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COMMENTARY AND DISCUSSION ARTICLE

ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level

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Abstract
Purpose Life cycle impact assessment (LCIA) translates emissions and resource extractions into a limited number of environmental impact scores by means of so-called characterisation factors. There are two mainstream ways to derive characterisation factors, i.e. at midpoint level and at endpoint level. To further progress LCIA method development, we updated the ReCiPe2008 method to its version of 2016. This paper provides an overview of the key elements of the ReCiPe2016 method.
Methods We implemented human health, ecosystem quality and resource scarcity as three areas of protection. Endpoint characterisation factors, directly related to the areas of protection, were derived from midpoint characterisation factors with a constant mid-to-endpoint factor per impact category. We included 17 midpoint impact categories.
Results and discussion The update of ReCiPe provides characterisation 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 characterisation factors at a country and continental scale. We also expanded the number of environmental interventions and added impacts of water use on human health, impacts of water use and climate change on freshwater ecosystems and impacts of water use and tropospheric ozone formation on terrestrial ecosystems as novel damage pathways. Although significant effort has been put into the update of ReCiPe, there is still major improvement potential in the way impact pathways are modelled. Further improvements relate to a regionalisation of more impact categories, moving from local to global species extinction and adding more impact pathways.
Conclusions Life cycle impact assessment is a fast evolving field of research. ReCiPe2016 provides a state-of-the-art method to convert life cycle inventories to a limited number of life cycle impact scores on midpoint and endpoint level.

Keywords Characterisation factors · Ecosystem quality · Endpoint indicator · Human health · Midpoint indicator · Resource scarcity

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1 Introduction

Life cycle impact assessment (LCIA) supports interpretation of LCA studies by translating emissions and resource extractions into a limited number of environmental impact scores (Hauschild and Huijbregts 2015). This is done by means of so-called characterisation factors, which indicate the environmental impact per unit of stressor (e.g. per kg of resource extracted or emission released). There are two mainstream ways to derive characterisation factors, i.e. at midpoint level and at endpoint level. Characterisation factors at the midpoint level are located somewhere along the cause-impact pathway, typically at the point after which the environmental mechanism is identical for each environmental flow assigned to that impact category (Goedkoop et al. 2009). Characterisation factors at endpoint level typically reflect damage at one of three areas of protection which are human health, ecosystem quality and resource scarcity. The two approaches are complementary in that the midpoint characterisation has a stronger relation to the environmental flows and comes in general with lower parameter uncertainty, while the endpoint characterisation is easier to interpret in terms of relevance of the environmental flows (Hauschild and Huijbregts 2015).

Recently, Hauschild et al. (2013) reviewed a large number of LCIA methods in order to provide recommended practice for both midpoint and endpoint characterisation factors. This consensus work had a significant influence on the establishment of LCIA in the environmental policy arena in Europe, e.g. via its testing in the Product and Organisational Environmental Footprint initiative (EC 2013). The review, however, also provided insight into a number of shortcomings of the models used to derive characterisation factors recommended by Hauschild et al. (2013). First of all, most models have a continental focus, particularly focussing on Europe. Moreover, for many impact categories at the endpoint level, the best among existing characterisation models was still not considered sufficiently mature for recommendation.

To further progress LCIA methods beyond the current consensus state of the art, we updated the ReCiPe2008 method to its version of 2016. ReCiPe provides a harmonised implementation of cause-effect pathways for the calculation of both midpoint and endpoint characterisation factors (Goedkoop et al. 2009). In order to make a step forward in overcoming the shortcomings mentioned above, the update of ReCiPe focused on (1) providing characterisation factors that are representative for the global scale, while maintaining the possibility for a number of impact categories to implement characterisation factors at a country and continental scale and (2) improving the methods applied to model midpoint-to-endpoint factors. Compared to ReCiPe2008, we added the following extra damage pathways in ReCiPe2016:

- Impacts of water use on human health, freshwater ecosystems and terrestrial ecosystems
- Impacts of climate change on freshwater ecosystems
- Impacts of tropospheric ozone formation on terrestrial ecosystems

For a number of impact categories, we also provide midpoint and endpoint characterisation factors on a country level, i.e. for photochemical ozone formation, particulate matter formation, terrestrial acidification, freshwater eutrophication and water use. This paper provides an overview of the key elements of the ReCiPe2016 method.

2 Methods

2.1 Framework

We followed the model framework proposed in ReCiPe2008 with human health, ecosystem quality and resource scarcity as areas of protection. The unit for human heath damage, DALYs (disability adjusted life years), represents the years that are lost or that a person is disabled due to a disease or accident. The unit for ecosystem quality is local relative species loss in terrestrial, freshwater and marine ecosystems, respectively, integrated over space and time (potentially disappeared fraction of species·m^2·year or potentially disappeared fraction of species·m^3· year). To aggregate the impacts of terrestrial, freshwater and marine ecosystems into one single unit (species.year), we included species densities for these three types of ecosystems in the same way as proposed by Goedkoop et al. (2009). The unit for resource scarcity is dollars ($), which represents the extra costs involved for future mineral and fossil resource extraction. Endpoint characterisation factors (*CFe*) are derived from midpoint characterisation factors (*CFm*) with a constant mid-to-endpoint factor per impact category:

$$CFe_{x,a} = CFm_x \times F_{M\rightarrow,E,a} \tag{1}$$

Where a denotes the area of protection, i.e. human health, (terrestrial, freshwater and marine) ecosystems or resource scarcity, x denotes the stressor of concern and $F_{M\rightarrow E,a}$ is the midpoint-to-endpoint conversion factor for area of protection a. These mid-to-endpoint factors are constant per impact category, because environmental mechanisms are considered to be identical for each stressor after the midpoint impact location on the cause-effect pathway.

Figure 1 shows the link between the environmental mechanisms, i.e. the 17 midpoint impact categories, and the three areas of protection, i.e. the endpoints, as included in ReCiPe2016.

2.2 Model selection criteria

The selection criteria for the environmental models in ReCiPe2016 were

- The models should refer to the global scale.
- The models should reflect the current state of the art in science.

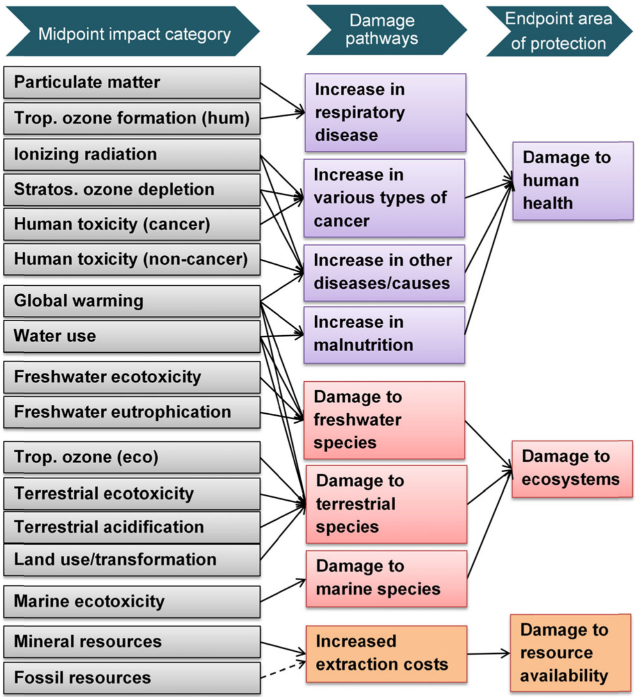

Fig. 1 Overview of the impact categories that are covered in the ReCiPe2016 method and their relation to the areas of protection. The *dotted line* means there is no constant mid-to-endpoint factor for fossil resources

– The models should maintain consistency between the modelling of different impact categories, particularly relevant for toxicity.
– In case of multiple suitable global models, we prefer models that can be run in-house by the ReCiPe consortium.

We performed a review of the existing literature within and outside the field of LCIA to select a preferred combination of environmental models and databases per midpoint impact category. We also selected models that were able to quantify damage pathways relevant for the mid-to-endpoint factors. For a number of impact categories, notably fine particulate matter formation, photochemical ozone formation, land use and water use, there is a fast increasing number of global models published in the literature. Here, we pragmatically selected the models that we were able to run within the consortium without claiming that ReCiPe2016 is necessarily superior compared to other global models out there.

2.3 Scenario analysis

Different sources of uncertainty and different methodological choices were grouped into three scenarios. This means that ReCiPe2016 does not provide one set, but three sets of midpoint and endpoint characterisation factors and users are encouraged to use all three of them for a sensitivity check of their LCA results. One prominent choice is the time horizon for long living pollutants. We included a 20-year, 100-years and 1000-year-infinite time horizon in each scenario, respectively. The time horizon for the third scenario was not always infinite, as not all the environmental models provided sufficient information to model steady-state conditions. Another important value choice included was the level of evidence available for the environmental effects considered for the impacts related to ozone depletion, ionising radiation, toxicity, fine particulate matter formation and water use. We coupled effects with only a very high level of evidence to a 20-year time horizon and all reported effects to a 1000-infinite time horizon to construct two extreme scenarios. The third scenario refers to a middle ground with a 100-year time horizon consistently included and effects with a level of evidence that is considered acceptable by international bodies, such as the World Health Organisation. More details on the scenario building can be found in Huijbregts et al. (2016).

3 Results

3.1 Midpoint indicators

Impact categories and their indicators at the midpoint level are summarised in Table 1 and briefly explained below. The full list of midpoint characterisation factors is available in spreadsheet format (see Electronic Supplementary Material).

3.1.1 Climate change

The midpoint characterisation factor selected for climate change is the widely used global warming potential (GWP), which quantifies the integrated infrared radiative forcing increase of a greenhouse gas (GHG), expressed in kg CO_2-eq (IPCC 2013; Joos et al. 2013).

3.1.2 Stratospheric ozone depletion

The ozone depleting potential (ODP), expressed in kg CFC-11 equivalents, was used as characterisation factor on the midpoint level. ODPs refer to a time-integrated decrease in stratospheric ozone concentration over an infinite time horizon (WMO 2011).

3.1.3 Ionising radiation

The collective dose resulting from the emission of a radionuclide is the point where the characterisation factor at midpoint level was derived. The midpoint characterisation factor, called ionising radiation potential (IRP), is reported in Cobalt-60 eq to air.

3.1.4 Fine particulate matter formation

For the midpoint characterisation factors of fine particulate matter formation, the human population intake of $PM_{2.5}$ was

Table 1 Overview of the midpoint impact categories and related indicators

Midpoint impact category	Indicator	CF_m	Unit	Key references
Climate change	Infrared radiative forcing increase	Global warming potential (GWP)	kg CO_2-eq to air	IPCC 2013; Joos et al. 2013
Ozone depletion	Stratospheric ozone decrease	Ozone depletion potential (ODP)	kg CFC-11-eq to air	WMO 2011
Ionising radiation	Absorbed dose increase	Ionising radiation potential (IRP)	kBq Co-60-eq to air	Frischknecht et al. 2000
Fine particulate matter formation	PM2.5 population intake increase	Particulate matter formation potential (PMFP)	kg PM2.5-eq to air	Van Zelm et al. 2016
Photochemical oxidant formation: terrestrial ecosystems	Tropospheric ozone increase	Photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-eq to air	Van Zelm et al. 2016
Photochemical oxidant formation: human health	Tropospheric ozone population intake increase	Photochemical oxidant formation potential: humans (HOFP)	kg NOx-eq to air	Van Zelm et al. 2016
Terrestrial acidification	Proton increase in natural soils	Terrestrial acidification potential (TAP)	kg SO_2-eq to air	Roy et al. 2014
Freshwater eutrophication	Phosphorus increase in freshwater	Freshwater eutrophication potential (FEP)	kg P-eq to freshwater	Helmes et al. 2012
Human toxicity: cancer	Risk increase of cancer disease incidence	Human toxicity potential (HTPc)	kg 1,4-DCB-eq to urban air	Van Zelm et al. 2009
Human toxicity: non-cancer	Risk increase of non-cancer disease incidence	Human toxicity potential (HTPnc)	kg 1,4-DCB-eq to urban air	Van Zelm et al. 2009
Terrestrial ecotoxicity	Hazard-weighted increase in natural soils	Terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-eq to industrial soil	Van Zelm et al. 2009
Freshwater ecotoxicity	Hazard-weighted increase in freshwaters	Freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-eq to freshwater	Van Zelm et al. 2009
Marine ecotoxicity	Hazard-weighted increase in marine water	Marine ecotoxicity potential (METP)	kg 1,4-DCB-eq to marine water	Van Zelm et al. 2009
Land use	Occupation and time-integrated land transformation	Agricultural land occupation potential (LOP)	$m^2 \times$ yr annual cropland-eq	De Baan et al. 2013; Curran et al. 2014
Water use	Increase of water consumed	Water consumption potential (WCP)	m^3 water-eq consumed	Döll and Siebert 2002; Hoekstra and Mekonnen 2012
Mineral resource scarcity	Increase of ore extracted	Surplus ore potential (SOP)	kg Cu-eq	Vieira et al. 2016a
Fossil resource scarcity	Upper heating value	Fossil fuel potential (FFP)	kg oil-eq	Jungbluth and Frischknecht 2010

considered. Particulate matter formation potentials (PMFP) are expressed in kg primary $PM_{2.5}$-equivalents. The change in ambient concentration of $PM_{2.5}$ after the emission of a precursor, i.e. NH_3, NO_x, SO_2 and primary $PM_{2.5}$, was predicted with the emission—concentration sensitivities matrices for emitted precursors from the global source-receptor model TM5-FASST (Van Zelm et al. 2016).

3.1.5 Photochemical ozone formation

For the midpoint characterisation factors of photochemical ozone formation related to human exposure, the human population intake of ozone was considered. Human health ozone formation potential (HOFP) is expressed in kg NO_x-eq. The change in ambient concentration of ozone after the emission of a precursor (nitrogen oxides (NO_x) or non-methane volatile organic compounds (NMVOC)) was predicted with the emission—concentration sensitivities matrices for emitted precursors from the global source-receptor model TM5-FASST (Van Zelm et al. 2016). The ecosystem ozone formation potential (EOFP), also expressed in kg NO_x eq, relates to 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 (AOT40; Van Zelm et al. 2016).

3.1.6 Terrestrial acidification

For the midpoint characterisation factors of acidifying emissions, the fate of a pollutant in the atmosphere and the soil as calculated by Roy et al. (2014) were taken. Acidification potentials (AP) are expressed in kg SO_2-equivalents. Changes in acid deposition, following changes in air emission of NO_x, NH_3 and SO_2, were calculated with the GEOS-Chem model (Roy et al. 2012a). Subsequently, the change in acidity in the soil due to a change in acid deposition was derived with the geochemical steady-state model PROFILE (Roy et al. 2012b).

3.1.7 Freshwater eutrophication

The fate of phosphorus forms the basis of the midpoint characterisation factors for freshwater eutrophication. Freshwater eutrophication potentials (FEP) are expressed in kg P to freshwater-equivalents. Global fate factors for phosphorus emissions to freshwater were taken from Helmes et al. (2012). For emissions to agricultural soils, it was assumed that typically 10% of all P is transported from agricultural soil to surface waters (Bouwman et al. 2009).

3.1.8 Toxicity

The fate and effects of chemical emissions expressed in kg 1,4-dichlorobenzene-equivalents (1,4DCB-eq) was used as characterisation factor at the midpoint level for human toxicity, freshwater ecotoxicity, marine ecotoxicity and terrestrial ecotoxicity. We used the global multimedia fate, exposure and effects model USES-LCA 2.0, the Uniform System for the Evaluation of Substances adapted for LCA (Van Zelm et al. 2009), as a basis for our calculations, updated to deal with dissociating chemicals (Van Zelm et al. 2013) and using the chemical data from the USEtox database (Rosenbaum et al. 2008). The ecotoxicological effect factor represents the change in PDF of species due to a change in the environmental concentration of a chemical. The human-toxicological effect factors were derived for carcinogenic and non-carcinogenic effects separately, reflecting the change in lifetime disease incidence due to a change in intake of the substance. Note that we did not select USEtox model (Rosenbaum et al. 2008) for implementation in ReCiPe2016, as USEtox does not provide characterisation factors for terrestrial and marine toxicity. Another practical reason for preferring USES-LCA compared to USEtox is that USEtox does not easily provide the possibility to assess the influence of value choices on the characterisation factors, such as the option to derive time horizon dependent characterisation factors.

3.1.9 Water use

The characterisation factor at midpoint level is m^3 of water *consumed* per m^3 of water *extracted*. For agriculture, the consumptive part of the withdrawal was estimated with water requirement ratios based on Döll and Siebert (2002). For industry and domestic water use, assumptions were made based on Hoekstra and Mekonnen (2012).

3.1.10 Land use

The midpoint characterisation factors (in $m^2 \cdot yr$ annual crop equivalents) refer to the relative species loss caused by a specific land use type (annual crops, permanent crops, mosaic agriculture, forestry, urban land, pasture). Relative species loss was determined by comparing field data on local species richness in specific types of natural and human-made land covers (De Baan et al. 2013; Elshout et al. 2014). For land conversion, passive recovery towards a (semi-)natural, old growth habitat was assumed, based on average recovery times from Curran et al. (2014).

3.1.11 Mineral resource scarcity

The midpoint characterisation factor for mineral resource scarcity is Surplus Ore Potential (SOP), expressed as kg Cu-eq. The primary extraction of a mineral resource will lead to an overall decrease in ore grade, meaning the concentration of that resource in ores worldwide, which in turn will increase the amount of ore produced per kilogramme of mineral resource extracted. The SOP expresses the average extra amount of ore produced in the future caused by the extraction of a mineral resource considering all future production of that mineral resource (Vieira et al. 2016a).

3.1.12 Fossil resource scarcity

The midpoint indicator for fossil resource use, determined as the Fossil Fuel Potential (FFP in kg oil-eq), is defined as the ratio between the higher heating value of a fossil resource and the energy content of crude oil (Jungbluth and Frischknecht 2010).

3.2 Mid-to-endpoint factors

The damage pathways considered to go from the midpoint to the endpoint level in ReCiPe2016, sorted per environmental problem, are summarised in Table 2 and briefly explained below. The midpoint-to-endpoint factors are available in spreadsheet format (see Electronic Supplementary Material).

3.2.1 Climate change

The first step in the midpoint-to-endpoint model quantifies the link between time-integrated radiative forcing and time-integrated temperature increase for CO_2 (Joos et al. 2013). Concerning human health damage, De Schryver et al. (2009) was used to quantify the increase in risk of diseases (malnutrition, malaria, and diarrhoea) and increased flood risk. For terrestrial ecosystems, the increase in potentially disappeared fraction of species (PDF) due to an increase in global temperature was derived from the review by Urban (2015). Finally,

Table 2 Damage pathways in ReCipe2016

Environmental problem	Area of protection	Damage pathways	References
Climate change	Human health	Years of life lost and disabled related to increased malaria, diarrhoea, malnutrition and natural disasters due to increased global mean temperature	IPCC 2013; Joos et al. 2013; De Schryver et al. 2009
	Ecosystems (terrestrial)	Species loss related to changing biome distributions due to increased global temperature	IPCC 2013; Joos et al. 2013; Urban 2015
	Ecosystems (freshwater)	Fish species loss due to decrease river discharge	Hanafiah et al. 2011
Stratospheric ozone depletion	Human health	Years of life lost and disabled related to increased skin cancer and cataract due to UV-exposure	WMO 2011; Hayashi et al. 2006
Ionising radiation	Human health	Years of life lost and disabled related to an increase in cancer and hereditary diseases due to exposure to radiation	Frischknecht et al. 2000; De Schryver et al. 2011
Particulate matter formation	Human health	Years of life lost related to an increase in cardiopulmonary and lung cancer caused by exposure to primary and secondary aerosols	Van Zelm et al. 2016
Photochemical ozone formation	Human health	Years of life lost related to an increase in respiratory diseases caused by exposure to ozone	Van Zelm et al. 2016
	Ecosystems (terrestrial)	Loss of plant species due to increase in ozone exposure	Van Zelm et al. 2016
Terrestrial acidification	Ecosystems (terrestrial)	Loss of plant species due to decrease in soil pH	Roy et al. 2014
Freshwater eutrophication	Ecosystems (aquatic)	Loss of aquatic species due to increased phosphorus concentrations	Helmes et al. 2012; Azevedo et al. 2013a, b
Toxicity	Human health	Years of life lost and disabled due to cancer and non-cancer effects due to ingestion and inhalation of toxic substances	Van Zelm et al. 2009
	Ecosystems (marine)	Species loss due to chemical exposure in marine waters	Van Zelm et al. 2009
	Ecosystems (terrestrial)	Species loss due to chemical exposure in soils	Van Zelm et al. 2009
	Ecosystems (freshwater)	Species loss due to chemical exposure in freshwater	Van Zelm et al. 2009
Water consumption	Human health	Malnutrition caused by water shortage	Pfister et al. 2009
	Ecosystems (terrestrial)	Decrease in Net Primary Productivity because of water shortage as proxy for total species loss	Pfister et al. 2009
	Ecosystems (aquatic)	Fish species loss due to decreased river discharge	Hanafiah et al. 2011
Land use	Ecosystems (terrestrial)	Species loss due to different types of land use (agriculture, forestry, built up). Species loss caused by transformation of natural land to used land, including the time it takes to back-transform to natural land	De Baan et al. 2013; Curran et al. 2014
Mineral resource scarcity	Resource scarcity	Cost increase due to mineral extraction increase	Vieira et al. 2016b
Fossil resource scarcity	Resource scarcity	Cost increase due to fossil extraction increase	Vieira et al. 2016c

the influence of global temperature increase on river discharge and subsequent expected changes in fish species occurrences was taken from Hanafiah et al. (2011).

3.2.2 Stratospheric ozone depletion

The human health effect of a decrease in stratospheric ozone concentration, as modelled in the mid-to-endpoint calculation, was derived in two consecutive steps, following Hayashi et al. (2006). The first step relates a change in ozone depletion to an increase in UVB radiation and the second step couples this increase in UVB radiation to an increase in burden of disease. To calculate the damage to human health, the increased incidence and related loss of DALYs of three types of skin cancers (malignant melanoma, basal cell carcinoma and squamous cell carcinoma) and cataract due to UVB exposure were included.

3.2.3 Ionising radiation

In the mid-to-endpoint calculations, the human health effect of the collective dose on the incidence of different cancer types was assessed by first taking the fatal and non-fatal cancer incidence per cancer type from Frischknecht et al. (2000).

This information was combined with the disability weight per cancer type (Frischknecht et al. 2000; De Schryver et al. 2011).

3.2.4 Fine particulate matter formation

Starting from the intake fraction, human effect and damage due to cardiopulmonary and lung cancer mortality of fine particulate matter were determined by Van Zelm et al. (2016).

3.2.5 Photochemical ozone formation

Starting from the intake fraction, effect and damage factors of respiratory mortality due to ozone exposure were determined by Van Zelm et al. (2016). For damage to terrestrial ecosystems, the effect factor describes the change in PDF of forest and grassland species due to the change in ground level ozone exposure over forest and grassland area (Van Goethem et al. 2013a, b).

3.2.6 Terrestrial acidification

An effect factor was added to the endpoint calculations, describing the absence of species due to acidity of soils (Roy et al. 2014). The effect factor quantifies the change in the PDF of vascular plant species due to a change in the H^+ concentration and was derived for specific biomes, such as temperate broadleaf mixed forest, tundra and (sub)tropical moist broadleaf forest (Azevedo et al. 2013a).

3.2.7 Freshwater eutrophication

The effect factor, added to the midpoint calculations, describes the absence of species due to phosphorus concentrations in freshwater (Azevedo et al. 2013b, c). It reflects the change in PDF of species due to a change in total P concentration and depends on the freshwater type (rivers or lakes), species group (heterotrophs and autotrophs) and climate type (warm, temperate, xeric or cold).

3.2.8 Toxicity

Ecotoxicological damage factors, added to the midpoint calculations, were considered to equal one, as the effects estimated with acute toxicity data may approximate toxic effects in field conditions (Posthuma and De Zwart 2006). For human health, damage factors for carcinogenic or non-carcinogenic effects were included (Huijbregts et al. 2005).

3.2.9 Water use

Impacts of water consumption on human health refer to DALYs due to malnutrition, as caused by water shortage in low development countries (Pfister et al. 2009). Impacts of water consumption on terrestrial ecosystems were taken from Pfister et al. (2009), who quantified them based on the damage for vascular plant species using net primary productivity (NPP) as a proxy. Impacts of water consumption on freshwater ecosystems were taken from Hanafiah et al. (2011), who quantified them as the change in fish species lost associated with a decrease in discharge.

3.2.10 Land use

The mid-to-endpoint modelling for land use does not add further steps to the cause-impact pathway, as the midpoint characterisation factors already refer to local species loss.

3.2.11 Mineral resource scarcity

The mid-to-endpoint factor for mineral resource scarcity refers to the conversion from surplus ore to surplus costs. Cumulative tonnage relationships for surplus costs of 12 metals, as developed by Vieira et al. (2016b), were used as input in the calculations.

3.2.12 Fossil resource scarcity

Endpoint characterisation factors for the extraction of crude oil, natural gas and hard coal, expressed as Surplus Cost Potential (SCP), were based on cumulative cost-tonnage relationships for these three fossil resources (Vieira et al. 2016c). Note that we were not able to arrive at a constant mid-to-endpoint factor for fossil resources due to lack of understanding about the full cause-effect pathway.

4 Discussion

Although significant effort has been put into the development of ReCiPe2016, there is still major improvement potential in the way impact pathways are modelled. A number of improvement options are discussed below.

4.1 Scenario analysis

Due to lack of data, the influence of time horizon and level of evidence was not considered in the calculation of characterisation factors for photochemical ozone formation, terrestrial acidification, freshwater eutrophication, land use and fossil resource scarcity. This needs to be improved in future updates of ReCiPe, if more information on value choices becomes available in the underlying models employed.

4.2 Regionalisation

Country- or region-specific characterisation factors for midpoints and endpoints were included for a number of impact categories, including fine particulate matter formation, photochemical ozone formation, acidification, freshwater eutrophication and water use. Country-specific characterisation factors for midpoints and endpoints were included for a number of impact categories, including fine particulate matter formation, photochemical ozone formation, acidification, freshwater eutrophication and water use. Particularly for the global models related to fine particulate matter formation and photochemical ozone formation, a higher spatial resolution at the global scale and with a closer spatial connection between fate, exposure and effects can further improve the reliability of LCIA (see, e.g. Apte et al. 2015; Brauer et al. 2016). For other impact categories, spatial differentiation has not been considered at all in ReCiPe2016 and major improvements are possible on this point. Most prominent impact categories for providing regionalised results are land use (Chaudhary et al. 2015) and toxicity (Kounina et al. 2014). For toxicity, spatial differentiation can be considered particularly relevant for the modelling of ecological impacts of metals, if speciation is taken into account in fate, exposure and effect calculations (see, e.g. Dong et al. 2016).

4.3 Global species extinction

Damage to ecosystem quality in ReCiPe2016 refers to the aggregated local loss of species over space and time. Global species extinction risk may, however, also be considered as an indicator for ecosystem quality in addition to local species loss. For both water use and land use, there are already possibilities to account for global species decline in life cycle impact assessment (see Chaudhary et al. 2015; Verones et al. 2015). Further research is needed to expand this also to other impact categories.

4.4 Missing pathways

With ReCiPe2016, we firstly focused on advancing the impact modelling of categories that were classified as interim by Hauschild et al. (2013). Not all exposure and damage pathways could, however, be modelled in ReCiPe2016. First, human exposure pathways related to indoor emissions to chemicals and fine particulate matter (Rosenbaum et al. 2015; Hodas et al. 2016) and direct application of pesticides to food items (Fantke and Jolliet 2015) were not included and should be considered in future updates of ReCiPe. There are also missing pathways in the endpoint modelling of existing impact categories due to lack of global information, such as the change in incidence of infectious diseases due to climate change (see, e.g. Fan et al. 2015). For fossil resource scarcity, we were not able to establish a mid-to-endpoint factor which requires further improvement. Finally, additional impact categories should be considered, particularly related to the marine environment, such as marine eutrophication, invasive species and plastic debris (Woods et al. 2016). For human health, noise is a potentially relevant impact category to be considered in a future update (see, e.g. Cucurachi and Heijungs 2014). Impacts from emerging activities and substances, such as impacts from nanoparticles, are also potentially relevant for further expansion (Pini et al. 2016).

5 Conclusions

Life cycle impact assessment is a fast evolving field of research. ReCiPe2016 provides a state-of-the-art method to convert life cycle inventories to a limited number of life cycle impact scores on midpoint and endpoint level. Three endpoint categories (human health, ecosystem quality and resource scarcity) and 17 midpoint categories were included with a focus on providing characterisation factors that are representative on the global scale in line with the global nature of many product life cycles.

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