Value choices in life cycle impact assessment of stressors causing human health damage

An M. De Schryver*, Rosalie van Zelm, Sebastien Humbert, Stephan Pfister, Thomas E. McKone, Mark A.J. Huijbregts

*E-mail: an.schryver@gmail.com

This is an earlier version of the following article: De Schryver A.M., Van Zelm R., Humbert S., Pfister S., Huijbregts M.A.J. 2011. Value choices in life cycle impact assessment of stressors causing human health damage. Journal of Industrial Ecology 15(5): 796-815, which was published in final form at http://onlinelibrary.wiley.com/doi/10.1111/j.1530-9290.2011.00371.x/abstract.

<heading level 1> Abstract

This article investigates how value choices in life cycle impact assessment can influence characterization factors (CFs) for human health (expressed as disability-adjusted life years or DALY). The Cultural Theory is used to define sets of value choices in the calculation of CFs, reflecting the individualist, hierarchist and egalitarian perspectives. CFs were calculated for interventions related to the impact categories water scarcity, tropospheric ozone formation, particulate matter formation, human toxicity, ionizing radiation, stratospheric ozone depletion and climate change.

With the Cultural Theory as a framework, we show that individual, hierarchical and egalitarian perspectives can lead to CFs that vary up to six orders of magnitude. For persistent substances, the choice in time horizon explains the differences among perspectives, while for non-persistent substances, the choice in age weighting and discount rate of DALY, and the type of effects or exposure routes, accounts for differences in CFs. The calculated global impact varies by two orders of magnitude, depending on the perspective selected and derives mainly from particulate matter formation and water scarcity for the individualist perspective, and from climate change for the egalitarian perspective.

Our results stress the importance of dealing with value choices in life cycle impact assessment and suggest further research for analyzing the practical consequences for life cycle assessment results.

Keywords

uncertainty analysis

value choices

life cycle impact assessment

human health

Cultural Theory

<heading level 1> Introduction

Uncertainties are inevitable in life cycle assessment (LCA), risk assessment, or any other analytical tool to assess environmental impacts (e.g., Huijbregts, 1998, Steen, 2006). Different types of uncertainty arise within each step of an assessment — for example, while collecting data, defining system boundaries, or calculating environmental impacts of emissions.

Several typologies are put forward to describe the different types of uncertainty (e.g., Morgan and Henrion, 1990, Wynne, 1992, van Asselt and Rotmans, 2002, Ascough et al., 2008). In general, three types of uncertainties can be distinguished: measurement uncertainty, uncertainty from assumptions and uncertainty from ignorance. In this paper we focus on uncertainties from assumptions in life cycle impact assessment. Uncertainties from assumptions most often involve value choices. Assumptions can derive from lack in knowledge, whereby the choice of one option above another can be influenced by personal values such as, what is commonly accepted or familiarity. Hertwich et al. (2000) describe these value choices as contextual values. On the other hand, assumptions can also be driven by personal beliefs and values that reflect what we care about, without any science being involved. A typical example is the equity of different age groups or species. These value choices are defined as preference values (Hertwich et al., 2000).

Scenario analyses can be used to investigate the uncertainties related to assumptions or choices that reflect different personal values. Several tools and frameworks exist to cluster different personal values and define model scenarios (e.g., Schwartz and Mark, 1992, Tukker, 2002). Within LCA, the Cultural Theory has been used as a tool, as it both reflects visions on society and views on nature (e.g., Hofstetter, 1998, Frischknecht et al., 2000, Goedkoop et al., 2008). The Cultural Theory distinguishes five different perspectives from which people perceive the world and behave in it. Three of these are generally used within environmental decision making: the individualist, hierarchist and egalitarian perspectives (Hofstetter, 1998, Hofstetter et al., 2000). Each perspective reflects a hypothetical stakeholder or decision maker with a specific set of preferences and contextual values that explains one’s view on society and nature (Schwarz and Thompson, 1990, Thompson et al., 1990, van Asselt and Rotmans, 1996). Several case studies have empirically shown a relationship between cultural perspectives and environmental concerns (e.g., Steg and Sievers, 2000, Lima and Castro, 2005, Leiserowitz, 2006). An analysis of the toxicity controversy in Sweden and the Netherlands indicates that within the specific study the individualist perspective has a link with opinions from industry, the hierarchist perspective with the Environmental Protection Agency (in Sweden) or the Dutch environmental ministry and the egalitarian perspective with environmentalists (Tukker et al., 2002). Therefore, the Cultural theory is recognized in (partly) contributing to a better understanding of different environmental perceptions.

Most impact assessment methodologies embed value choices without giving practitioners or decision makers the opportunity to assess the difference in result when applying a distinct world view (e.g., Jolliet et al., 2003, Hauschild and Potting, 2005). Some impact assessment methodologies do handle uncertainties arising from value choices by applying the Cultural Theory, but in a limited and not always consistent way (e.g., Goedkoop et al., 2008). Therefore, we argue for broader implementation of the Cultural Theory in an impact assessment methodology that combines several impact categories. In this case, each scenario basically reflect the choices made in the modeling using one specific line of reasoning throughout the analysis.

The goal of this paper is to address uncertainties related to assumptions and value choices in life cycle impact assessment. Three sets of characterization factors (CFs) for human health damage (expressed as disability-adjusted life years or DALYs) are developed, by implementing specific value choices for the individualist, hierarchist and egalitarian perspectives in existing impact assessment models. For each perspective, we defined value choices for seven human health impact categories: water scarcity, tropospheric ozone formation, particulate matter formation, human toxicity, ionizing radiation, stratospheric ozone depletion, and climate change. These categories address both local and global effects as well as short- and long-term effects, and are the most widely used environmental impact categories in life cycle assessment of human health (Hauschild et al., 2009). Our work focuses on human health damage, but is equally relevant to analyze impacts for ecosystem quality and resource depletion. The value choices recognized as main drivers for differences in CFs among perspectives are outlined and explained. The constructed impact assessment methodology is used to quantify the human health damage from annual global water consumption and outdoor emissions, and to analyze the differences among perspectives. Finally, the limitations of the analysis and future research needs are discussed.

<heading level 1> Methodology

<heading level 2> Value choices

The individualist, hierarchist and egalitarian perspectives each have their own contextual and preference values (Schwarz and Thompson, 1990, Hofstetter et al., 2000, Jager et al., 1997, Thompson et al., 1990, van Asselt and Rotmans, 1996). The individualist perspective is characterized by weak group cohesions (relationships) and regulations for social relations, and considers nature to be stable and able to recover from any disturbance. This coincides with the view that humans have a high adaptive capacity through technological and economic development. Known damages are considered as the most reliable basis for decisions and present effects are emphasized over future gains or losses. The hierarchist perspective is characterized by strong group cohesion with binding regulations for social relations and considers nature to be in equilibrium. This perspective coincides with the view that impacts can be avoided with proper management and the search for a balance between manageability and the precautionary principle. The egalitarian perspective has strong group cohesion coupled with few regulations and considers nature to be fragile and unstable. This vision gives high priority to the precautionary principle and equal importance to present and future effects.

Figure 1 presents an overview of the different contextual and preference values, projected along the cause effect pathway. For seven human health impact categories, existing damage models that calculate CFs were adapted to the three sets of value choices. The damage models selected are those included in ReCiPe 2008 (Goedkoop et al., 2008) with water scarcity added as extra impact category

(Pfister et al., 2009) and updated characterization factors for climate change (De Schryver et al., 2009). An exception holds for the impact category stratospheric ozone depletion, as it was not feasible to include time horizon specific calculations in the model employed in ReCiPe2008 (Struijs et al., 2010). For this impact category, the model developed by Hajashi et al. (2006) was adapted. Table 1 is a synopsis of the choices that are used in the calculations. For detailed descriptions see appendix 1 (table 1).

Preference values reflect what we care about, our moral values and ideas of what is good or bad for society, such as the concern for equity or future generations (Munthe, 1997, Hertwich et al., 2000). The following choices regarding different preferences were considered:

- The temporal vision of life and society is perspective-dependent (Jager et al., 1997). Time perspective can be applied by considering effects within a certain time horizon or by discounting future effects. Different time horizons were applied within the calculation from emission to effect, while discounting was applied to calculate the damage, namely discounting years of life lost in the future (Murray and Lopez, 1996, Hellweg et al., 2003). Based on Jager et al. (1997) and Janssen and Rotmans (1995), we selected a time horizon of 20 years and a discount rate of 5% for the individualist perspective, emphasizing present and short-term effects. The hierarchist perspective has a more balanced time perspective and follows a 100-year time horizon, which is most frequently used by several organizations (ISO/TR14047:2003, 2003, Steinfeld et al., 2006, PAS 2050, 2008). We propose a 3% discount rate, as this rate is used as default scenario in burden of disease calculations by the World Health Organization (Murray and Lopez, 1996). The egalitarian perspective gives importance to long-term effects as current and future effects are considered equal. This coincides with an infinite time horizon and 0% discount rate (Jager et al., 1997, Janssen and Rotmans, 1995).

- Assigning value to a year of life at different ages (defined as age weighting) depends on personal preference (Murray and Lopez, 1996). The individualist perspective gives a higher value to more economically relevant subpopulations. The strong group cohesion of the hierarchist and egalitarian perspectives results in equality and thus no differentiation between individuals of different ages (Hofstetter, 1998).

- Including or excluding positive effects can be considered as a preference value choice (Jager et al., 1997). Examples of positive environmental effects are the cooling effects from chlorofluorocarbons and halons that counter climate change, as well as nitrogen oxides that degrade tropospheric ozone, countering ozone formation. Positive effects were only included for the individualist perspective following their positive attitude towards environmental benefits (Hofstetter, 1998).

Contextual values relate to our idea of how the world works. They reflect the influence of personal and social judgment when choosing one scientific assumption over its alternative, such as familiarity with a certain dataset or common acceptance (Hertwich et al., 2000). The following choices regarding different contextual values were considered:

- Limited knowledge on causalities reflects a different level of risk that is or is not accepted by a certain perspective. According to Thompson et al. (1990) the egalitarian perspective is risk-adverse, while the individualist is risk taking. The hierarchist accepts a high level of risk, as long as the decision is made by experts (Thompson et al., 1990). Based on this consideration, the egalitarian perspective includes all known effects; the hierarchist perspective, likely effects; and for the individualist perspective, certain (proven) effects.

- Improved health care can reduce the DALYs attributable to a certain impact (Lorenzoni et al., 2005), while the level of legislation, education and research can increase protection and prevention. Differences in assumptions concerning the level of biological and socioeconomic adaptation possibilities, which also can be defined as management style (Ezzati et al., 2004), were considered in the definition of perspectives (Hofstetter et al., 2000). The individualist perspective coincides with an adaptive management style, the egalitarian with a preventive and comprehensive management style, and the hierarchist with a controlling and limited management style (Hofstetter et al., 2000, De Schryver et al., 2009).

- Future projections on demographic developments, population displacements, changes in gross domestic product, years of schooling and technology changes will alter the sensitivity, size and age composition of the population and thus influence the number of incidence cases attributable to a given emission (Mathers and Loncar, 2006). Future optimistic, baseline and pessimistic development scenarios, as defined by Mathers and Loncar (2006), coincide respectively with the individualist, hierarchist and egalitarian perspectives (De Schryver et al., 2009).

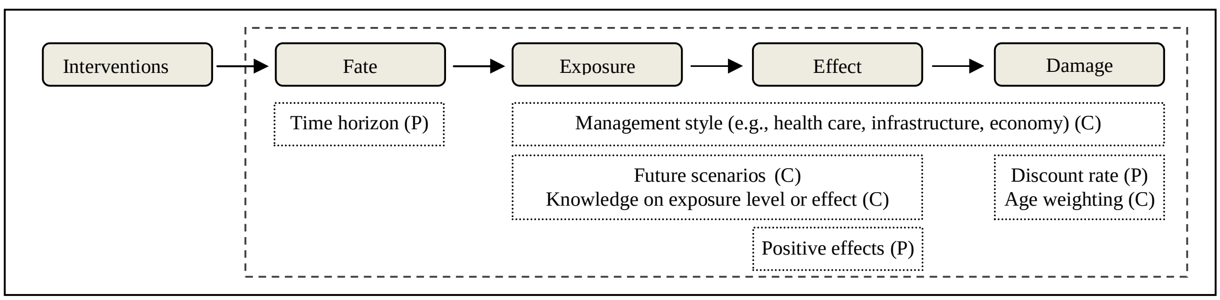

Figure 1. Overview of the cause effect pathway, from intervention to damage. The calculation steps of the characterization factors are presented in the dashed box. Choices deriving from preference values (P) and contextual values (C), considered at each calculation step, are presented in the dotted boxes.

<heading level 2> Global damage of water consumption and outdoor emissions

The global damage from outdoor emissions was calculated using inventory data for the year 2000 from Sleeswijk et al. (2008). For water scarcity, country-specific water consumption data for the year 1995 were derived from the Watergap2 global model (Alcamo et al., 2003). For each impact category, the substances contributing most to the global impact per capita (DALY/capita) were identified and presented. A population of 5.7 billion people in 1995 and 6.1 billion people in 2000 was considered (UNDESA, 2008). To evaluate the global damage caused by water consumption and outdoor emissions in the year 2000, the per capita global impact was multiplied with the 2000 population. Therefore, for water scarcity, it was assumed that the water impact per capita did not change between 1995 and 2000.

Table 1. Combination of value choices deriving from preference values (P) and contextual values (C) for the CFs, expressed for three different cultural perspectives.

Impact category	Original choices[a]	Value choices	P/C	Individualist	Hierarchist	Egalitarian
All impact categories		Time horizon	P	20 years	100 years	Infinite
		Discount rate	P	5%	3%	0%
		Age weighting	P	Yes	No	No
Water scarcity Pfister et al. (2009)	Age weighting: yes Discount rate: 3% Regulation of flow: standard Food water requirement: $1350m^3$/yr.capita	Regulation of flow (management style) Food water requirement (management style)	C C	High $1000m^3$/yr.capita (i.e., efficient management)	Standard $1350m^3$/yr.capita (i.e., standard management)	Standard $1350m^3$/yr.capita (i.e., standard management)
Ozone formation Van Zelm et al. (2008)	Age weighting: no Discount rate: 0% Morbidity effects: not included Positive effects from NO_x are included and excluded.	Morbidity effects[b] Positive effects from tropospheric ozone degradation from NO_x	C P	No Yes	No No	Yes No
Particulate matter Van Zelm et al. (2008)	Age weighting: no Discount rate: 0% Type of PM: primary PM_{10} and secondary PM from SO_2, NO_x and NH_3	Effects from primary PM_{10} and secondary PM from SO_2, NO_x and NH_3	C	Primary PM_{10}	Primary PM_{10} + Secondary PM from SO_2	Primary PM_{10} + Secondary PM from SO_2, NO_x and NH_3
Human toxicity Huijbregts et al. (2005)	Age weighting: no Discount rate: 0% Bioaccumulation essential metals: yes Carcinogenity: all substances Noncarcinogenic effects: included Time horizon: infinite	Bioaccumulation for essential metals Included substances on basis of carcinogenity Noncarcinogenic effects	C C	No IARC classification: 1 No	Yes IARC classification: 1, 2A, 2B Yes	Yes All Yes
Ionizing radiation Frischknecht et al. (2000)	All cancer types Discount rate: 0% time horizon: individualist, 100yr; hierarchist and egalitarian, 100,000yr Age weighting: same as presented here	Cancer types[c]	C	Definite cancers	Definite and probable cancers	Definite, probable, possible and remainder cancers without information
Ozone depletion Hayashi et al. (2006)	Age weighting: no Discount rate: 0% Cataract: included Time horizon: infinite	Cataract	C	No	No	Yes
Climate change De Schryver et al. (2009)	Individualist: same as presented here except discount rate is 3% Hierarchist: same as presented here Egalitarian: same as presented here	Positive effects from ozone depletion Management style (Ezzati et al., 2004) Future developments (Mathers and Loncar, 2006)	P C C	Yes Adaptive management style Optimistic	No Controlling management style Baseline	No Comprehensive management style Pessimistic

Note: Detailed descriptions can be found in the appendix 1 table 1. m^3/yr.capita= cubic meter per year per capita; IARC= International Agency for Research on Cancer; PM= particulate matter; PM_{10} particulates, <10µm.

[a]For all impact categories, except climate change and ionizing radiation, the original method developers presented one set of CFs embedding a certain set of value choices. For ionizing radiation and climate change, the original method developers presented CFs for the individualist, hierarchist and egalitarian perspectives.

[b]Morbidity effects included are asthma attacks, minor restricted activity days, respiratory hospital admissions, symptom days.

[c]Definite cancers are thyroid, bone marrow, lung, breast cancer; probable cancers are bladder, colon, ovary, liver, oesophagus, skin and stomach cancer; cancers without information are bone surface and all other cancers.

<heading 1> Results

Figure 2 presents the CFs for a subset of interventions (in DALY/kg, DALY/kBq or DALY/m^3) for the three cultural perspectives. The full list of CFs for 1239 substances and water consumption can be found in appendix 2. The number of substances included for the impact categories particulate matter and human toxicity depends on the level of knowledge about effects or exposure assumed for each perspective. For particulate matter, effects of secondary particulates from sulphur dioxide (SO_2), ammonia (NH_3) and nitrogen oxides (NO_x) are excluded for the individualist perspective, while effects from NH_3 and NO_x are excluded for the hierarchist perspective. For human toxicity, the availability in knowledge about carcinogenity and including or excluding non-carcinogenic effects results in CFs for 25 substances when applying the individualist perspective, 620 substances for the hierarchist perspective, and 1002 substances for the egalitarian perspective. For the individualist perspective positive effects are included and therefore the CF of some substances turns negative, such as nitrogen oxides for ozone formation and chlorofluorocarbons and halons for climate change.

Table 2 lists the differences in CFs for each impact category and the relevant choices that lead to differences among perspectives. Table 2 does not cover, however, the differences in case a CF becomes zero due to specific choices concerning the certainty of effects. It also does not address the fact that for ozone formation and climate change, some CFs range from negative (i.e., reducing the impacts) to positive (i.e., causing impacts) values, depending on whether positive effects are included for the perspectives. The type of DALY refers to the combination of age weighting and discount rate, which both influence the number of DALYs calculated per case (see tables 5 and 6 in appendix 1). The difference in CFs among perspectives is the largest for substances with a relatively long residence time in the environment (> 100 years). This is particularly the case for a number of emissions connected to the impact categories human toxicity (metals), ionizing radiation, ozone depletion and climate change. For example, the difference in CF between the individualist and egalitarian perspectives is five orders of magnitude for tetrafluoromethane (PFC-14; for climate change) and four orders of magnitude for iodine-129 (I-129; for ionizing radiation). For toxicity of metals, the difference in CFs among perspectives can be as much as six orders of magnitude, due to the long lifetime and inclusion or exclusion of bioaccumulation of metals. For ozone depletion, the difference in CFs among perspectives is smaller, with two to three orders of magnitude between the individualist and egalitarian perspectives. Impact categories that cover substances with a shorter residence time in the environment, i.e., ozone formation and particulate matter, show smaller differences among perspectives (up to 1.2 orders of magnitude). However, combining the effects of particulate matter and ozone formation for NO_x gives a difference of three orders of magnitude between the hierarchist and egalitarian perspectives. This is due to the exclusion of highly uncertain effects for the hierarchist perspective. For water scarcity, the CFs show relatively small differences among perspectives attributable to value choices.

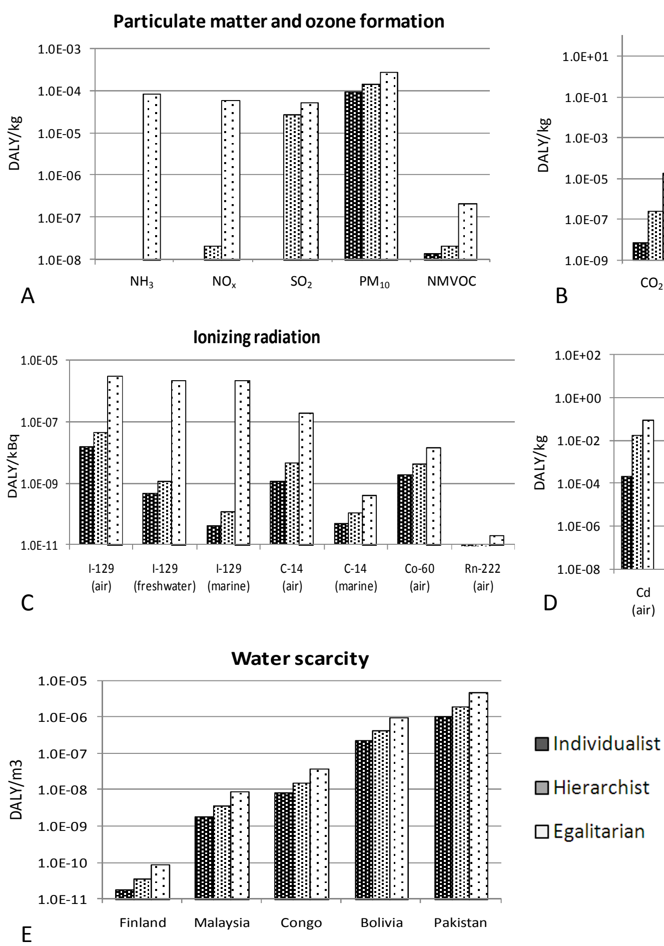

Figure 2. CFs for a range of selected substances following an individualist, hierarchist and egalitarian perspective. Graph A: combined CFs for particulate matter and ozone formation. Note that the negative CF for NO_x for the individualist perspective, $-4.2.10^{-8}$ DALY/kg, is not presented. Graph B: combined CFs for climate change and ozone depletion. Graph C: CFs for ionizing radiation. Graph D: CFs for human toxicity. Graph E: CFs for water scarcity in different regions. Note: CFs are expressed in DALY/kg, DALY/kBq or DALY/m^3 using a log-scale. DALY/kg= DALY per kilogram; DALY/kBq= DALY per kilobecquerel; DALY/m^3= DALY per cubic meter; NH_3=ammonia; NO_x= nitrogen oxides; SO_2= sulphur dioxide; PM_{10}= particulates, <10 µm; NMVOC= non-methane volatile organic compounds; CO_2= carbon dioxide; CH_4= methane; N_2O= dinitrogen oxide; CFC-11= trichlorofluoromethane; PFC-14= tetrafluoromethane; I-129= iodine-129; C-14= carbon-14; Co-60= cobalt-60; Rn-222= radon-222; Formal= formaldehyde; Mo= molybdenum; Cd= cadmium; Hg= mercury; Dioxin= 2,3,7,8-tetrachlorodibenzo-p-dioxin.

Table 2. Difference in CFs among perspectives, per impact category (IC). For impact categories for which the time horizon is important (human toxicity, ionizing radiation, ozone depletion and climate change) a difference is made between long-lived (LL, i.e., > 100 years) and short-lived (SL, i.e., < 100 years) substances.

IC	egalitarian/ individualist	egalitarian/hierarchist	hierarchist/ individualist
Water scarcity	Max. difference is a factor of 18	Max. difference is a factor of 2.3	Max. difference is a factor of 8
	The regulation of flow is the most important choice, followed by the choice in type of DALY and water requirement	The choice in type of DALY is the only choice responsible for the difference	The regulation of flow, the choice in type of DALY and water requirement are all equally important
Ozone formation[a]	Max. difference is a factor of 15	Max. difference is a factor of 10	Max. difference is a factor of 1.5
	The choice in including effects with low amount of knowledge is 1.8x more important than the choice in type of DALY	The choice in including effects with low amount of knowledge is 2.5x more important than the choice in type of DALY	The choice in type of DALY is the only choice responsible for the difference
Particulate matter	Max. difference is a factor of 2.8	Max. difference is a factor of 1.9	Max. difference is a factor of 1.5
	The choice in type of DALY is the only choice responsible for the difference	The choice in type of DALY is the only choice responsible for the difference	The choice in type of DALY is the only choice responsible for the difference
Human toxicity[a]	Metals: max. 6 orders of magnitude Non metals: max. factor of 10	Metals: max. 4 orders of magnitude Non metals: max. factor of 22	Metals: max. 5 orders of magnitude Non metals: max. factor of 7
	Metals: the choice in time horizon and bioaccumulation determines the difference in perspective Non metals: the choice in including noncarcinogenic effects is 2x more important than the choice in type of DALY	Metals: the choice in time horizon determines the difference in perspective Non metals: the choice in including carcinogenic effects (IARC classification) is 12x more important than the choice in type of DALY	Metals: the choice in time horizon and bioaccumulation mainly determines the difference in perspective Non metals: the choice in including noncarcinogenic effects is 2x more important than the choice in type of DALY
Ionizing radiation	LL: max. 4.4 orders of magnitude SL: max. factor of 11	LL: max. 4 orders of magnitude SL: max. factor of 2.2	LL: max factor of 11 SL: max factor of 5.2
	LL: the choice in time horizon is more than 2000x more important than the choice in type of DALY or the knowledge about effects SL: the choice in type of DALY, the knowledge about effects and time horizon all contribute with the same importance to the difference between scenarios	LL: the choice in time horizon is more than 2000x more important than the choice in type of DALY or the knowledge about effects SL: the choice in type of DALY, the knowledge about effects and time horizon all contribute with the same importance to the difference between scenarios	LL: the choice in time horizon is 2x more important than the choice in type of DALY or the knowledge about effects SL: the choice in type of DALY, the knowledge about effects and time horizon all contribute with the same importance to the difference between scenarios
Ozone depletion	LL: max. 2.5 orders of magnitude SL: max. factor of 30	LL: max. 1.5 orders of magnitude SL: max. factor of 20	LL: max. factor of 9 SL: max. factor of 6
	LL: choice in time horizon can rise up to 60x more important than choice in type of DALY and up to 7x than the inclusion of cataract SL: the choice in including cataract is 8x more important and twice as important than choice in type of DALY and time horizon	LL: the choice in time horizon and including cataract are main important for the difference in scenario, being respectively 15x and 11x more important than the choice in type of DALY SL: the choice in including cataract is 9x and 11x more important than the choice in time horizon and type of DALY	LL: the choice in time horizon is 4 to 5x more important than the type of DALY or including cataract SL: the choice in time horizon is up to 2x more important than the type of DALY or including cataract
Climate change[b]	LL: max. 5 orders of magnitude SL: max. 2.5 orders of magnitude	LL: max. 3 orders of magnitude SL: max. factor of 10	LL: max. 2 orders of magnitude SL: max. 1.5 orders of magnitude
	LL: the choice in time horizon is max. 400x more important than choice in management style and future scenarios, that on its turn is 4x more important than the	LL: the choice in time horizon is max. 300x more important than choice in type of DALY or future scenarios and management style	Independent of the lifetime of the substance, the choice in time horizon is equally important than the choice in management style and future scenarios; The choice in

	choice in type of DALY SL: the choice in management style and future scenarios is 4x more important than choice in type of DALY, and 1.3x more important than the choice in time horizon	SL: the choice in time horizon, management style, future scenarios and type of DALY is equally important	DALY is less important

Note: The numerical values represent the maximum ratios of the egalitarian/individualist, egalitarian/hierarchist and hierarchist/individualist scenarios. The type of DALY refers to the combined choice in age weighting and discount rate.

[a]Only the max. differences for substances included in both perspectives are presented. For the egalitarian/individualist perspective vinylchloride shows a maximum difference of a factor of ten. For the egalitarian/hierarchist scenario the same substance shows a max. difference of a factor of 1.5.

[b]Both positive and negative CFs are reported (see appendix 2). Only positive CFs are considered in the ratio calculations. The negative and zero values are further discussed in the text.

The global human damage (temporal cumulated) caused by water consumption and outdoor emissions in the year 2000 is 4 million DALYs for the individualist, 21 million DALYs for the hierarchist perspective, and 570 million DALYs for the egalitarian perspective (table 3). This implies that the loss in (disability adjusted) life years caused by one average world citizen due to water consumption and emissions in the year 2000 is between 0.2 and 34 days, depending on the perspective considered.

Table 3. Interventions responsible for 95% of the global human damage caused by water consumption and outdoor emissions in the year 2000. The damage scores (in DALY/capita) and percentage damage contribution (in %) are presented.

Substance/source	**Compartment of emission**	**Individualist**		**Hierarchist**		**Egalitarian**		**Driving choices**
		DALY/ (capita.yr)	**%**	**DALY/ (capita.yr)**	**%**	**DALY/ (capita.yr)**	**%**	
Water consumed		1.4E-4	21.1%	2.8E-4	8.3%	6.7E-4	0.7%	Management style (regulation of flow) + type of DALY
Particulates, < 10 µm	Air	4.4E-4	66.9%	6.5E-4	19.1%	1.2E-3	1.3%	Type of DALY
Carbon dioxide, fossil	Air	3.5E-5	5.3%	1.2E-3	35.2%	8.2E-2	87.8%	Time horizon
Methane[a]	Air	3.0E-5	4.6%	3.6E-4	10.7%	2.5E-3	2.6%	Management style-future scenarios
Sulfur dioxide	Air	2.4E-8	0.0%	5.7E-4	16.8%	1.1E-3	1.2%	Type of effects included
Dinitrogen monoxide	Air	4.4E-6	0.7%	1.6E-4	4.6%	1.8E-3	1.9%	Management style-future scenarios + time horizon
CFC-12	Air	9.9E-7	0.2%	5.7E-5	1.7%	5.6E-4	0.6%	Management style-future scenarios + time horizon
Others		7.8E-6	1.2%	1.2E-4	3.6%	3.6E-3	3.8%	
Total damage (in DALY/capita)		6.5E-4	100%	3.4E-3	100%	9.3E-2	100%	
Total damage (in disability-adjusted life days/capita)		0.2		1.2		34		
Total global damage for the world (in DALY), using a population of 6.12 billion people		4.0E+6		2.1E+7		5.7E+8		

Note: The column "driving choices" presents the value choices responsible for the difference among perspectives. The type of DALY refers to the choice in age weighting and discount rate.

[a]Sum of methane from biogenic and fossil origin. No degradation products are included in the inventory dataset or CFs, therefore there is an underestimation of the damage from methane (more details can be found in the appendix 1).

Figure 3 illustrates the share of each impact category to the global human health damage (in %) caused by water consumption and outdoor emissions in the year 2000, for the three perspectives. Depending on the perspective, the damage is driven mainly by three impact categories: water scarcity, particulate matter and climate change. All other impact categories contribute less than 2% to the damage. Of the total damage score of the individualist perspective, 67% is attributable to particulate matter formation and 21% to water scarcity. For the egalitarian perspective, 95% of the total damage score is related to climate change (mainly CO_2 emissions). For the hierarchist perspective, the total damage score is distributed almost equally between climate change (±50%) and particulate matter (±40%), together with a ±10% contribution by the impact of water scarcity. Independent of perspective, six substances and water consumption are responsible for more than 95% of the total damage (see table 3). Substance contributions per impact category can be found in the appendix 1 (table 4).

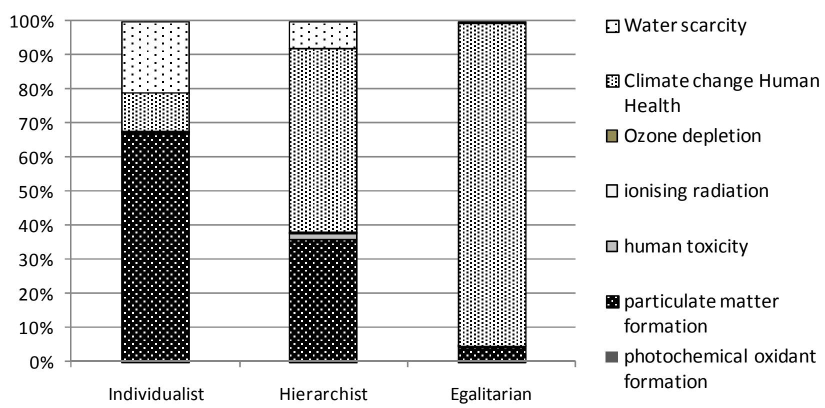

Figure 3. Global human health damage (share of each impact category, expressed in %) caused by outdoor emissions and water consumption in the year 2000, following the individualist, hierarchist and egalitarian perspectives.

<heading 1> Discussion

In this paper, existing models to calculate CFs for water consumption and 1239 substances (Pfister et al., 2009, Van Zelm et al., 2008, Huijbregts et al., 2005, Frischknecht et al., 2000, Hayashi et al., 2006, De Schryver et al., 2009) were adapted following the Cultural Theory, using different value choices for individualist, hierarchist and egalitarian perspectives (e.g., Schwarz and Thompson, 1990, van Asselt and Rotmans, 1996, Hofstetter, 1998, Hertwich et al., 2000, Hofstetter et al., 2000, Steen, 2006). This application allows for a transparent way of handling value choices for environmental assessments and decision making. While we illustrate this work by focusing on damage to human health, the technique can also be applied to assess impacts from other damage categories such as, ecosystem quality and resource depletion.

The calculations show that scenario-specific differences in CFs depend on the persistence of the substance in the environment. For persistent substances, such as long-lived greenhouse gases or metals, the difference in CFs can reach up to six orders of magnitude. The chosen time horizon used for the fate and exposure factor is mainly responsible for this difference (preference value). This also implies that for CFs on midpoint level (e.g., global warming potentials) the applied time horizon is an important value choice. For short-lived substances, the difference in CFs among perspectives mainly derives from choices regarding the effect and damage factor, namely the exposure or effects included based on the amount of knowledge (contextual value) and the choice in type of DALY (preference value). For water scarcity, the difference among perspectives is driven mainly by the management style that decides on how the water flow is regulated (contextual value).

<heading 2> Limitations in defined choices

Despite the substantial effort to create a coherent implementation of all value choices identified in the models employed, it was not possible to include all choices in the calculation of the CFs.

First, due to data limitations**,** perspectives on future scenarios (e.g., migration patterns and gross domestic product projections) and management style (socioeconomic adaptations) were not included, except for climate change. For climate change, the choices for future scenarios and socioeconomic adaptation made the CFs from the egalitarian and individualist perspectives differentiate by one order of magnitude. An improved health care system, better education or research can lower the damage factors, while demographic changes can influence the number of cases affected. The inclusion of future scenarios and management style can be an important contributor to the difference among perspectives for substances with long response times, such as a number of ozone-depleting chemicals. Further research on including future scenarios for all impact categories is therefore needed.

For ionizing radiation, limited data sources constrained the available exposure factors at the corresponding time horizon (see appendix 2). In total, CFs were derived for 52 ionizing substances. For the hierarchist perspective, CFs for three substances are missing (Pu-238 and Ra-226 emitted to air; Ra-229 emitted to freshwater) and for the individualist perspective, CFs for four substances are missing (Pu-238, Pb-210 and Ra-226 emitted to air; Ra-229 emitted to freshwater). This lack of CFs can lead to an underestimate of the damage score for the individualist and hierarchist perspectives when analyzing emission data that cover these substances (such as nuclear waste and electricity from nuclear and coal power plants). Note that for the global damage calculations, the missing substances were not present in the inventory dataset and thus no underestimation attributable to the lacking CFs arises.

Information on cause-effect relationships was not always available and therefore not all health effects could be included in the different scenarios (see appendix 1, table 1). Examples are diarrhea incidence from water scarcity (Banda et al., 2007), premature deaths from particulate matter (Reiss et al., 2007), solar keratosis from ozone depletion (Lucas et al., 2008) and dengue and tick-borne encephalitis from climate change (Haines et al., 2006). This omission results in an underestimation of CFs, particularly for the egalitarian perspective, as this perspective considers all possible effects, including those with limited knowledge.

<heading 2> Subjective assumptions

The ultimate goal for developing different scenarios is to provide tools to evaluate possible outcomes. Exploring various trajectories and considering alternative plausible states of the world widens stakeholder's or decision maker's perspective and highlights issues that otherwise would be missed (Mahmoud et al., 2009). In this study, we applied the Cultural Theory for exploring plausible states of the world (Thompson et al., 1990). However, subjective assumptions were inevitable in the construction of the scenarios:

- To account for different temporal visions of life and society, various time horizons were considered for the fate and exposure factor, while the damage factors included specific discount rates. The egalitarian perspective considers no discount rate, which is consistent with an infinite time horizon. A 5% discount rate for the individualist perspective results in a maximum of 20 life years lost at birth, and the same maximum DALYs result when applying a 20-year time horizon. A 3% discount rate for the hierarchist perspective results in a maximum of 30 life years lost at birth, which is lower than the maximum DALY obtained when applying a 100-year time horizon. In general, applying a 5% or 3% discount rate for the individualist or hierarchist perspectives respectively gives a lower damage factor than applying a time horizon of 20 or 100 years for the damage factor. The combined use of time horizon and discount rate is common practice in life cycle assessment (e.g., Hauschild and Potting, 2005, Jolliet et al., 2003). Consistently applying a time horizon or a discount rate throughout the calculation steps of CFs is recommendable and warrants further research.

- Which time horizon or discount method to select is difficult to underpin. Other time horizons or discount methods than those applied here could be selected. For example, for the egalitarian perspective one can argue that an infinite time horizon is unrealistic for some emissions (residence time of > 100,000 years) and a more appropriate time horizon could be selected, such as a 500-year time frame (IPCC, 2000). Furthermore, instead of a constant discount rate a non-linear discount rate could be applied, as suggested by Harvey (1994).
- In this paper only the effects of equal weights and unequal weights as provided by the WHO are assessed by age weighting (WHO, 2008). However, not all studies agree in assigning different weights to a year of life lost at different ages, nor in the relative magnitude of the weights (Lopez et al., 2006).
- Positive effects, such as from NO_x emissions regarding tropospheric ozone degradation, were only included for the individualist perspective following their positive attitude towards environmental benefits (van Asselt and Rotmans, 1996). However, in most cases positive effects are also uncertain. This is contradicting with the individualist perspective which only includes proven effects (Thompson et al., 1990). The high level of uncertainty argues for excluding positive effects for the individualist and hierarchist perspectives and including them for the egalitarian perspective. Here, positive effects are essentially assessed on basis of their positive environmental impacts and not their level of uncertainty.
- Causalities with limited knowledge are manifold, such as uncertainty in morbidity effects from ozone formation, and the effects from secondary aerosols. Effects or substances with limited scientific proof are excluded from the individualist perspective,

while included for the egalitarian perspective. However, for the hierarchist perspective, the required level of knowledge is more difficult to define. For instance, some researchers (Gloria et al., 2006, Ligthart, 2004) argue that the fate and exposure models used to address the human toxicity of metals, such as USES-LCA (Uniform System for the Evaluation of Substances; Van Zelm et al., 2009), are highly uncertain. Therefore, bioaccumulation of essential metals (i.e., cobalt, copper, manganese, molybdenum and zinc) is expected to be overestimated. Excluding bioaccumulation in the hierarchist perspective would decrease CFs for essential metals up to four orders of magnitude.

The Cultural Theory is recognized as not being able to account for the full variety of world visions and perspectives (conform van Asselt and Rotmans, 1996) and is sometimes criticized because it lacks full empirical validation (Marris et al., 1998, O'Riordan and Jordan, 1999, Steg and Sievers, 2000). We are aware that more research is needed to analyze how these perspectives are linked to realistic human actor groups (e.g., building further on Tukker et al., 2000). Using surveys would be another way of deriving at scenarios in life cycle impact assessment. Therefore, the constructed scenarios can be seen as default scenarios and depending on the questions to be answered, we recommend the development of a flexible system that allows users to adapt and construct their own scenarios.

<heading 2> Global damage of water consumption and outdoor emissions

Depending on the perspective chosen, the global damage caused by water consumption and outdoor emissions in the year 2000 is mainly caused by the impacts from climate change or particulate matter. The global human damage (temporal cumulated) caused by water consumption and outdoor emissions in the year 2000 (in DALY/capita) is for the individualist perspective two orders of magnitude lower than for the egalitarian perspective and derives mainly from the difference in time horizon chosen for climate change. The chosen time horizon determines how much damage caused by persistent substances, in this case carbon dioxide, is included in the damage score. For climate change, taking only part of the damage into account causes a difference of three orders of magnitude between the egalitarian and individualist perspectives. This makes the time horizon the most important value choice for the difference in global damage among perspectives. The damage from particulate matter dominates the global damage outcome for the individualist perspective. As a matter of comparison, our results for particulate matter represent approximately half (for individualist) to approximately the same (for egalitarian) burden of disease from outdoor air pollution in the year 2000 calculated by Cohen et al. (2005).

The global damage calculations have several limitations:

- Not all human health impacts were considered in this assessment, mainly due to lack of data. Impacts, such as from noise and indoor air emissions, should be included in order to improve the calculation of the global damage;
- Except for water scarcity, all impacts are calculated by combining global total emission data with average CFs. Further research is needed to evaluate both the inventory and the CFs of impacts at regional and local levels (e.g., urban versus rural versus remote emissions). Within this study, regionalization is especially required for ozone formation and particulate matter;
- For particulate matter, the CF of PM_{10} (from Van Zelm et al., 2008) is used to calculate the global damage from global PM_{10} emissions (from Sleeswijk et al. 2008). Because PM_{10} is an important contributor to the total damage, better assessment of the size distribution below PM_{10}, i.e. $PM_{2.5}$ and $PM_{0.1}$, would be necessary to reduce uncertainty in the results (Dockery et al., 1993);
- We considered total water consumption (industry, households and irrigation) to evaluate the damage from water scarcity. The result is the potential number of

DALYs/yr that can be avoided if all water consumed today was saved under current water scarcity conditions. It is however virtually impossible to save all water used for irrigation. This implies that the global damage from water consumption is probably overestimated in our current calculations, particularly because water from irrigation accounts for 85% of the global water consumption (Shiklomanov, 1999);

- To evaluate the damage caused by water consumption in 2000, water consumption per capita for 1995 is multiplied with the population in 2000. Therefore, pressure per capita is assumed not to change between 1995 and 2000, which is a source of uncertainty that needs further refinement.

<heading 1> Conclusion

Value choices in impact assessment modeling were implemented by applying the Cultural Theory. CFs for 1239 substances and water consumption are provided, covering the human health impact categories of water scarcity, ozone formation, particulate matter, human toxicity, ionizing radiation, ozone depletion and climate change. Depending on the chosen perspective, CFs can range from negative to positive values and differ up to six orders of magnitude. The most important value choice for substances with a relative long life time is the choice in time horizon (fate factor), followed by the effects included and the choice in age weighting and discount rate of the DALY calculation (damage factor). For substances with a relative short life time, the most important choices are the effects included and choice in age weighting and discount rate.

When applying the three sets of CFs to assess the global emissions and water consumption, the damage to human health differs by 2 orders of magnitude among the chosen perspectives and is mainly driven by the time horizon chosen for climate change. The global impact comes mainly from particulate matter when considering an individualist perspective, climate change when considering an egalitarian perspective, and particulate matter and climate change when considering a hierarchist perspective. Water scarcity should also not be neglected, as it contributes considerably to the global impact for the individualist and hierarchist perspectives. All other impact categories contribute less than 2% to the total global damage.

The results of this study clearly indicate that value choices within impact assessment modeling influence the absolute values of CFs and the overall damage calculation. Further research is required to evaluate whether cultural perspectives can also change the ranking among products and services, and conclusions of life cycle assessment studies.

<heading level 1> Acknowledgements

The authors would like to thank Kentaro Hayashi for his relevant input and contribution in the discussions regarding the value choices within the existing life cycle impact assessment models; Patrick Hofstetter for his interesting comments at the start of the paper; as well as Naomi Lubick for the editing. The research was partly funded by the European Commission under the 7th framework program on environment; ENV.2008.3.3.2.1: PROSUITE - Sustainability Assessment of Technologies, grant agreement number 227078.

<heading level 1> References

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T. & Siebert, S. (2003) Development and Testing of the WaterGAP 2 Global Model of Water Use and Availability. *Hydrolog Sci,* 48**,** 317-337.

Ascough, J. C., Maier, H. R., Ravalico, J. K. & Strudley, M. W. (2008) Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. *Ecol Model,* 219**,** 383-399.

Banda, K., Sarkar, R., Gopal, S., Govindarajan, J., Harijan, B. B., Jeyakumar, M. B., Mitta, P., Sadanala, M. E., Selwyn, T., Suresh, C. R., Thomas, V. A., Devadason, P., Kumar, R., Selvapandian, D., Kang, G. & Balraj, V. (2007) Water handling, sanitation and defecation practices in rural southern India: a knowledge, attitudes and practices study. *Trans R Soc Trop Med Hyg,* 101**,** 1124-1130.

Cohen, A. J., Anderson, H. R., Ostro, B., Pandey, K. D., Krzyzanowski, M., KÃ¼nzli, N., Gutschmidt, K., Pope, A., Romieu, I., Samet, J. M. & Smith, K. (2005) The Global Burden of Disease Due to Outdoor Air Pollution. *J Toxicol Environ Health, Part A: Current Issues,* 68**,** 1301 - 1307.

De Schryver, A. M., Brakkee, K. W., Goedkoop, M. J. & Huijbregts, M. A. J. (2009) Characterization Factors for Global Warming in Life Cycle Assessment based on Damages to Humans and Ecosystems. *Environ Sci Technol,* 43**,** 1689-1695.

Dockery, D. W., Pope, C. A., Xu, X., Spengler, J. D., Ware, J. H., Fay, M. E., Ferris, B. G. & Speizer, F. E. (1993) An Association between Air Pollution and Mortality in Six U.S. Cities. *New England Journal of Medicine,* 329**,** 1753-1759.

Ezzati, M., Lopez, A. D., Rodgers, A. & Murray, C. J. L. (2004) Comparative Quantification of Health Risks. Global and regional Burden of Diseases Attributable to Selected Major Risk Factors. Geneva, World Health Organization.

Frischknecht, R., Braunschweig, A., Hofstetter, P. & Suter, P. (2000) Human health damages due to ionising radiation in life cycle impact assessment. *Environ Impact Assess Rev,* 20**,** 159-189.

Gloria, T., Russell, A., Atherton, J., Baker, S. & Cook, M. (2006) Ecological Toxicity Methods and Metals. An examination of two case studies. *Int J LCA,* 11**,** 26-33.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A. M., Struijs, J. & Van Zelm, R. (2008) ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I. Characterisation. Den Haag, The Netherlands, VROM.

Haines, A., Kovats, R. S., Campbell-Lendrum, D. & Corvalan, C. (2006) Climate change and human health: Impacts, vulnerability and public health. *Public Health,* 120**,** 585-596.

Harvey, C. M. (1994) The reasonableness of non-constant discounting. *J Public Econ,* 53, 31-51.

Hauschild, M., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Jolliet, O., Margni, M. & De Schryver, A. (2009) Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment (LCA) Joint Research Center.

Hauschild, M. & Potting, J. (2005) Spatial differentiation in life cycle impact assessment - the EDIP2003 methodology. *Environmental News no. 80.* Copenhagen, The Danish Ministry of the Environment, Environmental Protection Agency.

Hayashi, K., Nakagawa, A., Itsubo, N. & Inaba, A. (2006) Expanded Damage Function of Stratospheric Ozone Depletion to Cover Major Endpoints Regarding Life Cycle Impact Assessment. *Int J LCA,* 11**,** 150-161.

Hellweg, S., Hofstetter, T. & Hungerbühler, K. (2003) Discounting and the Environment: Should Current Impacts be weighted Differently than Impacts Harming Future Generations? *Int J LCA,* 8**,** 8-18.

Hertwich, E., Hammitt, J. K. & Pease, W. (2000) A Theoretical Foundation for Life-Cycle Assessment: Recognizing the Role of Values in Environmental Decision Making. *J Ind Ecol,* 4**,** 13-28.

Hofstetter, P. (Ed.) (1998) Perspectives In Life Cycle Impact Assessment. A structured approach to combine models of the technosphere, ecosphere and valuesphere, Dordrecht, Kluwer Academic Publishers.

Hofstetter, P., Baumgartner, T. & Scholz, R. W. (2000) Modelling the Valuesphere and the Ecosphere: Integrating the Decision Makers' Perspectives into Life Cycle Assessment. *Int J LCA,* 5**,** 161-175.

Huijbregts, M., Rombouts, L., Ragas, A. & van de Meent, D. (2005) Human-toxicological effect and damage factors of carcinogenic and noncarcinogenic chemicals for life cycle impact assessment. *Integr Environ Assess Manag,* 1**,** 181-244.

Huijbregts, M. A. J. (1998) Application of uncertainty and variability in LCA. Part I: A General Framework for the Analysis of Uncertainty and Variability in Life Cycle Assessment. *Int J LCA,* 3**,** 273-280.

IPCC (2000) Emission Scenarios: Special report of Working Group III. *Summary for policy makers.* Geneva, IPCC.

ISO/TR14047:2003 (2003) Environmental management -- Life cycle impact assessment -- Examples of application of ISO 14042. Geneve, International Organization for Standardization.

Jager, W., Van Asselt, M. B. A., Rotmans, J., Vlek, C. A. J. & Costerman Boodt, P. (1997) Consumer Behaviour: A Modelling Perspective in the Context of Integrated Assessment of Global Change. *Globo Report Series* Bilthoven, RIVM.

Janssen, M. & Rotmans, J. (1995) Allocation of fossil CO2 emission rights quantifying cultural perspectives. *Ecol Econ,* 13**,** 65-79.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G. & Rosenbaum, R. (2003) IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. *Int J LCA,* 8**,** 324-330.

Leiserowitz (2006). Climate change risk perception and policy preference: the role of affect, imagery, and values. *Climatic Change,* 77, 45–72.

Ligthart, T. (2004) Declaration of Apeldoorn on LCIA of non-ferro metals. *SETAC Globe,* 5**,** 46-47.

Lima ML, Castro P (2005). Cultural theory meets the community: Worldviews and local issues. *J Environ Psychol,* 25, 23–35.

Lopez, A. D., Mathers, C. D., Ezzati, M., Jamison, D. T. & Murray, C. J. L. (Eds.) (2006) *Global Burden of Disease and Risk Factors*, Washington, International Bank for Reconstruction and Development / The World Bank, the World Health Organization, and the Fogarty International Center of the National Institutes of Health.

Lorenzoni, I., Lowe, T. & Pidgeon, N. (2005) A strategic assessment of scientific and behavioural perspectives on 'dangerous' climate change. *Technical report 28.* Norwich, Tyndall Centre for Climate Change Research.

Lucas, R. M., McMichael, A. J., Armstrong, B. K. & Smith, W. T. (2008) Estimating the global disease burden due to ultraviolet radiation exposure. *Int J Epidemiol,* 37**,** 14.

Mahmoud, M., Liu, Y., Hartmann, H., Stewart, S., Wagener, T., Semmens, D., Stewart, R., Gupta, H., Dominguez, D., Dominguez, F., Hulse, D., Letcher, R., Rashleigh, B., Smith, C., Street, R., Ticehurst, J., Twery, M., van Delden, H., Waldick, R., White, D. & Winter, L. (2009) A formal framework for scenario development in support of environmental decision-making. *Environ Modell Softw,* 24**,** 798-808.

Marris C, Langford IH, O’Riordan T (1998). A Quantitative Test of the Cultural Theory of Risk Perceptions: Comparison with the Psychometric Paradigm. *Risk Analysis*, 18, 635-647.

Mathers, C. D. & Loncar, D. (2006) Projections of Global Mortality and Burden of Disease from 2002 to 2030. *PLoS Medicine,* 3**,** 2011-2030.

Morgan, M. G. & Henrion, M. (Eds.) (1990) *A guide to dealing with uncertainty in quantitative risk and policy analysis,* New York, Cambridge University Press.

Munthe, C. (1997) Etiska aspekter på jordbruk (Ethical aspects on agriculture). Jorbruksverket, p 14. Steen, .B.A. (2006) Describing values in relation to choices in life cycle assessment. *Int J LCA,* 11**,** 277-283

Murray, C. & Lopez, A. (1996) Rethinking DALYs. *The Global Burden of Disease.* Boston, WHO.

O’Riordan T, Jordan A (1999). Institutions, climate change and cultural theory: Towards a common analytical framework. *Glob Env Change*, 9, 81–93.

PAS 2050 (2008) Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Institution.

Pfister, S., Koehler, A. & Hellweg, S. (2009) Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environ Sci Technol,* 43**,** 4098-4104.

Reiss, R., Anderson, E. L., Cross, C. E., Hidy, G., Hoel, D., McClellan, R. & Moolgavkar, S. (2007) Evidence of Health Impacts of Sulfate-and Nitrate-Containing Particles in Ambient Air. *Inhalation Toxicology: International Forum for Respiratory Research,* 19**,** 419 - 449.

Schwartz, S. H. & Mark, P. Z. (1992) Universals in the Content and Structure of Values: Theoretical Advances and Empirical Tests in 20 Countries. *Advances in Experimental Social Psychology.* Academic Press.

Schwarz, M. & Thompson, M. (Eds.) (1990) *Divided We Stand: Re-defining Politics, Technology And Social Choice,* Pennsylvania, University Of Pennsylvania Press.

Shiklomanov, A. I. (1999) World water resources at the beginning of the 21st century in International Hydrological Programme. St. Petersburg, State Hydrological Institute (SHI) / UNESCO.

Steen, B. A. (2006) Describing values in relation to choices in LCA. *Int J LCA,* 11**,** 277-283

Steg L, Sievers I (2000). Cultural theory and individual perceptions of environmental risks. *Environ Behav*, 32, 250-269.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M. & Haan, C. d. (Eds.) (2006) *Livestock's Long Shadow - Environmental Issues and Options*, Rome, Food and Agriculture Organization of the United Nations.

Thompson, M., Ellis, R. & Wildavsky, A. (1990) *Cultural Theory*, Boulder, Westview Press.

Tukker, A. (2002) Risk Analysis, Life Cycle Assessment;The Common Challenge of Dealing with the Precautionary Frame (Based on the Toxicity Controversy in Sweden and the Netherlands). *Risk Analysis,* 22**,** 821-832.

UNDESA (2008) World Population Prospects: The 2008 Revision. *Population Division.* United Nations Department of Economic and Social Affairs.

van Asselt, M. & Rotmans, J. (1996) Uncertainty in perspective. *Glob Environ Change,* 6**,** 121-157.

van Asselt, M. & Rotmans, J. (2002) Uncertainty in integrated assessment modelling: from Positivism to Pluralism. *Clim Change,* 54**,** 75-105.

Van Zelm, R., Huijbregts, M. & van de Meent, D. (2009) USES-LCA 2.0—a global nested multi-media fate, exposure, and effects model. *Int J LCA,* 14**,** 282-284.

Van Zelm, R., Huijbregts, M. A. J., Den Hollander, H. A., Van Jaarsveld, H. A., Sauter, F. J., Struijs, J., Van Wijnen, H. J. & Van de Meent, D. (2008) European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. *Atmos Environ,* 42**,** 441-453.

WHO (2008) The global burden of disease: 2004 update. 1.Cost of illness. 2.World health - statistics. 3.Mortality - trends. Geneva, World Health Organization.

Wynne, B. (1992) Uncertainty and environmental learning: Reconceiving science and policy in the preventive paradigm. *Glob Environ Change,* 2**,** 111-127.

About the Author:

An M. De Schryver carried out this work as a PhD student at the Department of Environmental Science of the Radboud University Nijmegen in The Netherlands and is currently working as a Postdoctoral researcher at the Swiss Federal Institute of Technology in Zurich, Switzerland.

Rosalie van Zelm is a Postdoctoral researcher at the Department of Environmental Science of the Radboud University Nijmegen in The Netherlands.

Sebastien Humbert is scientific director at Quantis in Lausanne, Switzerland.

Stephan Pfister is a PhD student at the Swiss Federal Institute of Technology in Zurich, Switzerland.

Thomas E. McKone is adjunct Professor at school of public health of the University of California in Berkeley, CA, USA.

Mark A.J. Huijbregts is Associate Professor at the Department of Environmental Science of the Radboud University Nijmegen in The Netherlands.