1. Overall framework

Francesca Verones[1,2], Stefanie Hellweg[3], Mark A.J. Huijbregts[1]*

[1] Department of Environmental Science, Radboud University Nijmegen, The Netherlands

[2] Industrial Ecology Programme and Department of Energy and Process Engineering, NTNU, Trondheim, Norway

[3] Institute for Environmental Engineering, ETH Zürich, Zurich, Switzerland

*francesca.verones@ntnu.no

1.1. Introduction

1.1.1. General background

Life Cycle Assessment (LCA) is a methodology for assessing the environmental impacts of a product or a service throughout its whole life cycle. In general LCA consists of four phases (ISO 2006b), as shown in Figure 1.1. In the first phase an explicit goal is defined, including the definition of a functional unit for which the LCA is performed. The boundaries of the investigated system are set, the required impact categories chosen and assumptions and limitations identified. During the inventory analysis the materials and inputs required, as well as emissions and outputs created during the complete life cycle are collected. The third step is the Life Cycle Impact Assessment (LCIA) that aims at quantifying the potential environmental impacts and their significance, based on the life cycle inventory (LCI) results. Within the impact assessment characterization models, such as the ones presented here for the LC-IMPACT methodology, are applied. The characterization factors developed in these models indicate the environmental impact per unit of stressor (e.g. per kg of resource used or emission released). In order to make impacts comparable, results are calculated in equivalence units, such as for example DALYs – disability adjusted life years for human health impacts or PDFs – potentially disappeared fractions of species for ecosystem quality.

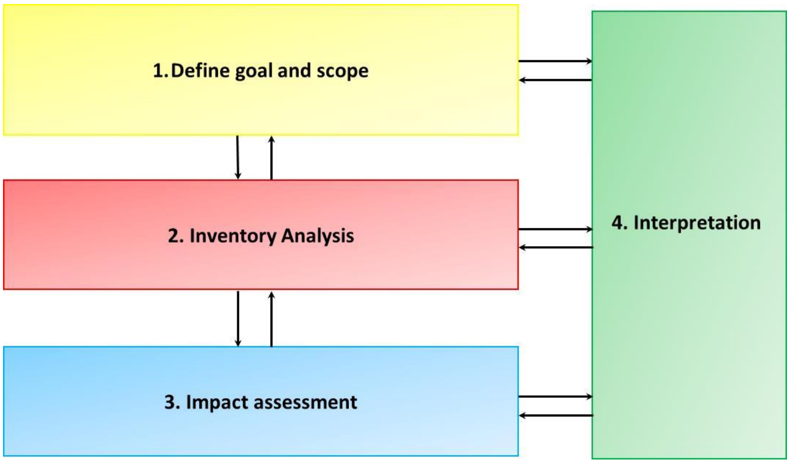

Figure 1.1: The four phases of performing an LCA according to ISO (ISO 2006a; ISO 2006b).

Optionally, normalization can be performed. Normalization factors are relating the characterised results of each impact category to a certain reference situation (e.g. global water consumption in the year 2010), thus introducing an adequate context. Typically, reference situations are chosen at the global level since the analysed product system often stretches the entire world. In doing this, normalisation provides the relative contribution of a certain product to the chosen reference situation, thus facilitating interpretation (Wegener Sleswijk et al. 2008).

1.1.2. Aim

The development and refinement of LCIA methodologies has made large progress during the last couple of years, incorporating new impact pathways (e.g. water use) and including spatial differentiation if relevant. The LC-IMPACT methodology is at the forefront of these developments and aims to provide a “living” life cycle impact assessment methodology, which aims to be regularly updated to include the most important developments in LCIA. In particular, LC-IMPACT aims to have global coverage for the three main areas of protection (humans, ecosystems, resources), including spatially differentiated information where appropriate.

Innovations include:

- Spatial resolution of CF according to the nature of impact (where possible) as well as spatially aggregated CF on country and global level, to facilitate coupling with LCI
- A new approach for assessing impacts to ecosystems, assessing global extinctions. This approach is more relevant and consistent than previous approaches, which mixed scales of extinctions.
- Explicit documentation of value judgments
- Explicit documentation of type of approach (marginal and/or average/linear)
- Quantitative uncertainty assessments for selected impact categories and qualitative discussion of uncertainties for all impact categories.

Normalization factors are also made available along with characterization factors.

The influence of value choices were quantified. Value choices are related to the level of robustness, temporal system boundary or level of inclusion of impacts. This includes the separation of results between short-term and long-term impacts as well as including only certain impacts or “all impacts”. This explicit distinction between up to four sets of factors allows the practitioner to make an informed and transparent choice (further explanation below).

Currently, only results on an endpoint level will be made available for the impact categories. Harmonized and common midpoint indicators, as well as additional impact categories are planned to be added in the future.

The main work of this harmonized methodology results from the outcomes of the FP7-funded project LC-IMPACT (http://www.lc-impact.eu). After this framework chapter, individual chapters for all the impact categories follow. 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.

1.2. Areas of protection and overview of impact categories

Human health, ecosystem quality and abiotic resources are commonly used in life cycle impact assessment (LCIA) methodologies (Goedkoop 2000; Goedkoop et al. 2009) as the three areas of protection. It was decided to keep the same broad, three areas of protection for the implementation of the LC-IMPACT methodology.

The overview of the link between the impact categories and the three areas of protection is shown in Figure 1.2. The category "ecosystem quality" covers the terrestrial, aquatic and marine environments. We recommend to keep the three ecosystem types separate for communication, as there is no generally agreed upon weighting mechanism to sum impacts across different ecosystem types.

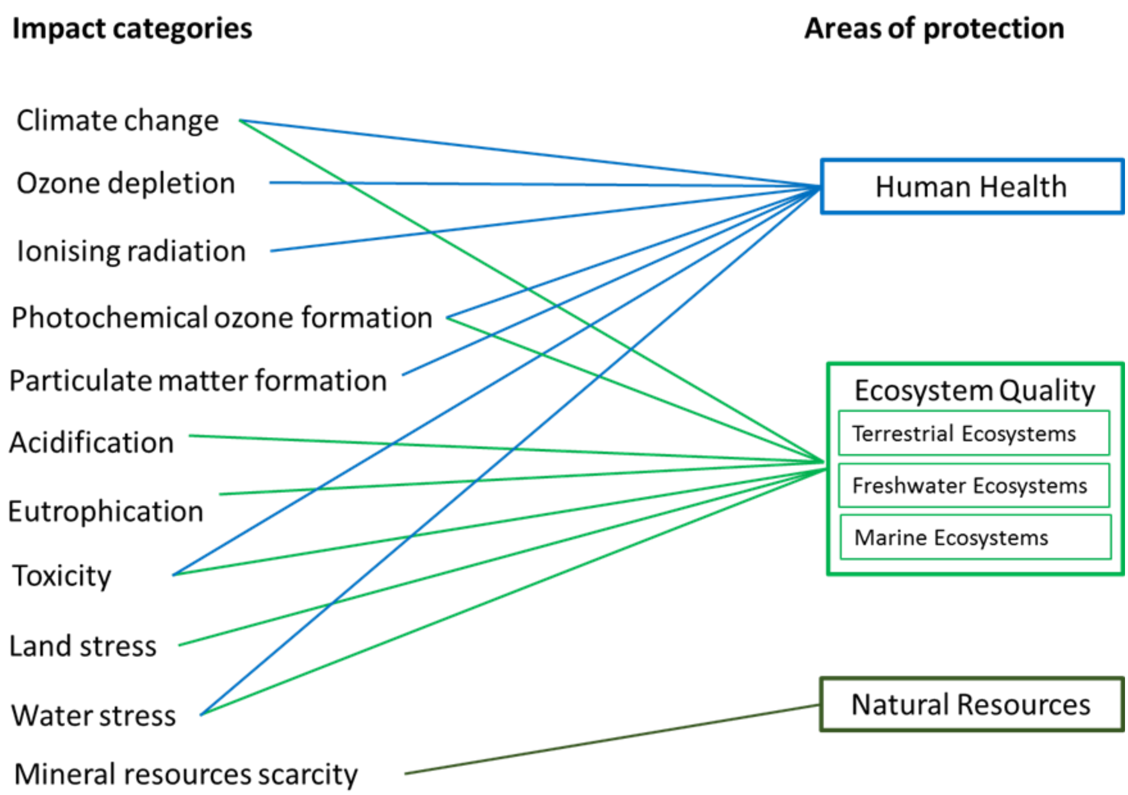

Figure 1.2: Overview of the environmental mechanisms that are covered in the LC-IMPACT methodology and their relation to the areas of protection. Note that "ecosystem quality" covers terrestrial, freshwater and marine ecosystems, thus multiple environmental compartments may be impacted (e.g. terrestrial and freshwater ecotoxicity)

The endpoints are related to the three areas of protection (see Table 1.1). Two basic equations for calculating endpoint characterization factors (CFs) are shown below. Equation 1.1 shows the basic CF for human health, with intake fraction iF, exposure factor XF, effect factor EF and damage factor DF. The intake fraction is a measure for the fate and exposure of people to a certain substance, the effect factor quantifies the effect of a certain substance on human health, while the damage factor is a measure for the severity of an impact on human health.

$$CF_{human} = iF \cdot XF \cdot EF \cdot DF$$

Equation 1.1

$$CF_{ecosystem\ quality} = FF \cdot XF \cdot EF \cdot VS$$

Equation 1.2 reflects the basic CF equation for ecosystems. Relative global species loss per unit of emission or extraction was calculated by the product of a vulnerability score VS, an exposure factor, as well as a fate factor FF and an effect factor EF. The exposure factor is omitted in some impact categories, as it is 1 (e.g. in land stress).

$$CF_{ecosystem\ quality} = FF \cdot XF \cdot EF \cdot VS$$

Equation 1.2

What is special in LC-IMPACT compared to other LCIA methods is that the CF quantifies the relative global species loss by putting the regional species loss in perspective of the global species pool. This is done for one or more taxa (fish, mammals, birds, amphibians, reptiles, and/or plants), depending on the data availability per impact category. For water and land use we follow the proposed approach in Verones et al. (2017) and modified the approach, depending on data availability for the other impact categories (see individual chapters for details). The VS varies between 0 and 1. A VS of 1 means that the species is highly threatened or probably endemic, while lower scores denote less vulnerable species (see also Verones et al. (2015)). We tested the differences between factors including a vulnerability score and those that do not include a vulnerability score, in order to avoid any bias. For land use, the ratio between the median aggregated regional and global CF is by definition 1 (see Chapter 11 on Land stress). Thus, we do not introduce a bias with the vulnerability scores.

Although it has been argued that mineral resources are available in almost infinite amounts in the earth crust, the actual availability of a mineral primarily depends on ore grades (Gerst 2008). When a mineral is extracted, the overall ore grade of that mineral declines (Prior et al. 2012). The lower the ore grade, the larger the amount of ore that is produced for extracting the same amount of mineral. According to Prior et al. (2012), ore grade decline can be used as an indicator for a range of societal impacts. For instance, larger amounts of ore produced for the same unit of mineral output, implies more waste (waste rock, tailings) to be handled. This is the mechanism that is captured in the area of protection 'Resources' for mineral resources as a means of extra future effort for resource extraction. The unit of the resource scarcity indicator is the extra amount of ore produced per unit of mineral extracted, averaged over the mining of the full mineral reserve that is currently available (see Figure 1.3 for illustration). Reserves are defined as economically proven reserves for the $CF_{certain\ effects}$ and ultimately extractable reserves for the $CF_{all\ effects}$.

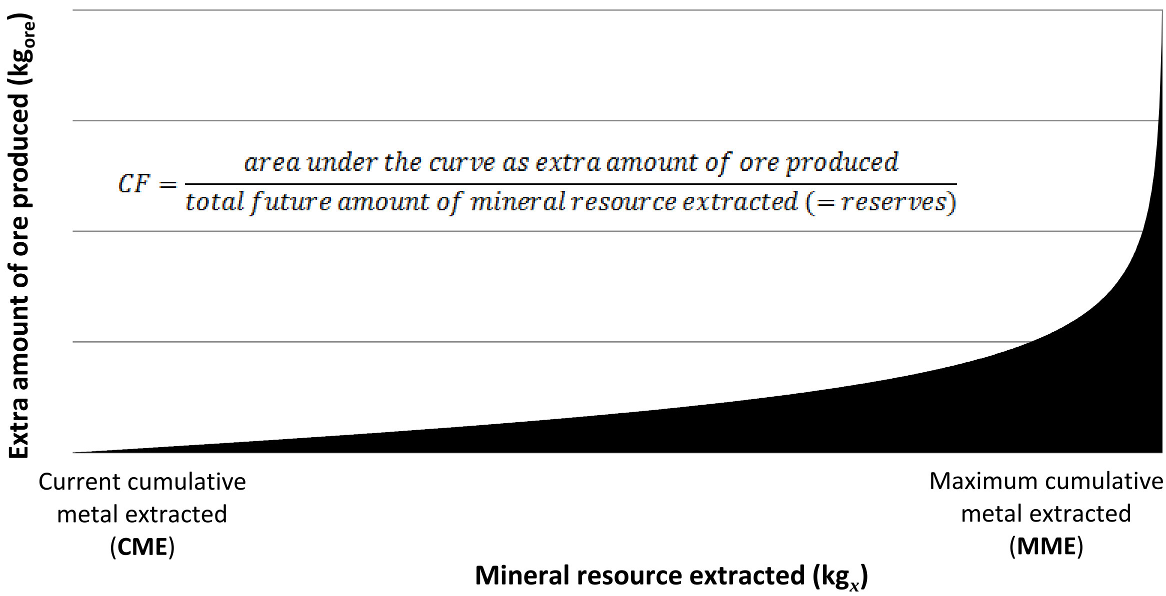

Figure 1.3: Illustrative example for the calculation of characterization factors for mineral resource scarcity.

Table 1.1: Overview of the areas of protection and respective endpoint units. DALY stands for disability adjusted life years and PDF stands for potentially disappeared fraction of species. kg_{ore} stands for the extra average amount of ore to be produced.

Area of protection	abbreviation	endpoint unit
damage to human health	HH	DALY
damage to ecosystem quality	EQ	PDF
damage to abiotic resources	R	kg_{ore}

DALYs (disability adjusted life years) represent the years that are lost or that a person is disabled for due to a disease or accident. DALYs are typically based on health statistics from the World Health Organization on the global burden of disease (for example, WHO (2014)).

The unit for ecosystem quality is a global fraction of potentially disappeared species (PDF). Although this unit sounds similar to previous LCIA approaches, the underlying concept of how to arrive at these fractions differs from previous methodologies. Instead of local losses based on locally present species, losses of species are considered in relation to the globally present species, leading to a globally normalized PDF of species.

The unit for resource is the surplus ore potential, i.e. kilogram of ore ($kg_{ore}/kg_{mineral}$) which represents the extra average amount of ore produced as a result of mineral resource extraction.

PDF and DALY are no standard units, a DALY basically being a year and a PDF being a fraction. The reason why the results are still presented including the DALY (instead of just year) or PDF (instead of nothing) notation is to clarify the targeted endpoint.

1.3. Linear/average vs. marginal approach

There are different possible approaches for calculating effect factors, namely marginal, and average/linear (see also Figure 1.4). According to the marginal approach, the influence of raising the background concentration/pressure by an incremental amount is investigated. This means that the reference state is today's situation or the current background concentration and the additional impact of a marginal change is quantified. By contrast, in the case of average modeling, rather than taking the derivative of the curve at the point of current level of impact, the average effect change per unit of change is used. The reference state is the current situation, relating the change either to a zero effect, a preferred state (e.g. environmental targets) or a prospective future state. The main difference between linear and average is that for an average approach the background level is known (highlighted with an asterisk in Table 1.2), while it is assumed to be 0.5 for the linear approach due to the absence of information on background pollution levels.

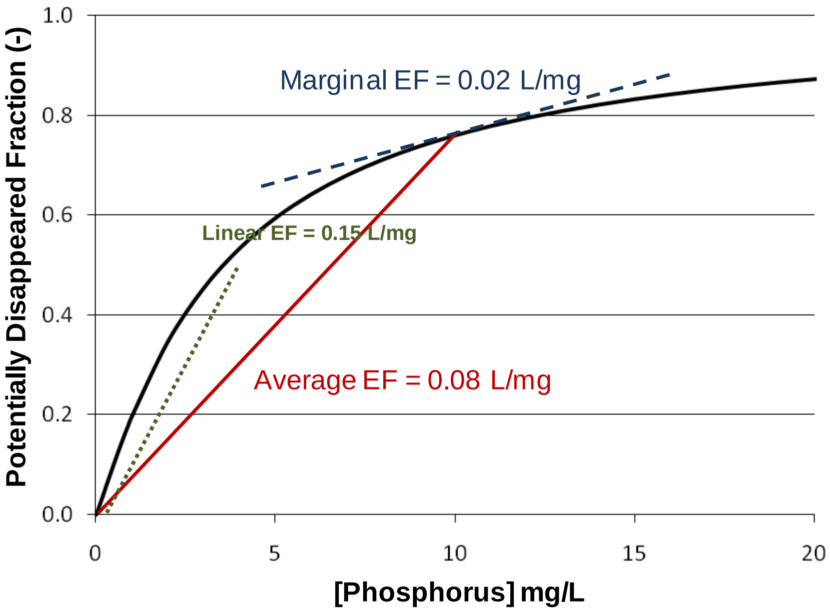

Figure 1.4: Derivation of effect factors (EF) following a linear approach, marginal approach and an average approach, for the impact of total phosphorus concentrations on freshwater macro-invertebrate diversity with a logistic response curve PDF = 1/(1+4.07·Cp-1.11) and working point of 10 mg/l (Huijbregts et al. 2011).

Different environmental mechanisms work with different approaches for calculating the required factors. If possible, more than one approach is used, in order to provide different factors. An overview of the approaches covered by environmental mechanism is given in Table 1.2. Table 1.3 shows that for various impact categories different approaches were chosen. This is not different from previous methods, but in contrast to other LCIA method, here we make the approach explicit so that the practitioner can consciously decide on which one to use. Depending on the scope of the study the practitioner may choose either marginal or linear/average values (if both are available). It is recommended to use, if possible, consistent sets of factors (e.g. either all marginal or all linear/average).

Table 1.2: Overview of approaches covered by each environmental mechanism. An asterisk indicates that the background level is known (average approach).

Environmental mechanism	marginal	average/linear
climate change	✓	✓*
stratospheric ozone depletion		✓
ionising radiation		✓
photochemical ozone formation		✓*
particular matter formation		✓
terrestrial acidification	✓	
freshwater eutrophication		✓
marine eutrophication		✓
freshwater ecotoxicity		✓
human toxicity (carcinogenic)		✓
human toxicity (non-carcinogenic)		✓
marine ecotoxicity		✓
terrestrial ecotoxicity		✓
land stress	✓	✓*
water stress (ecosystems)	✓	
water stress (human health)	✓	✓*
mineral resources extraction		✓

The different approaches have different strengths for applications. Approaches with marginal changes quantify the impact of small changes in emissions or resource uses (as stated in Huijbregts et al. (2011): "*what do we add in terms of environmental impact with the consumption of one liter of coffee?*"). However, if there are already high environmental impacts, the marginal impact may decrease and in extreme cases become zero, implying that if environmental impacts are already substantial, additional impacts are of no consequence. Average approaches, on the other hand, assess the impacts of larger changes than just marginal ones. Therefore, this type of approach potentially also opens a further field of application of life cycle impact assessment methods such as LC-IMPACT, by connecting it to the macro-scale assessments of input-output models. Input-output models quantify accurately what the resource use or footprint of a consumer is, but hardly ever attempt to quantify the environmental consequences related to this resource use. LC-IMPACT, as a spatially differentiated impact assessment method can potentially contribute to such an assessment.

1.4. Value choices

Important binary choices are the differentiation between low and high levels of robustness. Binary choices between the level of robustness can be related either (1) to the fact that it can be highly uncertain whether a specific effect is caused by the interventions that belong to an impact category (e.g. cataract for ozone depletion) and (2) to the timing of the impact (long-term or short-term effects), represented by the time horizon. In general, the further away in time the impact is, the more uncertain, i.e. the lower the level of robustness.

In contrast to the cultural perspectives (individualist, hierarchist and egalitarian) that are commonly used in LCA (e.g. Goedkoop et al. (2009)), we follow another approach here. Instead, the characterization factor is built in a modular way that allows the user to add or neglect impacts that are farther away (in a time perspective) and less certainly caused by a specific impact category. We therefore provide the user with four sets of CFs:

1) <u>all impacts, 100 years</u>: short (100 years) time horizon and high level of certainty for impact of a specific intervention,

2) <u>all impacts, long-term</u>: long time horizon and high level of certainty for impact of a specific intervention,

3) <u>certain impacts, 100 years</u>: short (100 years) time horizon and low level of certainty for impact of a specific intervention,

4) <u>certain impacts, long-term</u>: long time horizon and low level of certainty for impact of a specific intervention.

We recommend users to always calculate results with all sets of characterization factors, in order to understand the full extent and nature of the potential impacts.

Table 1.3 gives an overview of the value choices with low and high level of robustness for each environmental mechanism. Please note that these binary choices, in order to in- or exclude certain parts of a characterization factor do not reflect statistical uncertainty or confidence intervals.

Table 1.3: Overview of choices per impact category. Note that the time horizon for terrestrial acidification and mineral resources can be relevant (van Zelm et al. 2007; Vieira et al. 2012) but cannot be considered due to insufficient data (Verones et al. submitted).

Impact category	all impacts, long-term	all impacts, 100 years	certain impacts, long-term	certain impacts, 100 yrs
climate change (human health)	**Time horizon:** 1000 yrs **Included effects:** diarrhoea, malaria, coastal flooding, malnutrition, cardiovascular diseases, inland flooding	**Time horizon:** 100 yrs **Included effects:** diarrhoea, malaria, coastal flooding, malnutrition, cardiovascular diseases, inland flooding	**Time horizon:** 1000 yrs **Included effects:** diarrhoea, malaria, coastal flooding	**Time horizon:** 100 yrs **Included effects:** diarrhoea, malaria, coastal flooding
climate change (terrestrial ecosystems)	**Time horizon:** 1000 yrs **Included effects:** all species included	**Time horizon:** 100 yrs **Included effects:** all species included	**Time horizon:** 1000 yrs **Included effects:** all species included	**Time horizon:** 100 yrs **Included effects:** all species included
climate change (freshwater ecosystems)	**Time horizon:** 1000 yrs **Included effects:** impacts on fish below 42° latitude	**Time horizon:** 100 yrs **Included effects:** impacts on fish below 42° latitude	**Time horizon:** - **Included effects:** not considered due to uncertainty	**Time horizon:** - **Included effects:** not considered due to uncertainty
stratospheric ozone depletion	**Time horizon:** infinite **Included effects:** cataract, skin cancer	**Time horizon:** 100 yrs **Included effects:** cataract, skin cancer	**Time horizon:** infinite **Included effects:** skin cancer	**Time horizon:** 100 yrs **Included effects:** skin cancer
ionising radiation	**Time horizon:** 100,000 yrs **Included effects:** Cancers: Thyroid, bone marrow, lung, breast, bladder, colon, ovary, skin, liver, oesophagus, stomach, bone surface and remaining cancer. Hereditary disease	**Time horizon:** 100 yrs **Included effects:** Cancers: Thyroid, bone marrow, lung, breast, bladder, colon, ovary, skin, liver, oesophagus, stomach, bone surface and remaining cancer. Hereditary disease	**Time horizon:** 100,000 yrs **Included effects:** Cancers: Thyroid, bone marrow, lung and breast. Hereditary disease	**Time horizon:** 100 yrs **Included effects:** Cancers: Thyroid, bone marrow, lung and breast. Hereditary disease
photochemical ozone formation (human health)	**Time horizon:** not relevant **Included effects:** respiratory mortality	**Time horizon:** not relevant **Included effects:** respiratory mortality	**Time horizon:** not relevant **Included effects:** respiratory mortality	**Time horizon:** not relevant **Included effects:** respiratory mortality
photochemical ozone formation (terrestrial ecosystems)	**Time horizon:** not relevant **Included effects:** loss of productivity for forest and grassland plant species	**Time horizon:** not relevant **Included effects:** loss of productivity for forest and grassland plant species	**Time horizon:** not relevant **Included effects:** loss of productivity for forest and grassland plant species	**Time horizon:** not relevant **Included effects:** loss of productivity for forest and grassland plant species
particulate matter formation	**Time horizon:** not relevant **Included effects:** cardiopulmonary and lung cancer mortality due toprimary PM2.5 and secondary aerosols from SO2, NH3 and NOx	**Time horizon:** not relevant **Included effects:** cardiopulmonary and lung cancer mortality due toprimary PM2.5 and secondary aerosols from SO2, NH3 and NOx	**Time horizon:** not relevant **Included effects:** cardiopulmonary and lung cancer mortality due to primary PM2.5	**Time horizon:** not relevant **Included effects:** cardiopulmonary and lung cancer mortality due to primary PM2.5
terrestrial acidification	**Time horizon:** not relevant **Included effects:** reduction of plant species richness due to	**Time horizon:** not relevant **Included effects:** reduction of plant species richness due	**Time horizon:** not relevant **Included effects:** reduction of plant species richness due to	**Time horizon:** not relevant **Included effects:** reduction of plant species richness

	N and S emissions to air	to N and S emissions to air	N and S emissions to air	due to N and S emissions to air
freshwater eutrophication	**Time horizon:** not relevant **Included effects:** reduction of fish species richness due to P emissions to water	**Time horizon:** not relevant **Included effects:** reduction of fish species richness due to P emissions to water	**Time horizon:** not relevant **Included effects:** reduction of fish species richness due to P emissions to water	**Time horizon:** not relevant **Included effects:** reduction of fish species richness due to P emissions to water
marine eutrophication	**Time horizon:** not relevant **Included effects:** hypoxia-driven reduction of marine animal species richness due to dissolved inorganic nitrogen (DIN) emissions	**Time horizon:** not relevant **Included effects:** hypoxia-driven reduction of marine animal species richness due to dissolved inorganic nitrogen (DIN) emissions	**Time horizon:** not relevant **Included effects:** hypoxia-driven reduction of marine animal species richness due to dissolved inorganic nitrogen (DIN) emissions	**Time horizon:** not relevant **Included effects:** hypoxia-driven reduction of marine animal species richness due to dissolved inorganic nitrogen (DIN) emissions
human toxicity (carcinogenic)	**Time horizon:** infinite **Included effects:** via inhalation and ingestion exposure, all potentially carcinogenic substances from IARC	**Time horizon:** 100 yrs (relevant for metals) **Included effects:** via inhalation and ingestion exposure, all potentially carcinogenic substances from IARC	**Time horizon:** infinite **Included effects:** via inhalation and ingestion exposure, only substances with strong evidence for carcinogenicity (IARC-category 1, 2A and 2B)	**Time horizon:** 100 yrs (relevant for metals) **Included effects:** via inhalation and ingestion exposure, only substances with strong evidence for carcinogenicity (IARC-category 1, 2A and 2B)
human toxicity (non-carcinogenic)	**Time horizon:** infinite **Included effects:** via inhalation and ingestion exposure	**Time horizon:** 100 yrs (relevant for metals) **Included effects:** via inhalation and ingestion exposure	**Time horizon:** infinite **Included effects:** via inhalation and ingestion exposure	**Time horizon:** 100 yrs (relevant for metals) **Included effects:** via inhalation and ingestion exposure
freshwater ecotoxicity	**Time horizon:** infinite **Included effects:** affected fractions via exposure to toxic chemicals in freshwater	**Time horizon:** 100 yrs (relevant for metals) **Included effects:** affected fractions via exposure to toxic chemicals in freshwater	**Time horizon:** infinite **Included effects:** affected fractions via exposure to toxic chemicals in freshwater	**Time horizon:** 100 yrs (relevant for metals) **Included effects:** affected fractions via exposure to toxic chemicals in freshwater
marine ecotoxicity	**Time horizon:** infinite **Included effects:** affected fractions via exposure to toxic chemicals in seawater	**Time horizon:** 100 yrs (relevant for metals) **Included effects:** affected fractions via exposure to toxic chemicals in seawater	**Time horizon:** infinite **Included effects:** affected fractions via exposure to toxic chemicals in seawater	**Time horizon:** 100 yrs (relevant for metals) **Included effects:** affected fractions via exposure to toxic chemicals in seawater
terrestrial ecotoxicity	**Time horizon:** infinite **Included effects:** affected fractions via exposure to toxic chemicals in soil	**Time horizon:** 100 yrs (relevant for metals) **Included effects:** affected fractions via exposure to toxic chemicals in soil	**Time horizon:** infinite **Included effects:** affected fractions via exposure to toxic chemicals in soil	**Time horizon:** 100 yrs (relevant for metals) **Included effects:** affected fractions via exposure to toxic chemicals in soil
land stress (occupation)	**Time horizon:** not relevant	**Time horizon:** not relevant	**Time horizon:** not relevant	**Time horizon:** not relevant

	Included effects: occupation of 6 land use types	**Included effects:** occupation of 6 land use types	**Included effects:** occupation of 6 land use types	**Included effects:** occupation of 6 land use types
land stress (transformation)	**Time horizon:** total recovery times (up to 1200 yrs, depending on ecosystem) **Included effects:** transformation of 6 land use types	**Time horizon:** 100 yrs **Included effects:** transformation of 6 land use types	**Time horizon:** total recovery times (up to 1200 yrs, depending on ecosystem) **Included effects:** transformation of 6 land use types	**Time horizon:** 100 yrs **Included effects:** transformation of 6 land use types
water stress (ecosystems)	**Time horizon:** not relevant **Included effects:** surface water and groundwater consumption impacts on wetlands	**Time horizon:** not relevant **Included effects:** surface water and groundwater consumption impacts on wetlands	**Time horizon:** not relevant **Included effects:** only surface water consumption impacts on wetlands	**Time horizon:** not relevant **Included effects:** only surface water consumption impacts on wetlands
water stress (human health)	**Time horizon:** not relevant **Included effects:** Malnutrition	**Time horizon:** not relevant **Included effects:** Malnutrition	**Time horizon:** not relevant **Included effects:** Malnutrition	**Time horizon:** not relevant **Included effects:** Malnutrition
mineral resources extraction	**Time horizon:** not used **Included effects:** uses ‘ultimately extractable reserves’	**Time horizon:** not used **Included effects:** uses (economic) ‘reserves’	**Time horizon:** not used **Included effects:** uses ‘ultimately extractable reserves’	**Time horizon:** not used **Included effects:** uses (economic) ‘reserves’

1.5. Spatial variability

1.5.1. Level of spatial resolution

The level of spatial detail is varying greatly between the different impact categories, as is shown in Table 1.4. Some categories, for example climate change do not need spatial detail in the application of the characterization factors, since the damages are spreading on a global level. Others, for example water stress, have very local and specific impacts and incorporating spatial details in the methodological development is thus a large benefit. The approach for including spatial variability is, wherever possible, reflecting the nature and spatial extent of impact. However, for some impact categories it was data driven (Table 1.4). We include spatial variability, as soon as information is available and adapt the spatial resolution on which the final characterization factors are provided to the resolution of the available data.

Table 1.4: Spatial resolution for the different parts of the environmental mechanisms.

environmental mechanism	Spatial resolution fate factor	Spatial resolution effect factor	Spatial resolution characterization factor
climate change (ecosystems)	none	none	none
climate change (human health)	none	none	none
stratospheric ozone depletion	none	none	none
ionising radiation	global values for air, freshwater, marine	none	global values for air, freshwater, marine
photochemical ozone depletion (ecosystems)	56 world regions (averages of base run of 1°x1°)	none	country level
photochemical ozone depletion (human health)	56 world regions (averages of base run of 1°x1°)	none	country level
particular matter formation	56 world regions (averages of base run of 1°x1°)	none	country level

terrestrial acidification	615'888 three dimensional compartments	2° x 2.5°	2° x 2.5°
freshwater eutrophication	0.5° x 0.5°	biogeographical habitats	0.5° x 0.5°
marine eutrophication	Country to large marine ecosystems (233 spatial units)	66 large marine ecosystems (5 climate zones)	Country to large marine ecosystems (233 spatial units)
freshwater ecotoxicity			sub-continental
human toxicity			sub-continental
marine ecotoxicity			sub-continental
terrestrial ecotoxicity			sub-continental
land stress	ecoregions	ecoregions	ecoregions
water stress (ecosystems)	more than 20'000 individual points	more than 20'000 individual points	0.05° x 0.05°
water stress (human health)	watersheds (11'000 units)	country level	watersheds (11'000 units)
mineral resources extraction	none		none

1.5.2. Ecosystem impacts: Procedures for maps of taxonomic classes

Maps with number of species present and, if possible, vulnerability scores (VS) are calculated for different taxonomic groups. An overview of the taxonomic groups covered in each impact category is given in Table 1.5.

Table 1.5: Overview of the taxonomic groups used for calculating maps of species counts and vulnerability scores (only possible for taxa with available IUCN data). All groups consist of animals except tracheophyta (vascular plants). FEOW stands for freshwater ecoregions of the world.

Environmental mechanism	taxonomic group	taxonomic classification	Spatial resolution	VS map available?	Data origin
Acidification	Tracheophyta	Phylum	0.53°x0.53°	no, species numbers used as proxy	Kier et al. (2009)
Freshwater eutrophication	Fish	Classes	FEOW	no, fish richness density and total fish number used as proxy	Abell et al. (2008)
Marine eutrophication	Lobsters, bony fish, cartilaginous fish and sea cucumbers	Classes (note: only species occurring in marine neritic habitats are included)	Large Marine Ecosystems	yes	IUCN (2018)
Photochemical ozone formation	Tracheophyta	Phylum	0.53°x0.53°	no	Kier et al. (2009)
Water	Mammalia Aves Amphibia Reptilia	Classes	0.05°x0.05°	yes	IUCN (2018)
Land	Mammalia Aves Amphibia Reptilia Tracheophyta	Classes	0.05°x0.05°	yes	IUCN (2018)
Climate change	Global average	-	-	no	
Ecotoxicity	Tracheophyta Freshwater Fish Lobsters, bony fish, cartilaginous fish and sea cucumbers	Classes/Phylum	-	No, proxies used. Terrestrial:species numbers tracheophyta; freshwater: fish numbers; marine: species numbers	Abell et al. (2008); Kier et al. (2009); IUCN (2018)

	Lobsters, bony fish, cartilaginous fish and sea cucumbers

Species maps were calculated with as much and detailed data as possible according to the following data priority setting:

1) Maps calculated with IUCN data

For a wide variety of species IUCN provides geographic range sizes, including explicit spatial information, compatible for use in geographical information systems. As taxonomic classification level we chose "classes" for calculating these maps (Table 1.5). Classes are the third level of the taxonomic classification after "Kingdom" (e.g. plants, animals) and "Phylum" (e.g. chordate, tracheophyta). In order to represent the number of species on a global grid, the geographical ranges of all relevant species were overlaid and summed in Matlab (MathWorks 2016). Species that are already extinct nowadays were excluded from the analysis, because the aim of the maps is to give present species counts. The procedure is also described in Verones et al. (2013). The resolution of these maps is 0.05°x0.05°.

2) Species maps from other authors

If no species-specific information on geographic range sizes were available, a search for existing species maps was performed. The map for tracheophyta (vascular plants) is a map that was made available by Kreft et al. (2007). Tracheophyta is a phylum and not a class, but there is no map available for all 12 classes of vascular plants that are grouped into the phylum tracheophyta. The resolution is fixed and we do not have species lists available for different classes at each location.

3) Using relationships with abiotic parameters to estimate species occurrences

If the search for existing maps yielded no results, relationships with abiotic parameters were applied for estimating the number of species in a spatially differentiated way. This is the case for freshwater fish species. We used a species-discharge relationship (Oberdorff et al. 1995) and the modelled yearly average discharge from WaterGap (WATCH 2011) to come up with a map of estimated fish species numbers.

For the fish map (for freshwater eutrophication) the fate and effect factor are made compatible to the resolution of the species map because we have explicit relationships for modelling the fish counts at spatial level. However, the map of tracheophyta for terrestrial acidification cannot be resampled. Thus, we upsize the resolutions of the fate and effect factor for terrestrial acidification, in order to match the resolution of the tracheophyta map. This species map is an existing map we are using with species richness information. However, we do not know which species exactly are present in which cell. Thus we cannot resample the map, since the same species number (e.g. 3) in two pixels does not mean that the species composition is exactly the same (e.g. species A, B and C in pixel 1 and A, B and D in pixel 2).

1.5.3. Spatial aggregation

All spatially-differentiated characterization factors are also available on a country and a continental level to facilitate application. A single global default value will also be provided.

Spatial aggregation is done by calculating weighted averages. Averaging at higher spatial scales will be based on actual emissions, except for land and water stress, which will be based on water withdrawal and land use, respectively. Population density can be used as a fallback proxy weighting scheme. The aggregation based on emission and resource consumption patterns reflects the best knowledge we currently have about activity levels. Note that with this approach we assume that a new activity (emission, consumption) is more likely to happen in regions where activities are already taking place, i.e. this is an attributional assessment (Mutel et al. 2009). Table 1.6 shows the data sources and method used for aggregating.

Table 1.6: Overview of data sources and aggregation type for impact categories that include spatial differentiation.

impact category	aggregation based on	Reference year	Data source for aggregation
freshwater eutrophication	emissions/ crop areas (for erosion)	2000	Scherer et al. (2015)
terrestrial acidification	population density	2000	CIESIN (2005)
water stress	water consumption	2010	WATCH (2011), Pfister et al. (2011), UN (2011)
land stress	ecoregion size	-	Olson et al.(2001)
particulate matter	emissions	2000	Lamarque et al. (2010)
photochemical ozone formation	emissions	2000	Lamarque et al. (2010)

1.6. Literature

Abell, R., Thieme, M. L., Revenga, C., Bryer, M., Kottelat, M., et al. (2008). "Freshwater Ecoregions of the World: A New Map of Biogeographic Units for Freshwater Biodiversity Conservation." BioScience **58**(5): 403-414.

CIESIN, (Center for Interantional Earth Science Information Network, Columbia University) and CIAT, (Centro Internacional de Agricultura Tropical) (2005). Gridded Population of the World, Version 3 (GPWv3): Population Density Grid. Palisades,NY: NASA Socieoeconomic Data and Applictions Center (SEDAC). http://dx.doi.org/10.7927/H4XK8CG2 (03.09.2014).

Gerst, M. D. (2008). "Revisiting the cumulative grade-tonnage relationship for major copper ore types." Economic Geology **103**(3): 615-628.

Goedkoop, M. (2000). The Eco-indicator 99 LCIA methodology - an introduction. Eco-Indicator 99 - eine schadensorientierte Bewertungsmethode. Nachbereitung zum 12. Diskussionsforum Ökobilanzen vom 30. Juni and der ETH Zürich. T. Baumgartner and A. Braunschweig. Zurich, Switzerland.

Goedkoop, M., Heijungs, R., Huijbregts, M. A. J., De Schryver, A., Struijs, J. and van Zelm, R. (2009). ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and endpoint levels. First edition. Report i: Characterization. The Netherlands, Ruimte en Milieu, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer.

Huijbregts, M. A. J., Hellweg, S. and Hertwich, E. (2011). "Do We Need a Paradigm Shift in Life Cycle Assessment?" Environ. Sci. Technol. **45**: 3833-3834.

ISO (2006a). Environmental Management - Life Cycle Assessment - Principles and Framework. International Standard ISO 14040. International Organisation for Standardisation. Geneva, Switzerland.

ISO (2006b). Environmental management - Life Cycle Assessment - Requirements and guidelines. International Standard ISO 14044, International Organisation for Standardisation. Geneva, Switzerland.

IUCN, (International Union for Conservation of Nature and Natural Resources). (2018). "Spatial Data Download." Retrieved 3 October, 2018, from http://www.iucnredlist.org/technical-documents/spatial-data.

Kier, G., Kreft, H., Lee, T. M., Jetz, W., Ibisch, P. L., Nowicki, C., Mutke, J. and Barthlott, W. (2009). "A global assessment of endemism and species richness across island and mainland regions." PNAS **106**(23): 9322-9327.

Kreft, H. and Jetz, W. (2007). "Global patterns and determinants of vascular plant diversity." PNAS **104**(14): 5925-5930.

Lamarque, J. F., Bond, T. C., Eyring, V., Granier, C., Heil, A., et al. (2010). "Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application." Atmos. Chem. Phys. **10**(15): 7017-7039.

MathWorks (2016). "Matlab Version 2016b."

Mutel, C. L. and Hellweg, S. (2009). "Regionalized Life Cycle Assessment: Computational Methodology and Application to Inventory Databases." Environ. Sci. Technol. **43**: 5797-5803.

Oberdorff, T., Guégan, J.-F. and Hugueny, B. (1995). "Global scale patterns of fish species richness in rivers." Ecography **18**: 345-352.

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N., Powell, G. V. N., Underwood, E., D'Amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P. and Kassem, K. R. (2001). "Terrestrial Ecoregions of the World: A New Map of Life on Earth (Note: data update from 2004 used)." BioScience **51**(11): 933-938.

Pfister, S., Bayer, P., Koehler, A. and Hellweg, S. (2011). "Environmental Impacts of Water Use in Global Crop Production: Hotspots and Trade-Offs with Land Use." Environ. Sci. Technol. **45**(13): 5761-5768.

Prior, T., Giurco, D., Mudd, G., Mason, L. and Behrish, J. (2012). "Resource depletion, peak minerals and the implications for sustainable resource management." Global Environmental Change **22**(3): 577-587.

Scherer, L. and Pfister, S. (2015). "Modelling spatially explicit impacts from phosphorus emissions in agriculture." The International Journal of Life Cycle Assessment **20**(6): 785-795.

United Nations and Department of Economic and Social Affairs, Population Divison, (2011). "World Population Prospectes: The 2010 Revision, CD-ROM edition."

van Zelm, R., Huijbregts, M. A. J., van Jaarsveld, H. A., Reinds, G. J., de Zwart, D., Struijs, J. and van de Meent, D. (2007). "Time Horizon Dependent Characterization Factors for Acidification in Life-Cycle Assessment Based on Forest Plant Species Occurrence in Europe." Environmental Science & Technology **41**(3): 922-927.

Verones, F., Hellweg, S., Antón, A., Azevedo, L. B., Chaudhary, A., et al. (submitted). "LC-IMPACT: a regionalized life cycle damage assessment method ".

Verones, F., Huijbregts, M. A. J., Chaudhary, A., De Baan, L., Koellner, T. and Hellweg, S. (2015). "Harmonizing the Assessment of Biodiversity Effects from Land and Water Use within LCA." Environ. Sci. Technol. **49**(6): 3584-3592.

Verones, F., Pfister, S., van Zelm, R. and Hellweg, S. (2017). "Biodiversity impacts from water consumption on a global scale for use in life cycle assessment." The International Journal of Life Cycle Assessment **22**(8): 1247-1256.

Verones, F., Saner, D., Pfister, S., Baisero, D., Rondinini, C. and Hellweg, S. (2013). "Effects of consumptive water use on wetlands of international importance." Environ. Sci. Technol. **47**(21): 12248-12257.

Vieira, M. D. M., Goedkoop, M. J., Storm, P. and Huijbregts, M. A. J. (2012). "Ore Grade Decrease As Life Cycle Impact Indicator for Metal Scarcity: The Case of Copper." Environmental Science & Technology **46**(23): 12772-12778.

WATCH. (2011). "Water and global change." Retrieved August, 2012, from http://www.eu-watch.org/; download of data from: https://gateway.ceh.ac.uk/terraCatalog/Start.do.

Wegener Sleswijk, A., van Oers, L. F. C. M., Guinée, J. B., Struijs, J. and Huijbregts, M. A. J. (2008). "Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000." Science of the total environment **390**(1): 227-240.

WHO, (World Health Organization). (2014). "Estimaters for 2002-2012: Disease burden." Retrieved 1 December, 2014, from http://www.who.int/healthinfo/global_burden_disease/estimates/en/index2.html.