USD2008/kg or Nm3 *x*)** | **Reserves (R in kg or $Nm^3$ *x*)** |
| Crude oil | 40.0 | -4.45 | 1.61E+14 | 7.33E-02 | 8.05E+14 |
| Hard coal | 36.6 | -5.19 | n.a. | 2.85E-02 | 7.19E+14 |
| Natural gas | 23.2 | -2.42 | 1.01E+14 | 6.85E-03 | 7.99E+14 |

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