Freshwater Biodiversity and Life Cycle Analysis

Developing Characterization Factors for the Effect of Climate Change on Riverine Fish Species

Sif de Visser

A thesis proposal presented for the Master of Science in Industrial Ecology

A joint degree between Leiden University and Delft University of Technology | First supervisor: Dr. V. Barbarossa, Department of Industrial Ecology, Institute of Environmental Sciences, Leiden University | Second supervisor: Dr. L. A. Scherer, Department of Industrial Ecology, Institute of Environmental Sciences, Leiden University | Student number: S2666693 (Leiden University), 5178975 (TU Delft) | Submitted on 19-07-2021

Universiteit Leiden
The Netherlands

TU Delft

Abstract

Human pressures increasingly threaten the highly biodiverse freshwater ecosystems. Life Cycle Analysis (LCA) is a useful tool to reveal the impacts of products and services on freshwater biodiversity. Current methodologies in LCA address the impact of climate change driven by reduced average river discharge on freshwater biodiversity. However, given the ectothermic nature of fish, previous studies have highlighted the importance of including water temperature changes as a driver of species loss. In addition, the impact of climate-driven changes in extremes might be more important than changes in average conditions. This thesis develops a novel methodology to include the impacts of climate change on freshwater biodiversity in LCA. A novel dataset of range contractions, based on extreme streamflow and water temperature parameters, is converted into extinction risk via a metric originating from the classic Species Area Relationship (SAR). A characterization factor is derived for each of the 63 greenhouse gases (GHGs) included in the study. The recommended sets of global characterization factors range from $1.33 \cdot 10^{-15}$ - $7.16 \cdot 10^{-11}$ $\mathrm{PDF} \cdot \mathrm{yr} \cdot \mathrm{kg}^{-1}$ for the average approach and $4.62 \cdot 10^{-16}$ - $2.49 \cdot 10^{-11}$ $\mathrm{PDF} \cdot \mathrm{yr} \cdot \mathrm{kg}^{-1}$ for the average and marginal approach respectively. The results imply that freshwater biodiversity impacts per unit of GHG have been underestimated in previous LCA methods that excluded the impact of extreme values and water temperature-driven losses. Future contributions can help to increase taxonomic coverage (e.g., by including lentic species and macro-invertebrates) and by developing complementary models to reflects all the various levels of biodiversity.

Acknowledgement

I had the pleasure to work with Valerio Barbarossa and Laura Scherer as my supervisors. They gave me a glimpse into the life of an academic at the CML Institute. Valerio Barbarossa has been both a great supervisor as well as a mentor. I value the interesting discussions on developing a methodology, the sharp feedback and enthusiasm Valerio brought to the table. Laura Scherer has provided me with a lot of valuable feedback also. It is great that she could step in at the last moment as the second supervisor, a role she had actually fulfilled from the start. I am thankful for the time both supervisors devoted to helping me, as I can imagine there are always better fish to fry as a researcher. As for my fellow study mate Hidde Boom, I look forward to reading his thesis soon and wish him the best of luck in finalizing his thesis.

Utrecht, July 18 2021

Contents

1 Introduction

1.1 Threats to freshwater biodiversity

Freshwater ecosystems are characterized by a rich diversity of species and habitats. While they span only 2.3% of the global surface, they accommodate 9.5% of the animal species (Reid et al., 2019). Freshwater species are considered disproportionally threatened in comparison to terrestrial species (Collen et al., 2014; Wiens, 2016). Freshwater biodiversity decline in terms of average proportional change in population sizes is estimated at 84% between 1970 and 2016, remarkably higher than the average decline for all species of 68% (World Wildlife Fund, 2020).

There are multiple drivers responsible for the freshwater biodiversity decline, many of which are considered human-induced (Reid et al., 2019). Dudgeon (2019) categorizes the threats into six categories: (I) over-exploitation; (II) pollution; (III) flow regulation; (IV) land-use change; (V) invasive species invasion; and (VI) climate change. Climate change is considered a rising threat to freshwater species and can exacerbates some of the aforementioned threats (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2019; World Wildlife Fund, 2018).

A freshwater biodiversity crisis can have devastating impacts on water and food availability for humans, human health, resilience to natural hazards, and even climate change (Cowx & Portocarrero Aya, 2011). The ecosystem services provided by freshwater ecosystems exceed a value of 4 trillion US$ annually (Flitcroft et al., 2019). Thus, there is a high urgency for society to maintain healthy freshwater ecosystems, as they are essential to human well-being and sustain livelihoods of human settlements. One strategy forward is to tackle the lack of consideration in decision-making, which is considered a fundamental cause of the freshwater biodiversity crisis (Darwall et al., 2018).

1.2 The potential of Life Cycle Analysis

Life Cycle Analysis (LCA) is an important decision-making tool to guide the transition towards more sustainable products. It offers a standardized approach to quantify environmental sustainability and to identify hotspots (large impacts) across the life-cycle of products, processes, or supply chains (Chaplin-Kramer et al., 2017). LCA can address multiple impact categories as desired by the practitioner (e.g., climate change, eutrophication, land use) and is therefore praised for being an inclusive tool (Ciacci & Passarini, 2020). However, the inclusion of biodiversity in LCA is highly debated and incomplete, especially when it comes to freshwater species (Winter et al., 2017). The pitfall of excluding or underestimating impacts on biodiversity is that it could lead to decisions with undesired effects on biodiversity (Teillard et al., 2016).

1.3 State-of-the-art

Winter et al. (2017) mapped the current status of implementation of biodiversity and the various pressures in LCA and found that many pressures have not been covered yet. Land use is the most frequently addressed biodiversity pressure, especially for terrestrial species, a variety of models is available (e.g., Chaudhary et al., 2015), while freshwater species remain underrepresented. Within the LC-impact family, the impact categories global warming, water consumption, ecotoxicity, and eutrophication cover a freshwater species damage pathway (Verones et al., 2020).

The global warming and water consumption impact categories are modeled by Hanafiah et al. (2011). Hanafiah et al. (2011) developed a methodology that builds upon the species discharge relationship, which predicts species richness from the average discharge at the mouth of a river basin. Tendall et al. (2014) complemented the methodology for freshwater consumption by increasing the taxonomic coverage with macro-invertebrate species, by creating regionalized fish species-discharge relationships, and by considering the location of water consumption within a river basin.

The state-of-the-art LCA models considering global warming effects on freshwater biodiversity face several shortcomings. Firstly, water temperatures are not included. A recent study by Barbarossa et al. (2021) shows that freshwater fish species are more severely threatened by water temperature alterations than streamflow alterations. One explanation is that fish are directly influenced by the water temperature being an ectothermic species (Comte & Olden, 2017). Both water temperature and streamflow parameters are important habitat factors for freshwater species (Knouft & Ficklin, 2017; Poff, 2018). An impact pathway solely considering reduced river discharge may thus underestimate extinction risk.

Secondly, there is a lack of models that quantify the impacts of climate change based on altered extremes rather than average conditions. Extreme water temperatures are expected to occur more frequently due to climate change, yet the implications to freshwater fish life-history strategies are not fully understood (Desforges et al., 2021). Fish exposed to high-temperature fluctuations show high levels of cortisol and catecholamines, which in turn affects their stress-coping abilities to other stressors (Alfonso et al., 2020). Extreme thresholds have shown to be better predictors for estimating extinction risk than long-term averages (Barbarossa et al., 2021; Liu et al., 2015; Román-Palacios & Wiens, 2020).

Thirdly, the coverage in terms of river basins and species remains limited. Hanafiah et al. (2011) excluded river basins above 42 °N since the recent glaciation period affects the species discharge relationship. To overcome these shortcomings and to further improve the reliability of characterization factors, this study aims to develop a novel methodology to complement the knowledge on freshwater biodiversity in LCA.

1.4 Research objective

The main research question, 'How can the impact of climate change extremes on freshwater biodiversity be translated into characterization factors for implementation into existing LCA frameworks?', demands a novel methodology to develop characterization factors. The characterization factors can be used in the impact assessment phase of an LCA study to convert inventory data on greenhouse gas (GHG) emissions into an estimate of environmental impact on freshwater biodiversity. The main research question is guided by the following sub-questions: (I) How can geographical range contractions be converted into extinction risk? and; (II) How can extinction risk be translated into characterization factors?

2 Methodology

The modeling of characterization factors is performed in R software (R Core Team, 2020), the scripts are available in App. A. Characterization factors require fate factors and effect factors. The characterization factors report the risk of freshwater species extinction, expressed as the Potentially Disappeared Fraction (PDF), as a result of global warming. Verones et al. (2017) recommend the unit of PDF to stimulate consistency amongst LCA studies. Extinction risk is defined as the proportion of species that are committed to extinction (Thomas et al., 2004). Species extinction is not an instant process but takes place gradually over time. A time lag exists between the pressure and the effect, meaning that the duration of the pressure influences to what extent the effect will occur (Verones et al., 2020).

Fate factors translate the impact of GHGs emitted to the atmosphere to an increase in global air temperature. Effect factors translate the increase in global air temperature to extinction risk. Fate factors are readily available by De Schryver et al. (2010), while effect factors are derived using a novel approach developed in this study. The calculation of the global characterizations factors is summarized in eq. 1

$$CF_{global,x,c} = FF_{x,c} \cdot EF_{global} = \frac{dT}{dGHG} \cdot \frac{dE}{dT} \tag{1}$$

where CF is the characterization factor [PDF·yr·kg^{-1}] for the global scale, the type of GHG x, the cultural perspective c, FF is the fate factor [°C·yr·kg^{-1}], and EF is the effect factor [PDF·°C^{-1}]. FF equals the change in global air temperature T [°C] over the change in emitted GHGs [kg]. EF equals the change in extinction risk E [PDF] over the change in T.

The characterization factors are limited to the global scale due to the fate factors. Fate factors for global warming are of global nature since the short tropospheric mixing time of one year ensures that GHGs are spread during their lifetime (De Schryver et al., 2010; Hauschild & Huijbregts, 2015).

2.1 Fate factor

Fate factors are provided by De Schryver et al. (2009) for 63 GHGs directly related to global warming (Forster et al., 2007). De Schryver et al. (2009) adopted a linear stepwise calculation to account for global air temperature rise resulting from increasing radiative forcing due to increased GHG concentrations. Multiple value choices in the modeling of fate factors are summarized into three cultural perspectives: the individualist, the hierarchist, and the egalitarian perspective. An critical value choice is the time horizon, which determines the duration of the pressure. The hierarchist perspective serves as the benchmark in this study and considers a time horizon of 100 years. The other perspectives are included in App. B. Only direct fate factors are included for the ozone-depleting substances in the hierarchist perspective because of the high uncertainties involved in calculating indirect radiative forcing mechanisms (Hanafiah et al., 2011).

2.2 Effect factor

2.2.1 Converting range contractions to extinction risk

The extinction risk needed for the numerator of the effect factor in eq. 1 is calculated based on data on species-specific range contractions by Barbarossa et al. (2021) for a scenario assuming no dispersal. The dataset comprises 11,425 riverine fish species. A range loss is calculated from the number of five arc-minute grid cells in which at least one or more extreme thresholds are exceeded. Thresholds are set for water flow and temperature parameters, specifically the minimum and maximum weekly flow, the number of zero flow weeks and, the minimum and maximum weekly water temperature. Scenarios are created by combining five global climate models and four representative concentration pathways, aggregated for the warming targets 1.5, 2.0, 3.2 and, 4.5 °C.

The range contractions by Barbarossa et al. (2021) are converted into extinction risk using the extinction metrics from Thomas et al. (2004), outlined in Eqs 2, 3, and 4. Both Eqs 2 and 3 sum up the range contractions before multiplying with the z coefficient. These metrics tend to be weighted more heavily towards species with large distributional areas. Endemic species tend to have small ranges and are prone to extinction due to being restricted to a single geographic range (Lewis, 2006; Parmesan, 2006). For this reason, Eq. 4 is chosen as the benchmark metrics, while the remaining metrics are used for a comparison exercise.

$$E_1 = 1 - \left(\frac{\Sigma A_{new}}{\Sigma A_{original}} \right)^z \tag{2}$$

$$E_2 = 1 - \left\{ \frac{1}{n} \left[\Sigma \left(\frac{A_{new}}{A_{original}} \right) \right] \right\}^z \tag{3}$$

$$E_B = \frac{1}{n} \Sigma \left[1 - \left(\frac{A_{new}}{A_{original}} \right)^z \right] \tag{4}$$

The extinction risks E_1, E_2 and E_B are expressed in PDF. The n refers to the number of species [-], and z is a coefficient [-] derived from the Species-Area Relationship (SAR). $A_{original}$ refers to the area available before the range contraction, and A_{new} refers to the area available after range contraction, both expressed in km^2. A_{new} can be calculated with the percentage of the area threatened [%] and $A_{original}$ (eq. 5), both provided by Barbarossa et al. (2021).

$$A_{new} = \frac{RT}{100} \cdot A_{original} \tag{5}$$

The extinction metrics are based on the SAR, a law that predicts the scaling of species richness with the increasing area available to species. In eq. 6, the SAR is expressed as a power relationship where S is species richness [-], A is the area [km^2], and c and z are constants [-]. The z constant is derived by developing a SAR specific to freshwater riverine species. The classic power SAR is linearized by double-logarithmic transformation (see App. C). Data provided by Tedesco et al. (2017) on species richness [-] and drainage area [km^2] for 3,116 river basins globally are used. Only native freshwater species are considered since exotic species can influence the z component (Baiser & Li, 2018).

$$S = c\, A^z \tag{6}$$

2.2.2 Marginal effect factors

After retrieving the extinction risk, there are two approaches to extract an effect factor: the average and the marginal approach (elaborated in App. D). Verones et al. (2019) recommend providing both effect factors to remain consistent with other LCA methodologies and allow practitioners to choose the most suitable set for their case study.

The marginal effect factors show the effect of an increase in pressure by an incremental amount. To this end, the derivative at the reference state is taken, which is the current situation in this case. The World Meteorological Organization (2021) annually reports the global mean temperature increase compared to the pre-industrial baseline (1850-1900), averaged from five different climate models. The global air temperature increase at the current situation is calculated as the mean annual global temperature increase between 2011 to 2020 and amounts to 1.04 °C. A time period of 10 years is taken to consider potential outliers and remain close to the current situation, and reflect the recent stark increase in global mean temperatures (World Meteorological Organization, 2021).

The relationship between extinction risk and temperature increase is assumed to be linear between 0 and 1.5 °C; therefore, the derivative at 1.2 °C equals the slope between the two points (eq. 7).

$$EF_{marginal} = \left.\frac{dE}{dT}\right|_{T=1.2} = \frac{E(1.5)}{1.5} \tag{7}$$

2.2.3 Average effect factors

The average effect factors reflect the average change in extinction risk per unit of temperature increase. Two data points are required for calculating the average effect factors (Verones et al., 2019): the reference state, i.e., the current situation, and the prospective future state, set at the highest warming target of 4.5 °C. The extinction risk at the current situation is determined in eq. 8, using the slope from eq. 7. Then, the average effect factor is calculated in eq. 9.

$$E(1.2) = \frac{E(1.5)}{1.5} \cdot 1.2 \tag{8}$$

$$EF_{average} = \frac{E(4.5) - E(1.2)}{4.5 - 1.2} \tag{9}$$

2.2.4 Basin level effect factors

The same approach as described above is repeated to calculate effect factors at the basin scale. For each river basin, E is calculated for a subset of species occurring in the river basin in question. To this end, the species' geographic ranges are overlaid with the river basins to determine the proportion of the range of each species belonging to a specific basin. Then, following the methodology from Barbarossa et al. (2021), basin-level ranges are estimated by summing up the area of the grid cells in which none of the extreme thresholds are exceeded for each climate scenario. The different climate scenarios are aggregated at the four warming targets, and the arithmetic mean values are taken for each warming target. Rivers basins with a drainage area smaller than 500 km^2 are excluded due to higher uncertainties in the delineation of species ranges based on hydrological units coarser than km^2 (International Union for Conservation of Nature, 2018). Furthermore, in case of geographic range expansion, A_{new} is capped to $A_{original}$ to simulate zero extinction risk.

2.2.5 Comparison with other approaches

Since there are multiple ways to estimate extinction risk, this section describes other available metrics to compare the range of plausible effect factors. Here, the alternative metrics E_1 and E_2 provided by Thomas et al. (2004) are examined. Other metrics evolve around the unit of Potentially Affected Fraction (PAF). For example, studies assume that half of the affected species or all affected species face extinction (Hauschild & Huijbregts, 2015; Jolliet et al., 2003). Barbarossa et al. (2021) define the PAF for each grid cell and warming target as the proportional number of species threatened over the total number of species. The grid cell-based PAFs are converted to global PAFs using the following weighting approach to account for the varying grid cell sizes (eq. 10)

$$PAF_{g,w} = \frac{\Sigma(PAF_{i,w}A_i)}{\Sigma A_i} \tag{10}$$

where g refers to the global scale, w to the warming target, and i to the grid cell, extinction risks are derived from PAF by either setting PAF values equal to PDF (E_{PAF1}) or by a factor of 0.5 ($E_{PAF0.5}$).

$$E_{PAF1} = PAF \tag{11}$$

$$E_{PAF0.5} = 0.5 \cdot PAF \tag{12}$$

3 Results

3.1 Species Area Relationship

Linear regression of the logarithms of species richness (S) and area (A) provided the following SAR (eq. 13)

$$log_{10}(S) = 0.21 \cdot log_{10}(A) + 1.19 \tag{13}$$

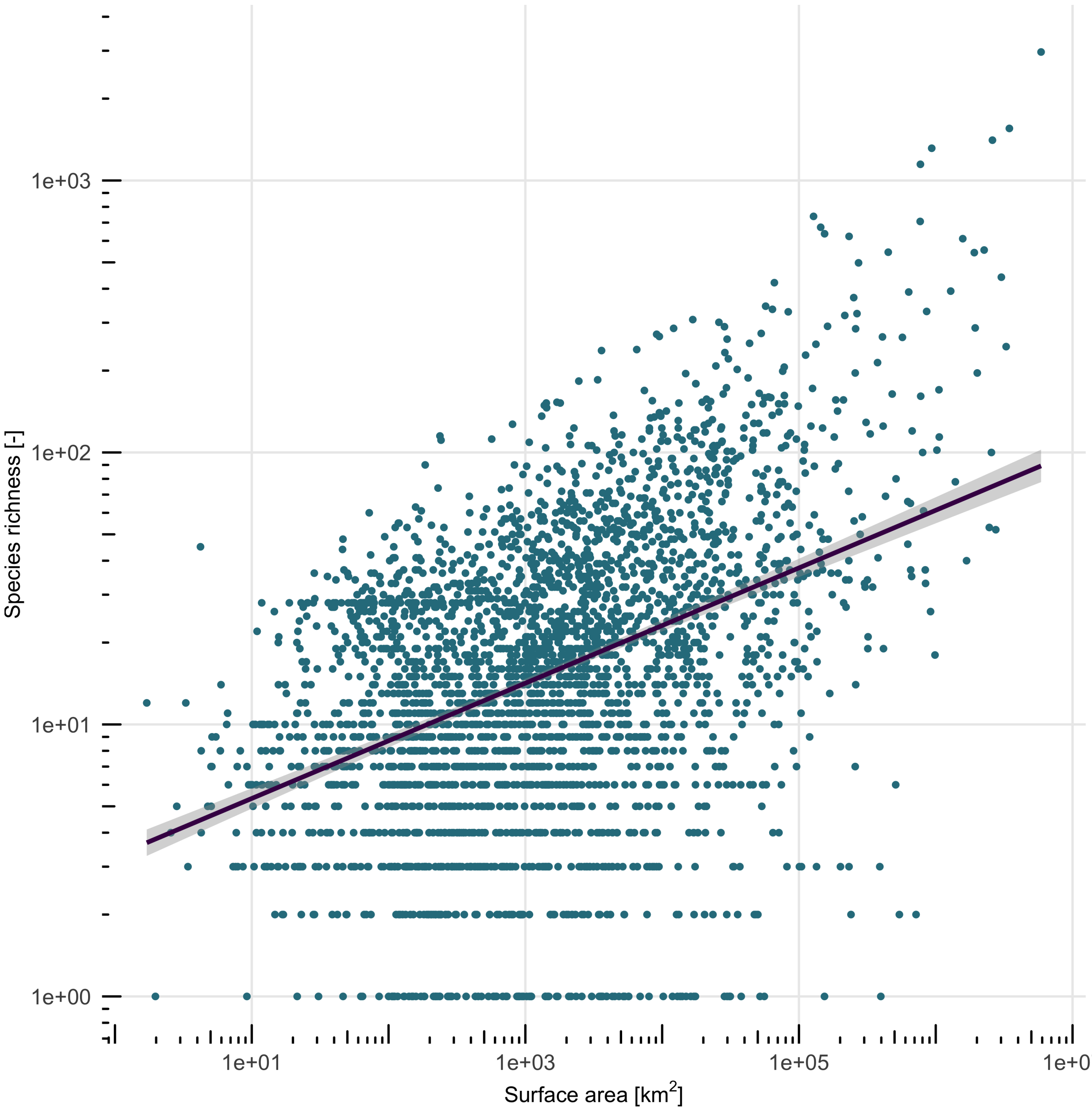

Figure 1: Species Area Relationship plotted as a power function. The sample number of rivers is 3116, each shown as a dot. The line represents a linear regression line, and the shaded area shows the 95% confidence interval.

where 0.21 and 1.19 are regression coefficients. The SAR is depicted in Fig. 1. The z value of 0.21 (r^2 = 0.18) is used to calculate the extinction risk.

3.2 Global characterization factors

The average global characterization factors span a wider range than the marginal global characterization factors (Fig. 2). The ranges amount to $1.33 \cdot 10^{-15}$ - $7.16 \cdot 10^{-11}$ PDF·yr ·kg^{-1} and $4.62 \cdot 10^{-16}$ - $2.49 \cdot 10^{-11}$ PDF·yr· kg^{-1} for the average and marginal approach respectively. The ranges are caused by fate factors specific to each GHG, resulting in characterization factors specific to each GHG. The largest characterization factors found are for the GHG sulfur hexafluoride. Most characterization factors are skewed to the lower end of the ranges (Fig. 2). The average approach is also characterized by higher arithmetic mean and the median values (respectively $1.44 \cdot 10^{-11}$ & 5.17 PDF·yr·kg^{-12}) than the marginal approach (respectively $4.99 \cdot 10^{-12}$ & $1.79 \cdot 10^{-12}$ PDF·yr·kg^{-1}).

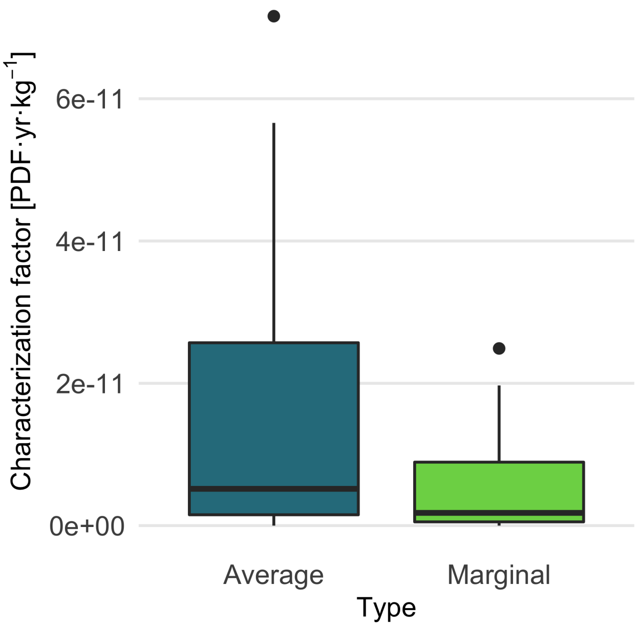

Figure 2: Ranges of the global characterization factors for the average and marginal approach, providing a characterization factor for each of the 63 GHG. The boxes represent the interquartile ranges, the marked lines inside the boxes represent the medians, and the dots represent the minima and maxima.

3.3 Basin level effect factors

The range describing the effect factors specific to each river basin spans from 0 - $1.57 \cdot 10^{-1}$ PDF·°C^{-1} for the average effect factors and 0 - $2.41 \cdot 10^{-1}$ PDF·°C^{-1} for the marginal effect factors. Thus, the marginal approach is associated with a wider range of effect factors on the river basin level than the average approach. High marginal effect factors are found for river basins expected to be highly affected by climate change at a 1.5 °C warming target. However, the arithmetic mean and median values are higher for the average approach ($1.55 \cdot 10^{-2}$ & $6.42 \cdot 10^{-3}$ PDF·°C^{-1} respectively) than for the marginal approach ($1.45 \cdot 10^{-2}$ & $2.61 \cdot 10^{-3}$ PDF·°C^{-1} respectively).

A weighted mean is calculated to consider the size of each river basin. The weighted mean values for the various river basins range from $2.69 \cdot 10^{-2}$ PDF·°C^{-1} for the average effect factor and $1.96 \cdot 10^{-2}$ PDF·°C^{-1} for the marginal effect factor. This finding implies that, on average, 2.69% or 1.96% of the species are committed to local extinction per °C increase. Fig. 3 shows the average and marginal effect factors. The spatial pattern is similar in both subplots; higher effect factors are typically found in the arid regions in Australia, Northern Africa, the Middle East and, Central Asia. Basins at higher altitudes are less prone to extinction. South America has high average effect factors. The regional effect factors are highly variable among the river basins.

It was not possible to derive effect factors for all river basins. For the average approach, missing values are slightly higher due to missing data for the 4.5 °C warming target. The effect factors for 22.3 % (marginal approach) and 29.7 % (average approach) of the river basins equal zero, meaning these river basins are not expected to be affected by climate change.

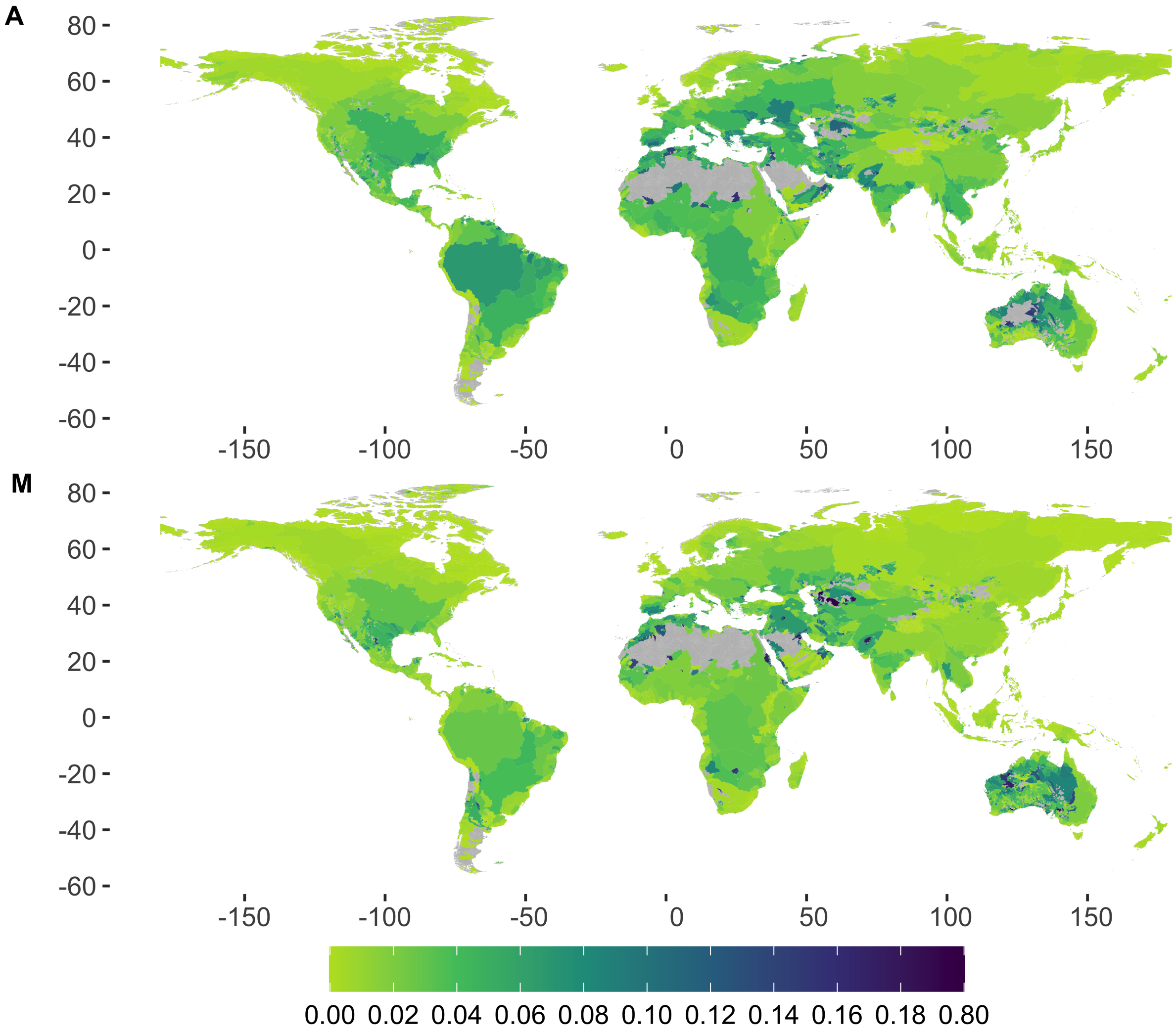

Figure 3: Basin level average (A) and marginal (M) effect factors [PDF·°C^{-1}]. Missing values are grey.

3.4 Comparing effect factors

The effect factors are compared with the metrics of E_1, E_2, E_{PAF1}, and $E_{PAF0.5}$ in Fig. 4. Most extinction metrics provide lower effect factors compared to the benchmark effect factor (E_B). Only E_{PAF1}, which assumes that all potentially affected species are committed to extinction, provides remarkably higher effect factors.

4 Discussion

4.1 Comparison of results

Hanafiah et al. (2011) derived characterization factors via the species discharge relationship, while the new characterization factors proposed in this study are derived via assessing range contractions due to exceeding extremes in water temperature and flow habitat factors. Although direct comparison of the global characterization factors is not possible due to varying units, the ranges of marginal effect factors on the river basin scale can be compared. The range consisting of marginal effect factors for the various river basins reported by Hanafiah et al. (2011), $3 \cdot 10^{-3}$ - $2 \cdot 10^{-2}$ PDF·°C^{-1}, is smaller than found in this study (0 - $2.41 \cdot 10^{-1}$ PDF·°C^{-1}).

LC-IMPACT adapted the effect factor calculated by Hanafiah et al. (2011) to consider non-marginal changes by estimating the number and change of fish species per river basin and dividing by the total number of species for the global effect factor (Steinmann & Huijbregts, 2019). They arrive at an average weighted effect factor of $1.15 \cdot 10^{-2}$ PDF·°C^{-1}, which is almost half the area-weighted basin-average effect factor of $2.69 \cdot 10^{-2}$ derived in this study. Furthermore, the provided global characterization factors of $5.47 \cdot 10^{-16}$ - $1.08 \cdot 10^{-12}$ PDF·yr·kg^{-1} (the range describes characterization factors specific to a GHG) by Steinmann and Huijbregts (2019) are up to 1 order of magnitude lower than calculated in this study.

A plausible explanation for the lower bound in the range of values can be found in the selection of river basins: this study calculated marginal and or average effect factors for 9,176 river basins, while Hanafiah et al. (2011) limited the selection to 326 rivers basins, which are all located below 42 °N. Indeed, the basins at higher latitudes have low effect factors, as highlighted in Fig. 3. A plausible explanation for the upper bound in the range of values lies in the inclusion of direct water temperature effects, which is not considered by Hanafiah et al. (2011). Hanafiah et al. (2011) acknowledge that temperature can have a significant influence and draws upon the example of Verones et al. (2010), where seasonal temperature effects resulted in differences up to five orders of magnitude for the effect of thermal pollution on freshwater fish in the Rhine. The highest effect factors were found in the summer months. Therefore the inclusion of water temperature is likely to explain the higher maximum effect factors.

In the impact category family ReCiPe 2016 (Huijbregts et al., 2016) and LC-impact 2016 (Steinmann & Huijbregts, 2019), a global average effect factor of $3.7 \cdot 10^{-2}$ PDF·°C^{-1} is used for terrestrial species. This future-oriented effect factor is based on a meta-analysis by Urban (2015). In comparison, the average effect factors from Fig. 4 all have slightly higher values. This finding is in line with the general expectation that freshwater species are more

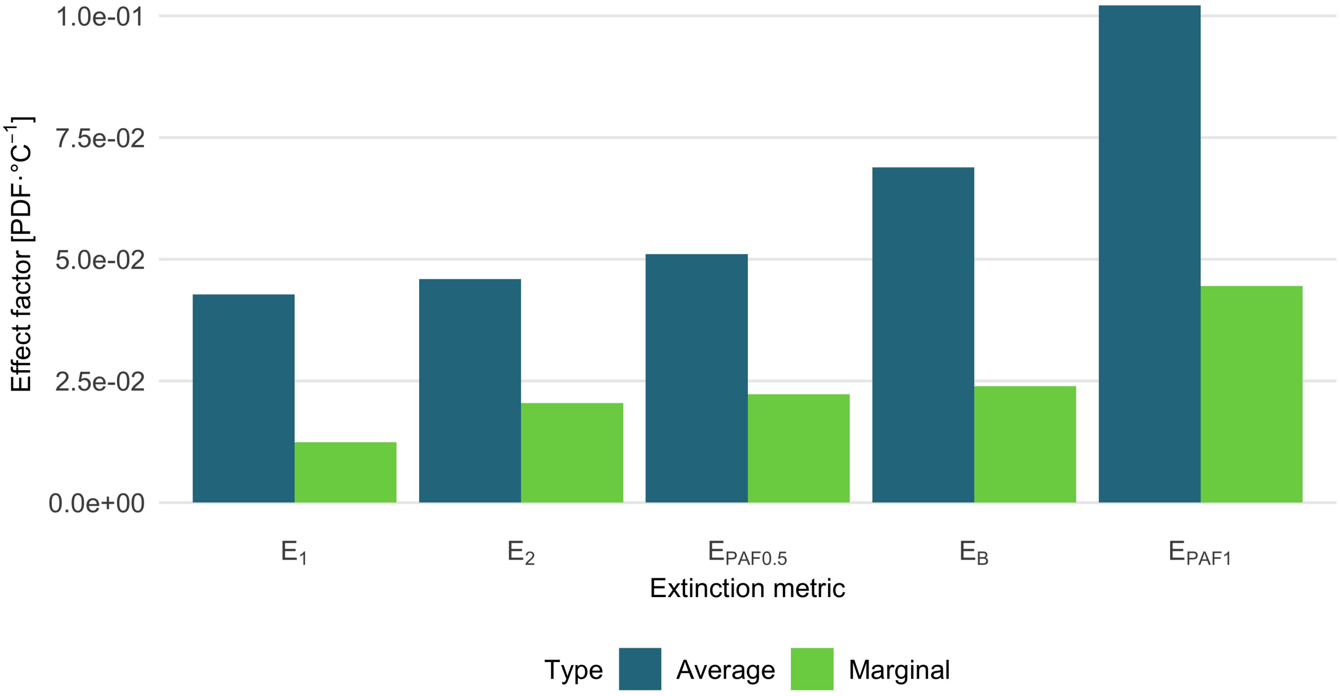

Figure 4: Bar chart displaying various effect factors in PDF·°C^{-1} for the average and marginal type. Extinction metrics adopted are the equations provided by Thomas et al. (2004): E_1, E_2, and the benchmark equation E_B. E_{PAF1} and $E_{PAF0.5}$ are based on Potentially Affected Fractions of species.

severely threatened by climate change than terrestrial species (Collen et al., 2014).

4.2 Limitations

4.2.1 Concerning fate factors

Limitations concerning the fate factors are the exclusion of indirect effects ozone-depleting chemicals. If included, the characterization factors of certain GHGs would be negative. For the long-lived GHGs, the egalitarian cultural perspective may be more suitable, as a large proportion of the radiation will occur after 100 years (Steinmann & Huijbregts, 2019). However, the egalitarian cultural perspective is characterized by higher uncertainties (Huijbregts et al., 2016).

4.2.2 Concerning range contractions

This study is based on the results of Barbarossa et al. (2021) that comprehensively assessed threats to geographic ranges of riverine fish species by examining hydrological extremes' species-specific thresholds for five habitat parameters concerning water temperature and streamflow. A set of variables cannot fully capture the effects of global warming on fish species. For example, seasonal effects are not considered but could be important, especially if species are adapted to specific water flow and temperature patterns (Barbarossa et al., 2021).

The hydrological model used for deriving the range contractions does not account for water stratification, which is why lentic species are excluded (Barbarossa et al., 2021). Riverine species are considered a representative proxy for freshwater biodiversity (Izzo et al., 2016). However, limiting to one taxon remains an important limitation in LCA as highly sensitive species can be overlooked (Curran et al., 2011). Tendall et al. (2014) included macro-invertebrates (Ephemera, Plecoptera, and Trichoptera) in their model and stated that these species better represent smaller streams. Tendall et al. (2014) found that these species are more vulnerable to changes in discharge compared to fish species.

4.2.3 Concerning extinction risk

Extinction risk is related to many ecological principles which do not fit easily within the LCA framework (Curran et al., 2011). Endpoint modeling in LCA is characterized by high uncertainty (Hauschild & Huijbregts, 2015), yet it provides more tangible value to society in understanding the state of freshwater biodiversity. Estimates of extinction risk cannot accurately reflect all ecological principles and have shown high variability among studies, both within the LCA and non-LCA fields (Curran et al., 2016). Bellard et al. (2012) classified multiple important factors according to their expected effect on extinction risk. The following factors are selected from the list as highly relevant to this study: the negligence of positive effects (classified as an overestimating factor), the negligence of species response (a highly overestimating factor), resource and biotic factors (a highly underestimating factor) and negligence of dynamics at the ecosystem level (a highly underestimating factor). The question remains to which extent this qualitative list of underestimating and overestimating effects balance out. A more detailed contextualization of these trade-offs for the results of this study is provided below.

Potential positive effects of climate change could be that the minimum water temperature is no longer exceeded for particular species in certain habitats.

Yousefi et al. (2020) show that climate change has winners and losers; some species lose habitat while others gain. A trade-off here is that the winners of climate change could be invasive species, which could displace native species and alter trophic webs (Flitcroft et al., 2019). Hanafiah et al. (2013) developed characterization factors for the introduction of exotic species for the transportation of goods through the Rhine-Main-Danube waterway. They assessed the relative contribution of the introduction of exotic species, global warming, and other impact categories by applying characterization factors (including the characterization factors for global warming developed by Hanafiah et al. (2011)) to a case study of transported goods. The introduction of exotic species was found to explain 70-85% of the effect on freshwater biodiversity. Positive effects are not expected to have a large overestimating effect on the calculation of extinction risk, since many positive effects are associated with negative effects such as invasive species expansion.

Species responses to climate change form a broad category, where dispersal abilities and adaptive capacity are highly relevant. While the speed of climate change is expected to exceed the adaptation or dispersal ability of freshwater species (Radinger et al., 2017; Radinger & Wolter, 2015; Reid et al., 2019), it requires careful consideration. Dispersal of riverine fish species remains poorly understood (Harte & Kitzes, 2012) and is restricted due to the dendritic structure of river basins, natural barriers, and fragmentation. Fragmentation is expected to increase due to drying impacts arising from climate change (Jaeger et al., 2014; Knouft & Ficklin, 2017). This might impair the ability of fish to combat climate change by dispersal. On the other hand, species adaptation frequently occurs at the edge of species' ranges and may be of importance for particular species (Knouft & Ficklin, 2017), especially for those with short generation time (Radinger et al., 2017). Therefore, not considering this factor in this study likely overestimates the extinction risks obtained.

Resource and biotic factors comprise inter-specific relationships, trophic webs, and ecological networks. While these are neglected in the assessment for complexity reasons, the interactions could result in cascading effects and co-extinctions, also called chains of extinction (Harte & Kitzes, 2012). One example is the Allee effect, which describes a positive relationship between fitness and population size (Dulvy et al., 2003; Tedesco et al., 2013). Various mechanisms could explain the Allee effect, e.g., low reproduction due to mate limitation. Predator satiation, cooperative breeding, and cooperative defense are proven mechanisms to explain the Allee effect in fish populations (Kramer et al., 2009). This factor is expected to underestimate the extinction risks derived in this study.

Finally, dynamics at the ecosystem level do not typically fit within the linear damage relationships adopted in LCA. Examples are tipping points or other stochastic processes leading to extinction (Curran et al., 2011; Tedesco et al., 2013). The vulnerability of species to stochastic events is highly variable, due to different habitat preferences, small population sizes, or limited ranges (Moyle et al., 2013). Examples of stochastic events triggered due to global warming are large floods (Mirza, 2011). This factor is also expected to underestimate the extinction risks derived in this study.

4.2.4 Concerning the Species-Area Relationship

There is no consensus in the literature whether the SAR potentially overestimates (He & Hubbell, 2011) or underestimates (Connor & McCoy, 2013; Harte & Kitzes, 2012) extinction risk. According to Harte and Kitzes (2012), the SAR depends not only on the size of habitats but also on the shape of habitats. Connor and McCoy (2013) state that the fragmentation will disturb the SAR for areas below 100 ha. Furthermore, the scale sensitivity of the SAR needs further research (Pereira et al., 2012). The SAR assumes that species are homogeneously distributed (He & Hubbell, 2011). And species richness may be overestimated for river basins above 42 °N by the SAR, since those basins have not reached their maximum species richness potential since the last glaciation period (Hanafiah et al., 2011).

The methodology in this study only requires the SAR for deriving the z component to be used in the extinction metric by Thomas et al. (2004). Therefore, a sensitivity analysis is carried out with the standard z value of 0.25 used by Thomas et al. (2004). The z component can be considered a sensitive modeling parameter: for a 16% increase in z, the effect factors increase by 10.7% (to $7.63 \cdot 10^{-2}$ PDF·°C^{-1}) for the average approach and 16.4% (to $2.78 \cdot 10^{-2}$ PDF·°C^{-1}) for the marginal approach. Despite the limitations, SAR approaches remain the best tool available to date (Oberdorff et al., 2011).

4.2.5 Concerning marginal and average effect factors

Both the marginal and average approaches to deriving effect factors have trade-offs (Heijungs, 2021; Huijbregts et al., 2011). The marginal approach is useful to address the question of incremental efficiency. In Fig. D.1 it can be seen that steeper slopes are expected at higher temperature increases. The marginal effect factors do not consider extinction risk at higher warming targets, explaining the conservative estimates compared to the average effect factor. Therefore, the average effect factor is better suitable for the long-term perspective.

4.3 Recommendations

Recommendations for future advancements are to expand taxonomic coverage to include lentic species and macro-invertebrates to improve the representativeness of species coverage for freshwater biodiversity. This study focuses on the species richness metric, which describes the community level and neglects the genetic and landscape levels of biodiversity. Complementary models can be useful to compare other facets of biodiversity to describe ecosystem health more accurately (Curran et al., 2011; Tendall et al., 2014). A valuable metric for complementary LCA studies is functional diversity, which considers functional traits of a species and reflects ecosystem functioning better than species richness (Scherer et al., 2020).

Another important task for future studies is to harmonize more impact categories containing an impact pathway for freshwater biodiversity into existing LCA impact assessment families such as LC-IMPACT. For example, the characterization factors for the impact of the introduction of exotic species (Hanafiah et al., 2013) on freshwater biodiversity can only be applied to the case of transported goods. Methodologies use differing units, and therefore conclusions on the contribution of the different stressors cannot be established. Besides, numerous stressors still need to be included in the LCA framework for freshwater biodiversity to cover all the threats mentioned by Dudgeon (2019).

5 Conclusion

A novel methodology has been developed to translate the impact of climate change on freshwater biodiversity into characterizations factors intended for LCA studies. Global and basin-level extinction risks are quantified based on the geographic range contractions estimated by Barbarossa et al. (2021), which are converted with the extinction metrics from Thomas et al. (2004) to extinction risk. The z coefficient needed for the extinction metrics is determined by developing a SAR specific to freshwater fish species. Marginal and average effect factors are derived from mapping extinction risk against corresponding global mean temperature increases. Finally, characterization factors are derived by multiplying the effect factors by the fate factors provided by De Schryver et al. (2009).

The recommended sets provide a global characterization factor for each of the 63 GHGs and range from $1.33 \cdot 10^{-15}$ - $7.16 \cdot 10^{-11}$ PDF·yr·kg^{-1} and $4.62 \cdot 10^{-16}$ - $2.49 \cdot 10^{-11}$ PDF·yr·kg^{-1} for the average and marginal approach respectively. LCA practitioners can use the characterization factors to translate inventory data on GHG emissions arising throughout the life-cycle of a product into an estimate of the fraction of freshwater species extinction. The new set of characterization factors is up to one order of magnitude higher than previously calculated ones, stressing the importance of considering extreme values and including water temperature variables besides streamflow variables when assessing impacts of climate change in LCA. The new advances can contribute to a better understanding of the environmental impact of products and attribute to more comprehensive sustainability assessments of climate change by including impacts on freshwater biodiversity.

A Code availability

The following files are available at https://github.com/Sifdevisser/LCA_Freshwater_biodiversity_MSc_thesis:

- *SAR.R*. This file contains all the code related to the development of the Species Area Relationship , e.g., for the results in section 3.1.
- *GlobalCF.R*. This file contains all the code related to the global effect- and characterization factors, e.g., for the results in sections 3.2 and 3.4.
- *Average_area_basin.R*. This file handles the geographical range contractions on the basin-level scale. The BasinEF.R file further elaborates upon the output table.
- *BasinEF.R*. This file contains all the code from basin-level range contractions to basin-level effect factors, e.g., for the results in section 3.3.

B Characterization factors

Multiple value choices are made in the modeling of the characterization factors. Firstly, the value choices in the modeling of the fate factors are summarized (Table B1) into the concept of cultural perspectives for consistency purposes (De Schryver et al., 2009). Each cultural perspective envisions a scenario. The individualist perspective is optimistic and considers a shorter time horizon. The egalitarian perspective, on the other hand, urges to consider long time horizons and worst-case scenarios. The hierachist perspective aims to include model aspects based on the level of scientific consensus and believes that with proper management, certain impacts can be avoided. Secondly, 5 different extinction metrics are available for translating range contractions into extinction risk (E_1, E_2, E_B, E_{PAF1}, and $E_{PAF0.5}$). The first 3 are extinction metrics provided by Thomas et al. (2004), while the other 2 are based on PAF values, where E_{PAF1} assumes all potentially affected species are commited to extinction and $E_{PAF0.5}$ considers half of the potentially affected species to be committed to extinction. Thirdly, there are 2 approaches for deriving effect factors from extinction risk: the marginal and the average approach.

Table B1: Cultural perspective

Category	Individualist	Hierarchist	Egalitarian
Time horizon	20 yr	100 yr	1000 yr
Climate-carbon feedbacks for non-CO^2 GHG	No	Yes	N/A
Future socio-economic developments	Optimistic	Baseline	Pessimistic
Adaptation potential	Adaptive	Controlling	Comprehensive
Indirect effects ozone-depleting chemicals included	Yes	No	No

Note. Adapted from *Recipe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level*, p.24, by Huijbregts et al., 2016. Retrieved October 10, 2020, from https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf

All 30 sets of characterization factors are provided so that the LCA practitioner can choose which set fits their research design best. The sets for the hierarchist perspective and the E_B extinction metrics are central in this study (Table B.2.1 and B.2.2). The characterization factors for the individualist perspective can be found in subsection B.1 (Table B.1.1 and B.1.2 for the average and marginal approach respectively), the hierarchical perspective can be found in subsection B.2 (Table B.2.1 and B.2.2 for the average and marginal approach respectively) and the egalitarian perspective can be found in subsection B.3 (Table B.3.1 and B.3.2 for the average and marginal approach respectively).

B.1 Individualist perspective

Table B.1.1: Average global characterization factors [PDF·yr·kg^{-1}] for the individualist cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
1	CO_2	$3.59 \cdot 10^{-16}$	$3.86 \cdot 10^{-16}$	$5.79 \cdot 10^{-16}$	$8.58 \cdot 10^{-16}$	$4.29 \cdot 10^{-16}$
2	CH_4	$2.99 \cdot 10^{-14}$	$3.2 \cdot 10^{-14}$	$4.81 \cdot 10^{-14}$	$7.13 \cdot 10^{-14}$	$3.57 \cdot 10^{-14}$
3	N_2O	$1.14 \cdot 10^{-13}$	$1.22 \cdot 10^{-13}$	$1.83 \cdot 10^{-13}$	$2.72 \cdot 10^{-13}$	$1.36 \cdot 10^{-13}$
Ozone-depleting substances						
4	CFC-11	$-6.33 \cdot 10^{-13}$	$-6.79 \cdot 10^{-13}$	$-1.02 \cdot 10^{-12}$	$-1.51 \cdot 10^{-12}$	$-7.56 \cdot 10^{-13}$
5	CFC-12	$9.16 \cdot 10^{-13}$	$9.82 \cdot 10^{-13}$	$1.47 \cdot 10^{-12}$	$2.19 \cdot 10^{-12}$	$1.09 \cdot 10^{-12}$

Table B.1.1 continued. Average global characterization factors [PDF·yr·kg^{-1}] for the individualist cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
6	CFC-13	$4.24 \cdot 10^{-12}$	$4.55 \cdot 10^{-12}$	$6.83 \cdot 10^{-12}$	$1.01 \cdot 10^{-11}$	$5.07 \cdot 10^{-12}$
7	CFC-113	$1.27 \cdot 10^{-12}$	$1.36 \cdot 10^{-12}$	$2.05 \cdot 10^{-12}$	$3.03 \cdot 10^{-12}$	$1.52 \cdot 10^{-12}$
8	CFC-114	$3.02 \cdot 10^{-12}$	$3.24 \cdot 10^{-12}$	$4.86 \cdot 10^{-12}$	$7.21 \cdot 10^{-12}$	$3.61 \cdot 10^{-12}$
9	CFC-115	$2.04 \cdot 10^{-12}$	$2.19 \cdot 10^{-12}$	$3.29 \cdot 10^{-12}$	$4.87 \cdot 10^{-12}$	$2.44 \cdot 10^{-12}$
10	Carbon tetrachloride	$-1.23 \cdot 10^{-12}$	$-1.32 \cdot 10^{-12}$	$-1.98 \cdot 10^{-12}$	$-2.93 \cdot 10^{-12}$	$-1.47 \cdot 10^{-12}$
11	Methyl bromide	$-2.02 \cdot 10^{-12}$	$-2.16 \cdot 10^{-12}$	$-3.24 \cdot 10^{-12}$	$-4.81 \cdot 10^{-12}$	$-2.41 \cdot 10^{-12}$
12	Methyl chloroform	$-2.71 \cdot 10^{-13}$	$-2.91 \cdot 10^{-13}$	$-4.36 \cdot 10^{-13}$	$-6.47 \cdot 10^{-13}$	$-3.23 \cdot 10^{-13}$
13	HCFC-22	$1.64 \cdot 10^{-12}$	$1.76 \cdot 10^{-12}$	$2.65 \cdot 10^{-12}$	$3.92 \cdot 10^{-12}$	$1.96 \cdot 10^{-12}$
14	HCFC-123	$1.05 \cdot 10^{-13}$	$1.13 \cdot 10^{-13}$	$1.69 \cdot 10^{-13}$	$2.51 \cdot 10^{-13}$	$1.26 \cdot 10^{-13}$
15	HCFC-124	$8.13 \cdot 10^{-13}$	$8.72 \cdot 10^{-13}$	$1.31 \cdot 10^{-12}$	$1.94 \cdot 10^{-12}$	$9.71 \cdot 10^{-13}$
16	HCFC-141b	$7.62 \cdot 10^{-13}$	$8.17 \cdot 10^{-13}$	$1.23 \cdot 10^{-12}$	$1.82 \cdot 10^{-12}$	$9.09 \cdot 10^{-13}$
17	HCFC-142b	$2.08 \cdot 10^{-12}$	$2.24 \cdot 10^{-12}$	$3.36 \cdot 10^{-12}$	$4.98 \cdot 10^{-12}$	$2.49 \cdot 10^{-12}$
18	HCFC-225ca	$1.69 \cdot 10^{-13}$	$1.81 \cdot 10^{-13}$	$2.71 \cdot 10^{-13}$	$4.03 \cdot 10^{-13}$	$2.01 \cdot 10^{-13}$
19	HCFC-225cb	$7.96 \cdot 10^{-13}$	$8.54 \cdot 10^{-13}$	$1.28 \cdot 10^{-12}$	$1.90 \cdot 10^{-12}$	$9.50 \cdot 10^{-13}$
20	Halon-1211	$-1.71 \cdot 10^{-11}$	$-1.83 \cdot 10^{-11}$	$-2.75 \cdot 10^{-11}$	$-4.08 \cdot 10^{-11}$	$-2.04 \cdot 10^{-11}$
21	Halon-1301	$-2.84 \cdot 10^{-11}$	$-3.05 \cdot 10^{-11}$	$-4.57 \cdot 10^{-11}$	$-6.78 \cdot 10^{-11}$	$-3.39 \cdot 10^{-11}$
22	Halon-2402	$-2.52 \cdot 10^{-11}$	$-2.71 \cdot 10^{-11}$	$-4.06 \cdot 10^{-11}$	$-6.03 \cdot 10^{-11}$	$-3.01 \cdot 10^{-11}$
Hydrofluorcarbons						
23	HFC-23	$4.71 \cdot 10^{-12}$	$5.05 \cdot 10^{-12}$	$7.58 \cdot 10^{-12}$	$1.12 \cdot 10^{-11}$	$5.62 \cdot 10^{-12}$
24	HFC-32	$9.16 \cdot 10^{-13}$	$9.82 \cdot 10^{-13}$	$1.47 \cdot 10^{-12}$	$2.19 \cdot 10^{-12}$	$1.09 \cdot 10^{-12}$
25	HFC-43-10mee	$1.63 \cdot 10^{-12}$	$1.74 \cdot 10^{-12}$	$2.62 \cdot 10^{-12}$	$3.88 \cdot 10^{-12}$	$1.94 \cdot 10^{-12}$
26	HFC-125	$2.49 \cdot 10^{-12}$	$2.68 \cdot 10^{-12}$	$4.02 \cdot 10^{-12}$	$5.96 \cdot 10^{-12}$	$2.98 \cdot 10^{-12}$
27	HFC-134a	$1.50 \cdot 10^{-12}$	$1.61 \cdot 10^{-12}$	$2.42 \cdot 10^{-12}$	$3.59 \cdot 10^{-12}$	$1.79 \cdot 10^{-12}$
28	HFC-143a	$2.31 \cdot 10^{-12}$	$2.48 \cdot 10^{-12}$	$3.72 \cdot 10^{-12}$	$5.52 \cdot 10^{-12}$	$2.76 \cdot 10^{-12}$
29	HFC-227ea	$2.08 \cdot 10^{-12}$	$2.24 \cdot 10^{-12}$	$3.36 \cdot 10^{-12}$	$4.98 \cdot 10^{-12}$	$2.49 \cdot 10^{-12}$
30	HFC-245fa	$1.33 \cdot 10^{-12}$	$1.42 \cdot 10^{-12}$	$2.14 \cdot 10^{-12}$	$3.17 \cdot 10^{-12}$	$1.58 \cdot 10^{-12}$
31	HFC-152a	$1.72 \cdot 10^{-13}$	$1.84 \cdot 10^{-13}$	$2.76 \cdot 10^{-13}$	$4.10 \cdot 10^{-13}$	$2.05 \cdot 10^{-13}$
32	HFC-236fa	$3.18 \cdot 10^{-12}$	$3.41 \cdot 10^{-12}$	$5.13 \cdot 10^{-12}$	$7.60 \cdot 10^{-12}$	$3.80 \cdot 10^{-12}$
33	HFC-365mfc	$9.93 \cdot 10^{-13}$	$1.06 \cdot 10^{-12}$	$1.60 \cdot 10^{-12}$	$2.37 \cdot 10^{-12}$	$1.19 \cdot 10^{-12}$
Perfluorinated compounds						
34	Sulphur hexafluoride	$6.38 \cdot 10^{-12}$	$6.84 \cdot 10^{-12}$	$1.03 \cdot 10^{-11}$	$1.52 \cdot 10^{-11}$	$7.61 \cdot 10^{-12}$
35	Nitrogen trifluoride	$5.26 \cdot 10^{-12}$	$5.65 \cdot 10^{-12}$	$8.47 \cdot 10^{-12}$	$1.26 \cdot 10^{-11}$	$6.28 \cdot 10^{-12}$
36	PFC-14	$2.05 \cdot 10^{-12}$	$2.19 \cdot 10^{-12}$	$3.29 \cdot 10^{-12}$	$4.88 \cdot 10^{-12}$	$2.44 \cdot 10^{-12}$
37	PFC-116	$3.39 \cdot 10^{-12}$	$3.64 \cdot 10^{-12}$	$5.46 \cdot 10^{-12}$	$8.09 \cdot 10^{-12}$	$4.05 \cdot 10^{-12}$
38	PFC-218	$2.48 \cdot 10^{-12}$	$2.66 \cdot 10^{-12}$	$4.00 \cdot 10^{-12}$	$5.93 \cdot 10^{-12}$	$2.96 \cdot 10^{-12}$
39	PFC-318	$2.87 \cdot 10^{-12}$	$3.08 \cdot 10^{-12}$	$4.62 \cdot 10^{-12}$	$6.86 \cdot 10^{-12}$	$3.43 \cdot 10^{-12}$
40	PFC-3-1-10	$2.49 \cdot 10^{-12}$	$2.67 \cdot 10^{-12}$	$4.00 \cdot 10^{-12}$	$5.94 \cdot 10^{-12}$	$2.97 \cdot 10^{-12}$
41	PFC-4-1-12	$2.56 \cdot 10^{-12}$	$2.74 \cdot 10^{-12}$	$4.12 \cdot 10^{-12}$	$6.11 \cdot 10^{-12}$	$3.06 \cdot 10^{-12}$
42	PFC-5-1-14	$2.60 \cdot 10^{-12}$	$2.79 \cdot 10^{-12}$	$4.19 \cdot 10^{-12}$	$6.21 \cdot 10^{-12}$	$3.11 \cdot 10^{-12}$
43	PFC-9-1-18	$2.16 \cdot 10^{-12}$	$2.32 \cdot 10^{-12}$	$3.48 \cdot 10^{-12}$	$5.16 \cdot 10^{-12}$	$2.58 \cdot 10^{-12}$
44	Trifluoromethyl sulphur pentafluoride	$5.18 \cdot 10^{-12}$	$5.55 \cdot 10^{-12}$	$8.34 \cdot 10^{-12}$	$1.24 \cdot 10^{-11}$	$6.18 \cdot 10^{-12}$
Fluorinated ethers						

Table B.1.1 continued. Average global characterization factors [PDF·yr·kg^{-1}] for the individualist cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
45	HFE-125	$5.43 \cdot 10^{-12}$	$5.83 \cdot 10^{-12}$	$8.75 \cdot 10^{-12}$	$1.30 \cdot 10^{-11}$	$6.49 \cdot 10^{-12}$
46	HFE-134	$4.79 \cdot 10^{-12}$	$5.14 \cdot 10^{-12}$	$7.72 \cdot 10^{-12}$	$1.14 \cdot 10^{-11}$	$5.72 \cdot 10^{-12}$
47	HFE-143a	$1.04 \cdot 10^{-12}$	$1.11 \cdot 10^{-12}$	$1.67 \cdot 10^{-12}$	$2.47 \cdot 10^{-12}$	$1.24 \cdot 10^{-12}$
48	HCFE-235da2	$4.84 \cdot 10^{-13}$	$5.19 \cdot 10^{-13}$	$7.78 \cdot 10^{-13}$	$1.15 \cdot 10^{-12}$	$5.77 \cdot 10^{-13}$
49	HFE-245cb2	$1.09 \cdot 10^{-12}$	$1.17 \cdot 10^{-12}$	$1.76 \cdot 10^{-12}$	$2.61 \cdot 10^{-12}$	$1.30 \cdot 10^{-12}$
50	HFE-245fa2	$8.94 \cdot 10^{-13}$	$9.59 \cdot 10^{-13}$	$1.44 \cdot 10^{-12}$	$2.14 \cdot 10^{-12}$	$1.07 \cdot 10^{-12}$
51	HFE-254cb2	$5.48 \cdot 10^{-13}$	$5.87 \cdot 10^{-13}$	$8.82 \cdot 10^{-13}$	$1.31 \cdot 10^{-12}$	$6.54 \cdot 10^{-13}$
52	HFE-347mcc3	$7.79 \cdot 10^{-13}$	$8.35 \cdot 10^{-13}$	$1.25 \cdot 10^{-12}$	$1.86 \cdot 10^{-12}$	$9.30 \cdot 10^{-13}$
53	HFE-347pcf2	$7.53 \cdot 10^{-13}$	$8.08 \cdot 10^{-13}$	$1.21 \cdot 10^{-12}$	$1.80 \cdot 10^{-12}$	$8.99 \cdot 10^{-13}$
54	HFE-356pcc3	$1.52 \cdot 10^{-13}$	$1.63 \cdot 10^{-13}$	$2.45 \cdot 10^{-13}$	$3.63 \cdot 10^{-13}$	$1.81 \cdot 10^{-13}$
55	HFE-449sl	$4.22 \cdot 10^{-13}$	$4.53 \cdot 10^{-13}$	$6.79 \cdot 10^{-13}$	$1.01 \cdot 10^{-12}$	$5.04 \cdot 10^{-13}$
56	HFE-569sf2	$7.87 \cdot 10^{-14}$	$8.45 \cdot 10^{-14}$	$1.27 \cdot 10^{-13}$	$1.88 \cdot 10^{-13}$	$9.40 \cdot 10^{-14}$
57	HFE-43-10pccc124	$2.48 \cdot 10^{-12}$	$2.66 \cdot 10^{-12}$	$4.00 \cdot 10^{-12}$	$5.93 \cdot 10^{-12}$	$2.96 \cdot 10^{-12}$
58	HFE-236ca12	$3.16 \cdot 10^{-12}$	$3.39 \cdot 10^{-12}$	$5.08 \cdot 10^{-12}$	$7.54 \cdot 10^{-12}$	$3.77 \cdot 10^{-12}$
59	HFE-338pcc13	$1.99 \cdot 10^{-12}$	$2.14 \cdot 10^{-12}$	$3.21 \cdot 10^{-12}$	$4.76 \cdot 10^{-12}$	$2.38 \cdot 10^{-12}$
Perfluoropolyethers						
60	PFPMIE	$3.00 \cdot 10^{-12}$	$3.21 \cdot 10^{-12}$	$4.82 \cdot 10^{-12}$	$7.15 \cdot 10^{-12}$	$3.58 \cdot 10^{-12}$
Hydrocarbons and other compounds						
61	Dimethylether	$5.86 \cdot 10^{-16}$	$6.29 \cdot 10^{-16}$	$9.44 \cdot 10^{-16}$	$1.40 \cdot 10^{-15}$	$7.00 \cdot 10^{-16}$
62	Methylene chloride	$1.21 \cdot 10^{-14}$	$1.29 \cdot 10^{-14}$	$1.94 \cdot 10^{-14}$	$2.88 \cdot 10^{-14}$	$1.44 \cdot 10^{-14}$
63	Methyl chloride	$1.78 \cdot 10^{-14}$	$1.91 \cdot 10^{-14}$	$2.87 \cdot 10^{-14}$	$4.26 \cdot 10^{-14}$	$2.13 \cdot 10^{-14}$

Table B.1.2: Marginal global characterization factors [PDF·yr·kg^{-1}] for the individualist cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
1	CO_2	$1.04 \cdot 10^{-16}$	$1.72 \cdot 10^{-16}$	$2.01 \cdot 10^{-16}$	$3.74 \cdot 10^{-16}$	$1.87 \cdot 10^{-16}$
2	CH_4	$8.66 \cdot 10^{-15}$	$1.43 \cdot 10^{-14}$	$1.67 \cdot 10^{-14}$	$3.11 \cdot 10^{-14}$	$1.55 \cdot 10^{-14}$
3	N_2O	$3.30 \cdot 10^{-14}$	$5.45 \cdot 10^{-14}$	$6.36 \cdot 10^{-14}$	$1.18 \cdot 10^{-13}$	$5.92 \cdot 10^{-14}$
Ozone-depleting substances						
4	CFC-11	$-1.84 \cdot 10^{-13}$	$-3.03 \cdot 10^{-13}$	$-3.54 \cdot 10^{-13}$	$-6.59 \cdot 10^{-13}$	$-3.29 \cdot 10^{-13}$
5	CFC-12	$2.66 \cdot 10^{-13}$	$4.38 \cdot 10^{-13}$	$5.12 \cdot 10^{-13}$	$9.52 \cdot 10^{-13}$	$4.76 \cdot 10^{-13}$
6	CFC-13	$1.23 \cdot 10^{-12}$	$2.03 \cdot 10^{-12}$	$2.37 \cdot 10^{-12}$	$4.41 \cdot 10^{-12}$	$2.21 \cdot 10^{-12}$
7	CFC-113	$3.68 \cdot 10^{-13}$	$6.08 \cdot 10^{-13}$	$7.10 \cdot 10^{-13}$	$1.32 \cdot 10^{-12}$	$6.61 \cdot 10^{-13}$
8	CFC-114	$8.76 \cdot 10^{-13}$	$1.45 \cdot 10^{-12}$	$1.69 \cdot 10^{-12}$	$3.14 \cdot 10^{-12}$	$1.57 \cdot 10^{-12}$
9	CFC-115	$5.92 \cdot 10^{-13}$	$9.77 \cdot 10^{-13}$	$1.14 \cdot 10^{-12}$	$2.12 \cdot 10^{-12}$	$1.06 \cdot 10^{-12}$
10	Carbon tetrachloride	$-3.56 \cdot 10^{-13}$	$-5.88 \cdot 10^{-13}$	$-6.86 \cdot 10^{-13}$	$-1.28 \cdot 10^{-12}$	$-6.39 \cdot 10^{-13}$
11	Methyl bromide	$-5.84 \cdot 10^{-13}$	$-9.64 \cdot 10^{-13}$	$-1.13 \cdot 10^{-12}$	$-2.10 \cdot 10^{-12}$	$-1.05 \cdot 10^{-12}$
12	Methyl chloroform	$-7.85 \cdot 10^{-14}$	$-1.30 \cdot 10^{-13}$	$-1.51 \cdot 10^{-13}$	$-2.82 \cdot 10^{-13}$	$-1.41 \cdot 10^{-13}$
13	HCFC-22	$4.76 \cdot 10^{-13}$	$7.86 \cdot 10^{-13}$	$9.18 \cdot 10^{-13}$	$1.71 \cdot 10^{-12}$	$8.54 \cdot 10^{-13}$
14	HCFC-123	$3.05 \cdot 10^{-14}$	$5.04 \cdot 10^{-14}$	$5.88 \cdot 10^{-14}$	$1.09 \cdot 10^{-13}$	$5.47 \cdot 10^{-14}$
15	HCFC-124	$2.36 \cdot 10^{-13}$	$3.89 \cdot 10^{-13}$	$4.54 \cdot 10^{-13}$	$8.45 \cdot 10^{-13}$	$4.23 \cdot 10^{-13}$
16	HCFC-141b	$2.21 \cdot 10^{-13}$	$3.64 \cdot 10^{-13}$	$4.26 \cdot 10^{-13}$	$7.92 \cdot 10^{-13}$	$3.96 \cdot 10^{-13}$

Table B.1.2 continued. Marginal global characterization factors [PDF·yr·kg^{-1}] for the individualist cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
17	HCFC-142b	$6.04 \cdot 10^{-13}$	$9.97 \cdot 10^{-13}$	$1.16 \cdot 10^{-12}$	$2.17 \cdot 10^{-12}$	$1.08 \cdot 10^{-12}$
18	HCFC-225ca	$4.89 \cdot 10^{-14}$	$8.07 \cdot 10^{-14}$	$9.42 \cdot 10^{-14}$	$1.75 \cdot 10^{-13}$	$8.77 \cdot 10^{-14}$
19	HCFC-225cb	$2.31 \cdot 10^{-13}$	$3.81 \cdot 10^{-13}$	$4.45 \cdot 10^{-13}$	$8.28 \cdot 10^{-13}$	$4.14 \cdot 10^{-13}$
20	Halon-1211	$-4.95 \cdot 10^{-12}$	$-8.17 \cdot 10^{-12}$	$-9.54 \cdot 10^{-12}$	$-1.78 \cdot 10^{-11}$	$-8.88 \cdot 10^{-12}$
21	Halon-1301	$-8.24 \cdot 10^{-12}$	$-1.36 \cdot 10^{-11}$	$-1.59 \cdot 10^{-11}$	$-2.95 \cdot 10^{-11}$	$-1.48 \cdot 10^{-11}$
22	Halon-2402	$-7.32 \cdot 10^{-12}$	$-1.21 \cdot 10^{-11}$	$-1.41 \cdot 10^{-11}$	$-2.63 \cdot 10^{-11}$	$-1.31 \cdot 10^{-11}$
Hydrofluorcarbons						
23	HFC-23	$1.36 \cdot 10^{-12}$	$2.25 \cdot 10^{-12}$	$2.63 \cdot 10^{-12}$	$4.89 \cdot 10^{-12}$	$2.45 \cdot 10^{-12}$
24	HFC-32	$2.66 \cdot 10^{-13}$	$4.38 \cdot 10^{-13}$	$5.12 \cdot 10^{-13}$	$9.52 \cdot 10^{-13}$	$4.76 \cdot 10^{-13}$
25	HFC-43-10mee	$4.71 \cdot 10^{-13}$	$7.78 \cdot 10^{-13}$	$9.09 \cdot 10^{-13}$	$1.69 \cdot 10^{-12}$	$8.45 \cdot 10^{-13}$
26	HFC-125	$7.23 \cdot 10^{-13}$	$1.19 \cdot 10^{-12}$	$1.39 \cdot 10^{-12}$	$2.59 \cdot 10^{-12}$	$1.30 \cdot 10^{-12}$
27	HFC-134a	$4.35 \cdot 10^{-13}$	$7.19 \cdot 10^{-13}$	$8.39 \cdot 10^{-13}$	$1.56 \cdot 10^{-12}$	$7.81 \cdot 10^{-13}$
28	HFC-143a	$6.70 \cdot 10^{-13}$	$1.11 \cdot 10^{-12}$	$1.29 \cdot 10^{-12}$	$2.40 \cdot 10^{-12}$	$1.20 \cdot 10^{-12}$
29	HFC-227ea	$6.04 \cdot 10^{-13}$	$9.97 \cdot 10^{-13}$	$1.16 \cdot 10^{-12}$	$2.17 \cdot 10^{-12}$	$1.08 \cdot 10^{-12}$
30	HFC-245fa	$3.85 \cdot 10^{-13}$	$6.35 \cdot 10^{-13}$	$7.41 \cdot 10^{-13}$	$1.38 \cdot 10^{-12}$	$6.90 \cdot 10^{-13}$
31	HFC-152a	$4.98 \cdot 10^{-14}$	$8.21 \cdot 10^{-14}$	$9.59 \cdot 10^{-14}$	$1.78 \cdot 10^{-13}$	$8.92 \cdot 10^{-14}$
32	HFC-236fa	$9.23 \cdot 10^{-13}$	$1.52 \cdot 10^{-12}$	$1.78 \cdot 10^{-12}$	$3.31 \cdot 10^{-12}$	$1.66 \cdot 10^{-12}$
33	HFC-365mfc	$2.88 \cdot 10^{-13}$	$4.75 \cdot 10^{-13}$	$5.55 \cdot 10^{-13}$	$1.03 \cdot 10^{-12}$	$5.16 \cdot 10^{-13}$
Perfluorinated compounds						
34	Sulphur hexafluoride	$1.85 \cdot 10^{-12}$	$3.05 \cdot 10^{-12}$	$3.56 \cdot 10^{-12}$	$6.63 \cdot 10^{-12}$	$3.32 \cdot 10^{-12}$
35	Nitrogen trifluoride	$1.53 \cdot 10^{-12}$	$2.52 \cdot 10^{-12}$	$2.94 \cdot 10^{-12}$	$5.47 \cdot 10^{-12}$	$2.74 \cdot 10^{-12}$
36	PFC-14	$5.93 \cdot 10^{-13}$	$9.79 \cdot 10^{-13}$	$1.14 \cdot 10^{-12}$	$2.13 \cdot 10^{-12}$	$1.06 \cdot 10^{-12}$
37	PFC-116	$9.83 \cdot 10^{-13}$	$1.62 \cdot 10^{-12}$	$1.89 \cdot 10^{-12}$	$3.52 \cdot 10^{-12}$	$1.76 \cdot 10^{-12}$
38	PFC-218	$7.20 \cdot 10^{-13}$	$1.19 \cdot 10^{-12}$	$1.39 \cdot 10^{-12}$	$2.58 \cdot 10^{-12}$	$1.29 \cdot 10^{-12}$
39	PFC-318	$8.32 \cdot 10^{-13}$	$1.37 \cdot 10^{-12}$	$1.60 \cdot 10^{-12}$	$2.99 \cdot 10^{-12}$	$1.49 \cdot 10^{-12}$
40	PFC-3-1-10	$7.21 \cdot 10^{-13}$	$1.19 \cdot 10^{-12}$	$1.39 \cdot 10^{-12}$	$2.59 \cdot 10^{-12}$	$1.29 \cdot 10^{-12}$
41	PFC-4-1-12	$7.42 \cdot 10^{-13}$	$1.22 \cdot 10^{-12}$	$1.43 \cdot 10^{-12}$	$2.66 \cdot 10^{-12}$	$1.33 \cdot 10^{-12}$
42	PFC-5-1-14	$7.54 \cdot 10^{-13}$	$1.24 \cdot 10^{-12}$	$1.45 \cdot 10^{-12}$	$2.71 \cdot 10^{-12}$	$1.35 \cdot 10^{-12}$
43	PFC-9-1-18	$6.27 \cdot 10^{-13}$	$1.03 \cdot 10^{-12}$	$1.21 \cdot 10^{-12}$	$2.25 \cdot 10^{-12}$	$1.12 \cdot 10^{-12}$
44	Trifluoromethyl sulphur pentafluoride	$1.50 \cdot 10^{-12}$	$2.48 \cdot 10^{-12}$	$2.89 \cdot 10^{-12}$	$5.38 \cdot 10^{-12}$	$2.69 \cdot 10^{-12}$
Fluorinated ethers						
45	HFE-125	$1.58 \cdot 10^{-12}$	$2.60 \cdot 10^{-12}$	$3.04 \cdot 10^{-12}$	$5.65 \cdot 10^{-12}$	$2.83 \cdot 10^{-12}$
46	HFE-134	$1.39 \cdot 10^{-12}$	$2.29 \cdot 10^{-12}$	$2.68 \cdot 10^{-12}$	$4.98 \cdot 10^{-12}$	$2.49 \cdot 10^{-12}$
47	HFE-143a	$3.00 \cdot 10^{-13}$	$4.95 \cdot 10^{-13}$	$5.79 \cdot 10^{-13}$	$1.08 \cdot 10^{-12}$	$5.38 \cdot 10^{-13}$
48	HCFE-235da2	$1.40 \cdot 10^{-13}$	$2.31 \cdot 10^{-13}$	$2.70 \cdot 10^{-13}$	$5.03 \cdot 10^{-13}$	$2.51 \cdot 10^{-13}$
49	HFE-245cb2	$3.16 \cdot 10^{-13}$	$5.22 \cdot 10^{-13}$	$6.10 \cdot 10^{-13}$	$1.13 \cdot 10^{-12}$	$5.67 \cdot 10^{-13}$
50	HFE-245fa2	$2.59 \cdot 10^{-13}$	$4.28 \cdot 10^{-13}$	$5.00 \cdot 10^{-13}$	$9.30 \cdot 10^{-13}$	$4.65 \cdot 10^{-13}$
51	HFE-254cb2	$1.59 \cdot 10^{-13}$	$2.62 \cdot 10^{-13}$	$3.06 \cdot 10^{-13}$	$5.70 \cdot 10^{-13}$	$2.85 \cdot 10^{-13}$
52	HFE-347mcc3	$2.26 \cdot 10^{-13}$	$3.73 \cdot 10^{-13}$	$4.35 \cdot 10^{-13}$	$8.10 \cdot 10^{-13}$	$4.05 \cdot 10^{-13}$
53	HFE-347pcf2	$2.18 \cdot 10^{-13}$	$3.60 \cdot 10^{-13}$	$4.21 \cdot 10^{-13}$	$7.83 \cdot 10^{-13}$	$3.92 \cdot 10^{-13}$
54	HFE-356pcc3	$4.40 \cdot 10^{-14}$	$7.27 \cdot 10^{-14}$	$8.49 \cdot 10^{-14}$	$1.58 \cdot 10^{-13}$	$7.90 \cdot 10^{-14}$
55	HFE-449sl	$1.22 \cdot 10^{-13}$	$2.02 \cdot 10^{-13}$	$2.36 \cdot 10^{-13}$	$4.39 \cdot 10^{-13}$	$2.19 \cdot 10^{-13}$

Table B.1.2 continued. Marginal global characterization factors [PDF·yr·kg^{-1}] for the individualist cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
56	HFE-569sf2	$2.28 \cdot 10^{-14}$	$3.77 \cdot 10^{-14}$	$4.40 \cdot 10^{-14}$	$8.19 \cdot 10^{-14}$	$4.09 \cdot 10^{-14}$
57	HFE-43-10pccc124	$7.20 \cdot 10^{-13}$	$1.19 \cdot 10^{-12}$	$1.39 \cdot 10^{-12}$	$2.58 \cdot 10^{-12}$	$1.29 \cdot 10^{-12}$
58	HFE-236ca12	$9.16 \cdot 10^{-13}$	$1.51 \cdot 10^{-12}$	$1.76 \cdot 10^{-12}$	$3.28 \cdot 10^{-12}$	$1.64 \cdot 10^{-12}$
59	HFE-338pcc13	$5.78 \cdot 10^{-13}$	$9.54 \cdot 10^{-13}$	$1.11 \cdot 10^{-12}$	$2.07 \cdot 10^{-12}$	$1.04 \cdot 10^{-12}$
Perfluoropolyethers						
60	PFPMIE	$8.68 \cdot 10^{-13}$	$1.43 \cdot 10^{-12}$	$1.67 \cdot 10^{-12}$	$3.11 \cdot 10^{-12}$	$1.56 \cdot 10^{-12}$
Hydrocarbons and other compounds						
61	Dimethylether	$1.70 \cdot 10^{-16}$	$2.81 \cdot 10^{-16}$	$3.28 \cdot 10^{-16}$	$6.10 \cdot 10^{-16}$	$3.05 \cdot 10^{-16}$
62	Methylene chloride	$3.50 \cdot 10^{-15}$	$5.77 \cdot 10^{-15}$	$6.74 \cdot 10^{-15}$	$1.25 \cdot 10^{-14}$	$6.27 \cdot 10^{-15}$
63	Methyl chloride	$5.17 \cdot 10^{-15}$	$8.54 \cdot 10^{-15}$	$9.97 \cdot 10^{-15}$	$1.86 \cdot 10^{-14}$	$9.28 \cdot 10^{-15}$

B.2 Hierarchist perspective

Table B.2.1: Average global characterization factors [PDF·yr·kg^{-1}] for the hierarchist cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
1	CO_2	$1.78 \cdot 10^{-15}$	$1.91 \cdot 10^{-15}$	$2.87 \cdot 10^{-15}$	$4.26 \cdot 10^{-15}$	$2.13 \cdot 10^{-15}$
2	CH_4	$3.53 \cdot 10^{-14}$	$3.78 \cdot 10^{-14}$	$5.68 \cdot 10^{-14}$	$8.42 \cdot 10^{-14}$	$4.21 \cdot 10^{-14}$
3	N_2O	$5.82 \cdot 10^{-13}$	$6.24 \cdot 10^{-13}$	$9.37 \cdot 10^{-13}$	$1.39 \cdot 10^{-12}$	$6.95 \cdot 10^{-13}$
Ozone-depleting substances						
4	CFC-11	$9.28 \cdot 10^{-12}$	$9.96 \cdot 10^{-12}$	$1.49 \cdot 10^{-11}$	$2.22 \cdot 10^{-11}$	$1.11 \cdot 10^{-11}$
5	CFC-12	$2.13 \cdot 10^{-11}$	$2.28 \cdot 10^{-11}$	$3.42 \cdot 10^{-11}$	$5.08 \cdot 10^{-11}$	$2.54 \cdot 10^{-11}$
6	CFC-13	$2.82 \cdot 10^{-11}$	$3.02 \cdot 10^{-11}$	$4.53 \cdot 10^{-11}$	$6.72 \cdot 10^{-11}$	$3.36 \cdot 10^{-11}$
7	CFC-113	$1.20 \cdot 10^{-11}$	$1.29 \cdot 10^{-11}$	$1.93 \cdot 10^{-11}$	$2.86 \cdot 10^{-11}$	$1.43 \cdot 10^{-11}$
8	CFC-114	$1.96 \cdot 10^{-11}$	$2.10 \cdot 10^{-11}$	$3.16 \cdot 10^{-11}$	$4.68 \cdot 10^{-11}$	$2.34 \cdot 10^{-11}$
9	CFC-115	$1.44 \cdot 10^{-11}$	$1.54 \cdot 10^{-11}$	$2.31 \cdot 10^{-11}$	$3.43 \cdot 10^{-11}$	$1.72 \cdot 10^{-11}$
10	Carbon tetrachloride	$2.73 \cdot 10^{-12}$	$2.93 \cdot 10^{-12}$	$4.40 \cdot 10^{-12}$	$6.53 \cdot 10^{-12}$	$3.26 \cdot 10^{-12}$
11	Methyl bromide	$9.37 \cdot 10^{-15}$	$1.01 \cdot 10^{-14}$	$1.51 \cdot 10^{-14}$	$2.24 \cdot 10^{-14}$	$1.12 \cdot 10^{-14}$
12	Methyl chloroform	$2.86 \cdot 10^{-13}$	$3.07 \cdot 10^{-13}$	$4.60 \cdot 10^{-13}$	$6.83 \cdot 10^{-13}$	$3.41 \cdot 10^{-13}$
13	HCFC-22	$3.53 \cdot 10^{-12}$	$3.78 \cdot 10^{-12}$	$5.68 \cdot 10^{-12}$	$8.42 \cdot 10^{-12}$	$4.21 \cdot 10^{-12}$
14	HCFC-123	$1.51 \cdot 10^{-13}$	$1.62 \cdot 10^{-13}$	$2.44 \cdot 10^{-13}$	$3.62 \cdot 10^{-13}$	$1.81 \cdot 10^{-13}$
15	HCFC-124	$1.19 \cdot 10^{-12}$	$1.28 \cdot 10^{-12}$	$1.92 \cdot 10^{-12}$	$2.84 \cdot 10^{-12}$	$1.42 \cdot 10^{-12}$
16	HCFC-141b	$1.42 \cdot 10^{-12}$	$1.52 \cdot 10^{-12}$	$2.28 \cdot 10^{-12}$	$3.38 \cdot 10^{-12}$	$1.69 \cdot 10^{-12}$
17	HCFC-142b	$4.49 \cdot 10^{-12}$	$4.82 \cdot 10^{-12}$	$7.23 \cdot 10^{-12}$	$1.07 \cdot 10^{-11}$	$5.36 \cdot 10^{-12}$
18	HCFC-225ca	$2.38 \cdot 10^{-13}$	$2.55 \cdot 10^{-13}$	$3.83 \cdot 10^{-13}$	$5.68 \cdot 10^{-13}$	$2.84 \cdot 10^{-13}$
19	HCFC-225cb	$1.16 \cdot 10^{-12}$	$1.25 \cdot 10^{-12}$	$1.87 \cdot 10^{-12}$	$2.78 \cdot 10^{-12}$	$1.39 \cdot 10^{-12}$
20	Halon-1211	$3.68 \cdot 10^{-12}$	$3.95 \cdot 10^{-12}$	$5.93 \cdot 10^{-12}$	$8.80 \cdot 10^{-12}$	$4.40 \cdot 10^{-12}$
21	Halon-1301	$1.39 \cdot 10^{-11}$	$1.50 \cdot 10^{-11}$	$2.25 \cdot 10^{-11}$	$3.33 \cdot 10^{-11}$	$1.67 \cdot 10^{-11}$
22	Halon-2402	$3.21 \cdot 10^{-12}$	$3.44 \cdot 10^{-12}$	$5.17 \cdot 10^{-12}$	$7.66 \cdot 10^{-12}$	$3.83 \cdot 10^{-12}$
Hydrofluorcarbons						
23	HFC-23	$2.88 \cdot 10^{-11}$	$3.09 \cdot 10^{-11}$	$4.64 \cdot 10^{-11}$	$6.89 \cdot 10^{-11}$	$3.44 \cdot 10^{-11}$

Table B.2.1 continued. Average global characterization factors [PDF·yr·kg^{-1}] for the hierarchist cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
24	HFC-32	$1.32 \cdot 10^{-12}$	$1.41 \cdot 10^{-12}$	$2.12 \cdot 10^{-12}$	$3.15 \cdot 10^{-12}$	$1.57 \cdot 10^{-12}$
25	HFC-43-10mee	$3.20 \cdot 10^{-12}$	$3.43 \cdot 10^{-12}$	$5.15 \cdot 10^{-12}$	$7.64 \cdot 10^{-12}$	$3.82 \cdot 10^{-12}$
26	HFC-125	$6.85 \cdot 10^{-12}$	$7.34 \cdot 10^{-12}$	$1.10 \cdot 10^{-11}$	$1.63 \cdot 10^{-11}$	$8.17 \cdot 10^{-12}$
27	HFC-134a	$2.79 \cdot 10^{-12}$	$2.99 \cdot 10^{-12}$	$4.49 \cdot 10^{-12}$	$6.66 \cdot 10^{-12}$	$3.33 \cdot 10^{-12}$
28	HFC-143a	$8.73 \cdot 10^{-12}$	$9.36 \cdot 10^{-12}$	$1.41 \cdot 10^{-11}$	$2.08 \cdot 10^{-11}$	$1.04 \cdot 10^{-11}$
29	HFC-227ea	$6.29 \cdot 10^{-12}$	$6.75 \cdot 10^{-12}$	$1.01 \cdot 10^{-11}$	$1.50 \cdot 10^{-11}$	$7.51 \cdot 10^{-12}$
30	HFC-245fa	$2.02 \cdot 10^{-12}$	$2.17 \cdot 10^{-12}$	$3.25 \cdot 10^{-12}$	$4.82 \cdot 10^{-12}$	$2.41 \cdot 10^{-12}$
31	HFC-152a	$2.43 \cdot 10^{-13}$	$2.60 \cdot 10^{-13}$	$3.91 \cdot 10^{-13}$	$5.79 \cdot 10^{-13}$	$2.90 \cdot 10^{-13}$
32	HFC-236fa	$1.91 \cdot 10^{-11}$	$2.05 \cdot 10^{-11}$	$3.08 \cdot 10^{-11}$	$4.57 \cdot 10^{-11}$	$2.28 \cdot 10^{-11}$
33	HFC-365mfc	$1.55 \cdot 10^{-12}$	$1.66 \cdot 10^{-12}$	$2.49 \cdot 10^{-12}$	$3.70 \cdot 10^{-12}$	$1.85 \cdot 10^{-12}$
	Perfluorinated compounds					
34	Sulphur hexafluoride	$4.45 \cdot 10^{-11}$	$4.77 \cdot 10^{-11}$	$7.16 \cdot 10^{-11}$	$1.06 \cdot 10^{-10}$	$5.31 \cdot 10^{-11}$
35	Nitrogen trifluoride	$3.52 \cdot 10^{-11}$	$3.77 \cdot 10^{-11}$	$5.66 \cdot 10^{-11}$	$8.40 \cdot 10^{-11}$	$4.20 \cdot 10^{-11}$
36	PFC-14	$1.44 \cdot 10^{-11}$	$1.55 \cdot 10^{-11}$	$2.32 \cdot 10^{-11}$	$3.44 \cdot 10^{-11}$	$1.72 \cdot 10^{-11}$
37	PFC-116	$2.38 \cdot 10^{-11}$	$2.56 \cdot 10^{-11}$	$3.84 \cdot 10^{-11}$	$5.69 \cdot 10^{-11}$	$2.85 \cdot 10^{-11}$
38	PFC-218	$1.72 \cdot 10^{-11}$	$1.85 \cdot 10^{-11}$	$2.78 \cdot 10^{-11}$	$4.12 \cdot 10^{-11}$	$2.06 \cdot 10^{-11}$
39	PFC-318	$2.00 \cdot 10^{-11}$	$2.15 \cdot 10^{-11}$	$3.22 \cdot 10^{-11}$	$4.78 \cdot 10^{-11}$	$2.39 \cdot 10^{-11}$
40	PFC-3-1-10	$1.73 \cdot 10^{-11}$	$1.85 \cdot 10^{-11}$	$2.78 \cdot 10^{-11}$	$4.13 \cdot 10^{-11}$	$2.06 \cdot 10^{-11}$
41	PFC-4-1-12	$1.79 \cdot 10^{-11}$	$1.92 \cdot 10^{-11}$	$2.88 \cdot 10^{-11}$	$4.27 \cdot 10^{-11}$	$2.14 \cdot 10^{-11}$
42	PFC-5-1-14	$1.81 \cdot 10^{-11}$	$1.95 \cdot 10^{-11}$	$2.92 \cdot 10^{-11}$	$4.33 \cdot 10^{-11}$	$2.17 \cdot 10^{-11}$
43	PFC-9-1-18	$1.47 \cdot 10^{-11}$	$1.57 \cdot 10^{-11}$	$2.36 \cdot 10^{-11}$	$3.50 \cdot 10^{-11}$	$1.75 \cdot 10^{-11}$
44	Trifluoromethyl sulphur pentafluoride	$3.47 \cdot 10^{-11}$	$3.73 \cdot 10^{-11}$	$5.59 \cdot 10^{-11}$	$8.30 \cdot 10^{-11}$	$4.15 \cdot 10^{-11}$
	Fluorinated ethers					
45	HFE-125	$2.91 \cdot 10^{-11}$	$3.12 \cdot 10^{-11}$	$4.68 \cdot 10^{-11}$	$6.95 \cdot 10^{-11}$	$3.47 \cdot 10^{-11}$
46	HFE-134	$1.23 \cdot 10^{-11}$	$1.32 \cdot 10^{-11}$	$1.98 \cdot 10^{-11}$	$2.94 \cdot 10^{-11}$	$1.47 \cdot 10^{-11}$
47	HFE-143a	$1.48 \cdot 10^{-12}$	$1.58 \cdot 10^{-12}$	$2.38 \cdot 10^{-12}$	$3.53 \cdot 10^{-12}$	$1.76 \cdot 10^{-12}$
48	HCFE-235da2	$6.80 \cdot 10^{-13}$	$7.30 \cdot 10^{-13}$	$1.10 \cdot 10^{-12}$	$1.62 \cdot 10^{-12}$	$8.12 \cdot 10^{-13}$
49	HFE-245cb2	$1.57 \cdot 10^{-12}$	$1.68 \cdot 10^{-12}$	$2.53 \cdot 10^{-12}$	$3.75 \cdot 10^{-12}$	$1.87 \cdot 10^{-12}$
50	HFE-245fa2	$1.29 \cdot 10^{-12}$	$1.38 \cdot 10^{-12}$	$2.07 \cdot 10^{-12}$	$3.08 \cdot 10^{-12}$	$1.54 \cdot 10^{-12}$
51	HFE-254cb2	$7.70 \cdot 10^{-13}$	$8.26 \cdot 10^{-13}$	$1.24 \cdot 10^{-12}$	$1.84 \cdot 10^{-12}$	$9.20 \cdot 10^{-13}$
52	HFE-347mcc3	$1.13 \cdot 10^{-12}$	$1.21 \cdot 10^{-12}$	$1.81 \cdot 10^{-12}$	$2.69 \cdot 10^{-12}$	$1.34 \cdot 10^{-12}$
53	HFE-347pcf2	$1.13 \cdot 10^{-12}$	$1.21 \cdot 10^{-12}$	$1.82 \cdot 10^{-12}$	$2.70 \cdot 10^{-12}$	$1.35 \cdot 10^{-12}$
54	HFE-356pcc3	$2.14 \cdot 10^{-13}$	$2.30 \cdot 10^{-13}$	$3.45 \cdot 10^{-13}$	$5.12 \cdot 10^{-13}$	$2.56 \cdot 10^{-13}$
55	HFE-449sl	$5.99 \cdot 10^{-13}$	$6.43 \cdot 10^{-13}$	$9.65 \cdot 10^{-13}$	$1.43 \cdot 10^{-12}$	$7.15 \cdot 10^{-13}$
56	HFE-569sf2	$1.11 \cdot 10^{-13}$	$1.19 \cdot 10^{-13}$	$1.79 \cdot 10^{-13}$	$2.66 \cdot 10^{-13}$	$1.33 \cdot 10^{-13}$
57	HFE-43-10pccc124	$3.66 \cdot 10^{-12}$	$3.92 \cdot 10^{-12}$	$5.89 \cdot 10^{-12}$	$8.74 \cdot 10^{-12}$	$4.37 \cdot 10^{-12}$
58	HFE-236ca12	$5.52 \cdot 10^{-12}$	$5.92 \cdot 10^{-12}$	$8.89 \cdot 10^{-12}$	$1.32 \cdot 10^{-11}$	$6.59 \cdot 10^{-12}$
59	HFE-338pcc13	$2.93 \cdot 10^{-12}$	$3.14 \cdot 10^{-12}$	$4.72 \cdot 10^{-12}$	$7.00 \cdot 10^{-12}$	$3.50 \cdot 10^{-12}$
	Perfluoropolyethers					
60	PFPMIE	$2.01 \cdot 10^{-11}$	$2.16 \cdot 10^{-11}$	$3.24 \cdot 10^{-11}$	$4.80 \cdot 10^{-11}$	$2.40 \cdot 10^{-11}$
	Hydrocarbons and other compounds					

Table B.2.1 continued. Average global characterization factors [$\mathrm{PDF \cdot yr \cdot kg^{-1}}$] for the hierarchist cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
61	Dimethylether	$8.26 \cdot 10^{-16}$	$8.86 \cdot 10^{-16}$	$1.33 \cdot 10^{-15}$	$1.97 \cdot 10^{-15}$	$9.86 \cdot 10^{-16}$
62	Methylene chloride	$1.71 \cdot 10^{-14}$	$1.83 \cdot 10^{-14}$	$2.75 \cdot 10^{-14}$	$4.08 \cdot 10^{-14}$	$2.04 \cdot 10^{-14}$
63	Methyl chloride	$2.52 \cdot 10^{-14}$	$2.70 \cdot 10^{-14}$	$4.05 \cdot 10^{-14}$	$6.01 \cdot 10^{-14}$	$3.00 \cdot 10^{-14}$

Table B.2.2: Marginal global characterization factors [$\mathrm{PDF \cdot yr \cdot kg^{-1}}$] for the hierarchist cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
1	CO_2	$5.17 \cdot 10^{-16}$	$8.54 \cdot 10^{-16}$	$9.97 \cdot 10^{-16}$	$1.86 \cdot 10^{-15}$	$9.28 \cdot 10^{-16}$
2	CH_4	$1.02 \cdot 10^{-14}$	$1.69 \cdot 10^{-14}$	$1.97 \cdot 10^{-14}$	$3.67 \cdot 10^{-14}$	$1.83 \cdot 10^{-14}$
3	N_2O	$1.69 \cdot 10^{-13}$	$2.78 \cdot 10^{-13}$	$3.25 \cdot 10^{-13}$	$6.05 \cdot 10^{-13}$	$3.03 \cdot 10^{-13}$
Ozone-depleting substances						
4	CFC-11	$2.69 \cdot 10^{-12}$	$4.44 \cdot 10^{-12}$	$5.19 \cdot 10^{-12}$	$9.66 \cdot 10^{-12}$	$4.83 \cdot 10^{-12}$
5	CFC-12	$6.17 \cdot 10^{-12}$	$1.02 \cdot 10^{-11}$	$1.19 \cdot 10^{-11}$	$2.21 \cdot 10^{-11}$	$1.11 \cdot 10^{-11}$
6	CFC-13	$8.16 \cdot 10^{-12}$	$1.35 \cdot 10^{-11}$	$1.57 \cdot 10^{-11}$	$2.93 \cdot 10^{-11}$	$1.46 \cdot 10^{-11}$
7	CFC-113	$3.47 \cdot 10^{-12}$	$5.73 \cdot 10^{-12}$	$6.70 \cdot 10^{-12}$	$1.25 \cdot 10^{-11}$	$6.23 \cdot 10^{-12}$
8	CFC-114	$5.68 \cdot 10^{-12}$	$9.38 \cdot 10^{-12}$	$1.10 \cdot 10^{-11}$	$2.04 \cdot 10^{-11}$	$1.02 \cdot 10^{-11}$
9	CFC-115	$4.17 \cdot 10^{-12}$	$6.88 \cdot 10^{-12}$	$8.03 \cdot 10^{-12}$	$1.50 \cdot 10^{-11}$	$7.48 \cdot 10^{-12}$
10	Carbon tetrachloride	$7.93 \cdot 10^{-13}$	$1.31 \cdot 10^{-12}$	$1.53 \cdot 10^{-12}$	$2.84 \cdot 10^{-12}$	$1.42 \cdot 10^{-12}$
11	Methyl bromide	$2.72 \cdot 10^{-15}$	$4.48 \cdot 10^{-15}$	$5.24 \cdot 10^{-15}$	$9.74 \cdot 10^{-15}$	$4.87 \cdot 10^{-15}$
12	Methyl chloroform	$8.29 \cdot 10^{-14}$	$1.37 \cdot 10^{-13}$	$1.60 \cdot 10^{-13}$	$2.97 \cdot 10^{-13}$	$1.49 \cdot 10^{-13}$
13	HCFC-22	$1.02 \cdot 10^{-12}$	$1.69 \cdot 10^{-12}$	$1.97 \cdot 10^{-12}$	$3.67 \cdot 10^{-12}$	$1.83 \cdot 10^{-12}$
14	HCFC-123	$4.39 \cdot 10^{-14}$	$7.25 \cdot 10^{-14}$	$8.47 \cdot 10^{-14}$	$1.58 \cdot 10^{-13}$	$7.88 \cdot 10^{-14}$
15	HCFC-124	$3.45 \cdot 10^{-13}$	$5.69 \cdot 10^{-13}$	$6.65 \cdot 10^{-13}$	$1.24 \cdot 10^{-12}$	$6.19 \cdot 10^{-13}$
16	HCFC-141b	$4.11 \cdot 10^{-13}$	$6.78 \cdot 10^{-13}$	$7.92 \cdot 10^{-13}$	$1.47 \cdot 10^{-12}$	$7.36 \cdot 10^{-13}$
17	HCFC-142b	$1.30 \cdot 10^{-12}$	$2.15 \cdot 10^{-12}$	$2.51 \cdot 10^{-12}$	$4.67 \cdot 10^{-12}$	$2.34 \cdot 10^{-12}$
18	HCFC-225ca	$6.90 \cdot 10^{-14}$	$1.14 \cdot 10^{-13}$	$1.33 \cdot 10^{-13}$	$2.47 \cdot 10^{-13}$	$1.24 \cdot 10^{-13}$
19	HCFC-225cb	$3.37 \cdot 10^{-13}$	$5.57 \cdot 10^{-13}$	$6.50 \cdot 10^{-13}$	$1.21 \cdot 10^{-12}$	$6.05 \cdot 10^{-13}$
20	Halon-1211	$1.07 \cdot 10^{-12}$	$1.76 \cdot 10^{-12}$	$2.06 \cdot 10^{-12}$	$3.83 \cdot 10^{-12}$	$1.92 \cdot 10^{-12}$
21	Halon-1301	$4.04 \cdot 10^{-12}$	$6.67 \cdot 10^{-12}$	$7.80 \cdot 10^{-12}$	$1.45 \cdot 10^{-11}$	$7.25 \cdot 10^{-12}$
22	Halon-2402	$9.30 \cdot 10^{-13}$	$1.54 \cdot 10^{-12}$	$1.79 \cdot 10^{-12}$	$3.34 \cdot 10^{-12}$	$1.67 \cdot 10^{-12}$
Hydrofluorcarbons						
23	HFC-23	$8.36 \cdot 10^{-12}$	$1.38 \cdot 10^{-11}$	$1.61 \cdot 10^{-11}$	$3.00 \cdot 10^{-11}$	$1.50 \cdot 10^{-11}$
24	HFC-32	$3.82 \cdot 10^{-13}$	$6.31 \cdot 10^{-13}$	$7.37 \cdot 10^{-13}$	$1.37 \cdot 10^{-12}$	$6.85 \cdot 10^{-13}$
25	HFC-43-10mee	$9.28 \cdot 10^{-13}$	$1.53 \cdot 10^{-12}$	$1.79 \cdot 10^{-12}$	$3.33 \cdot 10^{-12}$	$1.66 \cdot 10^{-12}$
26	HFC-125	$1.99 \cdot 10^{-12}$	$3.28 \cdot 10^{-12}$	$3.83 \cdot 10^{-12}$	$7.12 \cdot 10^{-12}$	$3.56 \cdot 10^{-12}$
27	HFC-134a	$8.09 \cdot 10^{-13}$	$1.33 \cdot 10^{-12}$	$1.56 \cdot 10^{-12}$	$2.90 \cdot 10^{-12}$	$1.45 \cdot 10^{-12}$
28	HFC-143a	$2.53 \cdot 10^{-12}$	$4.18 \cdot 10^{-12}$	$4.88 \cdot 10^{-12}$	$9.08 \cdot 10^{-12}$	$4.54 \cdot 10^{-12}$
29	HFC-227ea	$1.82 \cdot 10^{-12}$	$3.01 \cdot 10^{-12}$	$3.52 \cdot 10^{-12}$	$6.54 \cdot 10^{-12}$	$3.27 \cdot 10^{-12}$
30	HFC-245fa	$5.86 \cdot 10^{-13}$	$9.66 \cdot 10^{-13}$	$1.13 \cdot 10^{-12}$	$2.10 \cdot 10^{-12}$	$1.05 \cdot 10^{-12}$
31	HFC-152a	$7.03 \cdot 10^{-14}$	$1.16 \cdot 10^{-13}$	$1.36 \cdot 10^{-13}$	$2.52 \cdot 10^{-13}$	$1.26 \cdot 10^{-13}$
32	HFC-236fa	$5.55 \cdot 10^{-12}$	$9.15 \cdot 10^{-12}$	$1.07 \cdot 10^{-11}$	$1.99 \cdot 10^{-11}$	$9.95 \cdot 10^{-12}$
33	HFC-365mfc	$4.49 \cdot 10^{-13}$	$7.41 \cdot 10^{-13}$	$8.66 \cdot 10^{-13}$	$1.61 \cdot 10^{-12}$	$8.05 \cdot 10^{-13}$

Table B.2.2 continued. Marginal global characterization factors [PDF·yr·kg^{-1}] for the hierarchist cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
Perfluorinated compounds						
34	Sulphur hexafluoride	$1.29 \cdot 10^{-11}$	$2.13 \cdot 10^{-11}$	$2.49 \cdot 10^{-11}$	$4.63 \cdot 10^{-11}$	$2.31 \cdot 10^{-11}$
35	Nitrogen trifluoride	$1.02 \cdot 10^{-11}$	$1.68 \cdot 10^{-11}$	$1.97 \cdot 10^{-11}$	$3.66 \cdot 10^{-11}$	$1.83 \cdot 10^{-11}$
36	PFC-14	$4.18 \cdot 10^{-12}$	$6.90 \cdot 10^{-12}$	$8.06 \cdot 10^{-12}$	$1.50 \cdot 10^{-11}$	$7.50 \cdot 10^{-12}$
37	PFC-116	$6.91 \cdot 10^{-12}$	$1.14 \cdot 10^{-11}$	$1.33 \cdot 10^{-11}$	$2.48 \cdot 10^{-11}$	$1.24 \cdot 10^{-11}$
38	PFC-218	$5.00 \cdot 10^{-12}$	$8.25 \cdot 10^{-12}$	$9.64 \cdot 10^{-12}$	$1.79 \cdot 10^{-11}$	$8.97 \cdot 10^{-12}$
39	PFC-318	$5.81 \cdot 10^{-12}$	$9.58 \cdot 10^{-12}$	$1.12 \cdot 10^{-11}$	$2.08 \cdot 10^{-11}$	$1.04 \cdot 10^{-11}$
40	PFC-3-1-10	$5.01 \cdot 10^{-12}$	$8.27 \cdot 10^{-12}$	$9.66 \cdot 10^{-12}$	$1.80 \cdot 10^{-11}$	$8.99 \cdot 10^{-12}$
41	PFC-4-1-12	$5.19 \cdot 10^{-12}$	$8.56 \cdot 10^{-12}$	$1.00 \cdot 10^{-11}$	$1.86 \cdot 10^{-11}$	$9.30 \cdot 10^{-12}$
42	PFC-5-1-14	$5.26 \cdot 10^{-12}$	$8.68 \cdot 10^{-12}$	$1.01 \cdot 10^{-11}$	$1.89 \cdot 10^{-11}$	$9.43 \cdot 10^{-12}$
43	PFC-9-1-18	$4.26 \cdot 10^{-12}$	$7.02 \cdot 10^{-12}$	$8.20 \cdot 10^{-12}$	$1.53 \cdot 10^{-11}$	$7.63 \cdot 10^{-12}$
44	Trifluoromethyl sulphur pentafluoride	$1.01 \cdot 10^{-11}$	$1.66 \cdot 10^{-11}$	$1.94 \cdot 10^{-11}$	$3.61 \cdot 10^{-11}$	$1.81 \cdot 10^{-11}$
Fluorinated ethers						
45	HFE-125	$8.44 \cdot 10^{-12}$	$1.39 \cdot 10^{-11}$	$1.63 \cdot 10^{-11}$	$3.03 \cdot 10^{-11}$	$1.51 \cdot 10^{-11}$
46	HFE-134	$3.57 \cdot 10^{-12}$	$5.90 \cdot 10^{-12}$	$6.89 \cdot 10^{-12}$	$1.28 \cdot 10^{-11}$	$6.41 \cdot 10^{-12}$
47	HFE-143a	$4.28 \cdot 10^{-13}$	$7.06 \cdot 10^{-13}$	$8.25 \cdot 10^{-13}$	$1.54 \cdot 10^{-12}$	$7.68 \cdot 10^{-13}$
48	HCFE-235da2	$1.97 \cdot 10^{-13}$	$3.26 \cdot 10^{-13}$	$3.80 \cdot 10^{-13}$	$7.08 \cdot 10^{-13}$	$3.54 \cdot 10^{-13}$
49	HFE-245cb2	$4.55 \cdot 10^{-13}$	$7.51 \cdot 10^{-13}$	$8.78 \cdot 10^{-13}$	$1.63 \cdot 10^{-12}$	$8.17 \cdot 10^{-13}$
50	HFE-245fa2	$3.73 \cdot 10^{-13}$	$6.16 \cdot 10^{-13}$	$7.20 \cdot 10^{-13}$	$1.34 \cdot 10^{-12}$	$6.70 \cdot 10^{-13}$
51	HFE-254cb2	$2.23 \cdot 10^{-13}$	$3.69 \cdot 10^{-13}$	$4.30 \cdot 10^{-13}$	$8.01 \cdot 10^{-13}$	$4.00 \cdot 10^{-13}$
52	HFE-347mcc3	$3.26 \cdot 10^{-13}$	$5.38 \cdot 10^{-13}$	$6.29 \cdot 10^{-13}$	$1.17 \cdot 10^{-12}$	$5.85 \cdot 10^{-13}$
53	HFE-347pcf2	$3.28 \cdot 10^{-13}$	$5.41 \cdot 10^{-13}$	$6.31 \cdot 10^{-13}$	$1.17 \cdot 10^{-12}$	$5.87 \cdot 10^{-13}$
54	HFE-356pcc3	$6.22 \cdot 10^{-14}$	$1.03 \cdot 10^{-13}$	$1.20 \cdot 10^{-13}$	$2.23 \cdot 10^{-13}$	$1.11 \cdot 10^{-13}$
55	HFE-449sl	$1.74 \cdot 10^{-13}$	$2.87 \cdot 10^{-13}$	$3.35 \cdot 10^{-13}$	$6.23 \cdot 10^{-13}$	$3.11 \cdot 10^{-13}$
56	HFE-569sf2	$3.23 \cdot 10^{-14}$	$5.32 \cdot 10^{-14}$	$6.22 \cdot 10^{-14}$	$1.16 \cdot 10^{-13}$	$5.78 \cdot 10^{-14}$
57	HFE-43-10pccc124	$1.06 \cdot 10^{-12}$	$1.75 \cdot 10^{-12}$	$2.04 \cdot 10^{-12}$	$3.80 \cdot 10^{-12}$	$1.90 \cdot 10^{-12}$
58	HFE-236ca12	$1.60 \cdot 10^{-12}$	$2.64 \cdot 10^{-12}$	$3.08 \cdot 10^{-12}$	$5.74 \cdot 10^{-12}$	$2.87 \cdot 10^{-12}$
59	HFE-338pcc13	$8.50 \cdot 10^{-13}$	$1.40 \cdot 10^{-12}$	$1.64 \cdot 10^{-12}$	$3.05 \cdot 10^{-12}$	$1.52 \cdot 10^{-12}$
Perfluoropolyethers						
60	PFPMIE	$5.83 \cdot 10^{-12}$	$9.62 \cdot 10^{-12}$	$1.12 \cdot 10^{-11}$	$2.09 \cdot 10^{-11}$	$1.05 \cdot 10^{-11}$
Hydrocarbons and other compounds						
61	Dimethylether	$2.39 \cdot 10^{-16}$	$3.95 \cdot 10^{-16}$	$4.62 \cdot 10^{-16}$	$8.59 \cdot 10^{-16}$	$4.29 \cdot 10^{-16}$
62	Methylene chloride	$4.95 \cdot 10^{-15}$	$8.17 \cdot 10^{-15}$	$9.54 \cdot 10^{-15}$	$1.78 \cdot 10^{-14}$	$8.88 \cdot 10^{-15}$
63	Methyl chloride	$7.30 \cdot 10^{-15}$	$1.20 \cdot 10^{-14}$	$1.41 \cdot 10^{-14}$	$2.62 \cdot 10^{-14}$	$1.31 \cdot 10^{-14}$

B.3 Egalitarian perspective

Table B.3.1: Average global characterization factors [PDF·yr·kg^{-1}] for the egalitarian cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
1	CO_2	$2.54 \cdot 10^{-14}$	$2.73 \cdot 10^{-14}$	$4.09 \cdot 10^{-14}$	$6.07 \cdot 10^{-14}$	$3.03 \cdot 10^{-14}$
2	CH_4	$4.92 \cdot 10^{-14}$	$5.28 \cdot 10^{-14}$	$7.92 \cdot 10^{-14}$	$1.18 \cdot 10^{-13}$	$5.88 \cdot 10^{-14}$
3	N_2O	$1.39 \cdot 10^{-12}$	$1.50 \cdot 10^{-12}$	$2.25 \cdot 10^{-12}$	$3.33 \cdot 10^{-12}$	$1.67 \cdot 10^{-12}$
Ozone-depleting substances						
4	CFC-11	$1.45 \cdot 10^{-11}$	$1.56 \cdot 10^{-11}$	$2.34 \cdot 10^{-11}$	$3.46 \cdot 10^{-11}$	$1.73 \cdot 10^{-11}$
5	CFC-12	$4.71 \cdot 10^{-11}$	$5.05 \cdot 10^{-11}$	$7.58 \cdot 10^{-11}$	$1.12 \cdot 10^{-10}$	$5.62 \cdot 10^{-11}$
6	CFC-13	$2.72 \cdot 10^{-10}$	$2.91 \cdot 10^{-10}$	$4.37 \cdot 10^{-10}$	$6.49 \cdot 10^{-10}$	$3.24 \cdot 10^{-10}$
7	CFC-113	$2.41 \cdot 10^{-11}$	$2.59 \cdot 10^{-11}$	$3.89 \cdot 10^{-11}$	$5.76 \cdot 10^{-11}$	$2.88 \cdot 10^{-11}$
8	CFC-114	$9.67 \cdot 10^{-11}$	$1.04 \cdot 10^{-10}$	$1.56 \cdot 10^{-10}$	$2.31 \cdot 10^{-10}$	$1.15 \cdot 10^{-10}$
9	CFC-115	$3.51 \cdot 10^{-10}$	$3.77 \cdot 10^{-10}$	$5.66 \cdot 10^{-10}$	$8.39 \cdot 10^{-10}$	$4.19 \cdot 10^{-10}$
10	Carbon tetrachloride	$3.90 \cdot 10^{-12}$	$4.18 \cdot 10^{-12}$	$6.28 \cdot 10^{-12}$	$9.31 \cdot 10^{-12}$	$4.65 \cdot 10^{-12}$
11	Methyl bromide	$1.31 \cdot 10^{-14}$	$1.40 \cdot 10^{-14}$	$2.11 \cdot 10^{-14}$	$3.13 \cdot 10^{-14}$	$1.56 \cdot 10^{-14}$
12	Methyl chloroform	$3.99 \cdot 10^{-13}$	$4.28 \cdot 10^{-13}$	$6.43 \cdot 10^{-13}$	$9.53 \cdot 10^{-13}$	$4.77 \cdot 10^{-13}$
13	HCFC-22	$4.92 \cdot 10^{-12}$	$5.28 \cdot 10^{-12}$	$7.92 \cdot 10^{-12}$	$1.18 \cdot 10^{-11}$	$5.88 \cdot 10^{-12}$
14	HCFC-123	$2.11 \cdot 10^{-13}$	$2.27 \cdot 10^{-13}$	$3.40 \cdot 10^{-13}$	$5.05 \cdot 10^{-13}$	$2.52 \cdot 10^{-13}$
15	HCFC-124	$1.66 \cdot 10^{-12}$	$1.78 \cdot 10^{-12}$	$2.67 \cdot 10^{-12}$	$3.96 \cdot 10^{-12}$	$1.98 \cdot 10^{-12}$
16	HCFC-141b	$1.98 \cdot 10^{-12}$	$2.12 \cdot 10^{-12}$	$3.18 \cdot 10^{-12}$	$4.72 \cdot 10^{-12}$	$2.36 \cdot 10^{-12}$
17	HCFC-142b	$6.33 \cdot 10^{-12}$	$6.79 \cdot 10^{-12}$	$1.02 \cdot 10^{-11}$	$1.51 \cdot 10^{-11}$	$7.56 \cdot 10^{-12}$
18	HCFC-225ca	$3.32 \cdot 10^{-13}$	$3.56 \cdot 10^{-13}$	$5.35 \cdot 10^{-13}$	$7.93 \cdot 10^{-13}$	$3.96 \cdot 10^{-13}$
19	HCFC-225cb	$1.62 \cdot 10^{-12}$	$1.74 \cdot 10^{-12}$	$2.61 \cdot 10^{-12}$	$3.87 \cdot 10^{-12}$	$1.94 \cdot 10^{-12}$
20	Halon-1211	$5.13 \cdot 10^{-12}$	$5.51 \cdot 10^{-12}$	$8.27 \cdot 10^{-12}$	$1.23 \cdot 10^{-11}$	$6.13 \cdot 10^{-12}$
21	Halon-1301	$2.48 \cdot 10^{-11}$	$2.66 \cdot 10^{-11}$	$3.99 \cdot 10^{-11}$	$5.92 \cdot 10^{-11}$	$2.96 \cdot 10^{-11}$
22	Halon-2402	$4.49 \cdot 10^{-12}$	$4.82 \cdot 10^{-12}$	$7.23 \cdot 10^{-12}$	$1.07 \cdot 10^{-11}$	$5.36 \cdot 10^{-12}$
Hydrofluorcarbons						
23	HFC-23	$1.30 \cdot 10^{-10}$	$1.40 \cdot 10^{-10}$	$2.09 \cdot 10^{-10}$	$3.11 \cdot 10^{-10}$	$1.55 \cdot 10^{-10}$
24	HFC-32	$1.84 \cdot 10^{-12}$	$1.97 \cdot 10^{-12}$	$2.96 \cdot 10^{-12}$	$4.39 \cdot 10^{-12}$	$2.20 \cdot 10^{-12}$
25	HFC-43-10mee	$4.49 \cdot 10^{-12}$	$4.82 \cdot 10^{-12}$	$7.23 \cdot 10^{-12}$	$1.07 \cdot 10^{-11}$	$5.36 \cdot 10^{-12}$
26	HFC-125	$9.84 \cdot 10^{-12}$	$1.06 \cdot 10^{-11}$	$1.58 \cdot 10^{-11}$	$2.35 \cdot 10^{-11}$	$1.18 \cdot 10^{-11}$
27	HFC-134a	$3.89 \cdot 10^{-12}$	$4.18 \cdot 10^{-12}$	$6.27 \cdot 10^{-12}$	$9.30 \cdot 10^{-12}$	$4.65 \cdot 10^{-12}$
28	HFC-143a	$1.43 \cdot 10^{-11}$	$1.53 \cdot 10^{-11}$	$2.30 \cdot 10^{-11}$	$3.41 \cdot 10^{-11}$	$1.71 \cdot 10^{-11}$
29	HFC-227ea	$9.28 \cdot 10^{-12}$	$9.96 \cdot 10^{-12}$	$1.49 \cdot 10^{-11}$	$2.22 \cdot 10^{-11}$	$1.11 \cdot 10^{-11}$
30	HFC-245fa	$2.82 \cdot 10^{-12}$	$3.02 \cdot 10^{-12}$	$4.54 \cdot 10^{-12}$	$6.73 \cdot 10^{-12}$	$3.37 \cdot 10^{-12}$
31	HFC-152a	$3.38 \cdot 10^{-13}$	$3.63 \cdot 10^{-13}$	$5.45 \cdot 10^{-13}$	$8.08 \cdot 10^{-13}$	$4.04 \cdot 10^{-13}$
32	HFC-236fa	$7.83 \cdot 10^{-11}$	$8.40 \cdot 10^{-11}$	$1.26 \cdot 10^{-10}$	$1.87 \cdot 10^{-10}$	$9.35 \cdot 10^{-11}$
33	HFC-365mfc	$2.17 \cdot 10^{-12}$	$2.32 \cdot 10^{-12}$	$3.49 \cdot 10^{-12}$	$5.17 \cdot 10^{-12}$	$2.59 \cdot 10^{-12}$
Perfluorinated compounds						
34	Sulphur hexafluoride	$2.02 \cdot 10^{-9}$	$2.17 \cdot 10^{-9}$	$3.25 \cdot 10^{-9}$	$4.82 \cdot 10^{-9}$	$2.41 \cdot 10^{-9}$
35	Nitrogen trifluoride	$3.89 \cdot 10^{-10}$	$4.17 \cdot 10^{-10}$	$6.26 \cdot 10^{-10}$	$9.28 \cdot 10^{-10}$	$4.64 \cdot 10^{-10}$
36	PFC-14	$1.01 \cdot 10^{-8}$	$1.08 \cdot 10^{-8}$	$1.63 \cdot 10^{-8}$	$2.41 \cdot 10^{-8}$	$1.21 \cdot 10^{-8}$
37	PFC-116	$3.34 \cdot 10^{-9}$	$3.58 \cdot 10^{-9}$	$5.38 \cdot 10^{-9}$	$7.98 \cdot 10^{-9}$	$3.99 \cdot 10^{-9}$
38	PFC-218	$6.38 \cdot 10^{-10}$	$6.84 \cdot 10^{-10}$	$1.03 \cdot 10^{-9}$	$1.52 \cdot 10^{-9}$	$7.61 \cdot 10^{-10}$

Table B.3.1 continued. Average global characterization factors [PDF·yr·kg^{-1}] for the egalitarian cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
39	PFC-318	$9.07 \cdot 10^{-10}$	$9.73 \cdot 10^{-10}$	$1.46 \cdot 10^{-9}$	$2.17 \cdot 10^{-9}$	$1.08 \cdot 10^{-9}$
40	PFC-3-1-10	$6.38 \cdot 10^{-10}$	$6.84 \cdot 10^{-10}$	$1.03 \cdot 10^{-9}$	$1.52 \cdot 10^{-9}$	$7.61 \cdot 10^{-10}$
41	PFC-4-1-12	$1.04 \cdot 10^{-9}$	$1.11 \cdot 10^{-9}$	$1.67 \cdot 10^{-9}$	$2.47 \cdot 10^{-9}$	$1.24 \cdot 10^{-9}$
42	PFC-5-1-14	$8.22 \cdot 10^{-10}$	$8.81 \cdot 10^{-10}$	$1.32 \cdot 10^{-9}$	$1.96 \cdot 10^{-9}$	$9.81 \cdot 10^{-10}$
43	PFC-9-1-18	$2.15 \cdot 10^{-10}$	$2.31 \cdot 10^{-10}$	$3.47 \cdot 10^{-10}$	$5.14 \cdot 10^{-10}$	$2.57 \cdot 10^{-10}$
44	Trifluoromethyl sulphur pentafluoride	$4.13 \cdot 10^{-10}$	$4.43 \cdot 10^{-10}$	$6.65 \cdot 10^{-10}$	$9.86 \cdot 10^{-10}$	$4.93 \cdot 10^{-10}$
Fluorinated ethers						
45	HFE-125	$7.79 \cdot 10^{-11}$	$8.35 \cdot 10^{-11}$	$1.25 \cdot 10^{-10}$	$1.86 \cdot 10^{-10}$	$9.30 \cdot 10^{-11}$
46	HFE-134	$1.76 \cdot 10^{-11}$	$1.89 \cdot 10^{-11}$	$2.83 \cdot 10^{-11}$	$4.20 \cdot 10^{-11}$	$2.10 \cdot 10^{-11}$
47	HFE-143a	$2.06 \cdot 10^{-12}$	$2.21 \cdot 10^{-12}$	$3.31 \cdot 10^{-12}$	$4.91 \cdot 10^{-12}$	$2.46 \cdot 10^{-12}$
48	HCFE-235da2	$9.50 \cdot 10^{-13}$	$1.02 \cdot 10^{-12}$	$1.53 \cdot 10^{-12}$	$2.27 \cdot 10^{-12}$	$1.13 \cdot 10^{-12}$
49	HFE-245cb2	$2.19 \cdot 10^{-12}$	$2.35 \cdot 10^{-12}$	$3.53 \cdot 10^{-12}$	$5.23 \cdot 10^{-12}$	$2.62 \cdot 10^{-12}$
50	HFE-245fa2	$1.80 \cdot 10^{-12}$	$1.93 \cdot 10^{-12}$	$2.89 \cdot 10^{-12}$	$4.29 \cdot 10^{-12}$	$2.15 \cdot 10^{-12}$
51	HFE-254cb2	$1.07 \cdot 10^{-12}$	$1.15 \cdot 10^{-12}$	$1.73 \cdot 10^{-12}$	$2.56 \cdot 10^{-12}$	$1.28 \cdot 10^{-12}$
52	HFE-347mcc3	$1.57 \cdot 10^{-12}$	$1.68 \cdot 10^{-12}$	$2.52 \cdot 10^{-12}$	$3.74 \cdot 10^{-12}$	$1.87 \cdot 10^{-12}$
53	HFE-347pcf2	$1.57 \cdot 10^{-12}$	$1.69 \cdot 10^{-12}$	$2.54 \cdot 10^{-12}$	$3.76 \cdot 10^{-12}$	$1.88 \cdot 10^{-12}$
54	HFE-356pcc3	$2.99 \cdot 10^{-13}$	$3.21 \cdot 10^{-13}$	$4.82 \cdot 10^{-13}$	$7.14 \cdot 10^{-13}$	$3.57 \cdot 10^{-13}$
55	HFE-449sl	$8.34 \cdot 10^{-13}$	$8.95 \cdot 10^{-13}$	$1.34 \cdot 10^{-12}$	$1.99 \cdot 10^{-12}$	$9.96 \cdot 10^{-13}$
56	HFE-569sf2	$1.55 \cdot 10^{-13}$	$1.67 \cdot 10^{-13}$	$2.50 \cdot 10^{-13}$	$3.71 \cdot 10^{-13}$	$1.85 \cdot 10^{-13}$
57	HFE-43-10pccc124	$5.09 \cdot 10^{-12}$	$5.46 \cdot 10^{-12}$	$8.20 \cdot 10^{-12}$	$1.22 \cdot 10^{-11}$	$6.08 \cdot 10^{-12}$
58	HFE-236ca12	$7.70 \cdot 10^{-12}$	$8.26 \cdot 10^{-12}$	$1.24 \cdot 10^{-11}$	$1.84 \cdot 10^{-11}$	$9.20 \cdot 10^{-12}$
59	HFE-338pcc13	$4.09 \cdot 10^{-12}$	$4.39 \cdot 10^{-12}$	$6.59 \cdot 10^{-12}$	$9.77 \cdot 10^{-12}$	$4.88 \cdot 10^{-12}$
Perfluoropolyethers						
60	PFPMIE	$2.39 \cdot 10^{-10}$	$2.57 \cdot 10^{-10}$	$3.85 \cdot 10^{-10}$	$5.71 \cdot 10^{-10}$	$2.86 \cdot 10^{-10}$
Hydrocarbons and other compounds						
61	Dimethylether	$1.16 \cdot 10^{-15}$	$1.24 \cdot 10^{-15}$	$1.86 \cdot 10^{-15}$	$2.76 \cdot 10^{-15}$	$1.38 \cdot 10^{-15}$
62	Methylene chloride	$2.38 \cdot 10^{-14}$	$2.56 \cdot 10^{-14}$	$3.84 \cdot 10^{-14}$	$5.69 \cdot 10^{-14}$	$2.85 \cdot 10^{-14}$
63	Methyl chloride	$3.51 \cdot 10^{-14}$	$3.77 \cdot 10^{-14}$	$5.66 \cdot 10^{-14}$	$8.39 \cdot 10^{-14}$	$4.19 \cdot 10^{-14}$

Table B.3.2: Marginal global characterization factors [PDF·yr·kg^{-1}] for the egalitarian cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
1	CO_2	$7.37 \cdot 10^{-15}$	$1.22 \cdot 10^{-14}$	$1.42 \cdot 10^{-14}$	$2.64 \cdot 10^{-14}$	$1.32 \cdot 10^{-14}$
2	CH_4	$1.43 \cdot 10^{-14}$	$2.35 \cdot 10^{-14}$	$2.75 \cdot 10^{-14}$	$5.12 \cdot 10^{-14}$	$2.56 \cdot 10^{-14}$
3	N_2O	$4.04 \cdot 10^{-13}$	$6.67 \cdot 10^{-13}$	$7.80 \cdot 10^{-13}$	$1.45 \cdot 10^{-12}$	$7.25 \cdot 10^{-13}$
Ozone-depleting substances						
4	CFC-11	$4.21 \cdot 10^{-12}$	$6.94 \cdot 10^{-12}$	$8.11 \cdot 10^{-12}$	$1.51 \cdot 10^{-11}$	$7.54 \cdot 10^{-12}$
5	CFC-12	$1.36 \cdot 10^{-11}$	$2.25 \cdot 10^{-11}$	$2.63 \cdot 10^{-11}$	$4.89 \cdot 10^{-11}$	$2.45 \cdot 10^{-11}$
6	CFC-13	$7.88 \cdot 10^{-11}$	$1.30 \cdot 10^{-10}$	$1.52 \cdot 10^{-10}$	$2.83 \cdot 10^{-10}$	$1.41 \cdot 10^{-10}$
7	CFC-113	$7.00 \cdot 10^{-12}$	$1.15 \cdot 10^{-11}$	$1.35 \cdot 10^{-11}$	$2.51 \cdot 10^{-11}$	$1.25 \cdot 10^{-11}$
8	CFC-114	$2.80 \cdot 10^{-11}$	$4.63 \cdot 10^{-11}$	$5.40 \cdot 10^{-11}$	$1.01 \cdot 10^{-10}$	$5.03 \cdot 10^{-11}$

Table B.3.2 continued. Marginal global characterization factors [PDF·yr·kg^{-1}] for the egalitarian cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
9	CFC-115	$1.02 \cdot 10^{-10}$	$1.68 \cdot 10^{-10}$	$1.96 \cdot 10^{-10}$	$3.65 \cdot 10^{-10}$	$1.83 \cdot 10^{-10}$
10	Carbon tetrachloride	$1.13 \cdot 10^{-12}$	$1.87 \cdot 10^{-12}$	$2.18 \cdot 10^{-12}$	$4.05 \cdot 10^{-12}$	$2.03 \cdot 10^{-12}$
11	Methyl bromide	$3.80 \cdot 10^{-15}$	$6.27 \cdot 10^{-15}$	$7.32 \cdot 10^{-15}$	$1.36 \cdot 10^{-14}$	$6.81 \cdot 10^{-15}$
12	Methyl chloroform	$1.16 \cdot 10^{-13}$	$1.91 \cdot 10^{-13}$	$2.23 \cdot 10^{-13}$	$4.15 \cdot 10^{-13}$	$2.08 \cdot 10^{-13}$
13	HCFC-22	$1.43 \cdot 10^{-12}$	$2.35 \cdot 10^{-12}$	$2.75 \cdot 10^{-12}$	$5.12 \cdot 10^{-12}$	$2.56 \cdot 10^{-12}$
14	HCFC-123	$6.13 \cdot 10^{-14}$	$1.01 \cdot 10^{-13}$	$1.18 \cdot 10^{-13}$	$2.20 \cdot 10^{-13}$	$1.10 \cdot 10^{-13}$
15	HCFC-124	$4.81 \cdot 10^{-13}$	$7.94 \cdot 10^{-13}$	$9.28 \cdot 10^{-13}$	$1.73 \cdot 10^{-12}$	$8.63 \cdot 10^{-13}$
16	HCFC-141b	$5.73 \cdot 10^{-13}$	$9.46 \cdot 10^{-13}$	$1.10 \cdot 10^{-12}$	$2.06 \cdot 10^{-12}$	$1.03 \cdot 10^{-12}$
17	HCFC-142b	$1.84 \cdot 10^{-12}$	$3.03 \cdot 10^{-12}$	$3.54 \cdot 10^{-12}$	$6.59 \cdot 10^{-12}$	$3.29 \cdot 10^{-12}$
18	HCFC-225ca	$9.63 \cdot 10^{-14}$	$1.59 \cdot 10^{-13}$	$1.86 \cdot 10^{-13}$	$3.45 \cdot 10^{-13}$	$1.73 \cdot 10^{-13}$
19	HCFC-225cb	$4.70 \cdot 10^{-13}$	$7.76 \cdot 10^{-13}$	$9.06 \cdot 10^{-13}$	$1.69 \cdot 10^{-12}$	$8.43 \cdot 10^{-13}$
20	Halon-1211	$1.49 \cdot 10^{-12}$	$2.46 \cdot 10^{-12}$	$2.87 \cdot 10^{-12}$	$5.34 \cdot 10^{-12}$	$2.67 \cdot 10^{-12}$
21	Halon-1301	$7.18 \cdot 10^{-12}$	$1.19 \cdot 10^{-11}$	$1.38 \cdot 10^{-11}$	$2.58 \cdot 10^{-11}$	$1.29 \cdot 10^{-11}$
22	Halon-2402	$1.30 \cdot 10^{-12}$	$2.15 \cdot 10^{-12}$	$2.51 \cdot 10^{-12}$	$4.67 \cdot 10^{-12}$	$2.34 \cdot 10^{-12}$
Hydrofluorcarbons						
23	HFC-23	$3.77 \cdot 10^{-11}$	$6.22 \cdot 10^{-11}$	$7.27 \cdot 10^{-11}$	$1.35 \cdot 10^{-10}$	$6.76 \cdot 10^{-11}$
24	HFC-32	$5.33 \cdot 10^{-13}$	$8.80 \cdot 10^{-13}$	$1.03 \cdot 10^{-12}$	$1.91 \cdot 10^{-12}$	$9.57 \cdot 10^{-13}$
25	HFC-43-10mee	$1.30 \cdot 10^{-12}$	$2.15 \cdot 10^{-12}$	$2.51 \cdot 10^{-12}$	$4.67 \cdot 10^{-12}$	$2.34 \cdot 10^{-12}$
26	HFC-125	$2.85 \cdot 10^{-12}$	$4.71 \cdot 10^{-12}$	$5.50 \cdot 10^{-12}$	$1.02 \cdot 10^{-11}$	$5.12 \cdot 10^{-12}$
27	HFC-134a	$1.13 \cdot 10^{-12}$	$1.86 \cdot 10^{-12}$	$2.18 \cdot 10^{-12}$	$4.05 \cdot 10^{-12}$	$2.02 \cdot 10^{-12}$
28	HFC-143a	$4.14 \cdot 10^{-12}$	$6.84 \cdot 10^{-12}$	$7.99 \cdot 10^{-12}$	$1.49 \cdot 10^{-11}$	$7.43 \cdot 10^{-12}$
29	HFC-227ea	$2.69 \cdot 10^{-12}$	$4.44 \cdot 10^{-12}$	$5.19 \cdot 10^{-12}$	$9.66 \cdot 10^{-12}$	$4.83 \cdot 10^{-12}$
30	HFC-245fa	$8.18 \cdot 10^{-13}$	$1.35 \cdot 10^{-12}$	$1.58 \cdot 10^{-12}$	$2.93 \cdot 10^{-12}$	$1.47 \cdot 10^{-12}$
31	HFC-152a	$9.81 \cdot 10^{-14}$	$1.62 \cdot 10^{-13}$	$1.89 \cdot 10^{-13}$	$3.52 \cdot 10^{-13}$	$1.76 \cdot 10^{-13}$
32	HFC-236fa	$2.27 \cdot 10^{-11}$	$3.75 \cdot 10^{-11}$	$4.38 \cdot 10^{-11}$	$8.14 \cdot 10^{-11}$	$4.07 \cdot 10^{-11}$
33	HFC-365mfc	$6.28 \cdot 10^{-13}$	$1.04 \cdot 10^{-12}$	$1.21 \cdot 10^{-12}$	$2.25 \cdot 10^{-12}$	$1.13 \cdot 10^{-12}$
Perfluorinated compounds						
34	Sulphur hexafluoride	$5.86 \cdot 10^{-10}$	$9.66 \cdot 10^{-10}$	$1.13 \cdot 10^{-9}$	$2.10 \cdot 10^{-9}$	$1.05 \cdot 10^{-9}$
35	Nitrogen trifluoride	$1.13 \cdot 10^{-10}$	$1.86 \cdot 10^{-10}$	$2.17 \cdot 10^{-10}$	$4.04 \cdot 10^{-10}$	$2.02 \cdot 10^{-10}$
36	PFC-14	$2.93 \cdot 10^{-9}$	$4.83 \cdot 10^{-9}$	$5.64 \cdot 10^{-9}$	$1.05 \cdot 10^{-8}$	$5.25 \cdot 10^{-9}$
37	PFC-116	$9.69 \cdot 10^{-10}$	$1.60 \cdot 10^{-9}$	$1.87 \cdot 10^{-9}$	$3.48 \cdot 10^{-9}$	$1.74 \cdot 10^{-9}$
38	PFC-218	$1.85 \cdot 10^{-10}$	$3.05 \cdot 10^{-10}$	$3.56 \cdot 10^{-10}$	$6.63 \cdot 10^{-10}$	$3.32 \cdot 10^{-10}$
39	PFC-318	$2.63 \cdot 10^{-10}$	$4.34 \cdot 10^{-10}$	$5.07 \cdot 10^{-10}$	$9.43 \cdot 10^{-10}$	$4.72 \cdot 10^{-10}$
40	PFC-3-1-10	$1.85 \cdot 10^{-10}$	$3.05 \cdot 10^{-10}$	$3.56 \cdot 10^{-10}$	$6.63 \cdot 10^{-10}$	$3.32 \cdot 10^{-10}$
41	PFC-4-1-12	$3.00 \cdot 10^{-10}$	$4.95 \cdot 10^{-10}$	$5.79 \cdot 10^{-10}$	$1.08 \cdot 10^{-9}$	$5.38 \cdot 10^{-10}$
42	PFC-5-1-14	$2.38 \cdot 10^{-10}$	$3.93 \cdot 10^{-10}$	$4.59 \cdot 10^{-10}$	$8.54 \cdot 10^{-10}$	$4.27 \cdot 10^{-10}$
43	PFC-9-1-18	$6.24 \cdot 10^{-11}$	$1.03 \cdot 10^{-10}$	$1.20 \cdot 10^{-10}$	$2.24 \cdot 10^{-10}$	$1.12 \cdot 10^{-10}$
44	Trifluoromethyl sulphur pentafluoride	$1.20 \cdot 10^{-10}$	$1.98 \cdot 10^{-10}$	$2.31 \cdot 10^{-10}$	$4.29 \cdot 10^{-10}$	$2.15 \cdot 10^{-10}$
Fluorinated ethers						
45	HFE-125	$2.26 \cdot 10^{-11}$	$3.73 \cdot 10^{-11}$	$4.35 \cdot 10^{-11}$	$8.10 \cdot 10^{-11}$	$4.05 \cdot 10^{-11}$
46	HFE-134	$5.10 \cdot 10^{-12}$	$8.42 \cdot 10^{-12}$	$9.83 \cdot 10^{-12}$	$1.83 \cdot 10^{-11}$	$9.14 \cdot 10^{-12}$
47	HFE-143a	$5.97 \cdot 10^{-13}$	$9.85 \cdot 10^{-13}$	$1.15 \cdot 10^{-12}$	$2.14 \cdot 10^{-12}$	$1.07 \cdot 10^{-12}$

Table B.3.2 continued. Marginal global characterization factors [$PDF \cdot yr \cdot kg^{-1}$] for the egalitarian cultural perspective

	Unit	E_1	E_2	E_B	E_{PAF1}	$E_{PAF0.5}$
48	HCFE-235da2	$2.75 \cdot 10^{-13}$	$4.55 \cdot 10^{-13}$	$5.31 \cdot 10^{-13}$	$9.88 \cdot 10^{-13}$	$4.94 \cdot 10^{-13}$
49	HFE-245cb2	$6.35 \cdot 10^{-13}$	$1.05 \cdot 10^{-12}$	$1.22 \cdot 10^{-12}$	$2.28 \cdot 10^{-12}$	$1.14 \cdot 10^{-12}$
50	HFE-245fa2	$5.21 \cdot 10^{-13}$	$8.60 \cdot 10^{-13}$	$1.00 \cdot 10^{-12}$	$1.87 \cdot 10^{-12}$	$9.34 \cdot 10^{-13}$
51	HFE-254cb2	$3.11 \cdot 10^{-13}$	$5.14 \cdot 10^{-13}$	$6.00 \cdot 10^{-13}$	$1.12 \cdot 10^{-12}$	$5.58 \cdot 10^{-13}$
52	HFE-347mcc3	$4.54 \cdot 10^{-13}$	$7.49 \cdot 10^{-13}$	$8.75 \cdot 10^{-13}$	$1.63 \cdot 10^{-12}$	$8.14 \cdot 10^{-13}$
53	HFE-347pcf2	$4.57 \cdot 10^{-13}$	$7.53 \cdot 10^{-13}$	$8.80 \cdot 10^{-13}$	$1.64 \cdot 10^{-12}$	$8.19 \cdot 10^{-13}$
54	HFE-356pcc3	$8.67 \cdot 10^{-14}$	$1.43 \cdot 10^{-13}$	$1.67 \cdot 10^{-13}$	$3.11 \cdot 10^{-13}$	$1.56 \cdot 10^{-13}$
55	HFE-449sl	$2.42 \cdot 10^{-13}$	$3.99 \cdot 10^{-13}$	$4.66 \cdot 10^{-13}$	$8.68 \cdot 10^{-13}$	$4.34 \cdot 10^{-13}$
56	HFE-569sf2	$4.50 \cdot 10^{-14}$	$7.43 \cdot 10^{-14}$	$8.68 \cdot 10^{-14}$	$1.62 \cdot 10^{-13}$	$8.08 \cdot 10^{-14}$
57	HFE-43-10pccc124	$1.48 \cdot 10^{-12}$	$2.44 \cdot 10^{-12}$	$2.85 \cdot 10^{-12}$	$5.30 \cdot 10^{-12}$	$2.65 \cdot 10^{-12}$
58	HFE-236ca12	$2.23 \cdot 10^{-12}$	$3.69 \cdot 10^{-12}$	$4.30 \cdot 10^{-12}$	$8.01 \cdot 10^{-12}$	$4.00 \cdot 10^{-12}$
59	HFE-338pcc13	$1.19 \cdot 10^{-12}$	$1.96 \cdot 10^{-12}$	$2.29 \cdot 10^{-12}$	$4.25 \cdot 10^{-12}$	$2.13 \cdot 10^{-12}$
Perfluoropolyethers						
60	PFPMIE	$6.94 \cdot 10^{-11}$	$1.14 \cdot 10^{-10}$	$1.34 \cdot 10^{-10}$	$2.49 \cdot 10^{-10}$	$1.24 \cdot 10^{-10}$
Hydrocarbons and other compounds						
61	Dimethylether	$3.35 \cdot 10^{-16}$	$5.53 \cdot 10^{-16}$	$6.46 \cdot 10^{-16}$	$1.20 \cdot 10^{-15}$	$6.01 \cdot 10^{-16}$
62	Methylene chloride	$6.91 \cdot 10^{-15}$	$1.14 \cdot 10^{-14}$	$1.33 \cdot 10^{-14}$	$2.48 \cdot 10^{-14}$	$1.24 \cdot 10^{-14}$
63	Methyl chloride	$1.02 \cdot 10^{-14}$	$1.68 \cdot 10^{-14}$	$1.96 \cdot 10^{-14}$	$3.65 \cdot 10^{-14}$	$1.83 \cdot 10^{-14}$

C Double logarithmic transformation of the Species Area Relationship

The following eqs show how the logarithmic function used for linear regression (eq. C.5) can be rewritten to the classic SAR (eq. C.1). The S refers to species richness, z and b are regression coefficients, and A refers to the area. First, the terms in eq. C.1 are written as an exponent of 10, which isolates S (eq. C.2). Second, the exponents of the right-hand-side term are separated (eq. C.3). Third, the z coefficient, which is multiplied with the logarithm of A, can be rewritten as the exponent of the logarithm of A. Fourth, as the logarithm base of A and the base of the exponent are both equal to 10, it can be simplified to A. The last right-hand-side term is renamed c to simulate the classic SAR (eq. C.5).

$$log_{10}(S) = z \cdot log_{10}(A) + b \tag{C.1}$$

$$S = 10^{z \cdot log_{10}(A) + b} \tag{C.2}$$

$$S = 10^{z \cdot log_{10}(A)} \cdot 10^{b} \tag{C.3}$$

$$S = 10^{log_{10}(A)^{z}} \cdot 10^{b} \tag{C.4}$$

$$S = A^{z} \cdot c \tag{C.5}$$

D Deriving different types of effect factors

Fig. D.1 shows how the marginal and average effect factors are derived after plotting extinction risk against temperature increase.

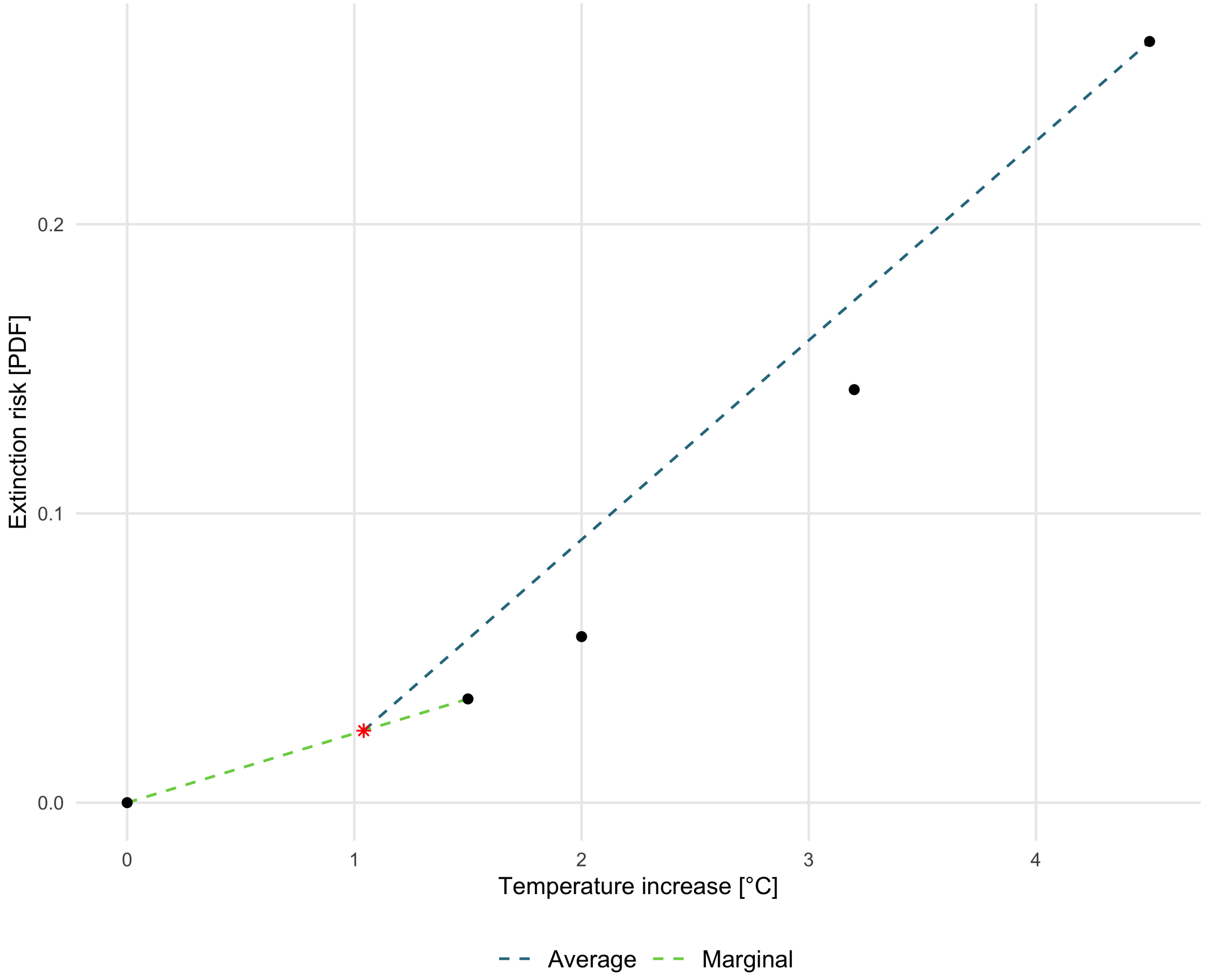

Figure D.1: The plot displays the extinction risk [PDF] against increased global air temperature [°C]. The current situation at 1.2 °C is plotted as a red asterisk and is derived using the slope between 0 and 1.5 °C. The average effect factor is based on the slope at the current situation, while the average effect factor is the distance between the current situation and the point at 4.5 °C.

References

Alfonso, S., Gesto, M., & Sadoul, B. (2020). Temperature increase and its effects on fish stress physiology in the context of global warming. *Journal of Fish Biology*, 1–13. https://doi.org/10.1111/jfb.14599

Baiser, B., & Li, D. (2018). Comparing species–area relationships of native and exotic species. *Biological Invasions*, *20*(12), 3647–3658. https://doi.org/10.1007/s10530-018-1802-4

Barbarossa, V., Bosmans, J., Wanders, N., Huijbregts, M. A. J., Schipper, A. M., King, H., & Bierkens, M. F. P. (2021). Threats of global warming to the world's freshwater fishes. *Nature Communications*, *12*(1), 1–10. https://doi.org/10.1038/s41467-021-21655-w

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., & Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. *Ecology Letters*, *15*(4), 365–377. https://doi.org/10.1111/j.1461-0248.2011.01736.x

Chaplin-Kramer, R., Sim, S., Hamel, P., Bryant, B., Noe, R., Mueller, C., Rigarlsford, G., Kulak, M., Kowal, V., Sharp, R., Clavreul, J., Price, E., Polasky, S., Ruckelshaus, M., & Daily, M. (2017). Life cycle assessment needs predictive spatial modelling for biodiversity and ecosystem services. *Nature Communications*, *8*(1), 1–8. https://doi.org/10.1038/ncomms15065

Chaudhary, A., Verones, F., De Baan, L., & Hellweg, S. (2015). Quantifying land use impacts on biodiversity: Combining species-area models and vulnerability indicators. *Environmental Science and Technology*, *49*(16), 9987–9995. https://doi.org/10.1021/acs.est.5b02507

Ciacci, L., & Passarini, F. (2020). Life Cycle Assessment (LCA) of environmental and energy systems. *Energies*, *13*(22), 5892. https://doi.org/10.3390/en13225892

Collen, B., Whitton, F., Dyer, E. E., Baillie, J. E., Cumberlidge, N., Darwall, W. R., Pollock, C., Richman, N. I., Soulsby, A.-M., & Böhm, M. (2014). Global patterns of freshwater species diversity, threat and endemism. *Global Ecology and Biogeography*, *23*(1), 40–51. https://doi.org/10.1111/geb.12096

Comte, L., & Olden, J. D. (2017). Climatic vulnerability of the world's freshwater and marine fishes. *Nature Climate Change*, *7*(10), 718–722. https://doi.org/10.1038/nclimate3382

Connor, E. F., & McCoy, E. D. (2013). Species-Area Relationships. In A. S. Levin (Ed.), *Encyclopedia of biodiversity* (2nd ed., pp. 640–650). Academic Press. https://doi.org/10.1016/B978-0-12-384719-5.00132-5

Cowx, I. G., & Portocarrero Aya, M. (2011). Paradigm shifts in fish conservation: Moving to the ecosystem services concept. *Journal of Fish Biology*, *79*(6), 1663–1680. https://doi.org/10.1111/j.1095-8649.2011.03144.x

Curran, M., De Baan, L., De Schryver, A. M., Van Zelm, R., Hellweg, S., Koellner, T., Sonnemann, G., & Huijbregts, M. A. (2011). Toward meaningful end points of biodiversity in life cycle assessment. *Environmental Science and Technology*, *45*(1), 70–79. https://doi.org/10.1021/es101444k

Curran, M., De Souza, D. M., Antón, A., Teixeira, R. F., Michelsen, O., Vidal-Legaz, B., Sala, S., & Milà I Canals, L. (2016). How well does LCA model land use impacts on biodiversity? - A comparison with approaches from ecology and conservation. *Environmental Science and Technology*, *50*(6), 2782–2795. https://doi.org/10.1021/acs.est.5b04681

Darwall, W., Bremerich, V., De Wever, A., Dell, A. I., Freyhof, J., Gessner, M. O., Grossart, H. P., Harrison, I., Irvine, K., Jähnig, S. C., Jeschke, J. M., Lee, J. J., Lu, C., Lewandowska, A. M., Monaghan, M. T., Nejstgaard, J. C., Patricio, H., Schmidt-Kloiber, A., Stuart, S. N., & Weyl, O. (2018). The Alliance for Freshwater Life: A global call to unite efforts for freshwater biodiversity science and conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *28*(4), 1015–1022. https://doi.org/10.1002/aqc.2958

De Schryver, A. M., Brakkee, K. W., Goedkoop, M. J., & Huijbregts, M. A. J. (2009). Policy analysis characterization factors for global warming in life cycle assessment based on damages to humans and ecosystems. *Environmental Science and Technology*, *43*(6), 1689–1695. https://doi.org/10.1021/es800456m

De Schryver, A. M., Goedkoop, M. J., Leuven, R. S., & Huijbregts, M. A. (2010). Uncertainties in the application of the species area relationship for characterisation factors of land occupation in life cycle assessment. *International Journal of Life Cycle Assessment*, *15*(7), 682–691. https://doi.org/10.1007/s11367-010-0205-2

Desforges, J. E., Birnie-Gauvin, K., Aarestrup, K., & Cooke, S. J. (2021). Upper thermal tolerance indicated by CTmax fails to predict migration strategy and timing, growth, and predation vulnerability in juvenile brown trout (salmo trutta). *Physiological and Biochemical Zoology*, *94*(4), 215–227. https://doi.org/10.1086/714636

Dudgeon, D. (2019). Multiple threats imperil freshwater biodiversity in the anthropocene. *Current Biology*, *29*(19), R960–R967. https://doi.org/10.1016/j.cub.2019.08.002

Dulvy, N. K., Sadovy, Y., & Reynolds, J. D. (2003). Extinction vulnerability in marine populations. *Fish and Fisheries*, *4*(1), 25–64. https://doi.org/10.1046/j.1467-2979.2003.00105.x

Flitcroft, R., Cooperman, M. S., Harrison, I. J., Juffe-Bignoli, D., & Boon, P. J. (2019). Theory and practice to conserve freshwater biodiversity in the Anthropocene. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *29*(7), 1013–1021. https://doi.org/10.1002/aqc.3187

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D., Haywood, J., Lean, J., Lowe, D., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., & Dorland, R. V. (2007). Changes in atmospheric constituents and in radiative forcing. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M.Tignor, & H. Miller (Eds.), *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge UK: Cambridge University Press.

Hanafiah, M. M., Leuven, R. S., Sommerwerk, N., Tockner, K., & Huijbregts, M. A. (2013). Including the introduction of exotic species in life cycle impact assessment: The case of inland shipping. *Environmental Science & Technology*, *47*(24), 13934–13940. https://doi.org/10.1021/es403870z

Hanafiah, M. M., Xenopoulos, M. A., Pfister, S., Leuven, R. S., & Huijbregts, M. A. (2011). Characterization factors for water consumption and greenhouse gas emissions based on freshwater fish species extinction. *Environmental Science and Technology*, *45*(12), 5272–5278. https://doi.org/10.1021/es1039634

Harte, J., & Kitzes, J. (2012). The use and misuse of species-area relationships in predicting climate-driven extinction. In L. Hannah (Ed.), *Saving a million species: Extinction risk from climate change* (pp. 73–86). Island Press. https://doi.org/10.5822/978-1-61091-182-5

Hauschild, M. Z., & Huijbregts, M. A. J. (2015). *LCA compendium: The complete world of Life Cycle Assessment*. Dordrecht, NL: Springer Science + Business Media. https://doi.org/10.1007/978-94-017-9744-3

He, F., & Hubbell, S. P. (2011). Species-area relationships always overestimate extinction rates from habitat loss. *Nature*, *473*, 368–371. https://doi.org/10.1038/nature09985

Heijungs, R. (2021). The average versus marginal debate in LCIA: paradigm regained. *International Journal of Life Cycle Assessment*, *26*(1), 22–25. https://doi.org/10.1007/s11367-020-01835-4

Huijbregts, M. A. J., Hellweg, S., & Hertwich, E. (2011). Do we need a paradigm shift in life cycle impact assessment? *Environmental Science and Technology*, *45*(9), 3833–3834. https://doi.org/10.1021/es200918b

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F. M., Stam, G., Verones, F., Vieira, M. D. M., Zijp, M., & Van Zelm, R. (2016). *ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization* (tech. rep. No. 2016-0104). National Institute for Public Health and the Environment. Retrieved October 10, 2020, from https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2019). *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (E. S. Brondizio, J. Settele, S. Díaz, & H. T. Ngo, Eds.). https://doi.org/10.5281/zenodo.3831673

International Union for Conservation of Nature. (2018). *The IUCN red list of threatened species* (2018-2). Retrieved June 1, 2020, from http://%20www.iucnredlist.org

Izzo, C., Doubleday, Z. A., Grammer, G. L., Gilmore, K. L., Alleway, H. K., Barnes, T. C., Disspain, M. C., Giraldo, A. J., Mazloumi, N., & Gillanders, B. M. (2016). Fish as proxies of ecological and environmental change. *Reviews in Fish Biology and Fisheries*, *26*(3), 265–286. https://doi.org/10.1007/s11160-016-9424-3

Jaeger, K. L., Olden, J. D., & Pelland, N. A. (2014). Climate change poised to threaten hydrologic connectivity and endemic fishes in dryland streams. *Proceedings of the National Academy of Sciences*, *111*(38), 13894–13899. https://doi.org/10.1073/pnas.1320890111

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., & Rosenbaum, R. (2003). Impact 2002+: A new life cycle impact assessment methodology. *The International Journal of Life Cycle Assessment*, *8*(6), 324–330. https://doi.org/10.1007/BF02978505

Knouft, J. H., & Ficklin, D. L. (2017). The potential impacts of climate change on biodiversity in flowing freshwater systems. *Annual Review of Ecology, Evolution, and Systematics*, *48*, 111–133. https://doi.org/10.1146/annurev-ecolsys-110316-022803

Kramer, A. M., Dennis, B., Liebhold, A. M., & Drake, J. M. (2009). The evidence for allee effects. *Population Ecology*, *51*(3), 341–354. https://doi.org/10.1007/s10144-009-0152-6

Lewis, O. T. (2006). Climate change, species-area curves and the extinction crisis. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *361*(1465), 163–171. https://doi.org/10.1098/rstb.2005.1712

Liu, J., Kattel, G., Arp, H. P. H., & Yang, H. (2015). Towards threshold-based management of freshwater ecosystems in the context of climate change. *Ecological Modelling*, *318*, 265–274. https://doi.org/10.1016/j.ecolmodel.2014.09.010

Mirza, M. Q. M. (2011). Climate change, flooding in south asia and implications. *Regional Environmental Change*, *11*(1), 95–107. https://doi.org/10.1007/s10113-010-0184-7

Moyle, B., P., Kiernan, J. D., Crain, P. K., & Quinones, R. M. (2013). Climate change vulnerability of native and alien freshwater fishes of california: A systematic assessment approach. *PloS one*, *8*(5), e63883. https://doi.org/10.1371/journal.pone.0063883

Oberdorff, T., Tedesco, P. A., Hugueny, B., Leprieur, F., Beauchard, O., Brosse, S., & Dürr, H. H. (2011). Global and regional patterns in riverine fish species richness: A review. *International Journal of Ecology*, *2011*. https://doi.org/10.1155/2011/967631

Parmesan, C. (2006). Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics*, *37*, 637–669. https://doi.org/10.1146/annurev.ecolsys.37.091305.110100

Pereira, H. M., Borda-De-Água, L., & Martins, I. S. (2012). Geometry and scale in species-area relationships. *Nature*, *482*, E3–E4. https://doi.org/10.1038/nature10857

Poff, N. L. (2018). Beyond the natural flow regime? Broadening the hydro-ecological foundation to meet environmental flows challenges in a non-stationary world. *Freshwater Biology*, *63*(8), 1011–1021. https://doi.org/10.1111/fwb.13038

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. Vienna, Austria. Retrieved April 5, 2021, from https://www.R-project.org/

Radinger, J., Essl, F., Hölker, F., Horký, P., Slavík, O., & Wolter, C. (2017). The future distribution of river fish: The complex interplay of climate and land use changes, species dispersal and movement barriers. *Global Change Biology*, *23*(11), 4970–4986. https://doi.org/10.1111/gcb.13760

Radinger, J., & Wolter, C. (2015). Disentangling the effects of habitat suitability, dispersal, and fragmentation on the distribution of river fishes. *Ecological Applications*, *25*(4), 914–927. https://doi.org/10.1890/14-0422.1

Reid, A. J., Carlson, A. K., Creed, I. F., Eliason, E. J., Gell, P. A., Johnson, P. T., Kidd, K. A., MacCormack, T. J., Olden, J. D., Ormerod, S. J., Smol, J. P., Taylor, W. W., Tockner, K., Vermaire, J. C., Dudgeon, D., & Cooke, S. J. (2019). Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews*, *94*(3), 849–873. https://doi.org/10.1111/brv.12480

Román-Palacios, C., & Wiens, J. J. (2020). Recent responses to climate change reveal the drivers of species extinction and survival. *Proceedings of the National Academy of Sciences*, *117*(8), 4211–4217. https://doi.org/10.1073/pnas.1913007117

Scherer, L., van Baren, S. A., & Van Bodegom, P. M. (2020). Characterizing land use impacts on functional plant diversity for life cycle assessments. *Environmental Science & Technology*, *54*(11), 6486–6495. https://doi.org/10.1021/acs.est.9b07228

Steinmann, Z., & Huijbregts, M. A. (2019). Climate change. In F. Verones, S. Hellweg, L. Azevedo, A. Chaudhary, N. Cosme, P. Fantke, M. Goedkoop, M. Hauschild, A. Laurent, C. Mutel, S. Pfister, T. Ponsioen, Z. Steinmann, R. Van Zelm, M. Vieira, & M. A. J. Huijbregts (Eds.), *LC-Impact Version 1.0: A spatially differentiated life cycle impact assessment approach* (pp. 21–53). https://doi.org/10.5281/zenodo.3663304

Tedesco, P. A., Beauchard, O., Bigorne, R., Blanchet, S., Buisson, L., Conti, L., Cornu, J. F., Dias, M. S., Grenouillet, G., Hugueny, B., Jézéquel, C., Leprieur, F., Brosse, S., & Oberdorff, T. (2017). Data Descriptor: A global database on freshwater fish species occurrence in drainage basins. *Scientific Data*, *4*, 170141. https://doi.org/10.1038/sdata.2017.141

Tedesco, P. A., Oberdorff, T., Cornu, J. F., Beauchard, O., Brosse, S., Dürr, H. H., Grenouillet, G., Leprieur, F., Tisseuil, C., Zaiss, R., & Hugueny, B. (2013). A scenario for impacts of water availability loss due to climate change on riverine fish extinction rates. *Journal of Applied Ecology*, *50*(5), 1105–1115. https://doi.org/10.1111/1365-2664.12125

Teillard, F., Maia de Souza, D., Thoma, G., Gerber, P. J., & Finn, J. A. (2016). What does Life-Cycle Assessment of agricultural products need for more meaningful inclusion of biodiversity? *Journal of Applied Ecology*, *53*(5), 1422–1429. https://doi.org/10.1111/1365-2664.12683

Tendall, D. M., Hellweg, S., Pfister, S., Huijbregts, M. A., & Gaillard, G. (2014). Impacts of river water consumption on aquatic biodiversity in life cycle assessment-a proposed method, and a case study for Europe. *Environmental Science and Technology*, *48*(6), 3236–3244. https://doi.org/10.1021/es4048686

Thomas, C. D., Cameron, A., Green, R. E., Bakkenes, M., Beaumont, L. J., Collingham, Y. C., Erasmus, B. F. N., De Siqueira, M. F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., Van Jaarsveld, A. S., Midgley, G. F., Miles, L., Ortega-Huerta, M. A., Peterson, A. T., Phillips, O. L., & Williams, S. E. (2004). Extinction risk from climate change. *Nature*, *427*(6970), 145–148. https://doi.org/10.1038/nature02121

Urban, M. C. (2015). Accelerating extinction risk from climate change. *Science*, *348*(6234), 571–573. https://doi.org/10.1126/science.aaa4984

Verones, F., Hanafiah, M. M., Pfister, S., Huijbregts, M. A., Pelletier, G. J., & Koehler, A. (2010). Characterization factors for thermal pollution in freshwater aquatic environments. *Environmental Science & Technology*, *44*(24), 9364–9369. https://doi.org/10.1021/es102260c

Verones, F., Hellweg, S., Antón, A., Azevedo, L. B., Chaudhary, A., Cosme, N., Cucurachi, S., De Baan, L., Dong, Y., Fantke, P., Golsteijn, L., Hauschild, M., Heijungs, R., Jolliet, O., Juraske, R., Larsen, H., Laurent, A., Mutel, C. L., Margni, M., … Huijbregts, M. A. (2020). LC-IMPACT: A regionalized life cycle damage assessment method. *Journal of Industrial Ecology*, *24*(6), 1201–1219. https://doi.org/10.1111/jiec.13018

Verones, F., Hellweg, S., & Huijbregts, M. A. J. (2019). Overall framework. In F. Verones, S. Hellweg, L. Azevedo, A. Chaudhary, N. Cosme, P. Fantke, M. Goedkoop, M. Hauschild, A. Laurent, C. Mutel, S. Pfister, T. Ponsioen, Z. Steinmann, R. Van Zelm, M. Vieira, & M. A. J. Huijbregts (Eds.), *Lc-impact version 1.0: A spatially differentiated life cycle impact assessment approach* (pp. 5–20). https://doi.org/10.5281/zenodo.3663304

Verones, F., Bare, J., Bulle, C., Frischknecht, R., Hauschild, M., Hellweg, S., Henderson, A., Jolliet, O., Laurent, A., Liao, X., et al. (2017). LCIA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative. *Journal of Cleaner Production*, *161*, 957–967. https://doi.org/10.1016/j.jclepro.2017.05.206

Wiens, J. J. (2016). Climate-related local extinctions are already widespread among plant and animal species. *PLoS Biology*, *14*(12), e2001104. https://doi.org/10.1371/journal.pbio.2001104

Winter, L., Lehmann, A., Finogenova, N., & Finkbeiner, M. (2017). Including biodiversity in life cycle assessment: State of the art, gaps and research needs. *Environmental Impact Assessment Review*, *67*, 88–100. https://doi.org/10.1016/j.eiar.2017.08.006

World Meteorological Organization. (2021). *State of the global climate 2020: Un* (tech. rep. No. 1264). Retrieved July 8, 2021, from https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate

World Wildlife Fund. (2018). *Living Planet Report - 2018: Aiming higher* (M. Grooten & R. E. A. Almond, Eds.). Retrieved August 15, 2021, from https://c402277.ssl.cf1.rackcdn.com/publications/1187/files/original/LPR2018_Full_Report_Spreads.pdf

World Wildlife Fund. (2020). *Living Planet Report 2020 - Bending the curve of biodiversity loss* (R. E. A. Almond, M. Grooten, & T. Petersen, Eds.). Retrieved August 15, 2021, from https://f.hubspotusercontent20.net/hubfs/4783129/LPR/PDFs/ENGLISH-FULL.pdf

Yousefi, M., Jouladeh-Roudbar, A., & Kafash, A. (2020). Using endemic freshwater fishes as proxies of their ecosystems to identify high priority rivers for conservation under climate change. *Ecological Indicators*, *112*, 106137. https://doi.org/10.1016/j.ecolind.2020.106137