Characterization Factors for Global Warming in Life Cycle Assessment Based on Damages to Humans and Ecosystems

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Human and ecosystem health damage due to greenhouse gas (GHG) emissions is generally poorly quantified in the life cycle assessment of products, preventing an integrated comparison of the importance of GHGs with other stressor types, such as ozone depletion and acidifying emissions. In this study, we derived new characterization factors for 63 GHGs that quantify the impact of an emission change on human and ecosystem health damage. For human health damage, the Disability Adjusted Life Years (DALYs) per unit emission related to malaria, diarrhea, malnutrition, drowning, and cardiovascular diseases were quantified. For ecosystem health damage, the Potentially Disappeared Fraction (PDF) over space and time of various species groups, including plants, butterflies, birds, and mammals, per unit emission was calculated. The influence of value choices in the modeling procedure was analyzed by defining three coherent scenarios, based on Cultural theory perspectives. It was found that the characterization factor for human health damage by carbon dioxide (CO_2) ranges from 1.1×10^{-2} to $1.8 \times 10^{+1}$ DALY per kton of emission, while the characterization factor for ecosystem damage by CO_2 ranges from 5.4×10^{-2} to $1.2 \times 10^{+1}$ disappeared fraction of species over space and time ((km^2•year)/kton), depending on the scenario chosen. The characterization factor of a GHG can change up to 4 orders of magnitude, depending on the scenario. The scenario-specific differences are mainly explained by the choice for a specific time horizon and stresses the importance of dealing with value choices in the life cycle impact assessment of GHG emissions.

Introduction

Climate change, partly caused by anthropogenic emissions, is a global threat to the health of humans and ecosystems. Within the next 50 years, it is expected that species can become extinct due to changing temperature, precipitation and seasonality (*1*). Concerning human health impacts, several studies show that climate change results in an increase of various diseases, such as malaria and diarrhea (*2*−*4*). In this context, it is important that the environmental impact of greenhouse gas emissions is taken into account in the environmental life cycle assessment of products (LCA). Global warming potentials (GWP) are widely used to convert product life cycle emissions of various greenhouse gases into a global warming score (*5*). The Intergovernmental Panel of Climate Change (IPCC) regularly updates the GWPs for a wide range of greenhouse gases (*6*).

While the GWP works well for the relative comparison of the importance of greenhouse gases in the life cycle of a product, this concept does not allow comparison of the environmental impact of greenhouse gas emissions with other types of environmental impacts, such as human health impacts due to ozone depletion and loss of species diversity due to changes in land use. Aggregation of different health effects can be achieved through the use of indicators positioned at the end of the cause−effect chain. For human health damage, the concept of Disability Adjusted Life Years (DALYs) has been proposed as endpoint indicator (*7*), while for ecosystem health damage, the loss of species diversity has been introduced (*8*).

Only a few researchers attempted to assess the damage of greenhouse gas emissions toward humans and ecosystems in product assessments. The Eco-indicator 99 methodology quantifies human damage for a number of greenhouse gases by considering the effects of thermal extremes, vector borne diseases and sea level rise with the FUND model (*9*, *10*). Ecosystem damage was excluded due to lack of data. The Environmental Priority System (EPS) accounts for effects on both human health and ecosystem damage (*5*). In particular, the influence of greenhouse gases on biodiversity are considered in EPS in a relatively simplistic way by assuming that the present rate of extinction will be doubled. Current LCA methodologies contain several limitations in addressing the influence of greenhouse gas emissions at the endpoint level. Only a limited number of human health impacts are included, while ecosystem damage is neglected or handled in a simplistic way and uncertainty is hardly addressed.

The goal of this study is to develop new characterization factors for 63 greenhouse gas emissions at the endpoint level for effects on both human health and terrestrial ecosystems. This makes it possible to integrate or compare the effects with other environmental impacts calculated at the endpoint level. The effects on human health per unit greenhouse gas emission are expressed in Disability Adjusted Life Years (DALY), caused by an increase in malnutrition, diarrhea, flooding, malaria and heat stress. The effects on terrestrial ecosystems per unit greenhouse gas emission are expressed in Potentially Disappeared Fraction (PDF) of species, including plants, butterflies, birds, and mammals. Results are presented for three scenarios, quantifying the influence of coherent sets of value choices in the modeling procedure. These scenarios include the choice for (i) a specific time horizon, (ii) including or excluding indirect negative radiative forcing of ozone depleting chemicals, (iii) including all species or currently threatened species only, (iv) including or excluding the ability to adapt to climate change by humans and ecosystems, and (v) considering age weighting or discount rate and the type of future scenario in the DALY calculations.

Methodology

Framework. Life Cycle Impact Assessment (LCIA) is the step in LCA where the impact of emissions caused by product life

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cycles is assessed. Within LCIA, damage to human health and ecosystem health is commonly quantified with endpoint models. These models produce so-called characterization factors that are used as weighting factors to aggregate life cycle emissions into scores for human health damage and ecosystem health damage. As product life cycles commonly contribute to total emissions in a marginal way (*11*), the endpoint models are applied with small emission perturbations only.

For global warming, we divided the endpoint modeling from emission to damage into four consecutive steps:

$$\mathrm{CF}_{x,e}=\frac{d\mathrm{C}_x}{d\mathrm{E}_x}\cdot\frac{d\mathrm{RF}}{d\mathrm{C}_x}\,\frac{d\mathrm{TEMP}}{d\mathrm{RF}}\cdot\frac{d\mathrm{IMPACT}_e}{d\mathrm{TEMP}} \quad (1)$$

where $d\mathrm{E}_x$ is the change in emission of greenhouse gas x (kg·year^{-1}), $d\mathrm{C}_x$ is the change in air concentration of greenhouse gas x (ppb), dRF is the change in radiative forcing (W·m^{-2}), dTEMP is the change in global mean temperature (°C), and $d\mathrm{IMPACT}_e$ is the marginal change in damage for environmental endpoint e (Potentially Disappeared Fraction of species for terrestrial ecosystems and Disability Adjusted Life Years for human health). Figure 1 gives a graphical overview of the framework. We selected the full set of 63 greenhouse gases that have a direct influence on global warming, as assessed in the GWP-calculations by the IPCC in their fourth assessment report (*6*).

From Emission to Concentration. The change in concentration caused by the change in emission is calculated using first-order decay rates of greenhouse gases in the atmosphere (*12*):

$$\frac{d\mathrm{C}_{x,t}}{d\mathrm{E}_x}=\mathrm{cv}_x\cdot\mathrm{LT}_x\cdot(1-\mathrm{e}^{-t/\mathrm{LT}_x}) \quad (2)$$

where cv is the substance specific mass to concentration conversion factor (ppb/kg), LT is the lifetime of the substance (year) and t is the time horizon after which the concentration change is assessed (year). $d\mathrm{C}/d\mathrm{E}$ was calculated for the time horizons 20 years, 100 years and infinite. Information on life times of greenhouse gases was taken from Forster et al. (*6*). For CO_2, the change in concentration due to an emission cannot be derived using a first order decay rate (*6*). Instead, we derived $d\mathrm{C}/d\mathrm{E}$ values for CO_2 directly from the CO_2 response function in Foster et al. (*6*), as based on the Bern carbon cycle model. The mass-to-concentration factor, specific for every greenhouse gas, was calculated using the Law of Boyle, taking an average air temperature of 263.7 K, a tropospheric volume of 7.2×10^{18} m^3 and an average air pressure of 49200 Pa. The life times and mass-to-concentration conversion factors for the greenhouse gases included and the $d\mathrm{C}/d\mathrm{E}$ factors for CO_2 are listed in the Supporting Information (Table S1).

From Concentration to Radiative Forcing. Greenhouse gases cause a change in radiative forcing due to their radiation capacity. Some gases, however, also cause indirect effects such as the change in radiation due to the formation of tropospheric ozone and stratospheric water vapor or the depletion of stratospheric ozone. The latter can result in a global cooling effect. The change in radiative forcing due to a concentration change is therefore equal to

$$\frac{d\mathrm{RF}}{d\mathrm{C}_x}=\frac{d\mathrm{RF}_{\mathrm{direct}}}{d\mathrm{C}_x}+\frac{d\mathrm{RF}_{\mathrm{indirect}}}{d\mathrm{C}_x} \quad (3)$$

where $d\mathrm{RF}_{\mathrm{direct}}$ is the direct change in radiative forcing and $d\mathrm{RF}_{\mathrm{indirect}}$ is the indirect change in radiative forcing (W m^{-2}).

The change in direct radiative forcing caused by the change in concentration is given by the following:

$$\frac{d\mathrm{RF}_{\mathrm{direct}}}{d\mathrm{C}_x}=\mathrm{re}_x \quad (4)$$

where re_x is the radiative efficiency coefficient of greenhouse gas x (W m^{-2} ppb^{-1}), provided by Forster et al. (*6*) and listed in the Supporting Information (Table S1).

The indirect effect of a greenhouse gas on radiative forcing is given by:

$$\frac{d\mathrm{RF}_{\mathrm{indirect}}}{d\mathrm{C}_x}=\frac{d\mathrm{S}}{d\mathrm{C}_x}\cdot\frac{d\mathrm{RF}}{d\mathrm{S}} \quad (5)$$

where dS is the change in the situation of a specific 'stressor', that is, the change in tropospheric ozone, water vapor or stratospheric ozone. The greenhouse gases for which indirect effects are included are methane (tropospheric ozone and water vapor), CFCs, HCFCs, carbon tetrachloride (CCl_4), methylchloroform (CH_3CCl_3) and Halons (stratospheric ozone). Further details on the indirect forcing calculations are given in the Supporting Information.

From Radiative Forcing to Temperature. The change in global mean temperature caused by the change in radiative forcing is given by the following:

$$\frac{d\mathrm{TEMP}_t}{d\mathrm{RF}_t}\approx\frac{\Delta\mathrm{TEMP}_t}{\Delta\mathrm{RF}_t} \quad (6)$$

The relation between temperature and radiative forcing depends on the climate sensitivity and on the rate of heat absorption by the oceans and does not depend on the type of greenhouse gas that is emitted (*14*). The climate sensitivity is a measure of the global surface temperature change for a given radiative forcing. It encompasses the complexity of processes responsible for the way the climate system responds to a radiative forcing, including nonlinear feedback processes, for example, clouds, sea ice and water vapor that have a delay over time.

As $d\mathrm{TEMP}/d\mathrm{RF}$ cannot be derived analytically, we applied the climate model IMAGE 2.2 (*13*) to empirically determine the temperature sensitivity factor for the time horizons 20 years, 100 years and infinite. IMAGE uses the Upwelling Diffusion Climate Model (UDCM) developed by Wigley and Raper (*15*) for this purpose. We increased the global CO_2 emission with 2.85 Gton per year in scenario A1b (*16*), starting in year 2000. The 2.85 Gton/year is equivalent to 10% of the global CO_2 emission in year 2000 and is added to the yearly

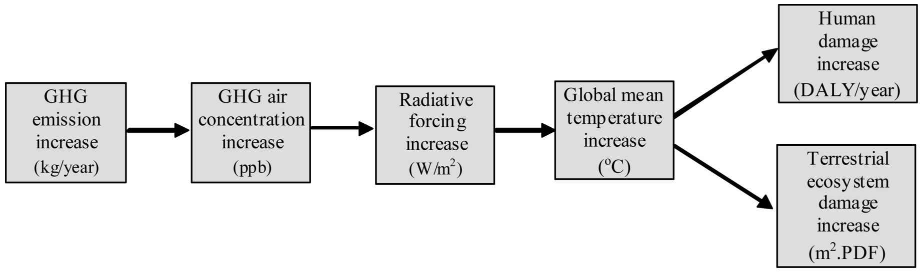

FIGURE 1. Framework used in the development of new endpoint characterization factors for greenhouse gas emissions.

global emissions over time. The ratio of the change in radiative forcing and temperature (ΔTEMP/ΔRF) after 20 years and 100 years due to the 10% yearly emission increase was, respectively, 0.34 and 0.48 °C W^{1-} m^2. As IMAGE is a dynamic model, ΔTEMP/ΔRF for an infinite time horizon cannot be explicitly calculated. Instead, it was set equal to the ΔTEMP/ΔRF that was found to be numerically stable over time, that is, a yearly change in dTEMP/dRF of smaller than 1%, which was equal to 0.67 °C W^{1-} m^2.

From Temperature Rise to Human Damage. The climate change damage factor for humans links the change in temperature to a change in Disability Adjusted Life Years (DALY) (yr/(yr·°C)) and is calculated by:

$$\frac{d\mathrm{IMPACT}_{\mathrm{human}}}{d\mathrm{TEMP}} \approx \frac{\Delta\mathrm{DALY}_{\mathrm{tot}}}{\Delta\mathrm{TEMP}} \tag{7}$$

where $\Delta\mathrm{DALY}_{\mathrm{tot}}$ stands for the change in the yearly total attributable burden of a population of getting a disease (yr/yr).

The attributable burden is calculated by:

$$\Delta\mathrm{DALY} = \sum_r \sum_h \Delta\mathrm{DALY}_{r,h} \tag{8}$$

and

$$\Delta\mathrm{DALY}_{r,h} = \Delta\mathrm{RR}_{r,h} \cdot \mathrm{DALY}_{r,h} \tag{9}$$

where $\Delta\mathrm{DALY}_{r,h}$ is the change in the yearly attributable burden in region r for health effect h (yr/yr), and $\Delta\mathrm{RR}_{r,h}$ is the change in relative risk of health effect h in region r, due to a temperature change (−) and $\mathrm{DALY}_{r,h}$ is the yearly burden of disease for region r and health effect h (yr/yr) in the year 2030. The results of $\Delta\mathrm{DALY}_{r,h}$ are presented in the Supporting Information (Table S7).

A wide range of health effects related to global warming are reported in the literature, including malnutrition, heat stroke, drowning and a large number of infectious diseases, such as malaria, dengue, cholera and tick-borne diseases (*5, 17*). Because of a lack of data, it was not possible to quantify all these human health impacts caused by global warming. We based our assessment on McMichael et al. and Ezzati et al. (*3, 18*), who derived region-specific relative risks related to global warming for malnutrition, diarrhea, malaria, coastal and inland flooding, and heat stress in the year 2030 compared to 1990 (see Tables S5 and S6 in the Supporting Information). The difference in relative risks in 2030 (ΔRR) and temperature rise (ΔTEMP) of two future scenarios, as given in McMichael et al. and Ezzati et al. (*3, 18*), were derived per geographical region and disease type.

DALY estimates for 2030 derived from Mathers and Loncar (*19*) for an optimistic, pessimistic and a baseline future scenario. In DALY calculations, value choices are related to whether age weighting and discount rate for future impacts are preferred (*20*). We combined the optimistic future scenario with age weighting and a 3% discount rate, the pessimistic scenario with no age weighting and no discount rate, and the baseline scenario with no age weighting and a 3% discount rate. The combination of value choices is further explained in the section on cultural perspectives (see Tables S5 and S6 in the Supporting Information).

From Temperature Rise to Terrestrial Ecosystem Damage. The endpoint damage factor for terrestrial ecosystem damage due to climate change links the marginal changes in temperature to marginal changes in the global disappeared fraction of species [km^2 PDF/°C] and can be calculated by:

$$\frac{d\mathrm{IMPACT}_{\mathrm{eco}}}{d\mathrm{TEMP}} \approx \frac{A \cdot \Delta\mathrm{PDF}}{\Delta\mathrm{TEMP}} \tag{10}$$

where ΔPDF is the average change in potentially disappeared fraction of species due a temperature change ΔTEMP (−) and A the total surface of (semi)natural terrestrial areas of the world, 10.8×10^7 km^2. The FAO Global Arable-ecological Zones database gives an overview (percentage) of the main types of land (http://www.fao.org/ag/agl/agll/gaez/index.htm) which was combined with the total land surface on earth (*21*).

TABLE 1. Combination of Value Choices for Time Horizon, Influence of Ozone Depleting Chemicals on Radiative Forcing, Burden of Disease (BoD), Human and Ecosystem Adaptation and the Species To Be Included, Expressed in Three Different Cultural Perspectives

value choice	individualist	hierarchical	egalitarian
Time horizon	20 year	100 year	Infinite
Indirect effects of ozone depleting chemicals	Yes	No	No
BoD:			
- age weighting	Yes	No	No
- discount rate	3%	3%	0%
- Future Scenario	Optimistic	Baseline	Pessimistic
Biological/sociological adaptation	Full	Mean	No
Species dispersal	Yes	Yes	No
Species protection level	All	All	Red list species

Thomas et al. (*1*) included in their review 9 studies that link regional extinction risk of various species groups (covering a total of 1084 species) with temperature increase in that region. We used his work as a basis for our calculations and assumed that extinction risk equals to the disappeared fraction of species. Extinction risks were calculated by Thomas et al. (*1*) for the species groups plants, butterflies, birds, and mammals. They assessed the influence of a number of methodological choices in their calculations, that is, extinction risks (i) with or without dispersal of species, (ii) for all species or Red list species only (*22*), and (iii) by applying three different interpretations of the species area relationship. Depending on the interpretations of species area relationships, the calculation method calculates the overall changes in the distribution areas summed across species, the average proportional change averaged across species or the risk of each species in turn. Further details on calculation steps and data use are presented in the Supporting Information (Table S8).

Cultural Perspectives. To handle value choices that arose in the modeling procedure in a consistent way, we applied the cultural perspective theory (*7*). Three cultural perspectives were used, that is, the individualistic, the hierarchical and the egalitarian perspective. The individualist coincides with the view that mankind has a high adaptive capacity through technological and economic development and that a short time perspective is justified. The egalitarian coincides with the view that nature is strictly accountable, that a long time perspective is justified, and a worst case scenario is needed (the precautionary principle). The hierarchical perspective coincides with the view that impacts can be avoided with proper management, and that the choice on what to include in the model is based on the level of (scientific) consensus (*9*).

Table 1 gives an overview of the value choices we were able to include in our study and how they relate to the three perspectives. Depending on the time horizon chosen, long-term or short-term processes are emphasized. The 20 year time horizon corresponds with the shortest time horizon employed in the GWP calculations of the Intergovernmental Panel of Climate Change (*6*) and is applied in the individualist perspective. The hierarchical perspective coincides with a 100 year time frame, which is most frequently used in the

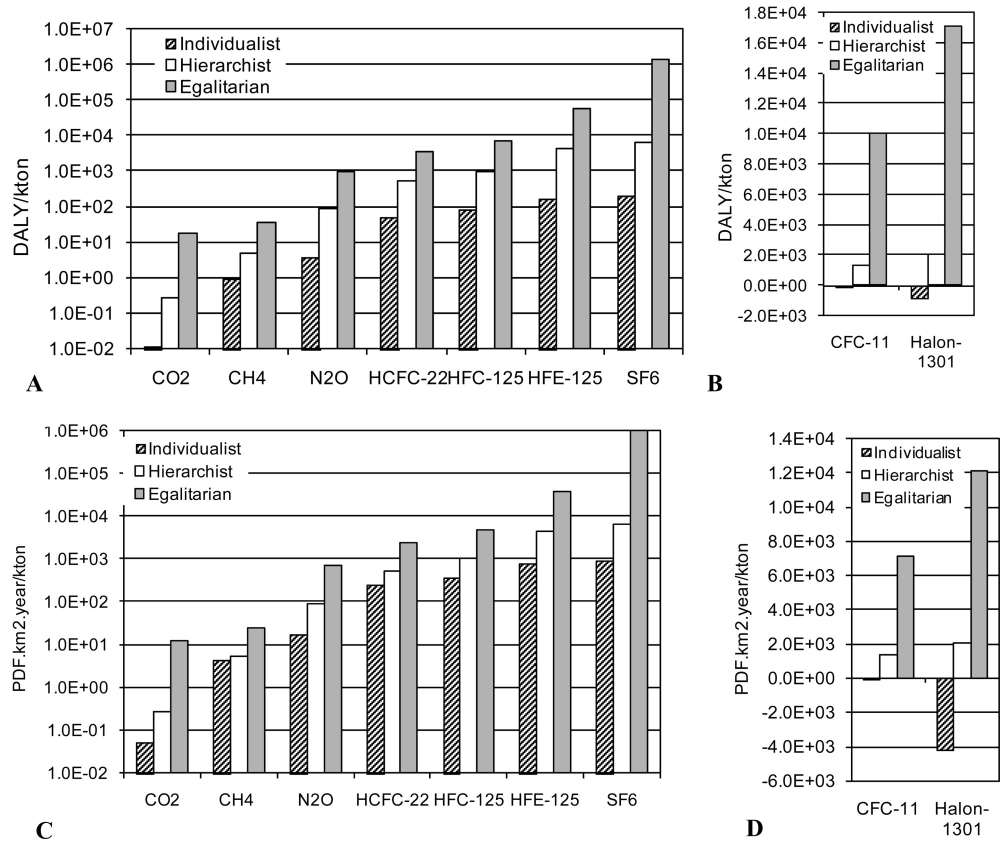

FIGURE 2. Characterization factors for 7 emissions with a net positive impact on global warming (A, C) and 2 ozone depleting emissions with a possible negative impact on global warming (B, D). The factors are related to human health damage (A, B) and the loss of biodiversity (C, D), for an Individualist (I), a Hierarchical (H), and an Egalitarian (E) perspective. Note that panels A and C are in log-scale, and panels B and D in normal scale.

ISO standards (*23*) and the Kyoto protocol (*24*). The egalitarian perspective follows an infinite time horizon that is in line with the precautionary principle.

A second value choice relates to the inclusion of indirect effects of ozone depletion chemicals on radiative forcing which are highly uncertain. A sharp decline in atmospheric concentration can appear by the legal restriction of these substances in products (*25*). This will reduce the indirect effects of ozone depleting chemicals near to zero (see Supporting Information). We consider the indirect effects of ozone depletion chemicals for the individualist perspective only.

For the relative risk estimates, differences in assumptions concerning future adaptation possibilities were considered in the definition of the perspectives. The individualist coincides with full human adaptation, the egalitarian perspective with a worst case scenario and the hierarchist perspective followed a midlevel relative risk for all effects (for details, see Supporting Information).

For the DALYs, the choice for a future scenario, age weighting and discount rate will influence the results. For the individualist perspective, we applied an optimistic future scenario with age weighting and a discount rate of 3%. The egalitarian perspective followed a worst case scenario that coincides with a pessimistic future scenario, no age weighting and no discount rate. The hierarchical perspective included a baseline future scenario with no age weighting and discount rate at 3%. The choice for age weighting per perspective was based on Hofstetter (*7*).

One of the uncertainties in ecosystem damage refers to the ability of dispersal of species (*26*). For the individualistic and hierarchical perspective, we assume nature will be partly able to adapt to the effects of climate change by the ability of species to disperse, while for the egalitarian perspective, we assume a precautionary scenario without species dispersal.

A second assumption for ecosystem damage is the inclusion of taxa. For the individualist and hierarchical, we assume all species are equally important. For the egalitarian perspective, the red list species identified by IUCN were included only, giving high importance to species that are already threatened in their existence.

Results

Figure 2shows the characterization factors of, respectively, human health damage and ecosystem damage for a subset of greenhouse gases for the three cultural perspectives. From the total set of 63 greenhouse gas emissions, we show the most important greenhouse gases CO_2, CH_4 and N_2O, and representatives from the substance groups CFCs, HCFCs, Halons, HFCs, HFEs and SF6. For the total list of characterization, see Supporting Information.

The characterization factor of SF6 is the largest of the greenhouse gases included and, depending on the cultural perspective chosen, 3.6−5.4 orders of magnitude larger compared to the characterization factor of CO_2 (Figure 2). The individualistic and the hierarchical perspective shows smaller differences between the substances compared to the egalitarian perspective.

Differences between the perspectives are the largest for chemicals with a long residence time in the air and range from 0.1 orders of magnitude for CH_4 up to 5.0 orders of magnitude for SF6. For ozone depleting chemicals, such as CFC-11 and Halon-1301, the difference between the perspectives is amplified by the fact that the individualistic perspective takes into account indirect effects leading to net cooling effects, while it is excluded for other perspectives. A

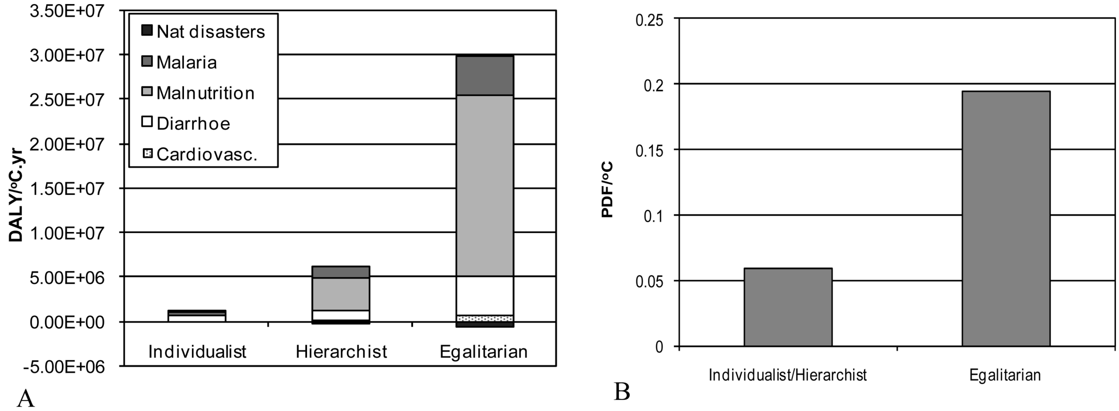

FIGURE 3. The human damage factors (A) and terrestrial ecosystem damage factors (B) related to climate change, following the three cultural perspectives.

net cooling effect results in negative characterization factors under the assumption of a global temperature increase as background situation.

Specifically focusing on the damage part of the characterization factor, Figure 3 shows that the human damage factor ranges from 1×10^6 to 3×10^7 yearly DALYs per °C temperature increase, depending on the cultural perspective. Climate change mainly influences the incidence of diarrhea, malaria and malnutrition. For the individualistic perspective, the effects of diarrhea and malaria play a dominant role. For the hierarchical and egalitarian perspective, malnutrition is most important.

The ecosystem damage factor is 0.06 PDF/°C when dispersal is assumed and all species are taken into account, as employed in the individualistic and hierarchiscal perspective. When considering no dispersal and using the red list species for the egalitarian perspective, the ecosystem damage factor increases to 0.19 PDF/°C.

Discussion

Value Choices. On the basis of a coherent modeling procedure and combining various data sources (*1, 2, 6, 19, 27*), we were able to calculate new characterization factors for 63 greenhouse gases. The calculated characterization factors can be used to quantify effects of greenhouse gas emissions in LCA case studies toward human health as DALYs and ecosystem quality as disappeared fraction of species. This opens the possibility to aggregate global warming effects with the effect of a wide range of other stressors relevant in life cycle studies, such as ozone depleting gases, radioactive pollutants and priority air pollutants. Compared to previous studies, we were able to include a larger number of human health impacts, including malnutrition and diarrhea. For ecosystem damage factors, a wide range of species was included, based on the review of Thomas et al. (*1*). Value choices in the calculation procedure were assessed by means of establishing three distinct scenarios following the theory of cultural perspectives (*7, 28*).

The analysis showed that scenario-specific differences in the characterization factor of a greenhouse gas can be up to 5 orders of magnitude, particularly for gases with a long residence time in air. The choice for a specific time horizon in the step from emissions to GHG air concentrations largely explains the differences between the scenarios. For ozone depleting substances, the choice whether to include indirect cooling effects can also have important consequences, as it can change the direction (positive to negative) of the characterization factors for climate related impacts. However, the effect on human health of ozone depletion via increase in skin cancer and cataract still results in net damage to human health due to emission of ozone depleting substances (*29*). Note that a number of priority air pollutants, such as sulfur dioxide, nitrogen oxides and carbon monoxide, were not included in our analysis. The inclusion of the highly uncertain indirect effects of these pollutants in a life cycle impact assessment context certainly needs further attention.

The scenario-specific differences in characterization factors caused by the choices for human and ecosystem damage were relatively small compared to the choice of a specific time horizon. The difference in the human damage factor is almost fully explained by the choice to what extent malnutrition may play a role in future human health impacts caused by climate change. The different DALYs applied for diarrhea take also a part of the difference. For the ecosystem damage factors, the value choices on including or excluding red list species and the choice for dispersal or nondispersal of species were equally important.

Data and Model Uncertainty. Apart from the differences in characterization factors due to value choices in the modeling procedure, uncertainties in the data employed and the models used may also influence the results (*30*). Because of data limitations, we were not able to carry out a complete and overall uncertainty analysis. Instead, we describe and quantify the uncertainties of each calculation step separately. Uncertainty in the change in radiative forcing due to a greenhouse gas emission change is mainly caused by uncertainty in the atmospheric lifetime and the radiative forcing efficiency of the greenhouse gas under consideration. Forster et al. (*6*) estimates a typical uncertainty of ±35% (90% confidence range) for the direct influence on radiative forcing by non-CO_2 greenhouse gas emissions and ±15% for CO_2. Forster et al. (*6*) also states that uncertainties for the indirect effects of emission changes on radiative forcing changes are generally much higher than those for the direct effects. The indirect effect of chlorides, halons and methane depends on actual background concentrations of the individual substances. We applied concentrations in year 2000 for this purpose. Atmospheric concentrations of halons and chlorides, however, are expected to significantly decline (*31*). The lower the concentrations, the smaller the expected indirect effects are. Therefore the indirect effects of ozone depleting chemicals are likely to reduce in the coming century.

The relationship between radiative forcing and temperature change is complex and potentially nonlinear. In this study, the calculation step from radiative forcing (RF) to temperature is numerically derived from the atmospheric model of IMAGE (*13*). Various factors, such as the choice for a specific background emission scenario and including land and oceanic feedback mechanisms on carbon sinks, may alter the outcomes. However, the influence of these factors on radiative forcing changes due to an emission change is expected to stay within a factor of 1.5 (*30*). Fuglestvedt et al. stated that calculations with different climate models show a range in the conversion factor of RF to temperature of $0.4-1.2$ °C/(W m^{-2}). The conversion factor used in this study ranges from 0.34 to 0.67 °C/(W m^{-2}), depending on the time horizon chosen, which falls mostly in the range reported by Fuglestvedt et al. (*32*).

Apart from uncertainties in the atmospheric part of the modeling procedure, uncertainties arise in the calculation of human health damage factors. The effects of climate change on human health are many and complex (*3, 4, 17*). Because of data limitations, not all human health effects were included in the analysis, such as dengue and tick-borne diseases. Additional data on worldwide relative risks of these infectious diseases due to global warming is required to further improve the calculation of human health damage factors. Most of the model uncertainties within the calculations of the Relative Risk factors are reflected in the scenario choices included in the different cultural perspectives (see Supporting Information). The uncertainties in the RR for diarrhea are mainly caused by the various pathogens and modes of transmission and the variability in severity of clinical symptoms of pathogens, and are expected to be in the range of 10% uncertainty (*18*). For malaria, McMichael et al. (*2*) applied the MARA model which uses a combination of biological and statistical approaches to quantify the effects of climate on Falciparum malaria. The uncertainty in the RR factors range from no increasing risk to a factor of 2 between the midrange and higher range (*18*). The effect of climate change on malnutrition is uncertain, mainly due to the predicted changes in regional precipitation. The uncertainty is expected to be in the range of no increasing risk to a factor of 2 between midrange and higher range RR estimates (*18*).

Uncertainties in DALY calculations, considering different future scenarios, are handled by the different perspectives. Note, however, that future projections in DALY development after 2030 are not taken into account, due to data limitations. This influences the results for the hierarchical and egalitarian perspective, as both have a time frame far beyond 2030, namely, 100 and 500 years after the baseline 1990.

Concerning damage toward ecosystems by global warming, IPCC (*33*) indicates that "20 to 30% of plant and animal assessed so far in an unbiased sample are likely to be at increasingly high risk of extinction as global mean temperatures exceed a warming of 2 to 3 °C above pre-industrial levels". From this information, we derive an ecosystem damage factor of typically 0.1 PDF/°C, which lies within the range of our results. The uncertainty range of the average extinction risk is $0.05-0.2$ PDF/°C global mean temperature rise (*33*). Note, however, that the temperature effect on individual species groups covers a much larger effect range of $0.005-0.43$/°C (*1*). Furthermore, the damage results on ecosystems do not take into account the possibility of human responses to protect biodiversity. The data provided by Thomas et al. (*1*) served as a basis for our results and did not consider this aspect in their analysis.

Comparison with Other LCIA Methods. When comparing our human health damage characterization factors for greenhouse gas emissions with previous studies (*5, 9*), it appears that the results of both other studies fall within our results. However, the differences in characterization factors between the studies are smaller than the differences caused by values choices within our study. This indicates that value choices generally have a larger influence on the human health damage characterization factors for greenhouse gases compared to differences caused by applying different modeling concepts that are currently available. A comparison of our ecosystem damage factors with the EPS method (*5*) was not possible, because the EPS method does not use the same modeling endpoint as used in our study, which is the time-integrated global disappearance of species.

In conclusion, the new characterization factors are suitable to compare the impacts of greenhouse gases with other types of stressors, such as substances causing acidification and respiratory impacts, for both human health and biodiversity. Particularly for impacts on biodiversity, greenhouse gas emissions have not been commonly included in LCA case studies. For human health damage, five different health effects were included, but still a number of other diseases related to global warming are missing in the calculations due to data limitations. We also showed that the choice of a specific perspective can substantially alter the characterization factors for greenhouse gases. This will alter the relative importance of greenhouse gas emissions compared to other stressors. It should be stressed that, by combining global warming damage scores with damage scores from other impact categories, inconsistent modeling assumptions may arise, such as differences in time horizon or assumptions on socio-economic adaptations. The influence of value choices and consistency between impact categories should be carefully assessed in LCA case studies.

Acknowledgments

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Supporting Information Available

Information on the calculation procedure of indirect radiative forcing of methane and ozone depletion chemicals, substance specific background data (Table S1), the lists of temperature factors (Table S2), assumptions on Relative Risk factors (Tables S3 an S4) and the list of DALYs and Relative Risk factors (Tables S5 and S6). Finally, a presentation of all human health damage factors (Table S7), ecosystem damage factors (Table S8) and characterization factors (Table S9). This material is available free of charge via the Internet at http://pubs.acs.org.

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