Quantifying effects of physical, chemical and biological stressors in life cycle assessment

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Quantifying the effects of physical, chemical and biological stressors in life cycle assessment

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Table of Contents

Chapter 1

Introduction

1.1 Life cycle assessment

Life cycle assessment (LCA) is a decision-support tool for both policy makers and industry to assess cradle-to-grave impacts of all the stages in a product's life and processes, from resource extraction, through production, manufacture, transportation and use to the management of the discarded product, either by reuse, recovery, or final disposal (ISO 1997, 2000, 2006; Guinée et al., 2002; Finnveden et al., 2009). LCA had its roots in the 1960's with the analysis of fossil fuel consumption (Curran, 1996). Since the 1980's, the industry showed interest in including environmental impacts as well. The development of the LCA method boosted in 1992, when the first framework for the impact assessment was proposed (ISO, 1997).

According to the ISO 14000 and 14044 standards (ISO, 1997; 2006), LCA is carried out in four distinct phases (Figure 1.1). The first phase encompasses the goal and scope of the study and defines the system under study, in terms of its functional unit, system boundaries, hypotheses and data requirement (Consoli et al., 1993). The second phase is a life cycle inventory (LCI) which involves data collection and modeling of the product system. In this phase, information about environmental inputs (raw materials, chemicals, energy, etc.) and outputs (air emissions, water emissions and waste) from all parts of the product system is gathered. The third phase is called life cycle impact assessment (LCIA). LCIA evaluates the potential environmental impacts (such as global warming, ozone depletion, smog, acidification, eutrophication, ecotoxicity, etc.) associated with identified inputs and releases. There are mandatory and optional elements in the LCIA phase. Mandatory elements include i) the selection of relevant environmental impact categories (selection) ii) the assignment of LCI results to the selected impact categories (classification), and iii) the calculation of environmental impact scores (characterization). Optional elements consist of i) comparison of the magnitude of the potential impacts with the reference values in a geographic area over a given period of time (normalization), ii) sorting or ranking impact indicators (grouping), and iii) aggregation of environmental impacts (weighting). Finally, interpretation in phase four leads to the conclusion whether the goal and scope was met. Interpretation of results helps to make an informed decision about the environmental impacts of products and processes. Conclusions, limitations and recommendations are given in this phase.

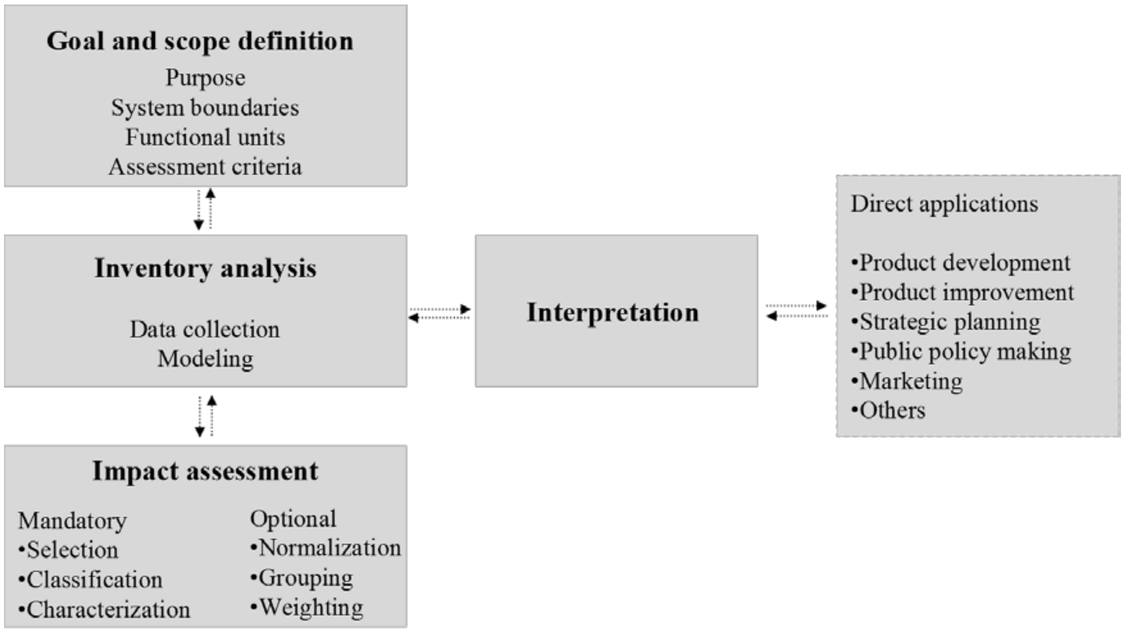

Figure 1.1: Phases of a life cycle assessment (adapted from ISO 14040, 1997; 2006).

This PhD thesis focuses on the third phase, the life cycle impact assessment. LCIA methodologies have been extensively developed during the last two decades (e.g. Heijungs et al., 1992; Hauschild and Wenzel, 1998; Goedkoop and Spriensma, 2000; Steen, 1999; Guinee et al., 2002; Itsubo and Inaba, 2003; Jolliet et al., 2004; Goedkoop et al., 2008). In this phase, each environmental impact is characterized using science-based conversion factors (called characterization factor). Characterization factors are used to convert emissions and extractions from the LCI into so called impact scores. The impact score (*IS*) for each impact category is calculated by the multiplication of the amount of emission *x* in compartment *j* ($m_{x,j}$) with characterization factor of emission *x* in compartment *j* ($CF_{x,j}$), and summed over every emission *x* and compartment *j*.

$$IS = \sum_j \sum_x m_{x,j} \cdot CF_{x,j}$$

The characterization factor can be defined at a midpoint or an endpoint level. On the midpoint level, impact category indicators are calculated at an intermediate position of the impact pathways (e.g. ozone depleting potential, eutrophication potential, acidification potential, etc.) (Jolliet et al., 2004). The midpoint approach avoids complexity with relatively low uncertainties but the indicator is less interpretable.

Endpoints are defined at the end of the cause-effect chain and aim to aggregate the impact of stressors with different modes of action, such as greenhouse gases, priority air pollutants and toxic chemicals (Bare et al., 2000; Jolliet et al., 2004; Bare and Gloria, 2008). The endpoint approach has been used in several LCIA methods, notably the EPS (Steen, 1999), Eco-indicator 99 (Goedkoop and Spriensma, 2000), LIME (Itsubo and Inaba, 2003), IMPACT 2002+ (Jolliet et al., 2004) and ReCiPe (Goedkoop et al., 2008). Damage-oriented methods intend to facilitate easier interpretation results in the form of damage indicators on the areas of protection (i.e. human health damage, ecosystem quality damage and resources depletion), and some specific methods address social welfare as well (e.g. LIME). The endpoint approach will make the indicator more environmentally relevant. However, modeling the cause-effect chain up to the environmental damages leads to relatively high uncertainties due to lack of available data and lack of robust models. Figure 1.2 illustrates the framework of impact categories in life cycle impact assessment at midpoint and endpoint levels.

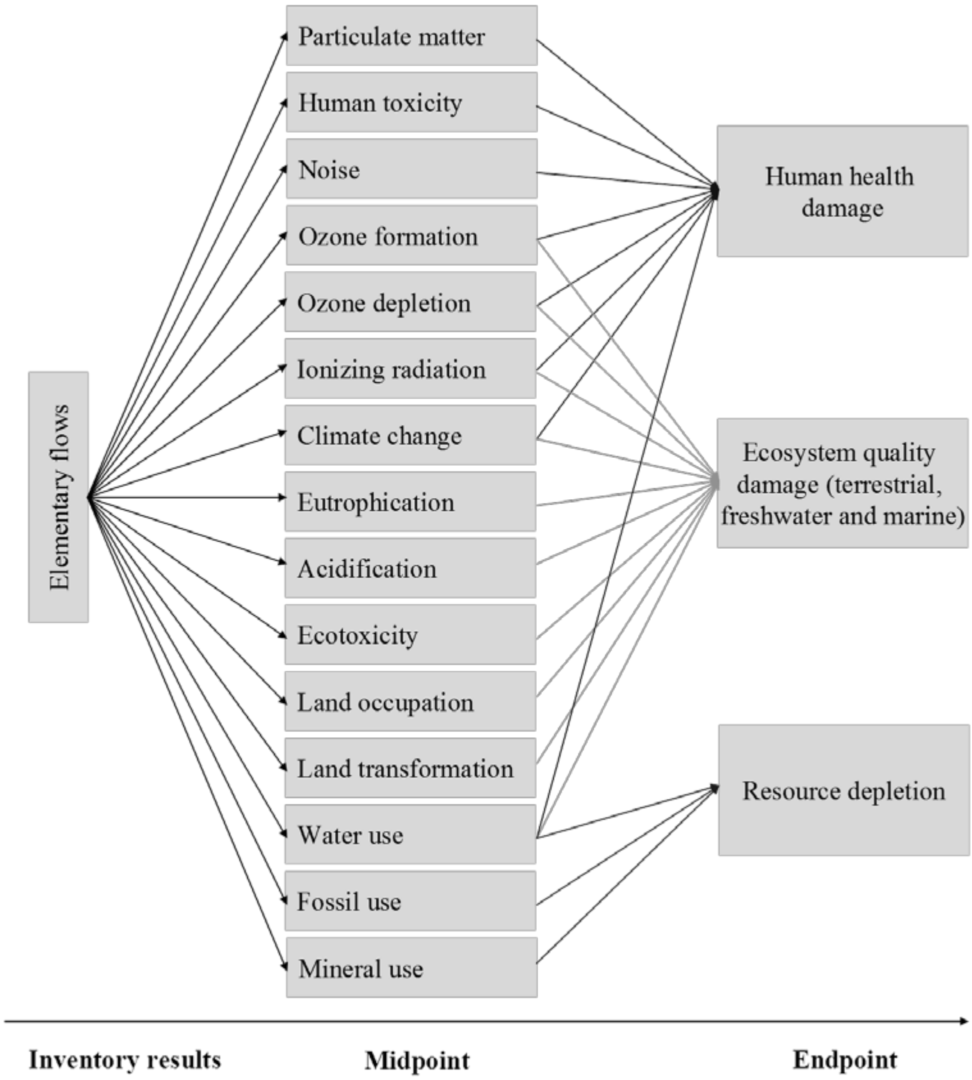

Figure 1.2: Framework of impact categories in life cycle impact assessment at midpoint and endpoint levels (adapted from JRC, 2010).

1.2 Problem setting

1.2.1 Terrestrial ecosystems

Characterization factors that assess impacts associated with terrestrial ecosystems in the LCIA methodology are available for a wide range of stressors such as, ecotoxicity (Huijbregts et al., 2005), acidification (Van Zelm et al., 2007), land use (Koellner and Scholz, 2008), water consumption (Pfister et al., 2009), and climate change (De Schryver et al., 2009). In addition, a simple environmental assessment method is available to examine the influence of human activities on terrestrial systems, called ecological footprint (EF)

(Wackernagel and Rees, 1996). The EF is an area-based indicator that accounts for human demand on nature and it is used as a relatively simple indicator to assess human impact on environmental sustainability (Rees, 1996; Moffatt, 2000). However, it is unknown to what extent the results of the ecological footprint can be biased due to the fact that it takes into account a limited number of stressors only (direct land use and CO_2 emissions) and whether the focus on bioproductivity gives different results compared to biodiversity-oriented impact indicators. Until now it is unknown whether the results would change if other stressors and biodiversity perspective are taken into account.

1.2.2 Freshwater ecosystems

Although the science underlying LCIA has greatly improved in the last 20 years, a number of aspects of its underlying methodological approach are still under development. This is particularly true for the assessment of effects on freshwater ecosystem quality which is grossly still lacking in the LCA framework. Global freshwater biodiversity is one of the areas of protection which has suffered major adverse effects in recent decades (Dudgeon et al., 2006; Millennium Ecosystem Assessment, 2006; Butchart et al., 2010). Relatively few freshwater-related impacts are currently included in LCA at the level of effects on biodiversity, notably eutrophication and ecotoxicity (Pennington et al., 2006; Van de Meent and Huijbregts, 2005; Larsen and Hauschild, 2007). Impact of thermal emissions, global warming, water use and exotic species on freshwater ecosystems have so far not been included in the LCIA.

1.3 Aim of the thesis

The overall aim of this PhD thesis is two-fold:

1. To include impacts of nutrients and non-CO_2 greenhouse gases on terrestrial ecosystems in the ecological footprint methods and to compare the common bioproductivity-based with a newly developed biodiversity-based ecological footprint.
2. To develop life cycle impact assessment methods to assess damages towards freshwater ecosystems related to thermal emissions, climate change, water use and introduction of exotic species.

The more specific background of these goals is further discussed below.

1.3.1 Terrestrial ecosystems

As originally defined, the EF refers to land area that a human population requires to produce the resources it consumes and to absorb its carbon dioxide emissions (Wackernagel and Rees, 1996; Kitzes et al., 2007). The ecological footprint method converts the consumption of energy and resources into a normalized measure of land area called global hectares (gha). This method, which is increasingly used to assess the sustainability of lifestyles at individual, regional and national levels, can also be applied to assess the impact of products and services (Wackernagel and Rees, 1996; Global Footprint Network, 2008).

Apart from the focus of the original EF on bioproductivity related to land use and CO_2 emissions, the pollution resulting from other stressors can be relevant as well (Kitzes et al., 2009). Biodiversity loss due to land use and climate change is another important aspect that should not be neglected in the EF calculations. The global terrestrial biodiversity loss is declining rapidly due to a factor such as land use change that is likely to produce severe impacts on biodiversity (Sala, 1995; Sala et al., 2000). As stating in Lenzen and Murray (2001), land use activities have a major impact on biodiversity particularly on terrestrial species extinction and this issue has been extensively documented in the Millennium Ecosystem Assessment (2006). Thus, the EF results may be much more meaningful if inclusion of other stressors and comparison of bioproductivity-based and biodiversity-based EFs are addressed (see Figure 1.3).

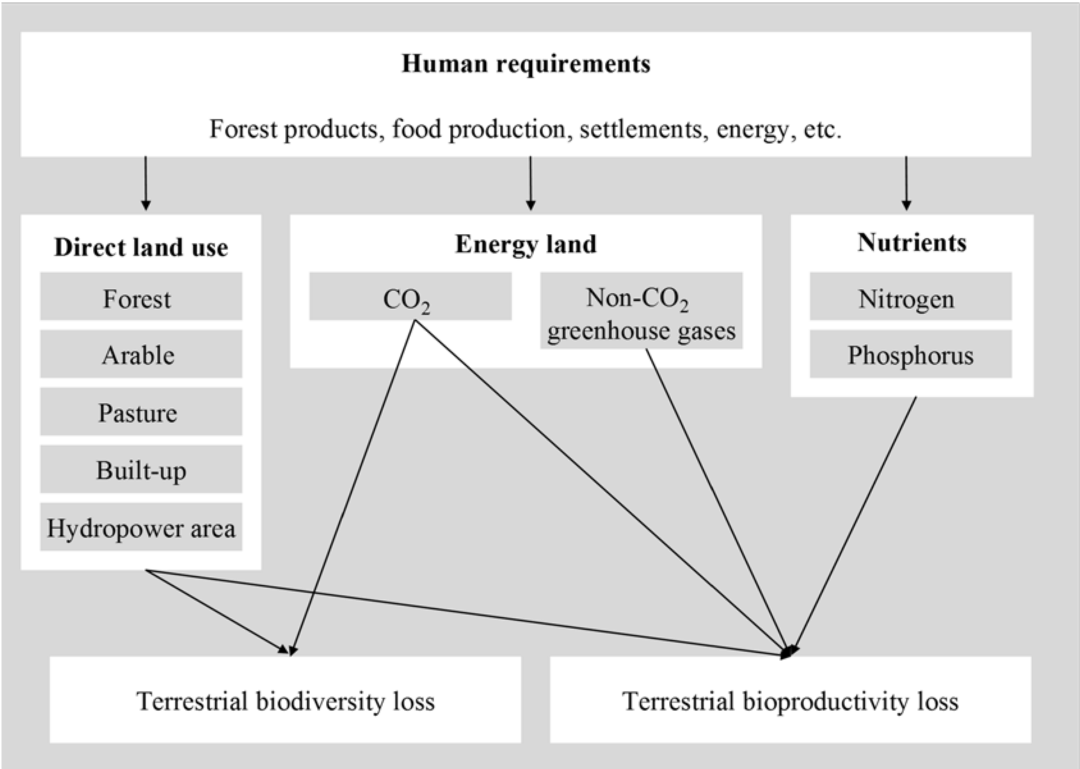

Figure 1.3: Simplified representation of impact pathway approach in the calculation of impacts towards terrestrial biodiversity in this PhD thesis.

1.3.2 Freshwater ecosystems

The environmental impact pathway from thermal pollution, global warming, water consumption and the introduction of exotic species by transport of goods causing freshwater species extinction is illustrated in Figure 1.4. Subtopics of the research are further elaborated below.

According to Caissie (2006), the thermal regime of rivers can be considered to be one of the crucial factors for aquatic ecosystem quality. Thermal pollution is defined as a reduction in water quality caused by the temperature change in natural water bodies resulting from human activities. A common cause of thermal pollution is the discharge of cooling water used by power plants and industrial facilities into water systems. Thermal pollution can have a large influence on aquatic ecosystems, as most aquatic organisms tolerate only a relatively small temperature range (Coutant, 1999). However, a method to derive characterization factors for thermal emissions was not available at the start of this PhD project.

Few studies have been conducted to evaluate the impact of greenhouse gas emissions on human health and terrestrial ecosystems in product assessments (De Schryver et al., 2009). Although climate change clearly represents an additional, significant threat to aquatic ecosystems (Carpenter et al., 1992; Firth and Fisher, 1992; Lake et al., 2000), so far no study has been conducted to develop characterization factors for greenhouse gases that address impacts on freshwater ecosystems.

Water consumption refers to the water that is extracted from the source for human activity, particularly for irrigation purposes that is not returned to the river. Water consumption due to anthropogenic activities can induce loss of freshwater biodiversity (Xenopoulos and Lodge, 2006). The inclusion in LCA of impacts on freshwater ecosystems of water consumption may be important, particularly for agricultural sector because of their high percentage of water consumption.

Exotic species are organisms that have been transported long distances from the place in which they evolved (Shrine et al., 2000). The introduction of exotic species biocontamination has significantly increased and has been suggested to change global biodiversity and ecosystem functioning (Mack et al., 2000; Rahel, 2002; Clavero and García-Berthou, 2005). Biological invasions can adversely affect freshwater ecosystems by altering habitats and causing the loss of native species (Moyle and Light, 1996; Rahel, 2002; Vila-Gispert et al., 2005). The introduction of invasive species increases with increasing international exchange and transportation (Chen and Xu, 2001). Study on the introduction of exotic species related to transport of good is still lacking in LCA.

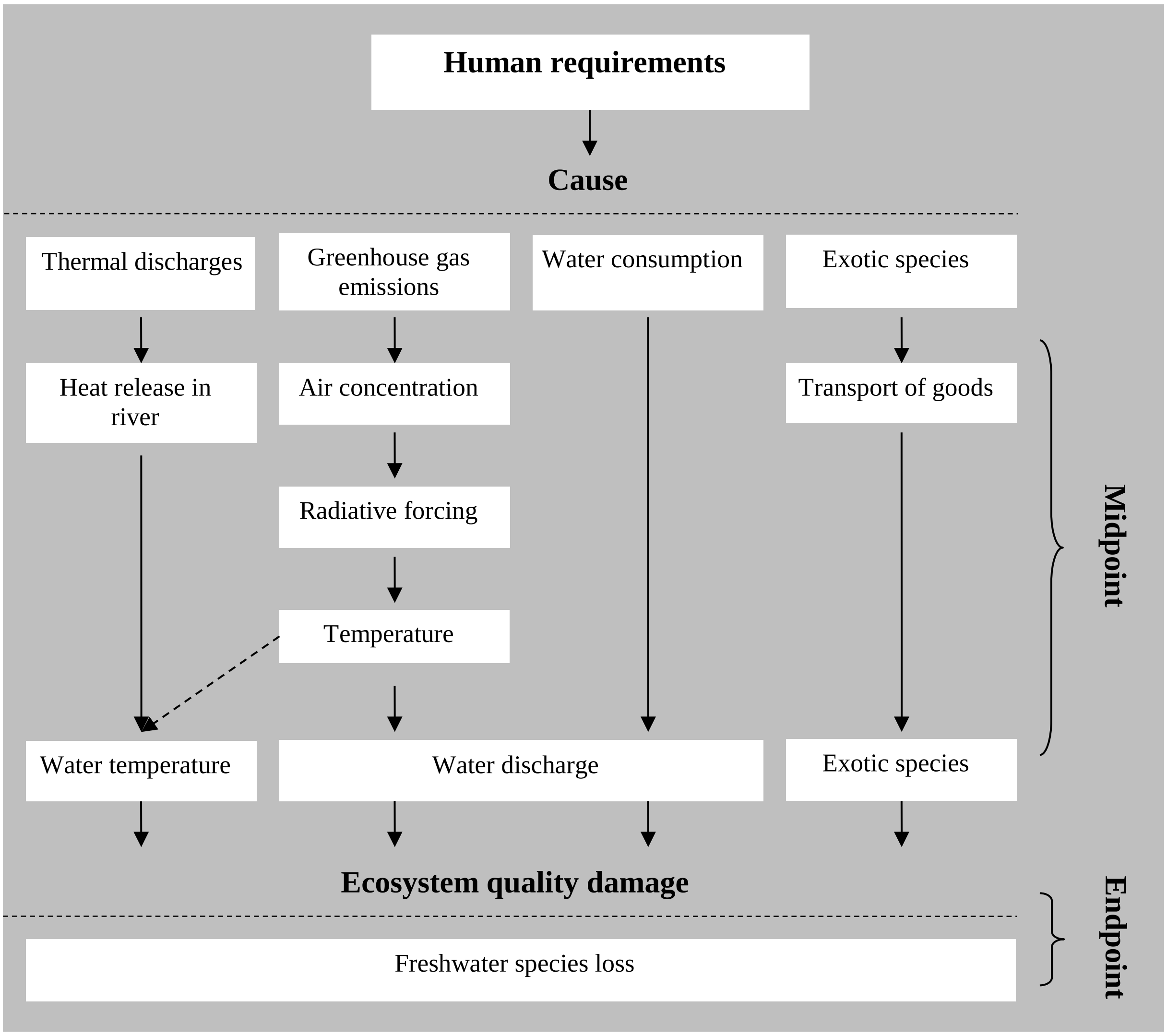

Figure 1.4: Simplified representation of impact pathway approach in the modeling of impacts towards freshwater biodiversity in this PhD thesis.

1.5 Outline of the thesis

The framework of the PhD thesis is illustrated in Figure 1.5.

Chapter 2 integrates non-CO_2 greenhouse gas emissions and nutrients in the ecological footprint calculation of products. The ranking of these stressors and their influence on the ecological footprint are identified.

Chapter 3 investigates the influence of including a biodiversity perspective in the ecological footprint analysis of products. This is done by comparing the biodiversity-based ecological footprint with the bioproductivity-based ecological footprint.

The incorporation of i) thermal pollution; ii) bio-contamination; iii) global warming and iv) water consumption in the assessment of freshwater ecosystem damages are addressed in chapters 4 to 6. Chapter 4 develops characterization factors for thermal pollution based on disappearance of freshwater species. The impact of thermal pollution on aquatic ecosystem is quantified for the rivers Rhine and Aare.

Chapter 5 provides new characterization factors for greenhouse gas emissions and direct water consumption based on the disappearance of freshwater fish species. In this chapter, the characterization factors are derived on a global scale.

Chapter 6 focuses on the development of characterization factors for bio-contamination in European waterways. The disappearance of native fish species due to exotic fish species dispersal in relation to transport of goods via the Rhine-Main-Danube (RMD) Canal is assessed in this chapter.

Finally, chapter 7 presents a synthesis and general discussion of results. Moreover, it will provide recommendations for future research.

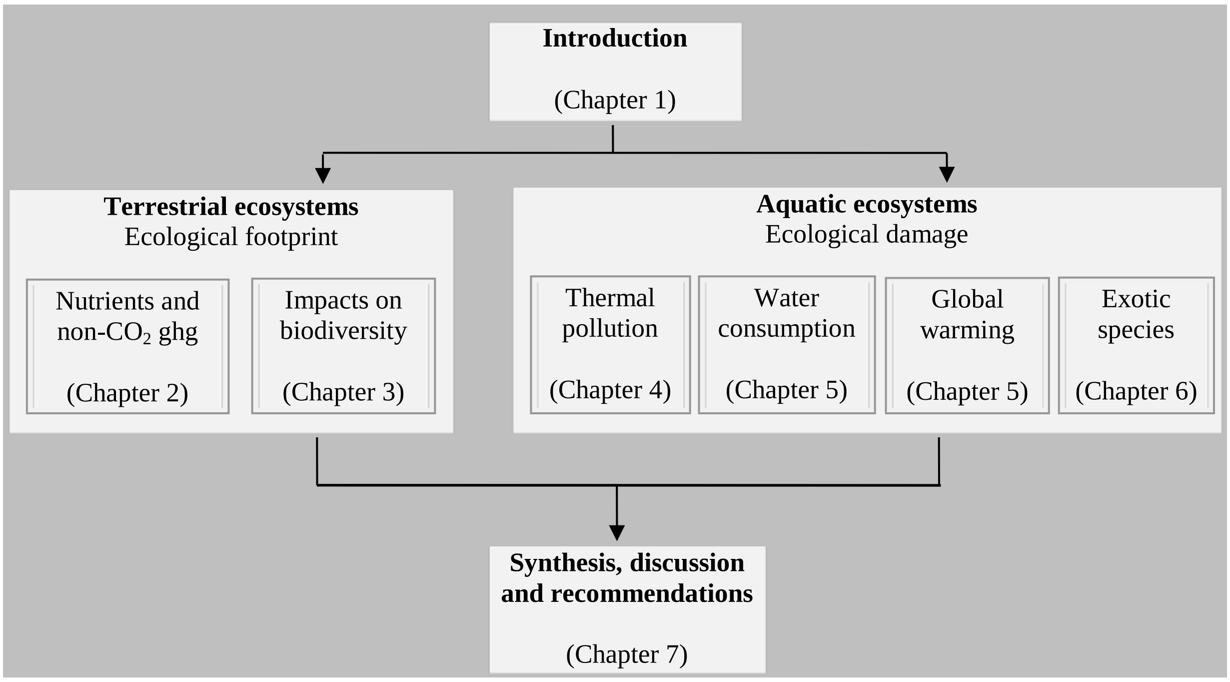

Figure 1.5: Set up of this PhD thesis.

Ghg: greenhouse gas emissions

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Chapter 2

The influence of nutrients and non-CO_2 greenhouse gas emissions on the ecological footprint of products

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A.J. Hendriks

Sustainability **2010, 2, 963-979**

Abstract

The ecological footprint (EF) commonly neglects the influence of other stressors than land use and CO_2 emissions on the land area required for human activities. This study analyzes the relevancy of including nutrients and non-CO_2 greenhouse gases in the EF assessment of products. The analysis was based on environmental information for 1,925 goods and services. Our findings suggest that within specific product categories, i.e., waste treatment processes, bio-based energy, agricultural products and chemicals, adding non-CO_2 greenhouse gases and nutrient emissions can have a dominant influence on the EF results.

Keywords: ecological footprint; non-CO_2 greenhouse gases; nutrient emissions; products

1. Introduction

The Ecological Footprint (EF) is widely used as an indicator for environmental performance (WWF, 2008). The EF has proven to be one of the most successful devices for communicating the concept of environmental sustainability. The EF concept, as introduced by Rees (1992) and further developed by Rees and Wackernagel (1994) and Wackernagel and Rees (1996), is an accounting tool for the resource consumption and waste assimilation of a defined human population in terms of productive land area. This productivity refers to the amount of biomass production required to renew the biotic resources used by humans and to absorb CO_2 emissions from energy use (Chambers et al., 2000; Lenzen et al., 2007a). Productivity area is measured in global hectares, which are measured from actual hectares by weighting with yield factors and equivalence factors which can be compared to the biocapacity of the earth to assess potential ecological overshoot by human activities (Wackernagel et al., 2005). The EF has been applied to evaluate impacts of human activities on the environment for different scales, such as on the international level (WWF, 2008), national level (Bicknell et al., 1998; Van Vuuren and Smeets, 2000; Haberl et al., 2001; Lenzen and Murray, 2001; Simmons et al., 2007), sub-national level (Folke et al., 1997; McDonald and Patterson, 2004; Collins et al., 2006; Kissinger et al., 2007) and product level (Huijbregts et al., 2008). Note that if the focus is on individual products, a biocapacity benchmark to assess ecological overshoot is not straightforward anymore.

In the life cycle assessment (LCA) of goods and services, the EF methodology can also be used to aggregate various types of land use and CO_2 emissions into a single indicator score. Recently, Huijbregts et al. (2008) calculated the EF for a large number of products including direct land use, nuclear energy use and CO_2 emissions. These EF-scores represent the traditional LCA approach, i.e. multiple-counting of ecological footprints for intermediate products in supply chains. Adding these producer's footprints to other producers' footprints would lead to double-counting. For implementation in a consumer-based approach, only final consumer products should be included in the footprint calculations. Avoiding double-counting could also follow a shared producer and consumer responsibility approach, for instance based on value added, as pointed out by Lenzen et al. (2007a).

An advantage of the EF is that the methodology avoids complex modeling of the environmental cause-effect chain and the indicator score (area of productive land required) is rather easy to understand (McDonald and Patterson, 2004). The EF methodology has, however, also been criticized for a number of reasons, such as the inclusion of only a limited number of stressors (Fiala, 2008; Walsh et al., 2009), the focus on impacts on bioproductivity instead of biodiversity (Lenzen et al., 2007a; Lenzen et al., 2007b), problems with the selection of appropriate spatial boundaries (Van der Bergh and Verbruggen, 1999), prejudice against international trade (Turner et al., 2007; Wiedmann, 2009), and limited use for policy-making (Ayers, 2000; Moffatt, 2000; Van Kooten and Bulte, 2000; Ferng, 2002). For a more in depth discussion of research needs to further enhance the EF method, the reader is referred to Kitzes et al. (2009a).

This paper addresses one aspect of this list of critical points, by expanding the list of stressors that can be taken into account in the EF calculation. More specifically, the goal of this paper is to assess the importance of non-CO_2 greenhouse gases and nutrient emissions in the EF calculation of products. We selected nutrients and non-CO_2 greenhouse gases as they can be (indirectly) linked to the bioproductivity approach and are released to the environment in relatively large quantities. A more complete picture of the EF may change the environmental ranking of products and may give new insights in the environmental improvement potential of supply chains. Although other stressors, such as heavy metals and persistent organic pollutants, are also candidates to include in the EF, we did not have the data to do so from a bioproductivity point of view.

We will show the influence of these methodological changes for 1,925 goods and services, subdivided into 19 product groups. The paper starts with an explanation of the original method applied to calculate the EF of products and the modifications introduced to add non-CO_2 greenhouse gas emissions and nutrient emissions to the EF. We will show the relative contribution of the nutrient and non-CO_2 greenhouse gas emissions to the EF of the products included as well as discuss the implications of our findings for the EF methodology.

2. Methods

In our assessment, the following four ‘stressor’ categories were considered: 1) 27 direct land use types (Supporting Information), 2) CO_2 emissions, 3) 31 non-CO_2 greenhouse gas emissions (Supporting Information), and 4) nutrient emissions, which include nitrogen (N) and phosphorus (P) emissions to land and water as well as nitrogen oxides (NOx), ammonia (NH_3), nitrate (NO^{3-}) and P emissions to air (Supporting Information). The original EF method (stressor categories 1 and 2) was based on Wackernagel and Rees (1996) and Huijbregts et al. (2008). The original and modified EF scores were calculated using the ecoinvent database v2.0 (2007).

2.1 Original EF method

In the context of life cycle assessment, a product's EF has been defined as the sum of time-integrated direct land use (EF_{direct}) and indirect land use, caused by CO_2 emissions from fossil-fuel combustion and cement production (EF_{CO2}) (Huijbregts et al., 2008).

$$EF_{original} = EF_{direct} + EF_{CO_2} \tag{1}$$

Six main high intensity land use types were classified; forest area (for timber and wood), arable land (for food, feed, etc.), pasture land (for animal grazing), urban land (for living, construction activities, etc.), land required to produce hydropower and marine area (for fish production). Direct land use was calculated by multiplying the area by land use type p (m^2 yr) with its equivalence factors (-):

$$EF_{direct} = \sum_p A_p \cdot EqF_p \tag{2}$$

The equivalence factors (EqF) based on Wackernagel et al. (2005) were applied in our study (Table 2.1). EqF is used to convert world-average land use of a specific type, such as forest or pasture, to global hectares. Wackernagel et al. (2005) defined the global hectares as hectares with world-average productivity for all of the bioproductive areas in the world. A high EqF represents high productivity land, such as cropland, while pastures have a low EqF. Wiedmann and Lenzen (2007) argued that using actual yields for the calculation of land-use requirements in combination with global average equivalence factors for assessing bioproductivity is not consistent. However, in the context of life cycle assessment of products, equivalence factors can be seen as generic factors to aggregate different types of land use in terms of 'bioproductive area' (Huijbregts et al., 2008). In life cycle assessment, aggregation of different types of stressors is generally done with average factors without further regional differentiation (Finnveden et al., 2009). Note that the use of generic equivalence factors implies that our results are not directly comparable with spatially explicit ecological footprint studies. The EqF for more detailed land use types as specified in the ecoinvent database v2.0 can be found in Supporting Information (Wackernagel et al., 2005; ecoinvent, 2007).

The productive area (m^2 yr) required to sequester fossil CO_2 emissions was obtained by:

$$EF_{CO2} = M_{CO2} \cdot \frac{1 - F_{CO2}}{S_{CO2}} \cdot EqF_f \qquad (3)$$

where M_{CO2} is the product-specific emission of CO_2 (kg CO_2), F_{CO2} is the fraction of CO_2 absorbed by oceans (-), S_{CO2} is the sequestration rate of CO_2 by biomass (kg CO_2 m^{-2} yr^{-1}) and EqF_f is the equivalence factor of forests (-).

We excluded nuclear energy in the EF calculations, as there are no suitable methods available to deal with nuclear energy in the EF calculation (Kitzes et al., 2009a).

2.2 Modified EF method

Here, we modify the basic EF equation to include the other pollutants as well. The summed EF ($EF_{modified}$) was calculated by:

$$EF_{modified} = EF_{direct} + EF_{CO_2} + EF_{ghg} + EF_{nutrient} \qquad (4)$$

where EF_{ghg} is the product-specific EF of non-CO_2 greenhouse gases (m^2 yr) and $EF_{nutrient}$ is the product-specific EF of nutrient emissions (m^2 yr).

2.2.1 Greenhouse gas emissions

To include non-CO_2 greenhouse gases into the EF calculation, global warming potentials (GWPs) for a time horizon of 100 years of greenhouse gases other than CO_2 were used to convert greenhouse gas emissions into CO_2 equivalents (IPCC, 2007). Using GWPs as weighting factors, the 'artificial' forest required to sequester the amount of additional CO_2 equal to the contribution of non-CO_2 greenhouse gas emissions was derived. The area needed for sequestration was calculated by:

$$EF_{ghg} = \sum_x M_{ghg,x} \cdot \frac{1 - F_{CO2}}{S_{CO2}} \cdot GWP_x \cdot EqF_f \qquad (5)$$

where EF_{ghg} is the product-specific EF of indirect land occupation by greenhouse gas emissions excluding CO_2 (m^2 yr), $M_{ghg,x}$ is the product-specific emissions of greenhouse gas *x* (kg ghg), and GWP_x is the global warming potentials of greenhouse gas x (kg CO_2-equivalents). The GWP for a time horizon of 100 years of the greenhouse gases included are listed in Appendix B (IPCC, 2007); IPCC, 2001).

2.2.2 Nutrient emissions

Nutrient emissions to water (ocean, groundwater and freshwater), industrial soil and air were included by calculating the area required to absorb these emissions (Folke et al., 1997). Appendix C lists the emissions that were included in the calculations. We determined how much area is needed to balance nutrient emissions by N and P uptake in plants and denitrification of N in agricultural soils. The EF was calculated separately for N and P. The area required to counterbalance emissions of P and N individually was calculated by:

$$EF_P = \sum_x M_{P,i} \cdot \frac{1}{U_P} \cdot EqF_{agri} \tag{6}$$

$$EF_N = \sum_x M_{N,i} \cdot \frac{1}{U_N + D_N} \cdot EqF_{agri} \tag{7}$$

where EF_P and EF_N are, respectively, the product-specific EF of indirect land occupation by P and N emissions to land, water and air (m^2 yr), $M_{P,i}$ and $M_{N,i}$ are, respectively, the product-specific P and N emissions to compartment i (kg), U_P and U_N are, respectively, the uptake rate of P and N by crops (kg m^{-2} yr^{-1}), D_N is the denitrification rate of N in agricultural soils and EqF_{agri} is the equivalence factor of agricultural soils (-). N and P uptake rates by crops were set to 62 and 9 kg ha^{-1} yr^{-1}, respectively, based on Antikainen and Haapanen (2008). A typical denitrification rate of 65 kg ha^{-1} yr^{-1} in agricultural soils was derived from Hofstra and Bouwman (2005).

The EF concept considers each land area as a single function of use, reflecting the mutually exclusive uses of the bioproductive land. To avoid double counting along the production chains, the same area can be used to compensate for more than one stressor (Holmberg et al., 1999). We assume that if the dominant stressor has been adequately assimilated, then other emissions were assimilated as well. In this study, the additional area required to balance the most dominant nutrient stressor was used in the modified footprint calculations. The EF for nutrients was calculated by:

$$EF_{nutrient} = \max(EF_P, EF_N) \tag{8}$$

where $EF_{nutrient}$ is the product-specific EF of nutrient emissions (m^2 yr). In fact, we assume that all N and P emissions within one supply chain can be compensated by one piece of additional agricultural land and that this land can be either P or N limited. N and P inputs to agricultural soils were not considered as emissions. Based on the fertilizing recommendations for agricultural products, the N and P inputs basically cover the agricultural crop needs (ecoinvent, 2007). Thus, N and P inputs to agricultural land and subsequent uptake by crops are readily covered in the agricultural supply chain. This implies that for N and P emissions to agricultural soils, additional crop land is only required to counterbalance excess N and P emissions to air and water. In this context, we specifically included net emissions of NH_3, NO_x and NO_3^- released to the air due to the high input of N fertilizers in intensive agriculture. For emissions to water, we included NO_3^- lost from the agricultural soil system by leaching to groundwater and run-off to surface water. P transported from agricultural soil to water via soil erosion, leaching and run-off was included as well.

Table 2.1: Parameters used for the EF calculation.

Parameter	Abbreviation	Unit	Value	References
Equivalence factor of forest area	EqF_f	-	1.4	Wackernagel et al. (2005)
Equivalence factor of urban area	EqF_u	-	2.2	Wackernagel et al. (2005)
Equivalence factor of arable land	EqF_a	-	2.2	Wackernagel et al. (2005)
Equivalence factor of pasture area	EqF_p	-	0.5	Wackernagel et al. (2005)
Equivalence factor of area required for hydropower	EqF_h	-	1	Wackernagel et al. (2005)
Equivalence factor of marine area	EqF_m	-	0.4	Wackernagel et al. (2005)
Fraction of CO_2 absorbed by oceans	F_{CO2}	-	0.3	Wackernagel et al. (2005)
Sequestration rate of CO_2 by biomass	S_{CO2}	kg CO_2 m^{-2} yr^{-1}	0.4	Wackernagel et al. (2005)
Phosphorus uptake in agricultural soils	U_P	kg P m^{-2} yr^{-1}	0.0009	Antikainen and Haapanen (2008)
Nitrogen uptake in agricultural soils	U_N	kg N m^{-2} yr^{-1}	0.0062	Antikainen and Haapanen (2008)
Denitrification rate in agricultural soils	D_N	kg N m^{-2} yr^{-1}	0.0065	Hofstra and Bouwman (2005)

2.3 Product database

Life cycle inventory data were taken from the ecoinvent database v2.0 (2007). A total of 1,925 goods and services comprising 19 product groups were considered in the study. The present study includes energy production processes by non-renewable energy sources (oil, natural gas, hard coal and lignite) and renewable energy sources (biomass, wind, solar and hydro), material production (chemicals, building materials, metals, glass, electronics, plastics, agricultural products, and paper and cardboard), transport (goods and passengers), waste management (landfill, incineration, waste water treatment and recycling) and infrastructure. Table 2.2 lists the product groups and the corresponding number of products included in our analysis.

Table 2.2: Product groups and number of goods and services included in the analysis as based on ecoinvent (2007).

Product group	Unit	Number of products
Fossil energy [a]	MJ	170
Nuclear energy	MJ	6
Biomass energy	MJ	79
Wind and solar energy	MJ	48
Hydro energy	MJ	31
Building materials [b]	kg	93
Metals	kg	157
Plastics	kg	62
Paper and cardboard	kg	47
Chemicals [c]	kg	450
Glass [d]	kg	12
Electronics	kg	66
Agricultural products [e]	kg	122
Landfill [f]	kg	99
Incineration [g]	kg	69
Waste water	m^3	26
Goods transport	tkm	39
Passengers transport	pkm	20
Infrastructure	unit	329

a Oil, natural gas, hard coal and lignite.

b Construction materials, insulation materials, mortar and plaster.

c Pesticides, mineral fertilizers, washing agents, paintings, inorganics and organics.

d Construction and packaging.

e Feed production, seed production, animal production and plant production.

f Residual material, sanitary landfill, underground deposit, land farming and inert material.

g Municipal waste and hazardous waste.

2.4 Data analysis

First, we analyzed the average relative contribution of direct land use (forestry, crops, pasture, built up, marine area and hydropower) and indirect land use (CO_2, non-CO_2 greenhouse gases and nutrient emissions) for the 19 product groups identified. Second, to assess the influence of non-CO_2 greenhouse gases and nutrients, we calculated the following ratio of the original EF and modified EF per product group ($R_{pollutant}$):

$$R_{pollutant} = \frac{EF_{direct} + EF_{CO2}}{EF_{direct} + EF_{CO2} + EF_{ghg} + EF_{nutrient}} \quad (9)$$

We plotted the median $R_{pollutant}$ together with the 5th, 25th, 75th and 95th percentiles per product group.

3. Results

The relative contributions to the EF of direct land use, CO_2, non-CO_2 greenhouse gases and nutrient emissions to water, land and air are illustrated in Figure 2.1. The EF of all of the product groups is dominated by CO_2 emissions, except for biomass energy, agricultural products, paper and cardboards, and landfill. These product groups are dominated by direct land use with an average contribution between 49% and 59%. Regarding non-CO_2 greenhouse gases, the average relative contribution is 3 to 16%. N or P emissions to water contribute on average less than 5% for most product categories, except for landfill, waste water treatment, incineration and agricultural products, in which the average contribution is as great as 34%. N or P emissions to land have a small contribution for all product categories involved with an average contribution less than 3%. N or P emissions to air add between 2% and 15% to the total EF, with the highest average contribution reported for the production of metals. We provide an alternative calculation for the relative contribution to the EF by using the summed EF instead of the maximum EF for nutrient emissions. A relatively large difference between the maximum and summed EF for nutrient emissions is reported for agricultural products. For the maximum EF, the average share of N and P emissions to water is lower compared to the summed EF (22% versus 26%). Results of the summed EF can be found in Supporting Information (Figure A1).

Figure 2.2 shows the ratios of the original and modified EF scores per product group ($R_{pollutant}$). For most product groups, the median $R_{pollutant}$ is larger than 0.8, indicating that nutrients and non-CO_2 greenhouse gas emissions contribute less than 20% to the EF scores. Contribution of nutrients and non-CO_2 greenhouse gases is, however, much higher for waste water treatment and landfill, for which they typically contribute 38% and 57%, respectively. Figure 2.2 also indicates that 5% of the processes within waste treatment categories (incineration, landfill and waste water treatment), biomass energy, metals, chemicals and agricultural products have an R smaller than 0.5. This implies that for 5% of the goods and services included in these product groups, the EF scores are more than 50% determined by nutrients and non-CO_2 greenhouse gases. We also calculated the ratios of the original and modified EF for the pollutants only, i.e. 'CO_2' versus 'CO_2, non-CO_2 greenhouse gases and nutrient emissions'. Box plots of these pollutants ratios can be found in Supporting Information (Figure A2).

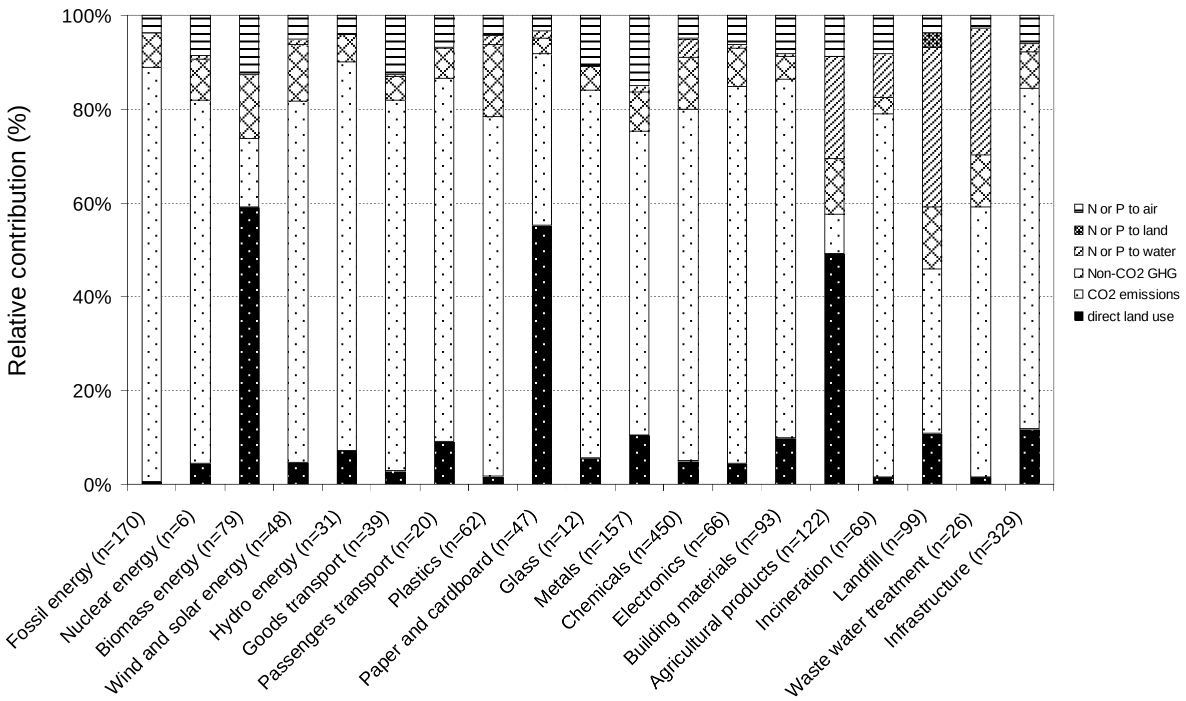

Figure 2.1: Relative contribution of direct land use, CO_2 emissions, non-CO_2 greenhouse gases, N or P emissions to water (include nitrate, nitrite, phosphate), N or P emissions land, and N or P emissions to air (include ammonia, nitrogen oxides, nitrate and phosphorus) to the ecological footprint for 19 product groups.

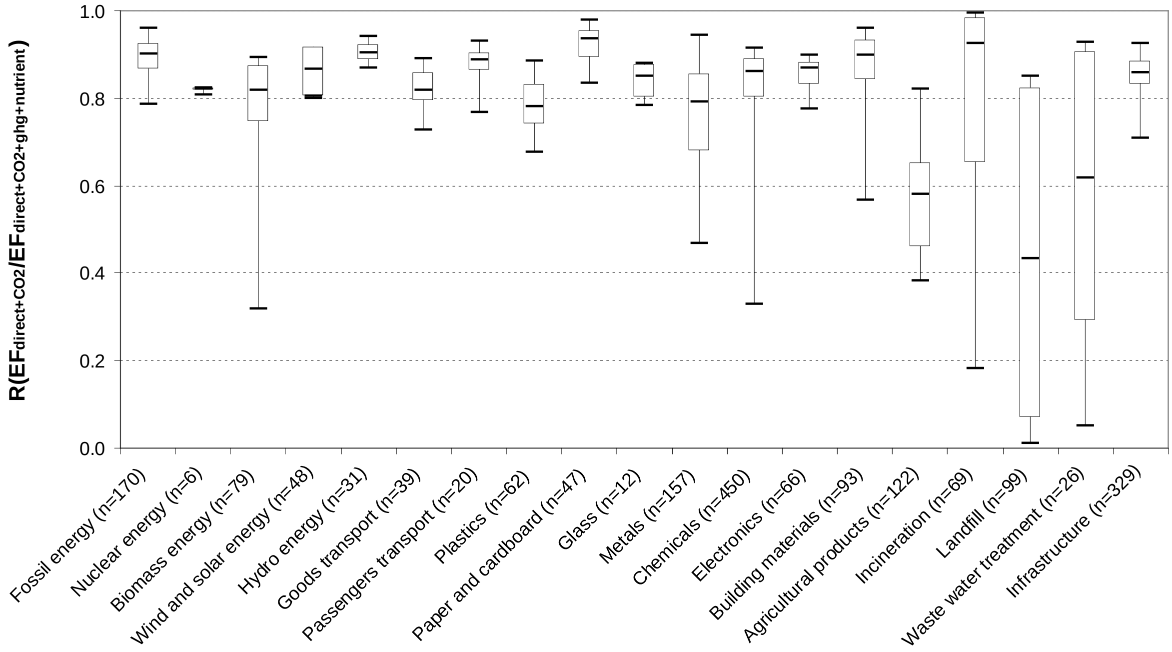

Figure 2.2: Box plots of the ratios of the original ecological footprint and the modified ecological footprint scores ($R_{pollutant}$). The centre of the box represents the median value, the edges of the box indicate the 25th and 75th percentiles and the whiskers represent the 5th and 95th percentiles of the distributions.

4. Discussion

4.1 Non-CO_2 greenhouse gas emissions

The importance of including emissions of other greenhouse gases into the standardized EF methodology has already been raised in Kitzes et al. (2009a). Adding non-CO_2 greenhouse gases emissions into the EF calculation in this study evidently resulted in a more complete picture of the environmental burden. CO_2 emissions undoubtedly remain the most important contributors to the EF for most goods and services due to high fossil fuel consumption and a large contribution of direct land use for agricultural products, biomass energy, and paper and cardboards because of extensive land used for crops and forest plantations as a source of wood. However, our results revealed that non-CO_2 greenhouse gases can also substantially contribute to product EFs. Examples are methane (CH_4) emitted from landfill sites, nitrous oxide (N_2O) emissions due to the application of fertilizer in the production of agricultural products, and chlorofluorocarbons (CFCs) emitted during the production of plastics. We used the direct global warming potentials (GWPs) with a time horizon of 100 years, as reported by the IPCC (2007), to add non-CO_2 greenhouse gases to our calculations. The 100-year time horizon is the most commonly used in the IPCC (2007) and the Kyoto Protocol (UNFCCC, 2006). The GWP model is the most up to date and scientifically robust model available, based on direct radiative forcing and residence time of the substance emitted.

It can, however, be argued that the GWPs do not reflect the actual bioproductive pathways of synthetic greenhouse gases. The inclusion of the synthetic greenhouse gases, such as CFCs, HFCs, PFCs and SF6, via their GWP can be considered artificial, because it is unrelated to the regenerative capacity of the biosphere for these greenhouse gases (Kitzes et al., 2009a). In fact, we implicitly assume that extra CO_2 absorption by the biosphere counterbalance the emissions of these synthetic greenhouse gas emissions. Furthermore, the inclusion of the GWP method is considered too complex for some air emissions with an indirect effect on global warming, such as NO_x, SO_2 and non-methane volatile organic compounds (NMVOCs). No GWP values are recommended by the IPCC (2001) for these gases that are short-lived and vary regionally in the atmosphere (IPCC, 2001). They are chemically active and even promote cooling effect.

Finally, apart from the 100-year time horizon, the IPCC (2007) also reports GWPs for a time horizon of 20 years and 500 years. The choice for a longer or shorter time horizon can change our results. For instance, compared to the GWP in the 100-year time horizon, the GWP of CH_4 is a factor of 3 higher for a time horizon of 20 years and a factor of 3 lower for a time horizon of 500 years. The GWP of N_2O hardly changes for a time horizon of 20 years, but is a factor of 2 lower for a time horizon of 500 years. This implies that for a time horizon of 20 years, CH_4 emissions become more prominent in the EF calculations. For a 500-year time horizon, however, the CH_4 and N_2O emissions become less influential compared to CO_2.

4.2 Nutrient emissions

Nutrient emissions to all emission compartments, as reported in Ecoinvent, were included in the analysis. Nutrient emissions to water were found to be relevant for the footprint of a number of production processes, particularly within the groups of agricultural products, landfill and waste water treatment. The high amounts of fertilizers used in agricultural practices explain the relatively high N and P emissions to water for this product category. Effluents of waste water treatment plants and leachates from landfill are also known important emission sources of N and P. The EF for nutrients is, however, not without uncertainty. First of all, in the new EF calculations, it is assumed that agricultural soil is the reference compartment to counterbalance N and P emissions, while another reference, such as floodplain soil, may also be used for that purpose [13]. This assumption can seriously influence the removal rates of N and P. Folke et al. (1997) applied removal rates of P in agricultural systems and N in floodplains of 3-4 and 4-11 kg ha^{-1} yr^{-1}, respectively. The typical removal rates of P and N in our study were, however, set representative for agricultural systems. Particularly for N, we included higher removal rates compared to Folke et al. (1997). Higher removal rates result in lower footprints per unit emission (see Equation 6 and 7). Using the removal rates of nutrients reported by Folke et al. (1997) would therefore result in higher product footprints for nutrient emissions compared to our calculations. Furthermore, the nutrient removal rates can vary within a specific soil system. For instance, the typical denitrification rate of nitrogen in agricultural soils is 65 kg ha^{-1} yr^{-1} but it can be a factor of 4 higher or lower, depending on soil drainage, N application rate and crop type considered. A relatively low denitrification rates can be found in well-drained, aerobic soil conditions with low N application rates and upland crop systems (Hofstra and Bouwman, 2005). The uncertainty associated with the nutrient footprints can be reduced by using the actual site-specific nutrient assimilative capacity of the system considered. In the original EF method, land area stands for specific mutually exclusive function. However, the bioproductive land does not function as a resource only, but also provides a system for waste and pollutant assimilation. The issue of double counting may arise if different types of nutrient emissions are summed together. To address this concern, only the most significant or critical emission that needs the largest land has been taken into account. In this analysis, additional agricultural land is being used as a sink for eutrophying substances.

4.3 Comparison to previous studies

In the last decade, several modifications have been proposed to improve the original method for calculating EFs (Stoeglehner and Narodoslawsky, 2008). Walsh et al. (2009) studied the incorporation of methane into the EF analysis in Ireland. They found that the inclusion of methane via the GWP increased Ireland's per capita footprint by 20%. We found that the average contribution of non-CO_2 greenhouse gases was up to 16% of the total EF in our study, which indicates a lower importance of non-CO_2 greenhouse gases in product studies compared to the EF calculation of Ireland due to its high methane emissions coming from the agricultural sector. Folke et al. (1997) calculated the EF of 29 cities within Baltic Europe. They showed that N and P emissions contribute 6.5 – 8.9% to the total footprint of cities.

These numbers correspond well to the typical contribution of nutrient emissions to the overall footprint of goods and services. In a study that included non-renewable resource consumption as an additional category, Nguyen and Yamamoto (2007) evaluated the scarcity of non-renewable resources using a thermodynamic approach. They found that the average value of the modified EF was 60% higher compared to the original EF due to the high consumption of mineral commodities such as gold, silver and copper.

5. Conclusion

In conclusion, adding more stressors inherently provides a more complete picture of the EF. We did so for nutrient emissions and non-CO_2 greenhouse gases, maintaining the bioproductivity line of reasoning of the current EF method and preventing double-counting between nutrient emissions. On the other hand, a disadvantage of adding more data is that this information can be uncertain and that the calculation procedure becomes more complex. Concerning the stressors we added to the EF, we show that for most of the products included in our study, the influence of the addition of emissions of nutrients and non-CO_2 greenhouse gases was typically smaller than 20%. The EF was generally dominated by CO_2 emissions or direct land use. However, for goods and services within specific product categories, i.e., waste treatment processes, bio-based energy, agricultural products and chemicals, adding non-CO_2 greenhouse gas emissions to air and nutrient emissions to water can have a dominant influence on the EF. We recommend carefully considering the inclusion of non-CO_2 greenhouse gases and nutrient emissions in EF analyses in which these product categories can play an important role. Our findings suggest that in specific cases, the inclusion of non-CO_2 greenhouse gases and nutrient emissions can indeed change the interpretation of the EF results.

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Supporting Information

Table A1: Equivalence factors (EqF) implemented in Ecoinvent for the land use type (Wackernagel et al., 2005; ecoinvent, 2007).

Ecoinvent classification	EqF for direct land use type (-)
Occupation, arable	2.2
Occupation, arable, non-irrigated	2.2
Occupation, construction site	2.2
Occupation, dump site	2.2
Occupation, dump site, benthos	0.4
Occupation, forest	1.4
Occupation, forest, intensive	1.4
Occupation, forest, intensive, normal	1.4
Occupation, industrial area	2.2
Occupation, industrial area, benthos	0.4
Occupation, industrial area, built up	2.2
Occupation, industrial area, vegetation	2.2
Occupation, mineral extraction site	2.2
Occupation, pasture and meadow	0.5
Occupation, pasture and meadow, extensive	0.5
Occupation, pasture and meadow, intensive	0.5
Occupation, permanent crop	2.2
Occupation, permanent crop, fruit	2.2
Occupation, permanent crop, fruit, intensive	2.2
Occupation, shrub land, sclerophyllous	1.4
Occupation, traffic area, rail embankment	2.2
Occupation, traffic area, rail network	2.2
Occupation, traffic area, road embankment	2.2
Occupation, traffic area, road network	2.2
Occupation, urban, discontinuously built	2.2
Occupation, water bodies, artificial	1
Occupation, water courses, artificial	1

Table A2: Global warming potentials (IPCC, 2007) for a time horizon of 100-years, except for (*) derived from IPCC (2001).

Greenhouse gases	GWP 100a (-)
carbon dioxide	1
carbon monoxide, fossil	1.6*
chloroform	30*
dinitrogen monoxide	298
ethane, pentafluoro-, HFC-125	3500
ethane, hexafluoro-, HFC 116	12200
ethane, chloropentafluoro-, CFC-115	7370
ethane, 2-chloro-1,1,1,2-tetra-fluoro-, HCFC-124	609
ethane, 2,2-dichloro-1,1,1-tri-fluoro-, HCFC-123	77
ethane, 1-chloro-1,1-difluoro-, HCFC-142b	2310
ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	10000
ethane, 1,1-difluoro-, HFC-152a	124
ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	725
ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	6130
ethane, 1,1,1-trifluoro-, HFC-143a	4470
ethane, 1,1,1,2-tetrafluoro-, HFC-134a	1430
methane	25
methane, bromo-, Halon 1001	5
methane, bromochlorodifluoro-, Halon 1211	1890
methane, bromotrifluoro-, Halon 1301	7140
methane, chlorodifluoro-, HCFC-22	1810
methane, chlorotrifluoro-, CFC-13	14400
methane, dichloro-, HCC-30	8.7
methane, dichlorodifluoro-, CFC-12	10900
methane, dichlorofluoro-, HCFC-21	210*
methane, difluoro-, HFC-32	675
methane, monochloro-, R-40	13
methane, tetrachloro-, R-10	1400
methane, tetrafluoro-, R-14	7390
methane, trichlorofluoro-, CFC-11	4600
methane, trifluoro-, HFC-23	14800
sulfur hexafluoride	22800

Table A3: Molar mass conversion factor for nutrient emissions to water, soil and air compartments included in our study.

Compartment	Compound	Molar mass of compound (g/mol)	Molar mass conversion factor
Water	N (nitrogen)	14	1
(freshwater, ocean,	NO_3 (nitrate)	62	14/62
groundwater and	NO_2 (nitrite)	46	14/46
unspecified)	P (phosphorus)	31	1
	PO_4^{3-} (phosphate)	95	31/95
Soil	N (nitrogen) - industrial	14	1
	P (phosphorus) - industrial	31	1
Air	NO_3 (nitrate)	62	14/62
(high population	NO_2 (nitrogen oxides)	44	14/44
density, low	NH_3 (ammonia)	17	14/17
population density,	P (phosphorus)	31	1
lower stratosphere			
and unspecified)			

Figure A1 shows per product group the relative contribution to the EF of direct land use, CO_2, non-CO_2 greenhouse gases and nutrient emissions to water, land and air, using the summed EF instead of the maximum EF for nutrient emissions. The same as for the maximum EF calculation for nutrient emissions, the EF of all product groups is dominated by CO_2 emissions and direct land use. N and P emissions to water contribute on average less than 11%, except for the EF of agricultural products, waste water treatment and landfill, with an average contribution of higher than 20%. N and P emissions to land contribute on average less than 5% for all product categories involved. N or P emissions to air typically add 3-15% to the total EF. The largest difference between summed and maximum EF for nutrient emissions can be found for the agricultural products. For the summed EF, the average share of N and P emissions to water doubles from around 10% to 20% compared to maximum EF.

Figure A2 presents box plots of the EF-ratio per product group taking into account pollutants only. The spread reflects the fact that not every product has the same EF-ratio. For most products, the median ratio is larger than 0.75, implying that the added pollutants typically contribute less than 25% to the EF scores. This is, however, not the case for biomass energy, agricultural products, landfill and waste water treatment. For these three product groups, the typical contribution of non-CO_2 greenhouse gases and nutrient emissions is larger, i.e., between 39% and 86%. Specific for the biomass energy, agricultural products and waste treatment categories (incineration, landfill and waste water), it was found that 5% of the processes have an R smaller than 0.2. This implies that for 5% of the waste treatment processes included, the pollutant EF scores are more than 80% determined by nutrients and non-CO_2 greenhouse gas emissions. Compared to the total EF ratios (Figure 2), the extra emissions have a larger influence on the pollutant EF ratios, particularly for the biomass energy and agricultural products.

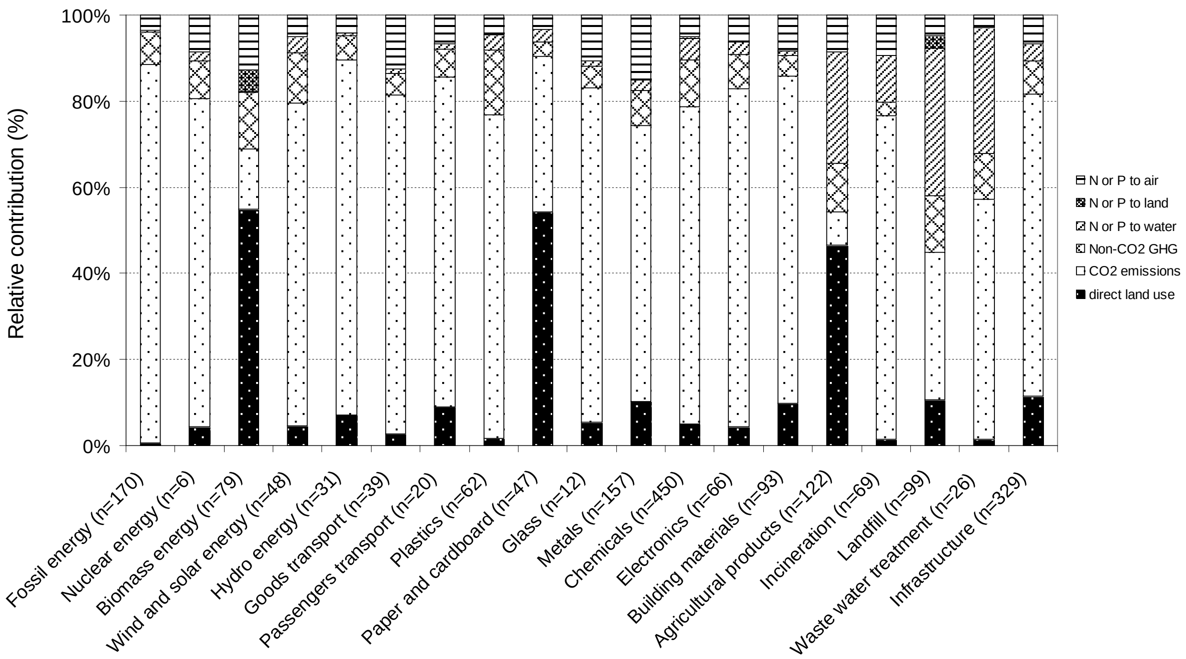

Figure A1: Relative contribution of direct land use, CO_2 emissions, non-CO_2 greenhouse gases, N and P emissions to water (include nitrate, nitrite, phosphate), N and P emissions land, and N or P emissions to air (include ammonia, nitrogen oxides, nitrate and phosphorus) to the summed EF for 19 product groups.

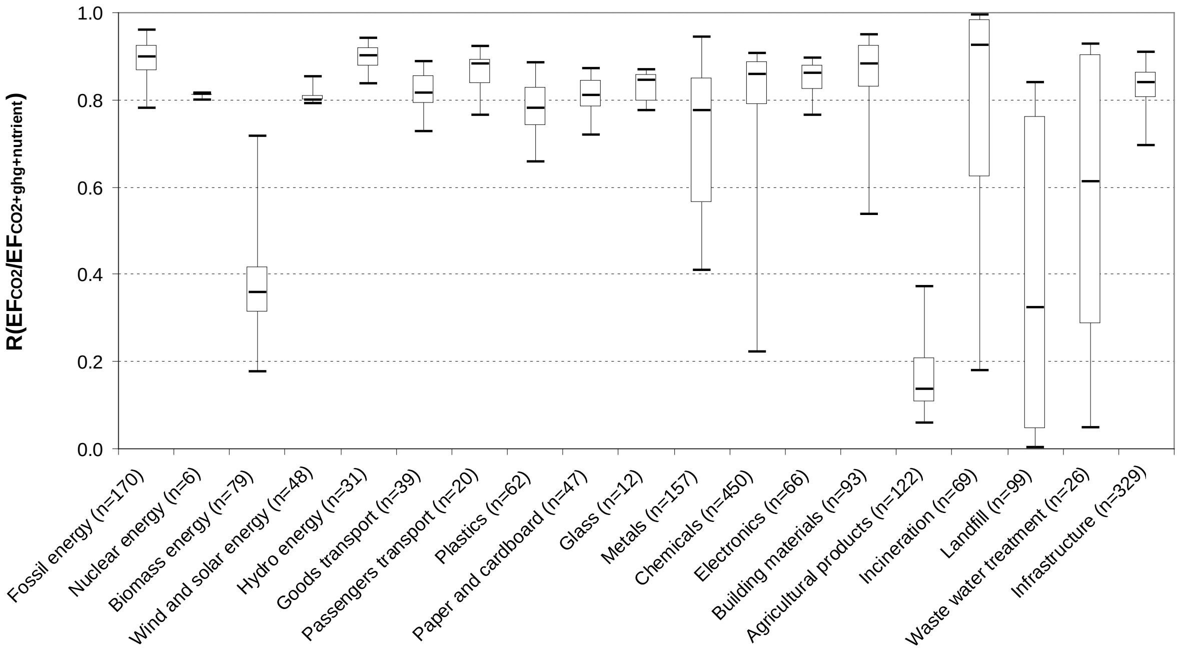

Figure A2: Box plots of the ratios of the EF for 'CO_2 emissions' and 'CO_2, greenhouse gases and nutrients emissions'. The centre of the box represents the median value, the edges of the box indicates the 25th and 75th percentiles and the whiskers represent the 5th and 95th percentiles of the distributions.

Chapter 3

Comparing the ecological footprint with the biodiversity footprint of products

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Abstract

This study compares the ecological footprints with the biodiversity footprints of products that result from land use and carbon dioxide emissions. The biodiversity footprints were quantified using mean species abundance statistics, whereas the ecological footprint refers to the impacts on bioproductivity. We used a data set of 1340 product systems subdivided into 13 product groups, which included various types of energy generation and material production. We found that the importance of direct land use vs. carbon dioxide emissions is different for biodiversity footprints compared to ecological footprints. This difference is particularly relevant if the environmental impact of bio-based products (dominated by direct land use) is compared with the environmental impact of fossil-based products (dominated by CO_2 emissions). Our results also show that the relative importance of different drivers can change over time within the biodiversity footprint and that the relative importance of climate change significantly increased for longer time horizons. As the interpretation of the biodiversity footprint can differ from the ecological footprint, the inclusion of impacts on biodiversity should be considered in the footprint calculation of products.

Keywords: mean species abundance; land use; ecoinvent; life cycle assessment

1. Introduction

The concept of the ecological footprint (EF) evaluates the impact of human activities on the environment (Lyndhurst, 2003; Simmons et al., 2007; WWF, 2010). The EF is defined as the amount of land that is used to meet human demands, and it is measured in the global hectares (gha) of the biologically productive land needed to renew the resources used by humans and to absorb anthropogenic CO_2 emissions (Wackernagel and Rees, 1996; Wackernagel et al., 2005). A global hectare is equal to one hectare of a biologically productive area having a worldwide average productivity for a given year (Wackernagel et al., 2006; Wiedmann and Lenzen, 2007; Ewing et al., 2010).

Although the focus of the EF is on bioproductivity, an increase in demand by humans could also increase the pressures on biodiversity and eventually lead to biodiversity loss. For instance, replacing woodlands with monoculture forests will increase bioproductivity, however, this replacement will also lead to drastic reductions in biodiversity. For agricultural lands, the conversion of conventional to organic practices have resulted in higher biodiversity values, in contrast to bioproductivity (Lenzen et al., 2007a). Furthermore, agricultural intensification, including the use of pesticides, has resulted in negative effects on species biodiversity (Geiger et al., 2010). Koellner (2007) found that, in addition to the development of infrastructure and urban areas, intensive agriculture and forestry have negative influences on biodiversity. Areas of highly intensive agriculture demonstrate the lowest species richness (5.7 plant species/m^2), whereas low-intensity agriculture exhibits the highest species richness (16.6 plant species/m^2) (Koellner, 2007).

Climate change can also influence species richness. According to Thomas et al. (2004), climate change is expected to drive a large fraction of terrestrial species into extinction over the next 50 years. However, impacts on biodiversity, such as the influence of the conversion of primary forests to croplands on species richness and species extinction due to increasing anthropogenic CO_2 emissions, have not been included in the common EF calculations (Kitzes et al., 2009). To address this shortcoming in EF analyses, the land disturbance concept that characterises ecosystem quality based on the land condition and occurrence of vascular plant species from a pristine state has been proposed (Lenzen and Murray, 2001; Lenzen et al., 2007a). This disturbance-based EF serves as an indicator for the measurement of the unsustainability that is related to the present and potential human activities on all land use types. The disturbance-based EF is measured by multiplying the actual land area by its land condition factor, expressed in disturbed hectares (Lenzen and Murray, 2003; Lenzen et al., 2007a; Lenzen et al., 2007b). Lenzen et al. (2007a) calculated the disturbance-weighted EF for direct land use and CO_2 emissions for Australia and found that the relative importance of the EF of direct land use doubles from approximately 43% to 79% compared to the bioproductivity-weighted EF calculation. However, such a comparison has not thus far been performed for product systems.

Several studies have been conducted to extend the original concept of EF methods (e.g., Folke et al., 1997; Stoglehner, 2003; Nguyen and Yamamoto, 2007; Walsh et al., 2009; Cerutti et al., 2010; Hanafiah et al., 2010). Here, we also expand the scope of the ecological footprint approach by assessing the impacts on biodiversity. The goal of the present study was to compare the ecological footprints with the biodiversity footprints within a product-specific context.

2. Methodology

2.1 Ecological footprints

The ecological footprint of a product refers to the time-integrated biologically productive land required to produce resources (EF_{direct}) and to absorb CO_2 emissions (EF_{CO2}) (Huijbregts et al., 2008; Hanafiah et al., 2010).

The ecological footprint for direct land use (EF_{direct}) was calculated using the following equation:

$$EF_{direct} = \sum_p A_p \cdot EqF_p \tag{1}$$

where EF_{direct} is the product-specific ecological footprint of the direct land use related to forestry, crops, pasture and built-up land (m^2yr), A_p is the product-specific occupation of the area by the land use type p (m^2yr) and EqF_p is the equivalence factor of land use type p (dimensionless). Table 1 gives further details of the EqFs values applied in the present study. In the EF method, EqF translates the available area of a specific land use type into units of world-average biologically productive area. EqF is calculated as the ratio of the maximum potential ecological productivity of the world-average land of a specific land use type and the average productivity of all of the biologically productive lands worldwide. Note that, in the

EF method, the EqF for built-up land has the same EqF as that for arable land because most housing and infrastructure are predominantly located on agriculturally fertile areas (Wackernagel et al., 2005).

The ecological footprint for the CO_2 emissions (EF_{CO2}) was calculated as follows:

$$EF_{CO2} = M_{CO2} \cdot \frac{1 - F_{CO2}}{S_{CO2}} \cdot EqF_f \tag{2}$$

where EF_{CO2} is the product-specific ecological footprint of the CO_2 emissions (m^2yr), M_{CO2} is the product-specific emission of CO_2 (kg CO_2), F_{CO2} is the fraction of CO_2 absorbed by oceans (0.3; Wackernagel et al., 2005), S_{CO2} is the sequestration rate of CO_2 by biomass (0.4 kg CO_2 m^{-2} yr^{-1}; Wackernagel et al., 2005) and EqF_f is the equivalence factor of forests (1.26; Wackernagel et al., 2005; Ewing et al., 2010). We excluded nuclear energy in the EF calculations, as there were no suitable methods available to include nuclear energy in the EF calculation (Kitzes et al., 2009).

2.2 Biodiversity footprints

The biodiversity footprint (BF) for the direct land use types identified was calculated as follows:

$$BF_{direct} = \sum_p A_p \cdot (1 - MSA_p) \tag{3}$$

where BF_{direct} is the product-specific biodiversity footprint of direct land use (m^2yr), A_p is the product-specific occupation of area by land use type p (m^2yr) and MSA_p is a biodiversity indicator that describes the mean species abundance of land use type p (dimensionless). The MSA is defined as the remaining mean species abundance of the original species, relative to their abundance in pristine or primary vegetation, which are assumed to be undisturbed by human activities (Alkemade et al., 2009). The MSA has been used in various integrated assessment studies that address current and future impacts on biodiversity, including scenarios for global biodiversity in the 21st century (Pereira et al., 2010) and the OECD

Environmental Outlook to 2050 (OECD, 2012). In our study, we applied the MSA of various land use types, based on Alkemade et al. (2009) (Table 1).

The biodiversity footprint for CO_2 emissions was calculated as follows:

$$BF_{CO_2} = M_{CO_2} \cdot TF_{CO_2} \cdot \sum_i (1 - MSA_{CC,i}) \cdot A_i \tag{4}$$

where BF_{CO2} is the product-specific biodiversity footprint of CO_2 emissions (m^2yr), M_{CO2} is the product-specific emission of CO_2 (kg), TF_{CO2} is the temperature factor of CO_2 emissions (°Cyrkg^{-1}), 1-$MSA_{CC,i}$ is the loss in the mean species abundance in biome type *i* due to a global mean temperature increase (°C^{-1}) and A_i is the area of biome type *i*.

There are three calculation steps involved in the derivation of the temperature factor of CO_2 emissions (De Schryver et al., 2009). The first step corresponds to the change in CO_2 concentration of the air due to a change in emissions (Forster et al., 2007), the second step describes the change in radiative forcing due to a change in the concentration (Forster et al., 2007), and the third step represents the change in the global-mean temperature due to the change in radiative forcing (Eickhout et al., 2004). These three steps can be summarised in a temperature factor for the CO_2 emissions (the change in the global mean temperature due to a change in the emissions). The temperature factors for CO_2 equal $8.4 \cdot 10^{-15}$ °C yr kg^{-1} (20-year time horizon), $4.2 \cdot 10^{-14}$ °C yr kg^{-1} (100-year time horizon) and $5.9 \cdot 10^{-13}$ °C yr kg^{-1} (infinite time horizon), as obtained from De Schryver et al. (2009).

Alkemade et al. (2009) reports changes in the mean species abundance with a global mean temperature increase (ºC) for 14 different terrestrial biomes, as derived from the species shifts predictions using the EUROMOVE model (Bakkenes et al., 2002) and the biome shifts using the IMAGE model (Prentice et al., 1992). We calculated the loss in the mean species abundance across the globe using the weighted aggregation across the biomes with the biome areas (m^2) reported in Olson et al. (2001) as a weighting factor.

Table 2 summarises the key features of the ecological footprint and biodiversity footprint of direct land use and CO_2 emissions.

Table 1: Equivalence factors (EqF) for direct land use and CO_2 emissions (Ewing et al., 2010), the loss in mean species abundance (1-MSA) for direct land use and CO_2 emissions (Alkemade et al., 2009; De Schryver et al., 2009) and the EqF/(1-MSA) ratio. The Ecoinvent classification (Ecoinvent, 2007) of direct land use types is used as a default classification and is connected to the land use classification of Alkemade et al. (2009).

Ecoinvent (2007) Ecoinvent classification	Alkemade et al. (2009) MSA classification	Unit	EqF	1-MSA	EqF/ (1-MSA)
Arable[a]	Intensive agriculture	-	2.51	0.9	2.8
Arable, intensive[b]	Intensive agriculture	-	2.51	0.9	2.8
Arable, extensive[b]	Low-input agriculture	-	2.51	0.7	3.6
Arable, non-irrigated, intensive[b]	Intensive agriculture	-	2.51	0.9	2.8
Arable, non-irrigated, extensive[b]	Low-input agriculture	-	2.51	0.7	3.6
Arable, organic farming[b]	Low-input agriculture	-	2.51	0.7	3.6
Arable, non-irrigated, diverse-intensive	Intensive agriculture	-	2.51	0.9	2.8
Arable, non-irrigated, fallow	Low-input agriculture	-	2.51	0.7	3.6
Arable, non-irrigated, monotone-intensive	Intensive agriculture	-	2.51	0.9	2.8
Construction site	Built-up areas	-	2.51	0.95	2.6
Dump site	Built-up areas	-	2.51	0.95	2.6
Dump site, benthos[c]		-	0	0	
Forest	Secondary forest	-	1.26	0.5	2.5
Forest, extensive	Lightly used natural forest	-	1.26	0.3	4.2
Forest, intensive	Secondary forest	-	1.26	0.5	2.5
Forest, intensive, clear cutting	Secondary forest	-	1.26	0.5	2.5
Forest, intensive, normal	Secondary forest	-	1.26	0.5	2.5
Forest, intensive, short-cycle	Forest plantation	-	1.26	0.8	1.6
Heterogeneous, agricultural	Agroforestry	-	2.51	0.5	5.0
Industrial area	Built-up areas	-	2.51	0.95	2.6
Industrial area, benthos[c]		-	0	0	
Industrial area, built up	Built-up areas	-	2.51	0.95	2.6
Industrial area, vegetation	Built-up areas	-	2.51	0.95	2.6

Mineral extraction site	Built-up areas	-	2.51	0.95	2.6
Pasture and meadow	Man-made pastures	-	0.46	0.9	0.5
Pasture and meadow, extensive	Livestock grazing	-	0.46	0.3	1.5
Pasture and meadow, intensive	Man-made pastures	-	0.46	0.9	0.5
Permanent crop	Intensive agriculture	-	2.51	0.9	2.8
Permanent crop, fruit	Intensive agriculture	-	2.51	0.9	2.8
Permanent crop, fruit, extensive	Low-input agriculture	-	2.51	0.7	3.6
Permanent crop, fruit, intensive	Intensive agriculture	-	2.51	0.9	2.8
Permanent crop, vine	Intensive agriculture	-	2.51	0.9	2.8
Permanent crop, vine, extensive	Low-input agriculture	-	2.51	0.7	3.6
Permanent crop, vine, intensive	Intensive agriculture	-	2.51	0.9	2.8
Sea and ocean[c]		-	0	0	
Shrub land, sclerophyllous	Primary vegetation (grass or scrublands)	-	0	0	
Traffic area, rail embankment	Built-up areas	-	2.51	0.95	2.6
Traffic area, rail network	Built-up areas	-	2.51	0.95	2.6
Traffic area, road embankment	Built-up areas	-	2.51	0.95	2.6
Traffic area, road network	Built-up areas	-	2.51	0.95	2.6
Urban, continuously built	Built-up areas	-	2.51	0.95	2.6
Urban, discontinuously built	Built-up areas	-	2.51	0.95	2.6
Water bodies, artificial[d]		-	1	1	1.0
Water courses, artificial[d]		-	1	1	1.0
Tropical rain forest	Primary vegetation: forest	-	0	0	
CO_2 emissions, 20-year time horizon		m^2 yr kg^{-1}	2.5	0.05	50.0
CO_2 emissions, 100-year time horizon		m^2 yr kg^{-1}	2.5	0.27	9.3
CO_2 emissions, infinite time horizon		m^2 yr kg^{-1}	2.5	3.87	0.6

[a]generic land use classes were considered to be the land that is intensively used

[b]new land use type classification by subdivision into intensive, extensive and organic farming

[c]marine area not included

[d]the equivalence factor for a hydroelectric reservoir area is set equal to one, reflecting the assumption that hydroelectric reservoirs flood the world-average land

Table 2: Key features of the ecological footprint and biodiversity footprint.

Environmental stressor	Ecological footprint	Biodiversity footprint
Direct land use	Global bioproductive area that is required to compensate for the area used for the life-cycle of a product.	Global area that is required to compensate for the mean species abundance loss caused by direct land use for the life-cycle of a product.
CO_2 emissions	Global forest area that is required to sequester fossil-based CO_2 emissions for the life-cycle of a product.	Global area that is required to compensate for the mean species abundance loss caused by fossil-based CO_2 emissions for the life-cycle of a product.

2.3 Comparison

The influence of assessing the product footprints following a bioproductivity versus a biodiversity perspective was shown by calculating the EF-BF ratio for every product included, as follows:

$$R = \frac{EF}{BF} \tag{5}$$

The median R, together with the 5^{th}, 25^{th}, 75^{th} and 95^{th} percentiles per product group, are presented.

A total of 1340 products and services subdivided into 13 product groups were included in the comparison. The product groups identified in the study include energy production processes and material production. These inventory data were obtained from the Ecoinvent database v2.0 (Ecoinvent Centre, 2007).

3. Results and discussion

3.1 Relative contribution of land use and CO_2 emissions

Figure 1 shows that the EF is mainly dominated by CO_2 emissions, except for the product groups of biomass energy, paper and cardboard and agricultural products. For these product groups, direct land use is most relevant, with an average contribution between 58% and 73%.

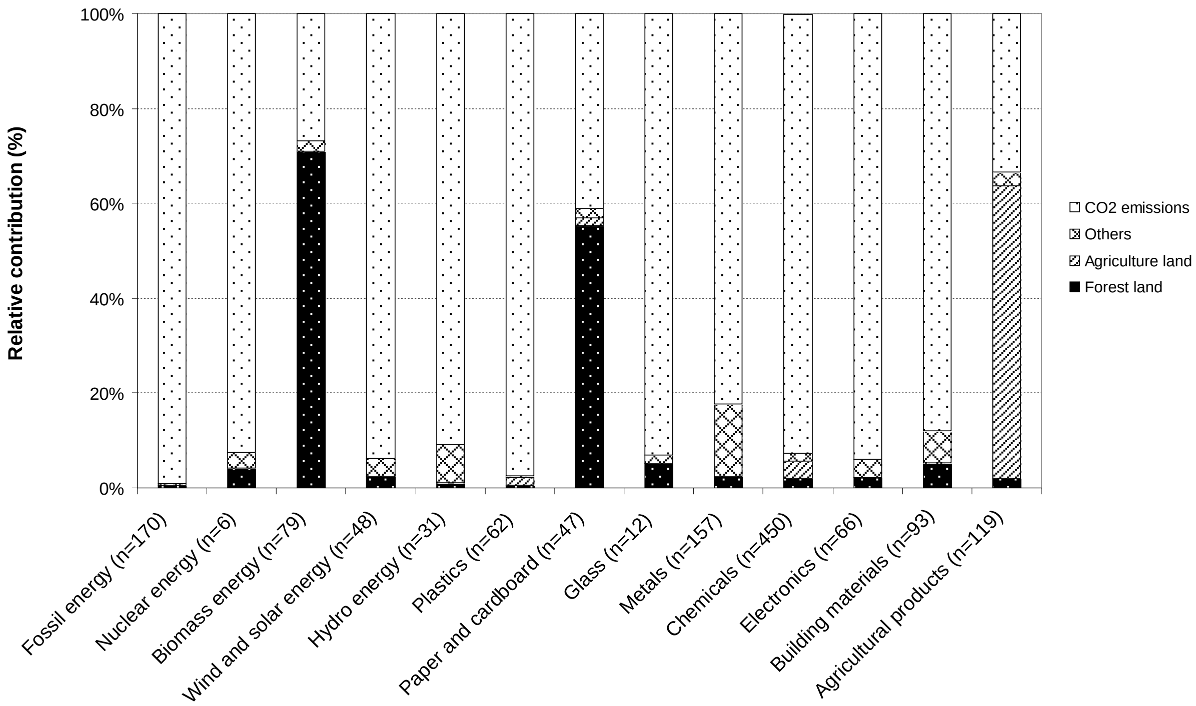


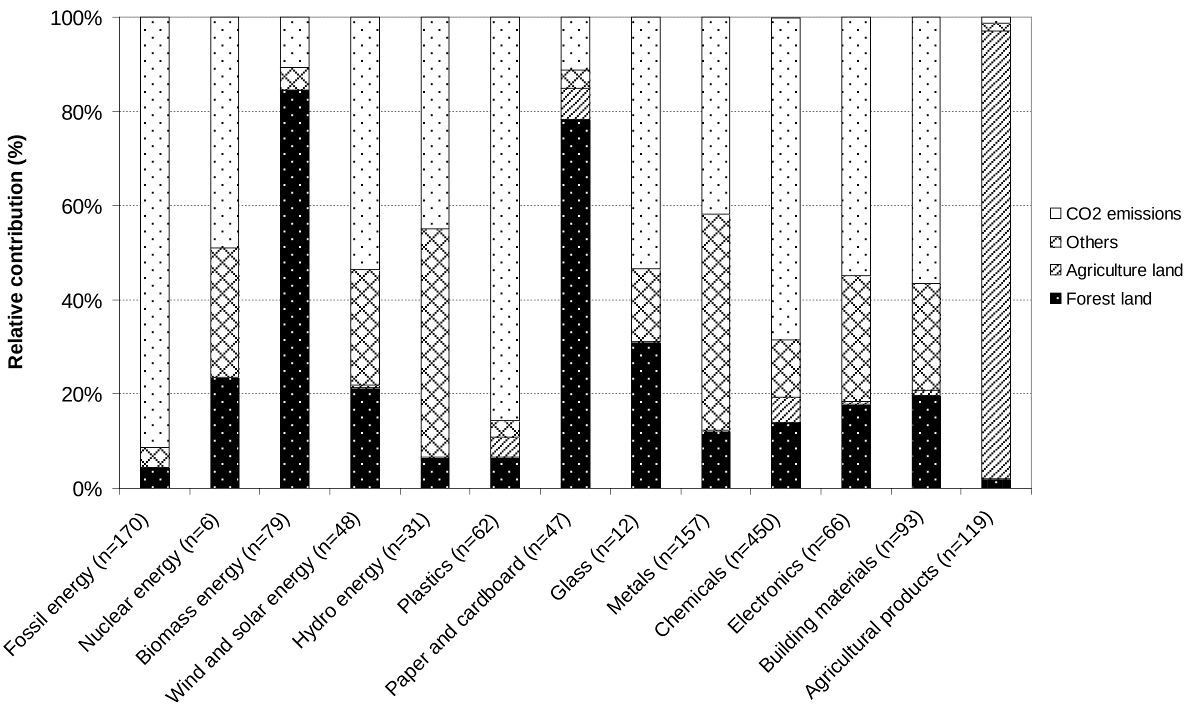
Figure 1: Relative contributions of direct land use and CO_2 emissions to the average ecological footprint of 13 product groups.

The average relative contribution of direct land use to the total BF is approximately 45% for eight product groups, more than 80% for three product groups and less than 20% for two other product groups if the BF of CO_2 emissions for a 20-year time horizon is used (Figure 2A).

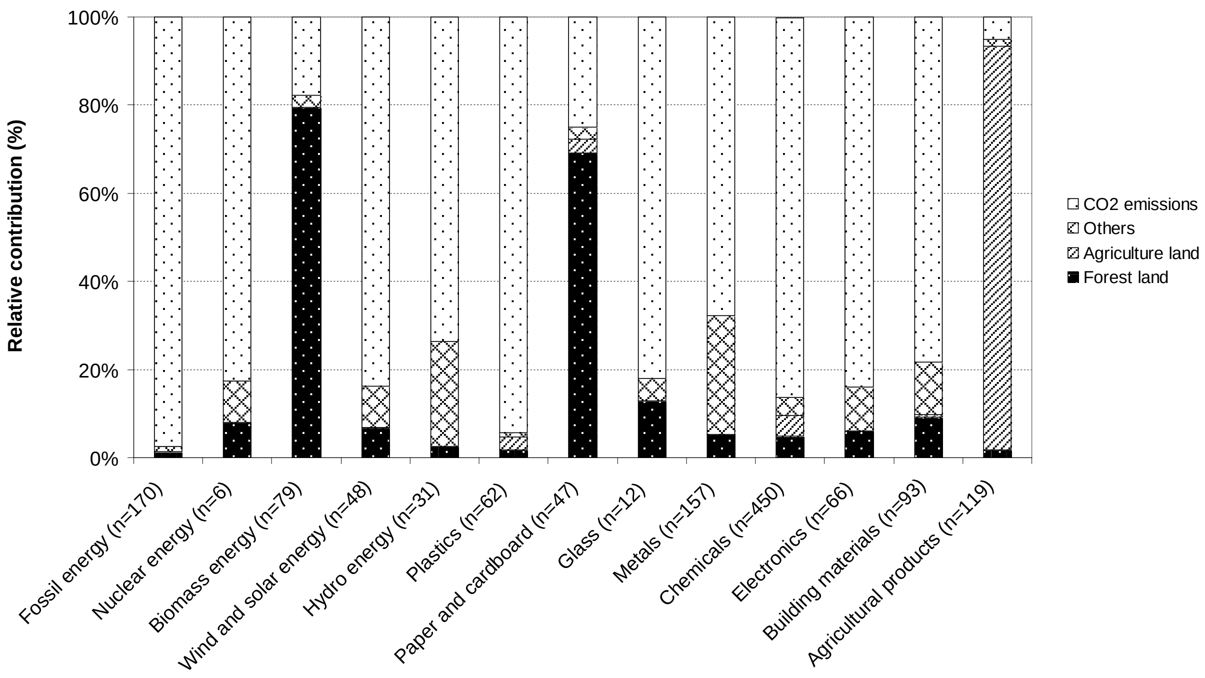
The relative contribution to the BF of direct land use and CO_2 emissions based on a 100-year time horizon is illustrated in Figure 2B. Similar to the EF, the CO_2 emissions dominantly contribute to the BF, except for biomass energy, paper and cardboard and agricultural products. The average share of direct land use to the overall impacts of these three product groups is higher when compared to the EF (75-95% vs. 58-73%).

Figure 2C shows that the relative average contribution to the BF of direct land use is negligible (< 5%) for 10 of the 13 product groups when the BF of CO_2 for an infinite time horizon is used. For the three other product groups (biomass energy, paper and cardboard and agricultural products), the average contribution of direct land use is between 33-63 %.

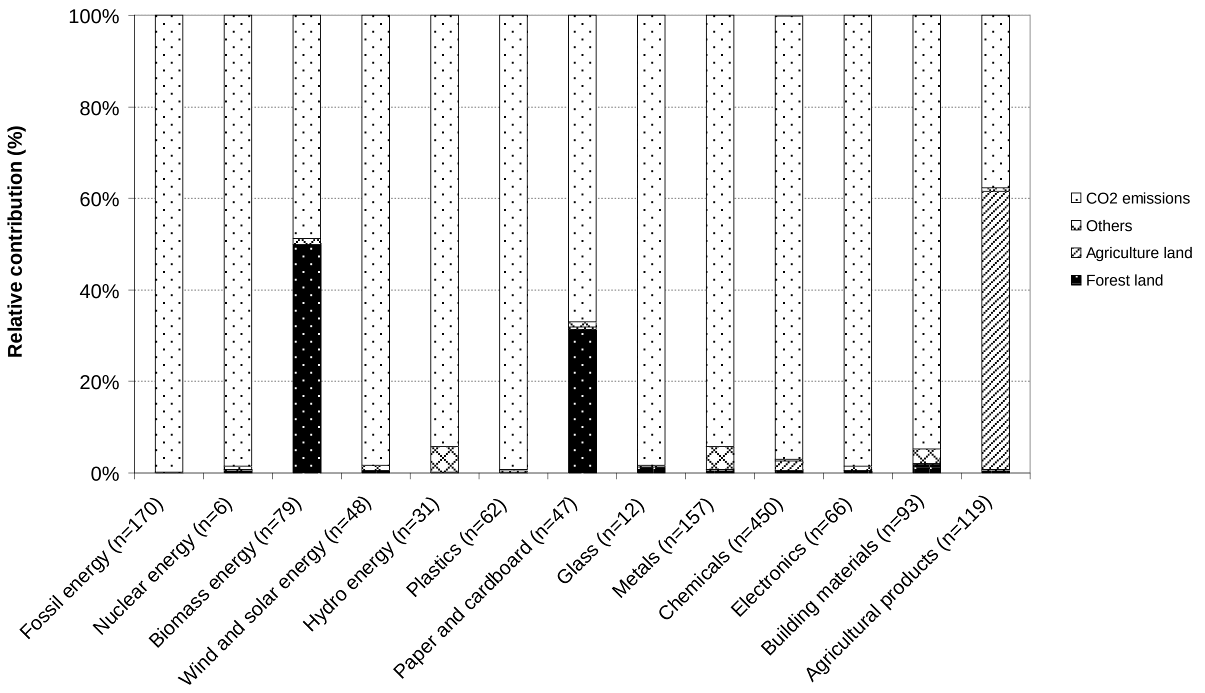
The influence of the CO_2 emissions on the BF calculations can significantly vary depending on the time horizon chosen, and the relative contribution of the CO_2 emissions for an infinite time horizon is much larger than that for the 20- and 100-year time horizons. The impact of CO_2 accumulates over a long time period (> 100 years), which influences the relative importance of CO_2 emissions compared with direct land use.



A



B



C

Figure 2: The relative contribution of direct land use and CO_2 emissions to the average biodiversity footprint of 13 product groups based on a 20-year time horizon (A), a 100-year time horizon (B) and an infinite time horizon (C).

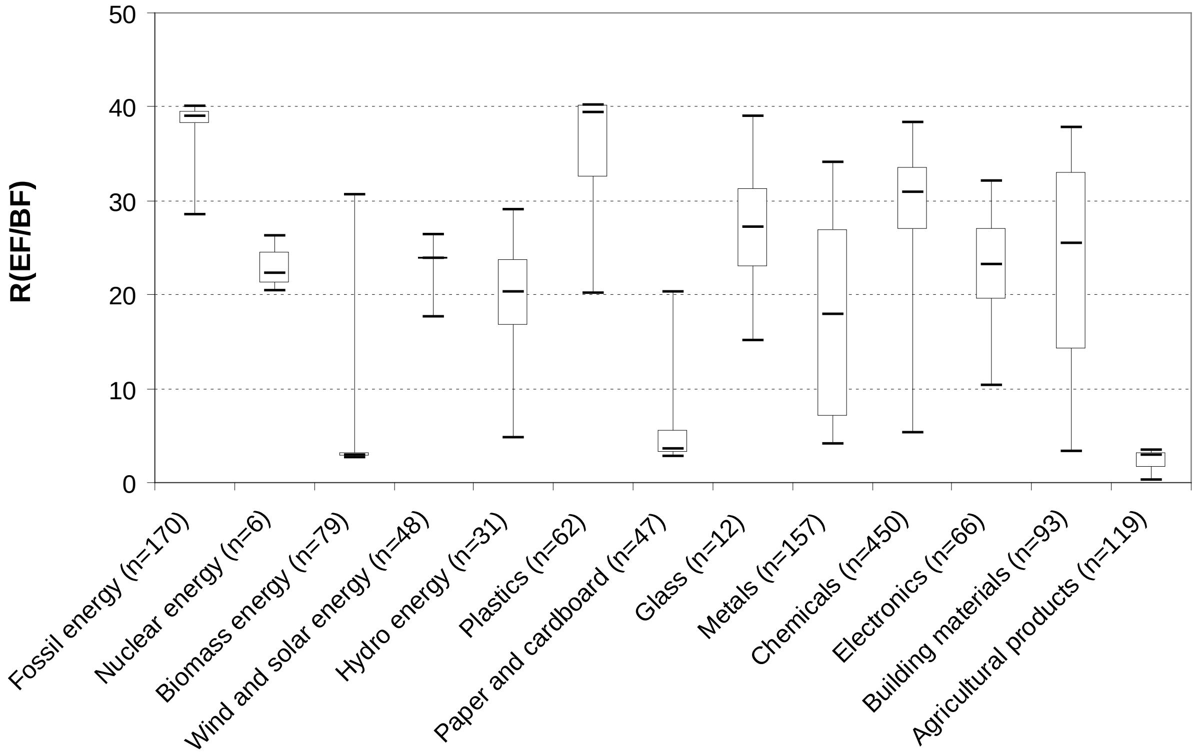
3.2 Biodiversity footprint vs. ecological footprint

Figure 3A shows the box plots of the EF-BF ratios per product group based on a 20-year time horizon. The median EF-BF ratio for the bio-based processes and products (biomass energy, paper and cardboard, agricultural products) is 2-4, whereas the median ratio for processes and products driven by fossil energy is much higher (17-40). This finding can be explained by the fact that the ecological footprint and biodiversity footprint factors for direct land use are more similar than those for CO_2 emissions. Large differences in the EF-BF ratios are found within most product groups (up to a factor of 11 differences between the 5th and 95th percentiles).

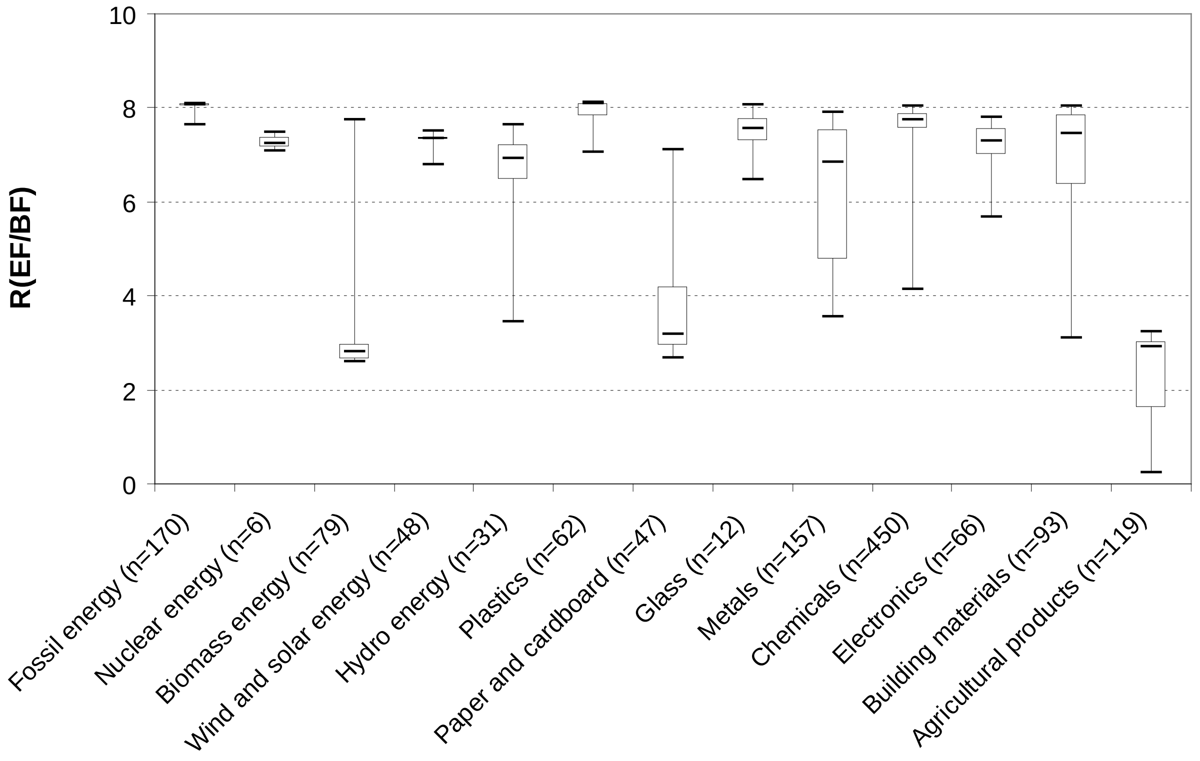
The ratios of the EF and BF for a 100-year time horizon are shown in Figure 3B. For most of the product groups, the median EF-BF ratio is approximately 7. Exceptions are noted for biomass energy, paper and cardboards and agricultural products. These product groups have a median EF-BF ratio smaller than 4. A number of product categories, notably fossil energy, nuclear energy, wind and solar energy, plastic production, glass and electronics have relatively stable EF-BF ratios (between 6 and 8). Other product groups, such as biomass energy, hydro energy, paper and cardboard, metals, chemicals and building materials, show relatively large differences in their EF-BF ratios (up to a factor of 3 differences between the 5th and 95th percentile).

The results for the EF-BF ratios based on an infinite time horizon are different from the other time horizons (Figure 3C). Based on an infinite time horizon, the median of the EF-BF ratios for most product groups is less than 1, except for biomass energy, paper and cardboard and agricultural products, which have median ratios between 1 and 2. The median ratio for fossil-based processes and products is 0.5-0.6, whereas the median ratio for bio-based processes and products (biomass energy, paper and cardboard and agricultural products) is higher (1.2-1.8). The differences in the EF-BF ratios for products driven by fossil energy are relatively small due to the dominance of the CO_2 emissions in both the EF and the BF for an infinite time horizon.

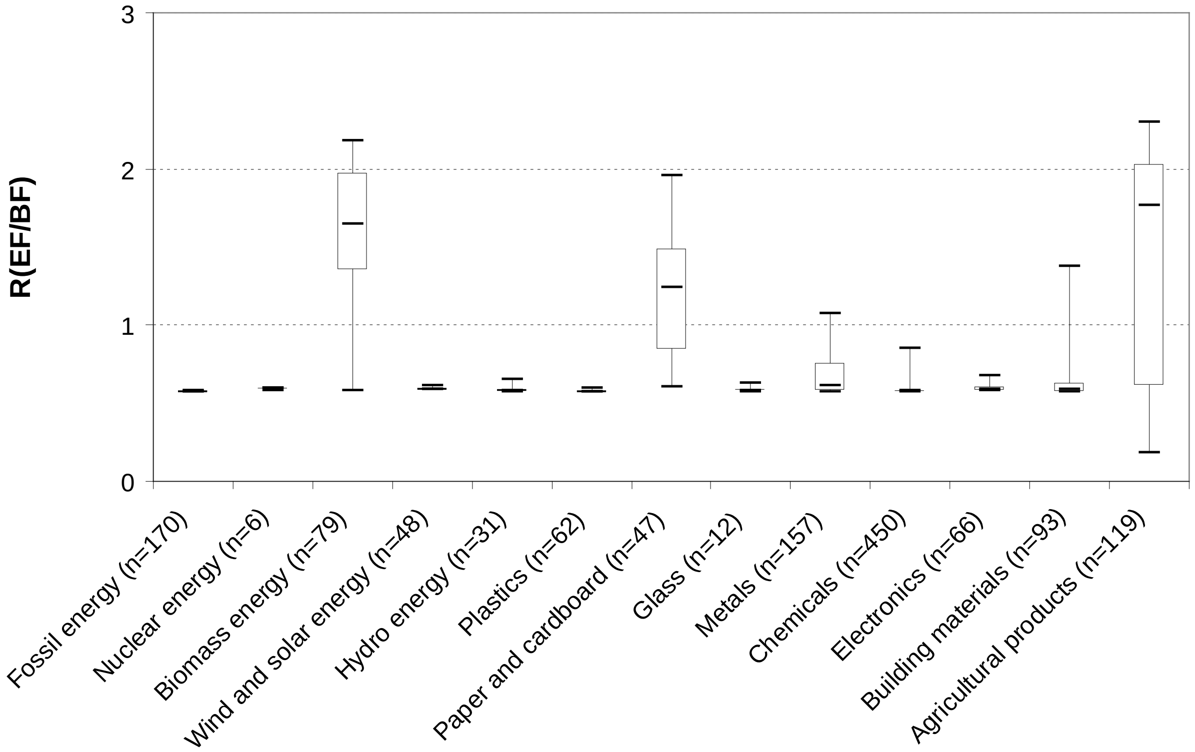
These results imply that differences in the EFs compared to BFs will arise particularly when the footprint for one product is determined on the basis of direct land use and the footprint for another product is dominated by CO_2 emissions. This is particularly true for the BFs derived for the time horizons of 20 or 100 years.


R(EF/BF)
50
40
30
20
10
0
Fossil energy (n=170)
Nuclear energy (n=6)
Biomass energy (n=79)
Wind and solar energy (n=48)
Hydro energy (n=31)
Plastics (n=62)
Paper and cardboard (n=47)
Glass (n=12)
Metals (n=157)
Chemicals (n=450)
Electronics (n=66)
Building materials (n=93)
Agricultural products (n=119)

A


R(EF/BF)
10
8
6
4
2
0
Fossil energy (n=170)
Nuclear energy (n=6)
Biomass energy (n=79)
Wind and solar energy (n=48)
Hydro energy (n=31)
Plastics (n=62)
Paper and cardboard (n=47)
Glass (n=12)
Metals (n=157)
Chemicals (n=450)
Electronics (n=66)
Building materials (n=93)
Agricultural products (n=119)

B



C

Figure 3: Box plots of the ratios of the ecological footprint (EF) and biodiversity footprint (BF) scores for 13 product groups based on a 20-year time horizon (A), a 100-year time horizon (B), and an infinite time horizon (C). The centre of the box represents the median value, the edges of the box indicate the 25th and 75th percentiles, and the whiskers represent the 5th and 95th percentiles of the distributions.

Our study compares the footprint results for bioproductivity with a biodiversity perspective, using the same stressors, i.e., direct land use and CO_2, as a starting point. Comparisons of EF methodology using life cycle impact assessment (LCIA) methods, including more stressors, have been previously performed (Huijbregts et al., 2008; Alvarenga et al., 2011). Huijbregts et al. (2008) compared the EF of products using the endpoint LCIA methodology called Eco-indicator 99 (EI) and found that the EF-EI ratio was relatively constant among most of the product groups, even though it can significantly vary for certain product categories (such as products with a high mineral consumption). Alvarenga et al. (2011) compared the EF and CML2001 methodology using a case study of broiler feed production in Brazil and concluded that the EF is not suitable for the agricultural sector because some of the important environmental impacts of this sector could be neglected. In the present study, we also found that the ranking of specific products, including from the agricultural sector, can change by selecting a biodiversity footprint.

3.3 Uncertainties

The BFs and EFs are not without uncertainty. For the BFs, the mean species abundance served as a proxy for the biodiversity indicator and does not fully cover all of the aspects of biodiversity (Alkemade et al., 2009; Chapin III et al., 2000; Pereira et al., 2010). Species abundance does not give an indication of, for example, the completeness and rarity of species and may not reflect the threat to biodiversity because a specific land use may favour some species more than others. The same shortcomings are true for the current methods in life cycle assessment that address the impacts of land use on the level of species richness (Lindeijer, 2000; Schmidt, 2008; Koellner and Scholz, 2008). Curran et al. (2011) recently reviewed the current biodiversity indicators applied in life cycle assessment (LCA) and concluded that the functional and structural attributes of biodiversity are largely neglected. Additional indicators, such as the changes in habitat quality, are required to obtain a more complete picture of land use impacts.

Furthermore, direct land use and CO_2 emissions are associated with impacts on biodiversity that have a significantly different time perspective (Lenzen et al., 2007b). Direct land use, such as forestry and agriculture, rather than climate changes, has been the most influential driver for biodiversity loss to date (Millennium Ecosystem Assessment, 2005). However, the relative importance of the different drivers can change over time. Ecosystems may recover or be restored after land has been abandoned, whereas the CO_2 emissions will remain in the atmosphere for many centuries (IPCC, 2001). This implies that the choice of a shorter or longer time horizon can greatly influence the results.

Concerning the EFs, the land requirements by the CO_2 emissions are particularly debatable. Currently, the fossil energy land requirements are derived by calculating the area of forest that would be required to sequester the CO_2 emissions. However, forests are not the only solution for the sequestration of CO_2 emissions, and other terrestrial ecosystems, such as grassland, could play important roles. The potential of grasslands to sequester atmospheric CO_2 emissions has been discussed in previous studies (Frank et al., 2000; Walsh et al., 2010).

4. Conclusion

We found that the impacts caused by direct land use are relatively more important in the calculation of biodiversity footprints than ecological footprints. This difference is particularly relevant if the environmental impact of bio-based products, which are dominated by direct land use, is compared with the environmental impact of fossil-based products, which are dominated by CO_2 emissions. Furthermore, the relative importance of the different drivers can change in the biodiversity footprint, depending on the time horizon chosen: for an infinite time horizon, the CO_2 emissions become more prominent in the biodiversity footprint calculations. Our study has taken a further step in the direction of incorporating the impacts on biodiversity, as based on relative mean species abundance, in the footprint calculations. As the biodiversity footprints can differ from the ecological footprints, it is preferable to address the impacts on both bioproductivity and biodiversity in footprint calculations.

Acknowledgements

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Chapter 4

Characterization factors for thermal pollution in freshwater aquatic environments

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Abstract

To date the impact of thermal emissions has not been addressed in Life Cycle Assessment despite the narrow thermal tolerance of most aquatic species. A method to derive characterization factors for the impact of cooling water discharges on aquatic ecosystems was developed which uses space and time explicit integration of fate and effects of water temperature changes. The fate factor is calculated with a 1-dimensional steady-state model and reflects the residence time of heat emissions in the river. The effect factor specifies the loss of species diversity per unit of temperature increase and is based on a species sensitivity distribution of temperature tolerance intervals for various aquatic species. As an example, time explicit characterization factors were calculated for the cooling water discharge of a nuclear power plant in Switzerland, quantifying the impact on aquatic ecosystems of the rivers Aare and Rhine. The relative importance of the impact of these cooling water discharges was compared with other impacts in life cycle assessment. We found that thermal emissions of once-through cooling systems can significantly contribute to freshwater ecosystem quality.

Keywords: cooling water; thermal pollution; life cycle assessment; aquatic ecosystems

1. Introduction

Warming of water bodies caused by thermal discharges, such as cooling water releases from nuclear power plants and industrial facilities (De Vries et al., 2008; Caissie, 2006), can significantly influence aquatic environments and their biota. The thermal regime of a water body is a crucial factor for ecosystem quality (Caissie, 2006) because of the limited temperature tolerance of most aquatic animal species (Coutant, 1999). Aquatic flora can tolerate higher temperatures (e.g.,Anderson, 1969; Langford, 1990). Water temperature is a very important factor for the survival of freshwater organisms (Varley, 1967), influencing all biochemical and physiological activities (Beitinger et al., 2000). Effects of warmer temperatures on aquatic species cover a wide range of direct and indirect effects that range from minor importance to lethal effects. Direct effects encompass among others increased activity with faster digestion and hence increased food demand and disturbed reproduction (Sandström et al., 1997). At lethal temperatures, death occurs mostly due to a break-down of sensitive nervous system tissue (Brett, 1956). Indirect effects are related to altered food availability and pathogen prevalences, chemical processes (modified oxygen content, increased effects of some pollutants) and competition with other, more adapted species (Fischnetz, 2004). The impacts of thermal emissions have been studied in an artificial basin of a nuclear power plant in Sweden, where fish were exposed to temperature increases for more than 10 years. Several disorders in fish were documented, including oocyte degeneration in about 50% of the females (Luksiene and Sandström, 1994). Apart from thermal emissions, aquatic ecosystems face a variety of threats such as the impacts of chemicals or radioactive substances released from nuclear facilities (Garnier-Laplace et al., 2009) which should also be considered in environmental assessments.

In Life Cycle Assessment (LCA) studies (ISO, 2006) potential adverse effects on aquatic species due to thermal pollution have not been addressed so far. Neither suitable inventory schemes nor impact assessment methods have been proposed. In life cycle impact assessment (LCIA) environmental interventions such as chemical and physical emissions are assessed with characterization factors which express the emissions' fate (reflecting the environmental residence time) and effect in the environment and quantify the potential environmental damages, for instance to ecosystems and biodiversity (ISO, 2006). The focus in LCA is always on marginal changes of the environmental interventions. Also, LCA tries to capture the overall contribution of the potential impacts to the background situation, even relatively small impacts that diminish with increasing distance from the source, without excluding impacts *a priori* by declaring them not relevant.

In order to overcome the methodological limitations in assessing thermal discharges in LCA, the aim of this study is to develop and apply a fate and effect model which calculates characterization factors for quantifying the potential disappearance of freshwater aquatic species due to thermal discharges. The included effects are solely related to a change in river temperature. We derive characterization factors at the level of disappearance of species to allow comparisons with other stressors in the aquatic environment. In this study we focus on thermal pollution from nuclear power production to illustrate the application of the methodological framework.

2. Methods

2.1 Cooling water discharges in the life cycle inventory (LCI)

Cooling water emissions are generally reported as cooling demand (MW (Bund Freunde der Erde, 2010; ICPR, 2006), $MWh \cdot a^{-1}$ (Bund Freunde der Erde, 2010), $MJ \cdot s^{-1}$ (ICPR, 2006), and cooling water volumes (in $m^3 \cdot MWh^{-1}$) (EPRI, 2002), $m^3 \cdot s^{-1}$ (Kernkraftwerk Gösgen, 2000). Information on the absolute temperature of the discharge is generally scarce. However, in present LCI merely cooling water volumes are reported and no indication on cooling systems and cooling demand is given. Describing cooling water (cw) discharges as point sources in terms of total heat energy embodied (MJ_{cw}) and volume discharged ($m^3 \cdot s_{cw}^{-1}$) is sufficient. The environmentally relevant surplus temperature released ($°C_{cw}$) which describes the temperature difference between the cooling water discharge and the ambient river temperature can be calculated from these inventory parameters using the heat capacity of water.

2.2 Characterization factor (CF)

Following the classical LCIA characterization scheme (Pennington et al., 2004), we calculated the CF for the assessment of thermal pollution, using a fate and effect factor (Equation 1).

$$CF_{cumulative,t} = \sum_j CF_{j,t} = \sum_j FF_{j,t} \cdot EF_{j,t} \tag{1}$$

where $FF_{j,t}$ is the fate factor ($days \cdot m^3_{river} \cdot °C_{river}/(°C_{cw} \cdot m^3_{cw})$) and $EF_{j,t}$ the effect factor ($PDF \cdot °C_{river}^{-1}$) for river section j in time period t. PDF stands for potentially disappeared fraction of species. The inclusion of different time periods (e.g., months) reflects the variability in environmental conditions throughout the year. The CF, given in $PDF \cdot days \cdot m^3_{river}/(°C_{cw} \cdot m^3_{cw})$, was calculated for each river section by multiplying the corresponding FF and EF. The partial CFs were summed along the distance to arrive at a total, cumulative CF. Combining the CF with the inventory parameters, i.e. the set of the amount of cooling water (m^3) and (calculated) surplus temperature above the natural water temperature ($°C_{cw}$) returns Ecosystem Quality damage scores in the unit $PDF \cdot day \cdot m^3_{river.}$ These are directly comparable with other life cycle impact categories (e.g. ecotoxicity) that address potential impacts on biodiversity.

2.3 Fate factor (FF)

The FF (Equation 2) describes the change in ambient river temperature accumulated over the volume of the river ($°C_{river} \cdot m^3_{river}$) due to a change in thermal discharges ($°C_{cw} \cdot m^3_{cw} \cdot day^{-1}$).

$$FF_{j,t} = \frac{\Delta T_{ex,j,t}}{\Delta T_{cw} \cdot Q_{cw}} \cdot V_{j,t} \tag{2}$$

where $\Delta T_{ex,j,t}$ ($°C_{river}$) is the residual river water excess temperature in river section j in time period t caused by thermal discharges, ΔT_{cw} ($°C_{cw}$) is the temperature difference of the cooling water discharge to the ambient water temperature, and Q_{cw} ($m^3_{cw} \cdot day^{-1}$) is the daily cooling water discharge from e.g. a power plant. Because of the changing river parameters, partial FFs for each river section were calculated. Associated river section volumes $V_{j,t}$ (m^3_{river}) were derived from the water depth (m), the length (m) and width (m) of river section j in time period t. These partial FFs were summed up to result in the cumulative FF with the unit ($day \cdot m^3_{river} \cdot °C_{river}/(°C_{cw} \cdot m^3_{cw})$).

For the calculation of the FF the model QUAL2Kw (version 5.1) was applied (Pelletier et al., 2006). Details and model description for QUAL2Kw can be found in the Supporting Information (SI, section 1). QUAL2Kw is a one-dimensional model that assumes vertically and laterally well-mixed conditions. It calculates steady-state hydraulics (Pelletier and Chapra, 2008) and spatially explicit river temperature profiles for every river section. Edinger et al. (2007) recommend considering five components of heat exchange across the air-water interface: shortwave solar radiation, longwave atmospheric radiation, back long wave radiation from the water, evaporative heat loss, and heat conduction and convection between air, water and sediment. QUAL2Kw accounts for these components of surface heat exchange (Edinger et al., 2007; Chapra, 1997). Applications of QUAL2Kw for water temperature modeling can be found for various regions in the world (e.g. Kannel et al., 2007; Pelletier and Bilhimer, 2004). In this study, QUAL2Kw simulations were performed for every month of the year to account for seasonal differences in ambient river temperature and flow volumes that influence the fate and effect factor values. Simulations were conducted twice for each month, comparing the natural situation (run 1) with river conditions affected by cooling water discharges (run 2) in order to derive residual excess river temperatures of the discharged heat amount.

2.4 Effect factor (EF)

The EF reflects the change in the potentially disappeared fraction (PDF) of aquatic species for direct temperature-induced mortality due to a change in ambient temperature (°C_{river}) for each river section. The EF (PDF·°C_{river}^{-1}) was calculated by means of a species sensitivity distribution (SSD) following a normal temperature-response function (Equation 3):

$$EF_{j,t} = \frac{\partial PDF_{j,t}}{\partial T_{h,j,t}} = \frac{-\mu_a}{\sigma_{TTI} \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{1}{2}\left(\frac{-\mu_{TTI,j,t}}{\sigma_{TTI}}\right)^2\right) \tag{3}$$

where $\mu_{TTI,j,t}$ (°C) is the average of the temperature tolerance interval (TTI) of a set of aquatic species in water body *j* at time period *t*, incorporating the ambient river water temperature (T_a (°C). σ_{TTI} (°C) is the constant standard deviation and μ_a is the mean regression parameter based on laboratory experiments. The calculation of the average TTI was based on the ambient river water temperature of each river section as simulated by QUAL2Kw and temperature-induced mortality information of 36 aquatic species, including fish, molluscs, meduzosa, crustacean and annelida from temperate regions (De Vries et al., 2008). The TTI of a species describes the range by which the temperature can increase above the ambient river temperature without killing more than 50% of the population. Via the TTI a potentially affected fraction of species (PAF) can be calculated (De Vries et al., 2008). In LCIA the PAF based on acute data is commonly set equal to the PDF in order to arrive at just one damage unit in the damage category Ecosystem Quality. As derived from De Vries et al. (2008) and shown in the SI, $\mu_{TTI,j,t}$ is equal to -0.9·T_a + 27°C for species that occur in temperate climate conditions. The corresponding standard deviation is set to 4.6 °C. A detailed description of the EF derivation can be found in the SI (part 3).

2.5 Application

Characterization factors were derived for cooling water discharges from the nuclear power plant Muehleberg (NPPM) in Switzerland for the rivers Aare and Rhine. The plant operates a boiling water reactor (BWR) with a once-through cooling water system (BKW, 2006). The rivers were assumed to have the shape of a rectangular canal and were subdivided into distinct sections. The first 1km river stretch was subdivided into a first section of 500 m length and five subsequent sections with a length of 100 m each. These finer subsections were applied to observe the progression of the excess temperature on a finer scale during the first kilometer, which is mainly influenced by mixing. For reasons of feasibility, the subsequent river sections covering the distance until the North Sea were set at a length of 10 km each. A mean cooling water amount of 11.6 $m^3 \cdot s^{-1}$ (BKW, 2009) and a mean released surplus temperature of 15°C (EAWAG, 1997) were used as average thermal discharge throughout the year. We simulated the thermal plume propagation for the 1320 km of river length downstream of the NPPM until the estuary mouth of the North Sea. Important tributaries were included using long-term mean monthly flows and mean monthly temperatures (SI, part 2). The nuclear power plant's (NPP) heat input was considered as a point source in QUAL2Kw. Detailed descriptions of the modeling procedures, assumptions made, estimated parameters, applied data and their sources are given in the SI (part2).

The FF was calculated as volume-accumulated temperature change along the river using the river excess temperature results from QUAL2Kw. With the modeled ambient river temperatures and the parameters $\mu_{TTI,j,t}$ and $\sigma_{TTI,j,t}$ (SI, part 3) the EF was calculated for each river section. The cumulative CF was computed by multiplying FF and EF in each section and summing the results along the distance. In order to obtain annually representative CF values two different approaches were used: computing arithmetic annual averages from the monthly CFs and annual averages based on the monthly electricity production of the NPPM (see SI).

2.6 Sensitivity analysis

The sensitivities of the CF towards changes in river width, river flow, ambient river temperature, wind speed, Manning coefficient, bottom slope, air temperature, cloud cover, and shade were evaluated for the months August and December (see SI, part 5) by calculating the percentage difference (Table 1) between results with changed parameters and the original results. Thereby, every parameter was changed by a variation factor reflecting approximately realistic cases (further explanations in SI, part 5). Sensitivities of CF are evaluated by the influence of varied parameters determining (i) FF only, (ii) EF only and (iii) both EF and FF. Sensitivities towards changes in released heat from the cooling system were tested with 10% variation in heat release and compared to the original results. Modified heat releases result either in a change in cooling water volume with the released surplus temperature remaining at 15°C or in an altered released surplus temperature with the cooling water volume remaining at 11.6 m^3/s. Sensitivities towards released heat were tested for CF with adapted FF only. For the calculation of the EF only the ambient river temperature is relevant, not the released surplus temperature.

2.7 Relevance analysis

To assess the environmental relevance of cooling water releases we compared such releases with the emissions and resource use of two NPPs over their life cycles. One NPP operates a once-through cooling system (represented by the Muehleberg NPP) and the other (hypothetical) NPP a cooling tower. Once-through cooling systems discharge a cooling water volume which is approximately 30 times larger than systems with a cooling tower. We assumed that both NPPs operate a BWR reactor and are placed at the same location. We evaluated and compared the overall environmental impact of the production of 1 kWh of electricity with the ReCiPe methodology (Goedkoop et al., 2009). This assessment method represents an LCIA method determining the damages to three areas of protection, namely Human Health, Resources and Ecosystem Quality. The Ecosystem Quality (EQ) damage incorporates impacts on soil, freshwater and marine ecosystems. The impact of thermal emissions is added to the freshwater ecosystem damage and thus to the overall EQ damage. We used the hierarchist perspective of ReCiPe for damage calculation and normalizing and the default weighting set of Eco-Indicator 99 (Goedkoop and Spriensma, 1999) for calculating the final single-score impacts in Eco-Points. For assessment assumptions and application of the ReCiPe methodology see SI (part 6).

3. Results

3.1 Fate factor

FFs were individually calculated for every river section and summed up along the distance (Figure 1A). They are highest in winter and lowest in summer, varying between 10.7 and 5.0 $day \cdot m^3_{river} \cdot °C_{river}/(°C_{cw} \cdot m^3_{cw})$. For all months the simulated river excess temperature decreases over the distance, resulting in a smaller partial FF with increasing distance. Changes of the FF are larger over distance than between individual months. At the river mouth the cumulative FF varies with seasonality within a factor of two. The main process responsible for the decrease of the excess temperature is dilution (see SI). The dissipated excess temperature varies between 54% (January) and 99% (July).

3.2 Effect factor

The EF is strongly dependent on the river water temperature. The higher the ambient water temperature, the higher the EF in the respective river section will be. Therefore, if the ambient river temperature increases due to additional thermal releases of other power plants along the same river, the simulated water temperatures will be higher and thus the EF for the considered power plant will increase as well. The highest EF at the river mouth for the month of July was found to be five orders of magnitude higher than the lowest EF value for January (Figure 1B and SI). River temperature also rises with the distance due to the natural temperature increase from mountainous regions to the sea. This causes the EF to increase in river sections further downstream. Changes of the EF between the months and over the distance are large. Changes within a certain month over the entire river distance indicate the same order of magnitude as changes between the seasons. The highest effect factor of $4.2 \cdot 10^{-2}$ $PDF \cdot °C_{river}^{-1}$ at the river mouth in the month of July implies that 4.2% of species will be lost per degree Celsius temperature increase. The contribution of the hottest months July and August to the production-averaged CF is 42% and 14%, respectively (Figure S11, SI). However, all months from June to September contribute more than 10% each. This shows that not only the hottest months (i.e. July and August) should be considered since other months contribute substantially to the CF as well.

3.3 Characterization factor

Cumulative CFs were computed from partial FFs and corresponding EFs (Figure 1C). Summer months show the highest CFs. Averaging the CF over the year in each river section leads to a cumulative CF of $1.5 \cdot 10^{-2}$ PDF·day·m^3/°C·m^3. Taking into consideration the electricity production cycle of the NPPM results in a lower cumulative CF of $1.1 \cdot 10^{-2}$ PDF·day·m^3/°C·m^3. This difference is due to the larger electricity share produced in the winter months and a shutdown of the plant in August for inspections.

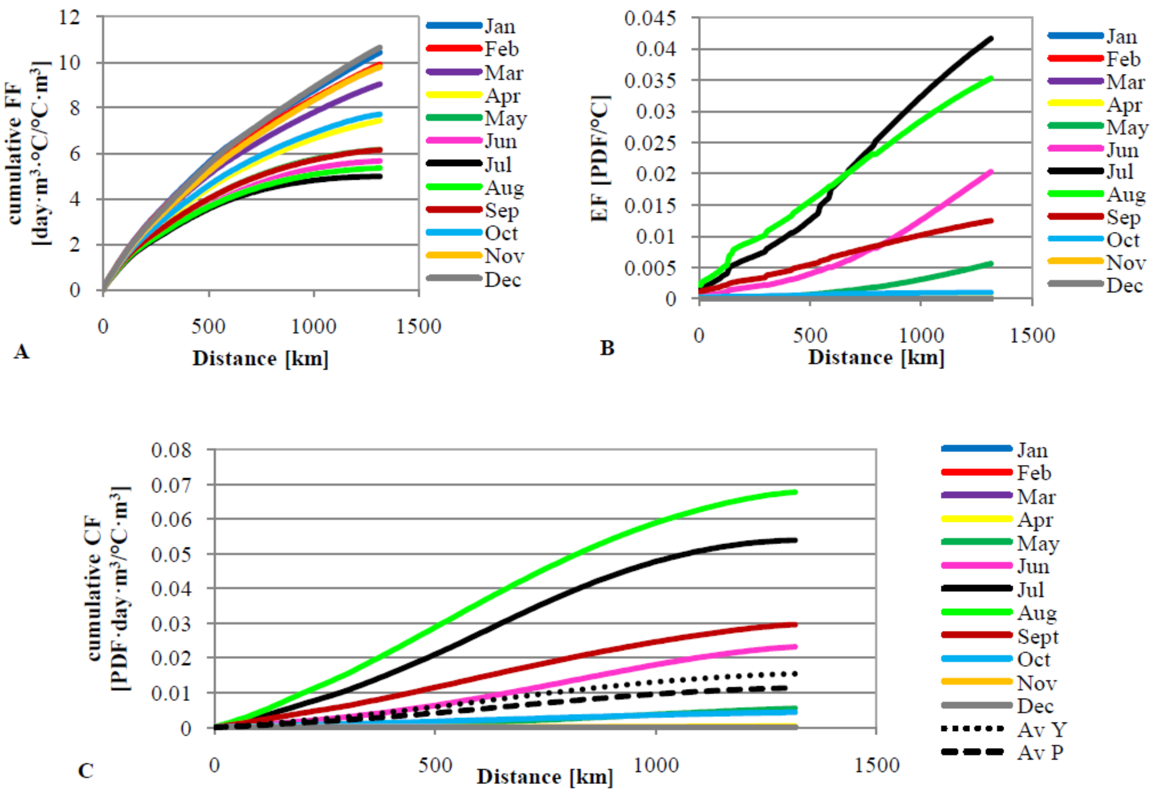

Figure 1: Results for the cumulative FF (A), the non-cumulative, specific EF per river section (B) and the cumulative CF (C) for the river distance from the NPPM until the North Sea. All results are calculated and shown on a monthly basis. In (C) "Av Y" is the arithmetic mean over all 12 months, while "Av P" symbolizes the average CF that is weighted by the monthly electricity production of the NPPM.

3.4 Sensitivity analysis

The most sensitive river parameter for the CF is by far the ambient water temperature, followed by the Manning coefficient and the river width (Table 1). These parameters reflect the most sensitive parameters of the CF's constituents EF and FF as shown in the cases with only one of them being changed. The CF calculated with adapted EF only is sensitive to parameters influencing heat exchange and dilution, such as river temperature and shade, with the river temperature being the most influential factor. Bottom slope and Manning coefficient have no influence if only the EF is adapted. If only the FF is varied the Manning coefficient, width and river flow lead to rather sensitive changes in CF. The sensitivities of the CF towards heat release are in most river sections below 1.5% for both analysis approaches, but the adaptation of the released surplus temperature shows higher influence than the adaptation of the cooling water volume (SI part 5 and Table 1). Table 1 shows that the season has an influence on the sensitivity as well.

Table 1: Mean sensitivities of the CF at the North Sea towards changes in river parameters and changes in cooling water heat release for August and December. "FF" denotes varied FF only, "EF" varied EF only and "FF+EF" pinpoints that both FF and EF were varied for calculating the CF. "Volume adjusted" denotes the values calculated with the adjusted thermal discharge volume and "Temperature adjusted" represents results for adjusted released excess temperature of the heat release.

River parameter (±change)	**Sensitivity result [%]**					
	August			**December**		
	FF	**EF**	**FF+EF**	**FF**	**EF**	**FF+EF**
Water temperature (30%)	18	148	167	1	194	199
Manning value (+70%/-50%)	30	0	30	43	0	43
Width (40%)	48	20	28	5	15	16
River flow (35%)	37	19	21	4	14	15
Wind (100%)	15	31	43	15	45	56
Bottom slope (40%)	8	0	8	12	0	12
Air temperarature (80%)	31	33	9	1	0	1
Cloud cover (100%)	75	55	34	5	29	25
Shade (10%)	11	11	2	1	5	5
Heat release: Volume adjusted (10%)	0	-	0	0	-	0
Heat release:Temperature adjusted (10%)	10	-	10	13	-	13

3.5 Relevance analysis

The difference in total environmental impact between power generation with once-through cooling systems and cooling towers is rather small (Figure 2). Thermal emissions from a cooling tower constitute 0.4%, while a once-through cooling system is 0.01% of the total environmental impact. For freshwater ecosystem quality, thermal emissions contribute 49% of the whole freshwater impact in the case of a once-through cooling system (for details, see SI part 6).

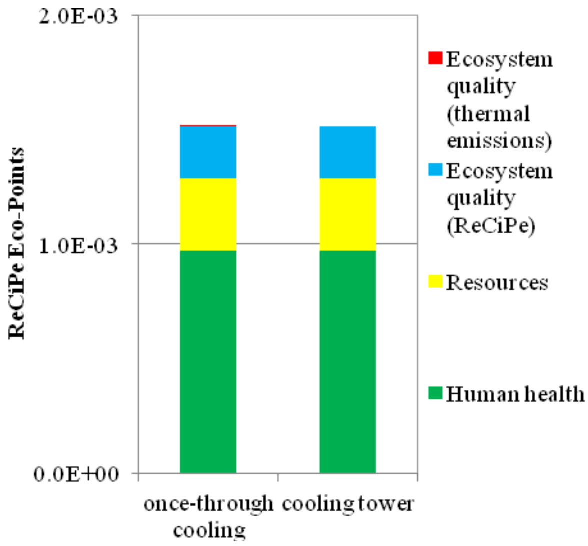

Figure 2: Total damage (expressed in ReCiPe Eco-points) of 1 kWh of nuclear electricity generated in BWRs with a once-through cooling system and alternatively with a cooling tower. The results are divided into the three different areas of protection (Human Health, Resources and Ecosystem Quality). Impacts caused by thermal emissions, which add to ecosystem quality damage, are displayed separately.

4. Discussion

4.1 Fate factor

The simulation of the FF is based on a simplified river system implemented in the QUAL2Kw model. The initial river sections have a length of 500m (first section) and 100m (subsequent five sections), which is considered appropriate to account for the rapid and most important initial changes in river excess temperature. The choice of longer subsequent river sections of 10km reflects a compromise between reasonable computation times and sufficient detail to arrive at representative CFs over long river distances. In terms of geometry, the rivers are assumed to be rectangular channels as is the case for many rivers in Europe, the US and other industrialized countries (Surian, 2008). Also the rivers Aare and Rhine are (partly) corrected and embanked over a considerable distance (e.g., ICPR, 2001). River widths were derived from various satellite pictures (SI, part 2) and assumed to be constant throughout the year. Since the assumption of a rectangular channel shape holds, it can be expected that the widths remain approximately the same over certain fluctuations of the water level.

In the QUAL2Kw simulation the whole river sections are impacted by the cooling water discharge. Discharged cooling water is relatively rapidly mixed within the first kilometer after release and diluted over the whole river width. An additional simulation with the mixing zone model CORMIX, which is specifically valid for near-field simulations (Doneker and Jirka, 2007) confirmed this observation. Mixing over the total river depth is reported to be even faster (e.g., Frey et al. 2003). Therefore, we consider the assumption of complete mixing in each river section as acceptable in our research context.

Model parameters such as wind speed, Manning roughness coefficient, shading, air temperature and bottom slope are assumed to be constant throughout the whole distance and sometimes invariable between months and thus introduce some uncertainty because they influence the temperature simulation outcomes. In contrast, constant parameters chosen to model the sediment-water heat transfer are insignificant because the hyporheic exchange is small.

4.2 Effect factor

An important component of the EF calculation is seasonality. The EF depends strongly on the varying river water temperatures, which is the most sensitive parameter of the whole model (Table 1) because the average TTI decreases with increasing temperature. Simulated natural river water temperatures are compared with measured values from refs. (FOEN, 2010; ICPR, 2010). This evaluation has shown a satisfactory match for most river stretches with a typical root mean squared error of 1.0 °C (see SI). QUAL2Kw overestimates, however, the EFs for the Rhine Delta, particularly during the summer, since mixing with seawater during tides has not been accounted for. Nevertheless, we expect only limited influence of this overestimation, as 95% of the total CFs are reached in every month before Maassluis in the Delta (see SI).

The application of a Species Sensitivity Distribution (SSD) for temperature effects implies considerable uncertainty. The dataset of De Vries et al. (2008) contained 36 species which occur in temperate regions, mainly consisting of fish and mollusc species. This subset of the complete sample of 50 species was chosen since De Vries et al. (2008) indicated a significant difference in sensitivity between fish from (sub)tropical and temperate regions. For further improvement, additional data on freshwater species from different taxonomic groups are required. De Vries et al. (2008) also indicated that a subgroup of mainly salmonids are more sensitive to thermal effects than the normal distribution would predict. This suggests the need for a region-specific approach for the LCIA of a thermal discharge if specifically sensitive species are present in the water body of concern. This is relevant since many cold and cool water species e.g. in alpine regions are more vulnerable towards temperature increases than warm water species living in habitats closer to the river mouth (Eaton and Scheller, 1996). Another shortcoming of the SSD applied is that it contains species that are not indigenous to the river Rhine. Also the data does not include different life phases of the species such as egg development and growth. Finally, the SSD does not consider that a change in temperature may be favorable to some species, resulting in indirect changes in species composition. However, it is common practice to exclude such favorable effects to certain species as these can be considered as "invasive" and hence potentially harmful in the long term for the ecosystem.

4.3 Characterization factor

The explicit integration over time and space is a relatively new approach in LCIA, that has e.g., also been applied in Struijs et al. (2010). Including the temporal dimension demonstrates a considerable variability over the year in the CF. If average annual temperature and flow values were taken for the calculation, the resulting factors would be smaller, underestimating effects in the warmest months, which are particularly crucial for the survival of aquatic species. Averaging the CF over the year using an electricity-production based break-down is recommended as heat releases are most probably not equally distributed throughout the year, as is the case for all NPPs in Switzerland (Swissnuclear, 2010) (see SI, part 6). Changes in released heat have little effect on the CF, with changes in released excess temperature generally leading to higher sensitivity values compared to altered cooling water volumes. We conclude that, on aggregate, no large sensitivities are recorded except for changes in ambient water temperatures, showing that the chosen parameters lead to robust results.

4.4 Relevance

Although the relative contribution of thermal emissions is small, the thermal emissions of once-through cooling systems can still significantly contribute to freshwater ecosystem quality in a life cycle context. The dominant contribution of thermal emissions to ecosystem quality damages is due to the absence of other significant emissions to freshwater ecosystems. The impact of nuclide emissions to freshwater ecosystems, for example, has not been assessed as it is not included in the ReCiPe methodology.

4.5 Practical implications

The relevance analysis of the derived factors shows that depending on the implemented cooling system, cooling water emissions can be relevant. Therefore, the inventory should indicate which cooling system is operated in the respective facilities. We further propose to report the cooling water intervention with monthly resolution specifying heat energy and water volume discharged. These data are known to industries and could therefore potentially be collected from the respective industries and literature. With these inventory parameters, the unit of the CF can also be given as ($days \cdot m^3_{river} \cdot °C_{river}/MJ_{cw}$), whereby conversion between the two options is achieved with a factor of 4.2 $MJ \cdot day/(°C \cdot m^3 \cdot day)$, reflecting the heat capacity of water. Also, the plant's geographic location shall be determined to facilitate the estimation of the absolute river water temperature in the life-cycle impact assessment stage. The location of a power plant can indeed be relevant since the ambient water temperature increases over distance not only due to natural processes but also due to the discharged cooling water of other power plants. In our case this was not relevant since upstream of Mühleberg there are no similarly large discharges of cooling water. However, the allocation of the cumulative heat impact to different power plants along one river is subject to further research.

Even though it is very difficult to derive an "average" river from the numerous rivers that exist within a region due to hydraulic and hydrologic differences, river systems should be generalized for different climatic zones and regions as the hydraulic and temperature regime of rivers in different climates vary. This minimizes the efforts needed for data collection and facilitates the calculation of EFs, FFs and CFs and the modeling of river water temperatures. For generalizing, it is important to collect data for the ambient water temperature and the river flow over time and space, as well as the distance to the sea. Other parameters such as Manning roughness coefficients and river widths can be taken from literature. The most important parameter is the ambient water temperature, which was determined as the most sensitive parameter. Due to seasonality, a temporal resolution such as a monthly disaggregation is required in order to account for the different magnitudes of impact. Water temperature data for rivers are often available from measuring stations. As the sensitivities of the above discussed parameters are rather small for the CF, with the exception of the ambient river temperature, further efforts on reducing these uncertainties might be of secondary importance compared to the need for generalizing the model and improving the robustness of the EF. For the EF, an adaptation of the species choice, based on the susceptibility of species in different climatic zones, should be established, in order to derive zone-specific CFs. We have shown that thermal emissions are indeed relevant, especially for a once-through cooling system, since the cooling water emissions are a major environmental impact on freshwater aquatic ecosystems. With the newly developed methodology we have provided a basis for further development to close an important methodological gap in LCA.

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Supporting Information

1. Model Description of QUAL2Kw water quality model

The one-dimensional QUAL2Kw model is an Excel-based model for the modeling of river and stream water quality (Pelletier et al., 2006; Washington State Department of Ecology, 2010). It calculates steady-state hydraulics and assumes vertically and laterally well-mixed conditions. Temperature and heat budget are calculated based on water temperatures in the river and tributaries and the meteorological conditions. In the following sections a short summary of the relevant processes and equations is given, based on (Pelletier and Chapra, 2008). The model is described in detail here to facilitate a good understanding of the fate modeling and the underlying processes and assumptions taken. Where no individual assumptions were taken, recommended values from the QUAL2Kw model itself have been applied.

1.1 Hydraulics

The river is segmented into length intervals with uniform hydraulic properties, such as e.g., width or channel slope. As shown in Figure S1 both point and non-point sources and withdrawals can be positioned anywhere along the river. Tributaries can be designed as point sources. Figure S1 shows the numbering of the different segments, also denoted as "reaches". Note that in the main manuscript of this publication and in the following sections of the Supporting Information, we chose to name the river segment "sections" in order to facilitate better understanding.

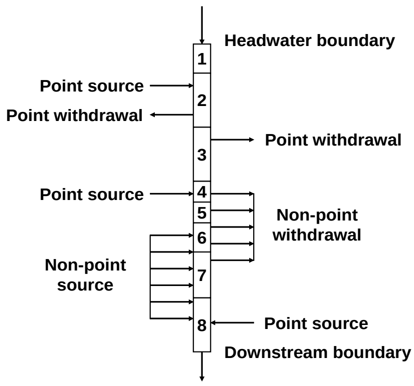


Figure S1: Segmentation of a river with non-point/point sources and withdrawals along the entire river. In every section the hydraulic properties are assumed uniform (Pelletier and Chapra, 2008).

Flow balance

For each section a steady state flow balance is computed:

$$Q_i = Q_{i-1} + Q_{in,i} - Q_{out,i} \tag{S1}$$

where Q_i is the flow from element i to the downstream element i+1, Q_{i-1} is the inflow from the upper section and $Q_{in,i}$ and $Q_{out,i}$ are the in- and outflows into section i from point and non-point sources and withdrawals, respectively.

Hydraulic characteristics

With the specified and calculated amount of water in each section, depth and flow velocity are calculated with the Manning equation. The Manning roughness coefficient, the channel slope, the channel bottom width were determined for this purpose (SI, part 2).
The channel shape is assumed to be a trapezoid (Figure S2) in Manning's equation (Equation S2)

$$\mathbf{Q} = \frac{\mathbf{S_0^{\frac{1}{2}}}}{\mathbf{n}} \frac{\mathbf{A_c^{\frac{5}{3}}}}{\mathbf{P^{\frac{2}{3}}}} \tag{S2}$$

where Q is the river flow [m^3/s], S_0 is the channel slope [m/m], n denotes the Manning roughness coefficient [s/$m^{1/3}$] , A_c stands for the area of the river cross-section [m^2] and P for the wetted perimeter [m].

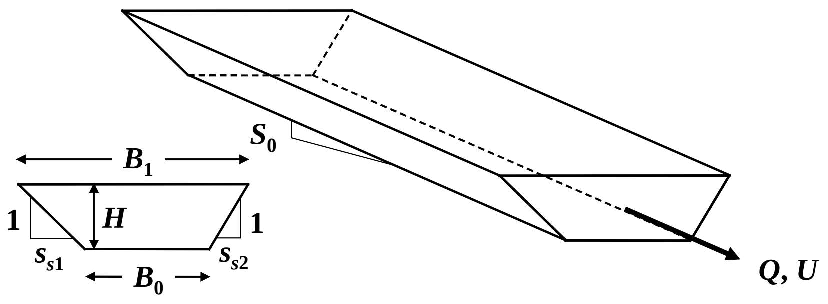


Figure S2: Trapezoidal channel (Pelletier and Chapra, 2008).

The area of the cross section A_c is calculated with Equation S3.

$$A_c = B_0 + 0.5(s_{s1} + s_{s2})HH \tag{S3}$$

where B_0 is the bottom width [m] and s_{s1} and s_{s2} are the side slopes [m/m], respectively, as depicted in Figure S2. H is the flow depth [m] of the specific section.
The wetted perimeter P is calculated according to Equation S4:

$$P = B_0 + H\sqrt{s_{s1}^2 + 1} + H\sqrt{s_{s2}^2 + 1} \tag{S4}$$

It is assumed here that the channel form of the river is a rectangle, which means that both side slopes have a value of zero. This assumption was taken because the river depth is not known, but would be required for calculating side slopes. Accordingly, bottom width B_0 and top width B_1 are equal, as depicted in Figure S2. The flow depth H can be calculated from Equation S5 by inserting Equation S3 and Equation S4.

$$H_k = \frac{(Q \cdot n)^{\frac{3}{5}} \left(B_0 + H_{k-1}\sqrt{s_{s1}^2 + 1} + H_{k-1}\sqrt{s_{s2}^2 + 1} \right)^{\frac{2}{5}}}{S_0^{\frac{3}{10}} [B_0 + 0.5(s_{s1} + s_{s2})H_{k-1}]} \tag{S5}$$

Equation S5 can then be solved iteratively (with iteration index k) in order to get the water depth H in the respective section. The QUAL2Kw model terminates the iteration when the estimated error is smaller than 0.001%.

1.2 Temperature

The temperature model that is implemented in the QUAl2Kw model is applied to every section of the river (see Figure S). It takes into account heat transfers from adjacent elements, heat loads and withdrawals, as well as heat transfers to the atmosphere and the sediments.

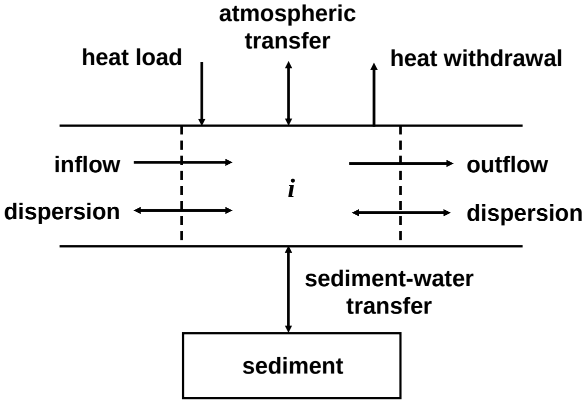


Figure S3: Heat balance for each individual river section i (Pelletier and Chapra, 2008).

The heat balance for section i is described in Equation S6:

$$\frac{dT_i}{dt} = \frac{Q_{i-1}}{V_i}T_{i-1} - \frac{Q_i}{V_i}T_i - \frac{Q_{ab,i}}{V_i}T_i + \frac{E'_{i-1}}{V_i}(T_{i-1} - T_i) + \frac{E'_i}{V_i}(T_{i+1} - T_i) + \frac{W_{h,i}}{\rho_w C_{pw} V_i}\left(\frac{m^3}{10^6 cm^3}\right) + \frac{J_{h,i}}{\rho_w C_{pw} H_i} \tag{S6}$$

where T_i is the temperature in section i [°C], t is the time , Q is the river flow [m^3/s], V_i is the volume of the section [m^3] and E' is the bulk dispersion coefficient between sections i-1 and i as well as i and i+1, respectively. $W_{h,i}$ denotes all net heat loads from point and non-point sources into section i [cal/d], while $J_{h,i}$ and $J_{s,i}$ symbolize the air-water heat flux [cal/(cm^2d)] and the sediment-water heat flux [cal/(cm^2d)], respectively. ρ_w stands for the density of water [g/cm^3] and C_{pw} is the specific heat of water [cal/(g°C)].

The surface heat flux consists of five components, namely the net solar short wave radiation at the water surface, the net atmospheric long wave radiation, the net long wave back radiation from water surface, conduction, convection, evaporation and condensation. The calculation of the net solar short wave radiation at the water surface includes a parameter called atmospheric attenuation which is computed via the Bras method (Bras, 1990). This method is used here since it is suggested as default method in the QUAl2Kw model (Chapra et al., 2006).

The atmospheric long wave radiation is calculated via the Stefan-Boltzmann law. To represent the effective emissivity the empirical method of Brunt (Brunt, 1932), a common method for water-quality modeling, has been applied.

To compute conduction and convection, the method after Brady, Graves and Geyer (Brady et al., 1969) has been chosen from the possible options in the QUAL2Kw model.

Since the heat balance (Equation S6) cannot be solved analytically a numerical method is needed. For the modeling purposes here the Euler's method was applied. This solution method is suggested as default method in the QUAL2Kw model because it is faster than the alternative fourth-order Runge-Kutta method while still attaining sufficiently accurate results (Pelletier and Chapra, 2008).

2 Fate modeling

2.1 Estimation and determination of QUAL2Kw model inputs for fate modeling

The fate modeling of the developed methodology encompasses the Aare/Rhine river system, starting from the location of the Muehleberg nuclear power plant (see Figure S4) which is the point source of heat discharge that is used for the case study. In order to calculate fate factors, the flow and temperature along these rivers have to be modeled and therefore various inputs and parameters are required for the QUAL2Kw model. These are described hereafter. The whole river distance to be modeled has to be segmented into sections. Different studies which applied the QUAL2Kw model used section lengths of 500 m to 1000 m (Turner et al., 2009; Kannel et al., 2007; Cristea and Burges, 2009; Pelletier et al., 2004; Carroll et al., 2006). However, in these surveys the modeled river lengths were significantly smaller (not longer than 100 km) than in our study. The model domain of the rivers Aare and Rhine as investigated in this study, includes a total length of over 1300 km. Therefore a considerably coarser resolution applying 10 km long sections is used. However, in the first kilometer one smaller section of 500 m and 5 sections with a length of 100 m are applied, since this is the distance with the fastest and largest change of temperature. Despite these overall long river sections the model still produces reasonable temperature results (SI, part 2.4).

In order to use the Manning equation for the computation of the river depth and flow velocity, channel slope, Manning's roughness coefficient and river widths have to be specified. In QUAL2Kw one measuring station is needed as starting point for the headwater of the river. The station used as headwater is the FOEN (Federal Office for the Environment) station in Bern, which is situated at 502 m altitude. The final elevation above the sea level at the North Sea is 0 m and the total flow distance is 1320 km (Aare from Muehleberg to the junction with the Rhine, Rhine from the junction to the North Sea). With this information a mean channel slope of 0.0004 has been calculated. It is assumed that this mean slope applies for all river sections. The Manning roughness coefficient n is estimated from Reichert et al. (2003) as indicated in Table S1. A Manning value of approximately 0.06 $s/m^{1/3}$ is applied to all river sections.

Table S1: Estimation of the Manning roughness coefficient according to Reichert et al. (2003). They define 6 categories which each comprise several levels of classifying the category parameters (e.g. small or large irregularities on the surface of the river bed). The classification levels chosen in this study with their associated partial Manning roughness coefficients are shown in columns two and three. Summation of the six values results in the total Manning roughness coefficient.

I **Categories**	II **Classification**	III **n [s/m$^{1/3}$]**
Surface properties of the river bed	Fine gravel	0.024
Irregularities on the surface of the river bed	small	0.005
Irregularities of the river cross-section	Once a in a while	0.005
Obstacles on the river bed	small	0.015
Vegetation growth	small	0.010
Effects of river meandering	small	0.000
TOTAL Manning roughness coefficient		0.059

The river width is a continuously changing feature of natural rivers. However, since long parts of the Rhine are channelized, we selected the same river widths from the entrance point of one tributary to the next tributary. Values for river widths were collected from Google Earth (2009) for all locations where the tributaries considered in the fate modeling join the Aare and the Rhine. The tributaries used are listed in Table S2. Generally, the Google Earth satellite pictures represent the river status in the month of March, however for varying years between 2003 and 2007. Along the Aare and Rhine there is one Google Earth satellite picture from July and two from May. Only one satellite picture at a time is available for a specific location along the Aare and Rhine and therefore, variations of the river widths between the months at a specific location cannot be determined.

Tributaries considered in the fate modeling are in general the larger tributaries. To account for several smaller but in the sum nonetheless substantial tributaries, the differences in river flow between two gauging stations has been used as the cumulated inflow volume of several smaller tributaries. For every tributary the location of entrance into the Rhine is known (Rhine-km). For an aggregation of several small tributaries the average Rhine-km value between their entering locations has been calculated. This procedure has been especially used for the tributaries located in Germany, since average monthly flow values were not available for every tributary. The measured river widths, as well as flow volume and water temperature for each tributary are displayed in Table S2Table S, Table S3 and Table S4.

Table S2: River width and the flow distance downstream from the Muehleberg nuclear power plant where the tributaries enter the rivers Rhine or Aare. The values in bold show an assumed entrance location of a group of smaller tributaries, where a mean value has been taken as km point between the grouped tributaries.

River/source	km entering Aare/ Rhine	Width [m][1)]
Aare (headwater), at Muehleberg	0	80
Saane	1.5	80
Bielersee outflow	16	80
Murg, Wigger, Dünnern	**102**	80
Reuss	132	130
Limmat	138	130
Rhine	151	100
Birs, Ergolz	**213**	150
Elz, Ill, Moder, Murg	**300**	220
Neckar	428	260
Main, Nahe, Lahn	**540**	300
Mosel	592	330
Wied, Sieg, Wupper, Erft	**675**	350
Ruhr, Emscher, Lippe	**797**	380

[1)]The river width is derived from Google Earth (2009).

Table S3: Mean monthly flow volume of the headwater (Aare) and all included tributaries until the North Sea.

River/source	River Flow [m³/s][1)]											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Aare (headwater)	60.2	61.2	69.4	108.0	178.0	221.0	213.0	191.0	134.0	86.4	75.6	65.4
Saane	43.7	48.6	56.0	68.0	74.0	72.7	54.9	48.5	45.3	42.8	48.0	42.6
Bielersee out	85.1	91.2	88.6	86.0	63.0	50.3	49.1	36.5	49.7	66.8	71.4	85.0
Murg, Wigger, Dünnern	47.8	54.0	58.1	59.5	52.2	48.3	41.2	36.8	36.9	37.5	43.1	47.7
Reuss	69.3	78.2	95.0	135.0	196.0	251.0	239.0	194.0	146.0	105.0	91.5	78.1
Limmat	73.3	80.5	83.3	101.0	134.0	155.0	140.0	116.0	98.3	78.8	76.7	78.4
Rhine	298.0	292.0	321.0	396.0	518.0	672.0	669.0	567.0	484.0	399.0	347.0	321.0
Birs, Ergolz	63.0	42.0	62.0	78.0	64.0	40.0	38.0	49.0	45.0	41.0	36.0	42.0
Elz, Ill, Moder, Murg	342.0	364.0	336.0	290.0	230.0	160.0	110.0	110.0	110.0	162.0	200.0	316.0
Neckar	160.0	190.0	190.0	150.0	90.0	110.0	140.0	110.0	100.0	100.0	150.0	130.0
Main, Nahe, Lahn	445.8	466.7	404.2	312.5	195.8	154.2	129.2	108.3	116.7	154.2	237.5	366.7
Mosel	624.2	653.3	565.8	437.5	274.2	215.8	180.8	151.7	163.3	215.8	332.5	513.3
Wied, Sieg, Wupper, Erft	120.0	120.0	110.0	100.0	60.0	50.0	60.0	50.0	50.0	60.0	80.0	100.0
Ruhr, Emscher, Lippe	260.0	260.0	240.0	220.0	140.0	120.0	130.0	120.0	120.0	120.0	150.0	220.0

[1)]Information on flow volumes stems from reference (FOEN, 2010) for Switzerland and from reference (DGJ, 2010) for Germany.

Table S4: Mean monthly water temperatures for the headwater (Aare) and all included tributaries until the North Sea. For the last two tributaries no mean monthly temperature values were available. Therefore it was assumed that they have the same temperature as the Mosel**.**

River/source	River water temperature [°C]											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**

Aare (headwater)[1]	5.2	5.1	6	7.7	10.9	13.9	16.3	17.2	15.5	12.9	9.4	6.6
Saane [1]	3.7	3.4	4.9	7.3	10.1	12.7	15	16	14.9	12.4	8.6	5.3
Bielersee outflow [1]	5.1	4.5	5.5	7.9	12.1	15.8	18.5	19.4	17.4	14.1	10.1	7
Murg, Wigger, Dünnern [1]	5.1	4.5	5.5	7.9	12.1	15.8	18.5	19.4	17.4	14.1	10.1	7
Reuss [1]	4.5	4.7	6.3	8.7	12.6	16.2	18.8	19.6	16.9	13.1	8.8	5.9
Limmat [1]	5	4.8	5.9	8.1	12.6	16.9	19.7	20.8	18.1	14.2	9.7	6.6
Rhine [1]	4.3	4.2	5.6	8.3	12.4	16.2	19	20.1	17.5	13.6	9.3	6
Birs, Ergolz [1]	5.1	5.1	6.7	9.2	13.1	16.6	19.2	20	17.5	13.9	9.6	6.5
Elz, Ill, Moder, Murg[2]	5	5	6	9	13	16	21	22	20	16	11	6
Neckar[2]	5	5	6	10	15	17	20	22	20	15	10	6
Main, Nahe, Lahn[3]	6.3	6.3	7	11	16	18	24.1	22	20	16	10	7
Mosel[4]	4.6	5.2	6.8	10.9	15.7	19.5	22.3	22	17.7	13.3	8.9	5.9
Wied, Sieg, Wupper, Erft	4.6	5.2	6.8	10.9	15.7	19.5	22.3	22	17.7	13.3	8.9	5.9
Ruhr, Emscher, Lippe	4.6	5.2	6.8	10.9	15.7	19.5	22.3	22	17.7	13.3	8.9	5.9

Information for water temperature stems from [1]reference (FOEN, 2010) for Switzerland and [2]reference (Kroner et al., 2004), [3]reference (Trockner et al., 2008) and [4]reference (ICPR, 2010) for Germany. When using reference (Trockner et al., 2008) assumptions on monthly values between some months have to be taken, since not all months have values available.

Further environmental parameters which were specified for the fate modeling can be found in Table S5 and Table S6. Cloud cover and shading of the river can also be indicated in QUAL2Kw. It was assumed that cloud cover and shade are both 0% which implies sunny conditions for the entire river length. Since both Aare and Rhine are large and relatively wide rivers it is safe to assume that shading overall will mostly only have a rather small effect on the heat balance of these rivers. The sensitivity to cloud cover is small. These assumptions are supported by the results of the sensitivity chapter (SI, part 0). For the heat transfer to the sediment, proposed default values from Pelletier et al. (2008) were used (see Table S6). As atmospheric turbidity factor, which is used for calculating the net solar shortwave radiation, a value of 2, i.e. a clear sky was assumed (no smog). Air temperature and dew point temperature vary over the year. It is assumed that the used values are also valid for Germany.

Table S5: Estimated environmental parameters for QUAL2Kw.

Parameter	Value
Wind speed [1]	3 m/s
Atmospheric turbidity[2]	2 (clear)
Air temperature[3]	Monthly values from Bern/Zollikofen
Dew point temperature[4]	Calculated from air temperature with 70% RH

Used references are [1]EC(2003), [2]Pelletier et al. (2008) and MeteoSchweiz ([3](2009) and [4](2002))

Table S6: Used default values for the sediment-water heat transfer.

Parameter	Value[1)]
Thermal conductivity	1.6 W/(m°C)
Thermal diffusivity	0.0064 cm^2/s
Sediment thickness	10 cm

[1)]Information from: Pelletier et al. (2008)

2.2 Simulated river depth over the river distance and over the year

The river depth H depends on a number of parameters, including the river flow Q which is variable over space and time (see Equation S5). This implies that the calculated river depth (see Table S7) varies over the distance and with the months, as related to the mean monthly flows. This results in higher water depths in summer months in the first few hundred kilometers in proximity to the Alps, since the flows, which are fed by melting snow and glaciers are highest during this season. On the other hand, further downstream flows are more pronounced in winter months due to feeding by winter precipitation. Therefore the water depths are higher during the winter season. The river depth peak is situated in the Swiss-German border region due to the present amount of water and river width. The latter is substantially increased after the Swiss border, therefore the river depth decreases. The mean river depth over all sections and months is 4.87 m.

Table S7: River depths of Aare and Rhine after the inflow of respective tributaries. Depths are differing for each month due to different flow volumes but constant river widths in each river section. The values for Reuss and Limmat are equal because they join the Aare within the same section**.**

River/source	River depth [m]											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Aare (headwater)	1.66	1.67	1.81	2.37	3.22	3.68	3.60	3.37	2.70	2.07	1.90	1.74
Saane	2.31	2.39	2.60	3.20	4.00	4.40	4.15	3.87	3.24	2.64	2.57	2.37
Bielersee outflow	3.34	3.47	3.61	4.10	4.60	4.86	4.61	4.23	3.77	3.42	3.41	3.39
Murg, Wigger, Dünnern	3.85	4.03	4.19	4.65	5.06	5.27	4.98	4.58	4.13	3.81	3.86	3.89

Reuss	3.76	3.96	4.18	4.76	5.47	5.95	5.66	5.10	4.51	3.99	3.92	3.87
Limmat	3.76	3.96	4.18	4.76	5.47	5.95	5.66	5.10	4.51	3.99	3.92	3.87
Rhine	4.36	4.47	4.72	5.38	6.25	7.02	6.83	6.16	5.52	4.89	4.66	4.52
Birs, Ergolz	5.17	5.21	5.57	6.35	7.26	8.05	7.83	7.11	6.38	5.66	5.38	5.26
Elz, Ill, Moder, Murg	5.12	5.21	5.37	5.79	6.28	6.68	6.39	5.86	5.31	4.94	4.85	5.10
Neckar	5.02	5.16	5.30	5.56	5.85	6.25	6.06	5.53	5.03	4.71	4.76	4.93
Main, Nahe, Lahn	5.53	5.69	5.68	5.72	5.74	6.01	5.80	5.29	4.86	4.66	4.89	5.30
Mosel	6.31	6.49	6.34	6.16	5.90	6.04	5.79	5.27	4.91	4.83	5.25	5.93
Wied, Sieg, Wupper, Erft	6.27	6.44	6.29	6.10	5.79	5.90	5.68	5.17	4.83	4.77	5.21	5.88
Ruhr, Emscher, Lippe	6.34	6.50	6.32	6.12	5.72	5.79	5.60	5.11	4.80	4.74	5.20	5.92

2.3 Comparison of temperature curves of the QUAL2Kw model results and different measuring stations along the Aare and Rhine

For validating the river temperature simulated with the QUAL2Kw model, the results are compared with measured temperatures from gauging stations at seven different locations (Figure S4 and Figure S5) along the rivers Aare and Rhine (Figure S6). The considered stations are Brügg-Ägerten, Rekingen, Weil am Rhein, Karlsruhe, Koblenz, Lobith and Maasluis. The river temperature data per the measuring station are mean monthly values. In the case of the stations at Brügg-Ägerten and Rekingen, data from FOEN (Federal Office for the Environment, 2010) provides long-term monthly values. For the locations Rekingen, Weil am Rhein, Karlsruhe, Koblenz, Lobith and Maassluis data from the ICPR (International Commission for the Protection of the Rhine, 2010) was averaged per month from two-weekly data for the years 2000 to 2007. Both long-term averages from the FOEN and the means from 2000-2007 from the ICPR station are shown for the station Rekingen. There are only small differences; therefore it can be assumed that the seven year mean values from ICPR are indeed sufficient to represent long-term mean river temperature values. Root mean squared errors (RMSE) of the simulated values compared to measured values are listed in Table S8. The overall mean RMSE is 1.02°C. In general the temperature values match reasonably well. Deviations between measurements and modeling become more pronounced at the measuring station Lobith (Dutch/German border). For the Delta (elevation in Maassluis 1 m a.s.l (Mongabay, 2010)), this can be explained by tidal variations in water level of almost 2 m (Ministerie van Verkeeren en Waterstaat, 2010) that leads to a mixing of river water with cooler seawater in the delta and thus lowers the temperature. Lobith is situated in a low lying area and groundwater tables will be high. Infiltrating groundwater into the river decreases the measured water temperature and augments the water volume in the river. However, the possible influence of both tidal flows and groundwater infiltration has not been accounted for in this work.

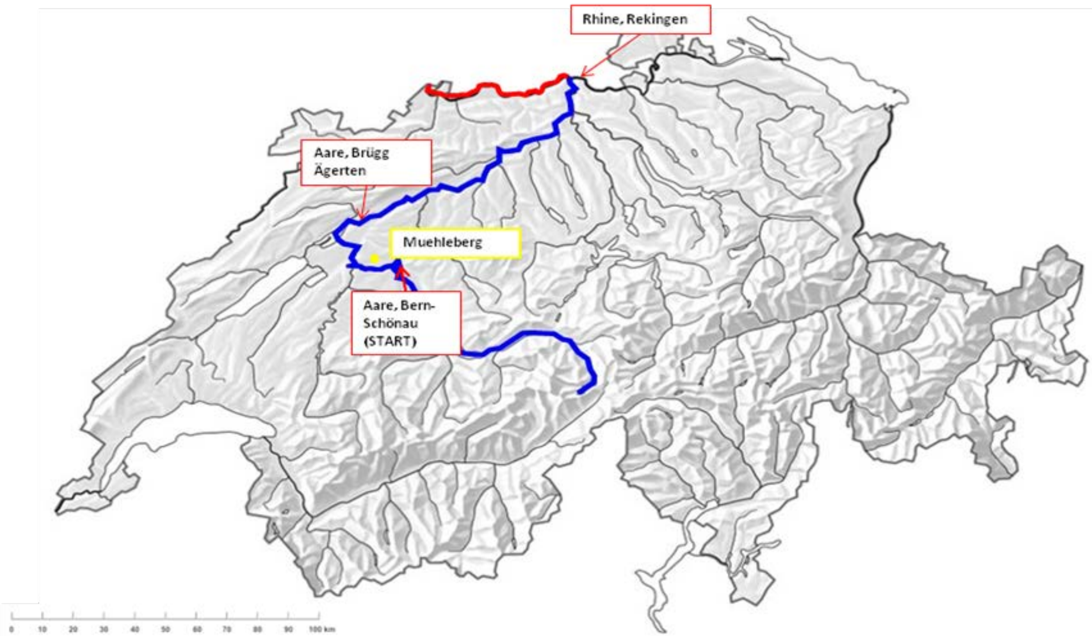


Figure S4: Map of Switzerland with the first hydrologic station at Bern-Schönau (START) and the temperature stations chosen for the temperature comparison. The Aare is symbolized with a blue line, the relevant part of the Rhine with a red line. The Muehleberg nuclear power plant is shown in yellow (modified from Koch, 2010).

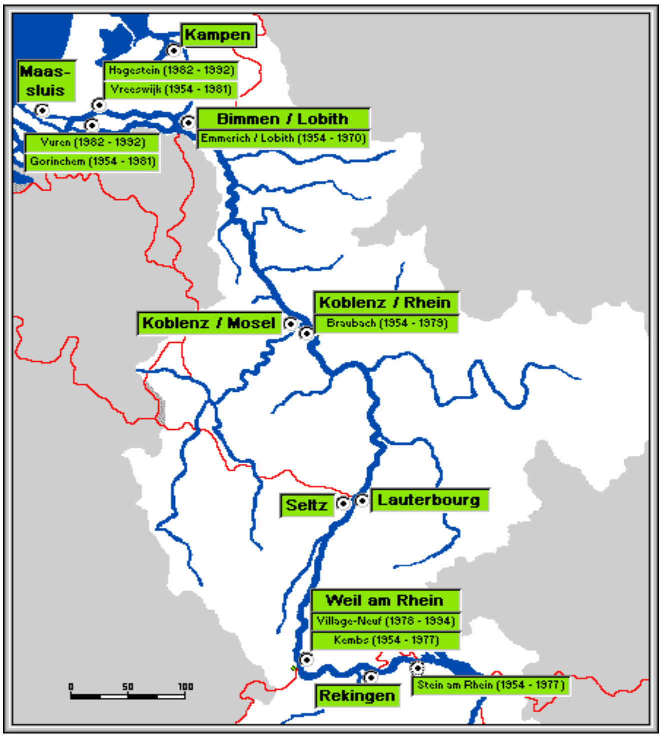
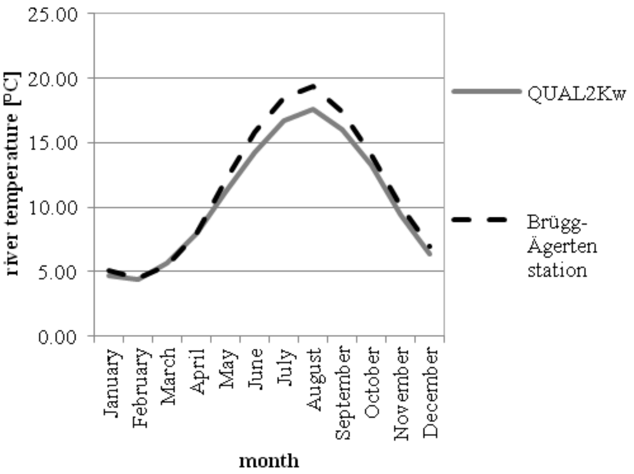
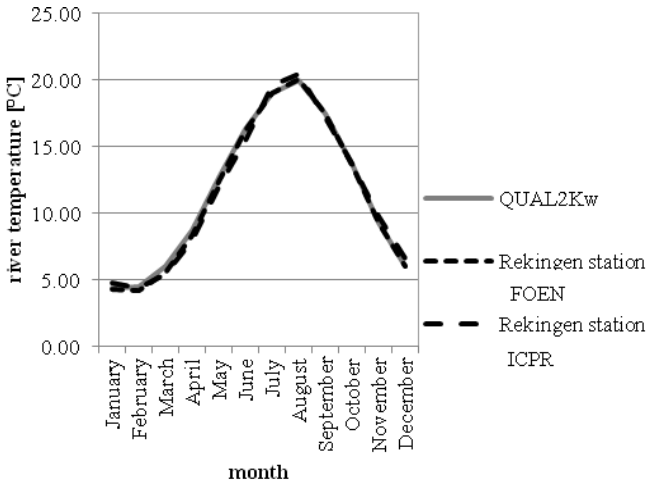


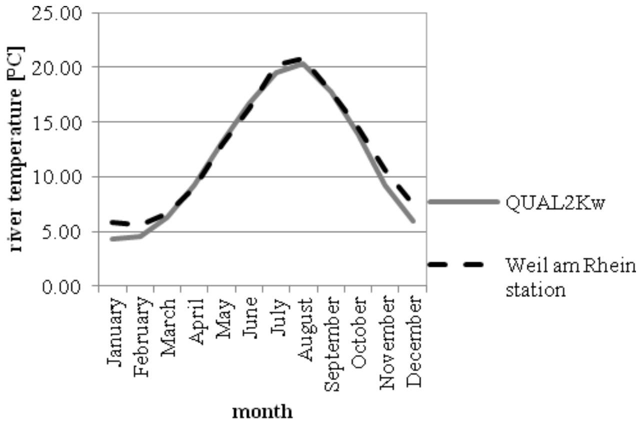
Figure S5: Map of the measuring stations of the ICPR along the Rhine (ICPR, 2010). For the temperature comparisons the stations at Rekingen, Weil am Rhein, Karlsruhe, Koblenz, Lobith and Maassluis were chosen.



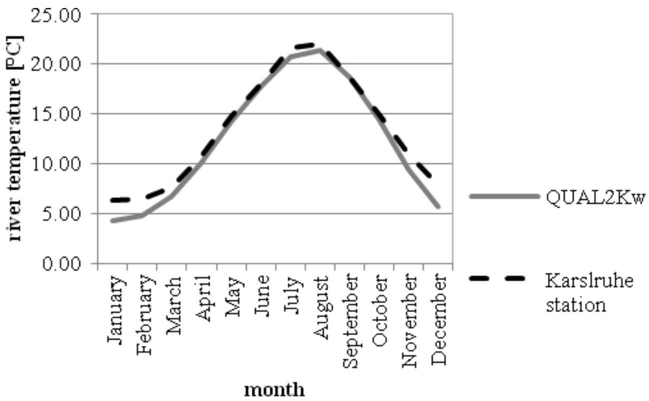
Brügg-Ägerten



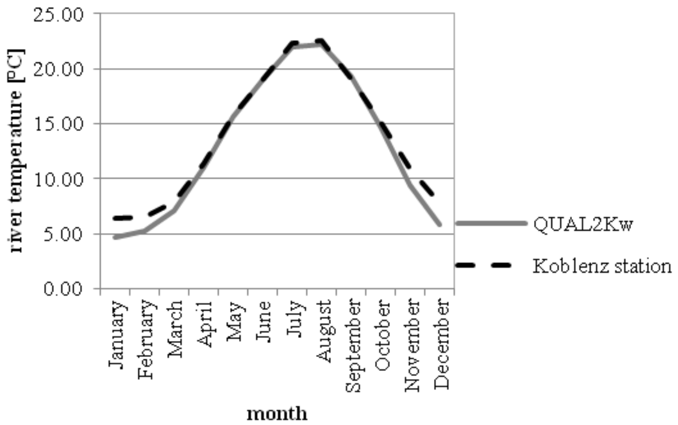
Rekingen



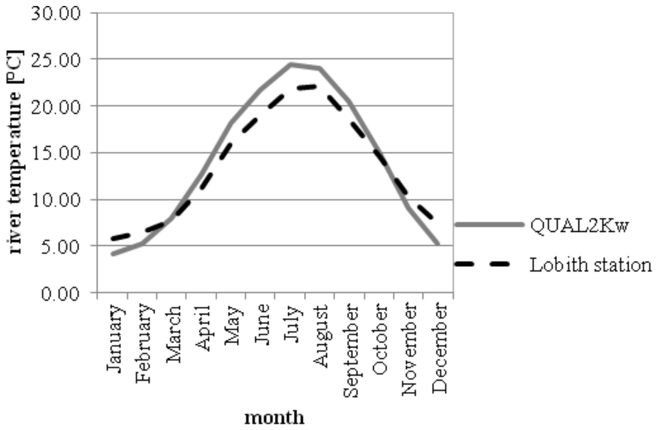
Weil am Rhein



Karlsruhe



Koblenz



Lobith

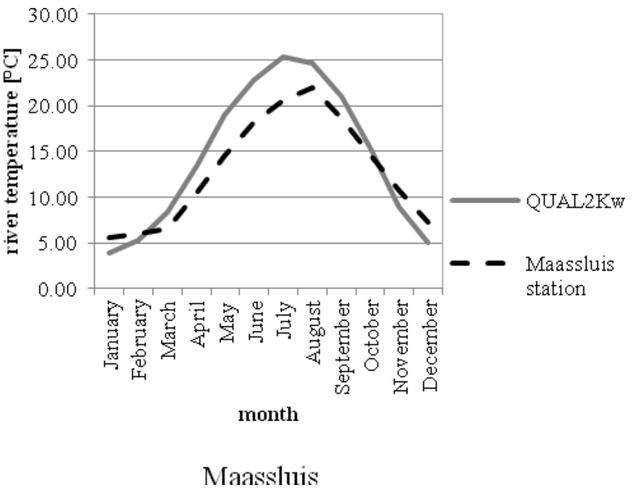


Figure S6: Comparison of the simulated ambient river temperature of the Aare and Rhine during one average year and the measured values of the seven measuring stations.

Table S8: Root mean squared errors (RMSE) [°C] for the comparison of measured and simulated temperatures for all seven measuring stations. Bold values show the largest deviations per river station.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Brügg-Ägerten	0.36	0.06	0.15	0.00	0.86	1.57	1.76	**1.83**	1.38	0.80	0.67	0.59
Rekingen FOEN	0.12	0.27	**0.44**	0.42	0.30	0.13	0.04	0.15	0.01	0.11	0.00	0.06
Rekingen ICPR	0.42	0.06	0.60	**0.80**	0.68	0.86	0.60	0.55	0.29	0.04	0.49	0.59
Weil am Rhein	**1.49**	1.01	0.30	0.17	0.20	0.54	0.70	0.47	0.01	0.59	1.33	**1.49**
Karlsruhe	1.99	1.65	0.85	0.69	0.50	0.22	0.93	0.69	0.05	0.50	1.44	**2.17**
Koblenz	1.69	1.32	0.81	0.36	0.17	0.08	0.28	0.35	0.15	0.44	1.53	**1.95**
Lobith	1.71	1.21	0.31	1.50	2.20	**2.83**	2.56	2.02	1.86	0.43	1.34	2.14
Maassluis	1.71	0.78	1.75	2.94	4.59	4.58	**4.76**	2.71	2.37	0.66	1.90	2.22

2.4 Results for river excess temperature of the fate model

In QUAL2Kw, two temperature simulations along the whole river system were performed. The first included the Muehleberg nuclear power plant (NPP) as point source, and the second did not (representing the natural state). The excess temperatures in the river at various locations were estimated by subtracting the temperature predicted for the natural state from the temperatures simulated with Muehleberg as additional point source, and are presented and discussed hereafter. The cooling water discharge leads to a warming of the rivers Aare and Rhine. The excess temperature is always greatest in the first reach of the river which receives the cooling water discharge, which extends to 500 m below the headwater. The largest values of excess temperature are found during the winter months (December to February), while the smallest values can be observed during the summer months (June to August) (Figure S7).

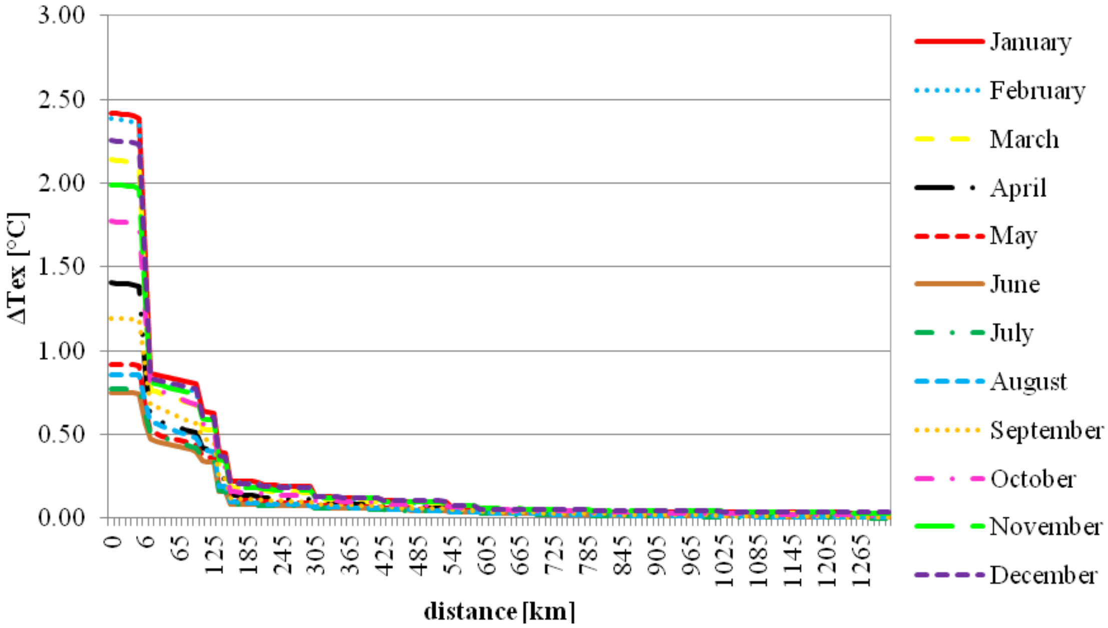


Figure S7: Excess river temperature resulting from dilution and decay after cooling water discharge by the Muehleberg NPP. The excess temperature is represented for each month and for the entire river distance from Muehleberg to the North Sea. The surplus temperature applied at the cooling water discharge point is 15°C, the mean cooling water flow modeled is 11.6 m^3/s.

According to Figure S7 the excess river temperature decreases very rapidly. We calculate the potential maximum excess river temperature that could be present in a river section j, considering the discharged surplus cooling water temperature, cooling water volume and the water volume of river section j. With the simulated temperature from QUAL2Kw the potential excess temperature that is remaining and the potential excess temperature that is dissipated can be calculated. This can be accumulated and leads to the cumulative fraction of temperature that is potentially dissipated in the water in section j (Figure S8A, red line). The cumulative fraction of excess temperature that is remaining over the distance is shown in Figure S8B. The results for the cumulative FF follow the line of potential dissipation and hence show that the largest portion of the decrease in excess temperature is caused by dilution (dissipation) based on comparison of the very rapid decrease in excess temperature due to dilution and decay (Figure S7) compared with the relatively slower response solely due to decay (Figure S8). The peaks in Figure S8A and B (red and blue lines) are caused by the inflowing tributaries. The first large peak/drop is caused by the inflow of the river Saane.

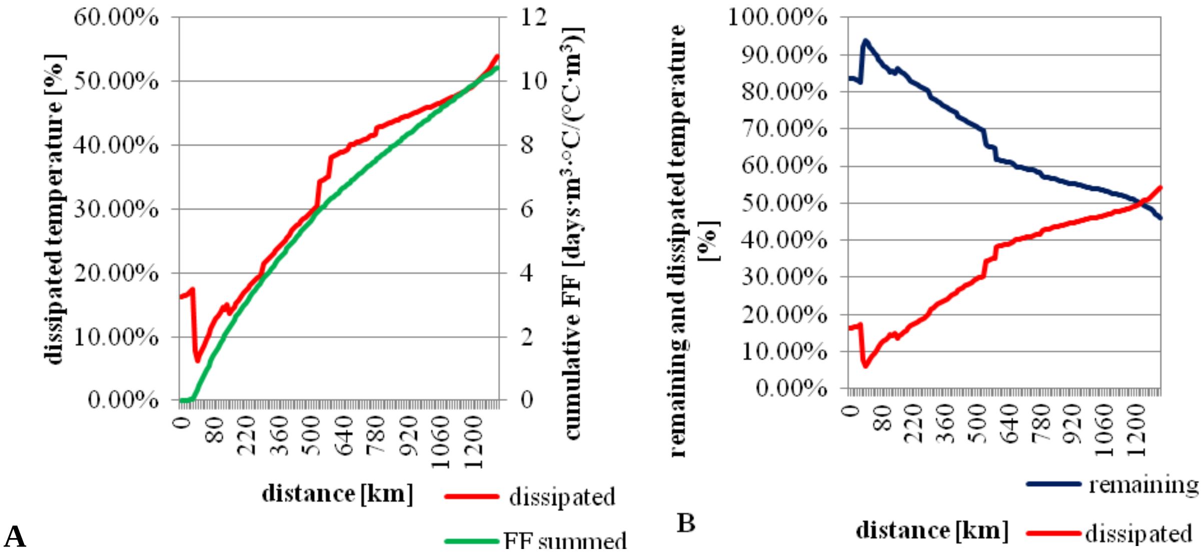


Figure S8: A) The percentage of dissipated temperature in comparison with the cumulative FF of January. B) The percentages of the potentially dissipated temperature and of the temperature which potentially still remains in the water. These values are shown for January.

2.5 Production cycle of the nuclear power plant Muehleberg

Since the nuclear power plant Muehleberg does not produce electricity equally distributed over the whole year (Table S10), it is necessary to have information for the variation in the production cycle. This information is needed for averaging the monthly results of the characterization factors (CF). If an arithmetic average was to be taken, the impact would be overestimated, since some months with high contribution (like August) would gain more importance than is justified. In the summer the plant is shut down for some weeks in order to exchange the nuclear fuel elements and carry out yearly revisions. This is the case in August, with July and September being concerned too because of the shut-down and start-up period of the nuclear power plant (Swissnuclear, 2010).

Table S9: Monthly electricity production of the Muehleberg NPP of the years 2006 to 2009. The percentages indicate monthly electricity production contribution to the yearly production. An average monthly percentage is given for the four years.

	2006		2007		2008		2009		Average 2006-2009
	[GWh]	[%]	[GWh]	[%]	[GWh]	[%]	[GWh]	[%]	[%]
January	283	9.4	182	6.3	286	9.3	292	9.4	8.6
February	252	8.4	250	8.6	267	8.6	264	8.5	8.5
March	282	9.4	282	9.7	286	9.3	290	9.4	9.4
April	273	9.1	272	9.3	274	8.9	282	9.1	9.1
May	279	9.3	278	9.5	284	9.2	290	9.4	9.4
June	261	8.7	268	9.2	268	8.7	277	9.0	8.9
July	228	7.6	274	9.4	278	9.0	285	9.2	8.8
August	102	3.4	31	1.1	75	2.4	69	2.2	2.3
September	205	6.8	223	7.7	214	6.9	189	6.1	6.9
October	279	9.3	287	9.9	292	9.5	289	9.3	9.5
November	269	9.0	278	9.5	273	8.8	275	8.9	9.1
December	282	9.4	287	9.9	292	9.5	290	9.4	9.5
Total	2995	100	2912	100	3089	100	3092	100	100

All information from (Swissnuclear, 2010).

3. Modeling the effect factor

As developed by Urban (1994), the temperature tolerance interval (TTI) of a species explains the interval by which the temperature can increase above the background river temperature without killing more than 50% of the population (LT50). Following De Vries et al. (2008), the TTI for a species i can be calculated by Equation S7.

$$TTI_i = a_i \cdot T_a + b_i \tag{S7}$$

where T_a is the background river temperature and a_j and b_j are regression parameters based on laboratory experiments to assess thermally induced mortality. This leads to a potentially affected fraction of species (PAF).

Starting from a normal response function (De Vries et al., 2008), the Potentially Disappeared Fraction (PDF) of species for temperature-induced mortality can be defined as given in Equation S8.

$$PDF_{j,t} = \frac{1}{2} \cdot \left[1 + ERF\left(\frac{-\mu_{TTI,j,t}}{\sigma_{TTI}\sqrt{2}}\right)\right] \tag{S8}$$

where ERF is the error function, $\mu_{TTI,j,t}$ is the average TTI in water body *j* at time *t* and σ_{TTI} is the standard deviation of the TTI. The standard deviation was set constant at 4.6 °C.

Following De Vries et al. (29), the average TTI is expressed by Equation S9.

$$\mu_{TTI} = \mu_a \cdot T_a + \mu_b \quad \text{(S9)}$$

where μ_a = -0.8663 and μ_b = 27.05 °C for LT50, considering only species that occur in temperate climate conditions.

If we focus on marginal changes in thermal pollution effects, the effect factor for water body i at time t is obtained through partial differentiation of Equation S8 as shown in the main manuscript.

Applying Equation 3 from the main manuscript, the dependency of the EF towards the ambient river temperature was calculated for water temperatures from 0 to 35 °C (Figure S9). The curve progression indicates the increase in the fraction of potentially disappeared aquatic species along with the increase of the river temperature until the turning point at 31°C has been reached.

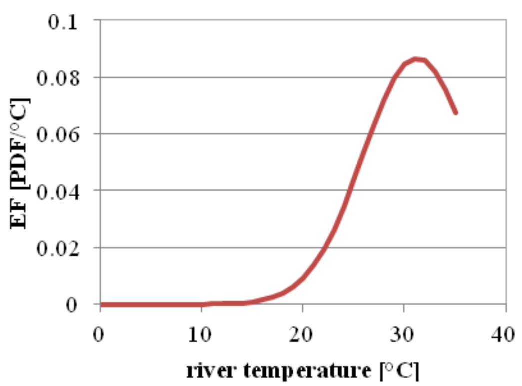


Figure S9: Curve of the EF indicating the water temperature dependency. After 31°C the EF decreases, showing that the SSD becomes flatter in this temperature range.

4. Results of Fate, Effect and Characterization factors

In the main manuscript the result figures show graphically the continuous course of the fate, effect and characterization factors, while in this Supporting Information numeric results are given for some specific locations along the rivers until the North Sea. As a complement visual results for EF and CF until the North Sea are shown with a logarithmic scale in Figure S10. In the following tables (Table S10 to Table S12) the results for the fate, effect and characterization factors are shown for each section where a tributary joins the main river (as milestones along the river system). Note that the EF is not cumulative, while the FF and CF are both cumulated over the distance.

Figure S11 shows the contribution of each month to both the arithmetic and production-averaged yearly characterization factor. The influence of the shut-down of the power plant for inspection in August is clearly visible since the contribution of August is around 37% for the arithmetic annual average and 14% for the production-averaged characterization factor. The months June to September all contribute more than 10% of the CFs, May and October still contribute more than 2.5% each. This shows that not only the hottest months (i.e. July and August) are relevant for the calculation of the CF.

Table S10: Results for the continuously cumulated fate factor for sections along the river distance and for all months of the year.

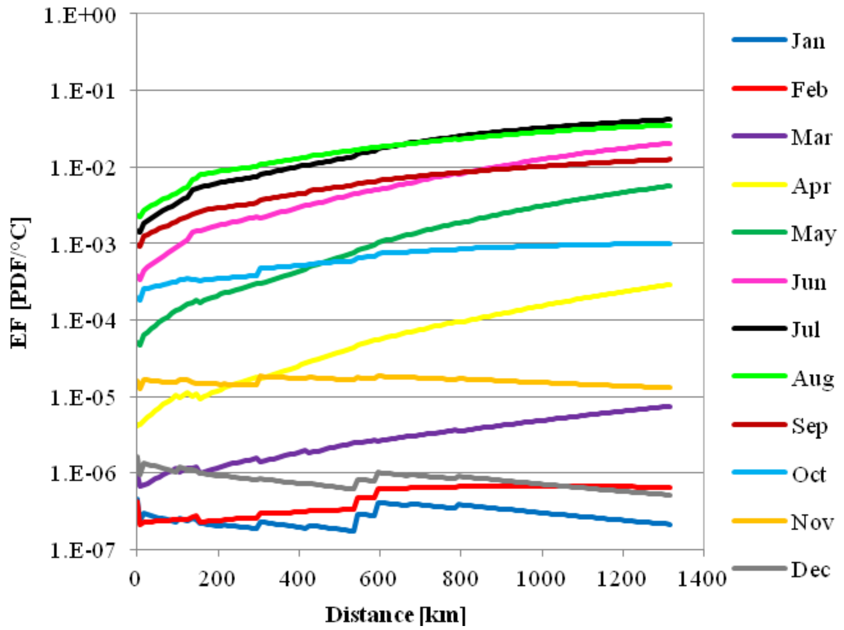
River/source	FF summed over distance [day·m^3·°C/(°C·m^3)]											
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Aare (headwater)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Saane	0.19	0.19	0.18	0.16	0.14	0.13	0.14	0.14	0.16	0.17	0.18	0.19
Bielersee outflow	0.35	0.34	0.33	0.29	0.27	0.26	0.26	0.27	0.29	0.32	0.33	0.34
Murg, Wigger, Dünnern	1.66	1.63	1.54	1.38	1.28	1.24	1.25	1.31	1.38	1.48	1.56	1.62
Reuss	2.04	2.01	1.89	1.70	1.57	1.51	1.52	1.58	1.67	1.81	1.92	1.99
Limmat	2.04	2.01	1.89	1.70	1.57	1.51	1.52	1.58	1.67	1.81	1.92	1.99
Rhine	2.28	2.24	2.11	1.89	1.74	1.66	1.66	1.73	1.84	2.01	2.14	2.22
Birs, Ergolz	2.95	2.90	2.72	2.42	2.20	2.06	2.05	2.13	2.29	2.53	2.75	2.87
Elz, Ill, Moder, Murg	4.12	4.04	3.75	3.32	3.00	2.78	2.73	2.82	3.06	3.45	3.82	4.01
Neckar	4.94	4.83	4.47	3.96	3.56	3.29	3.20	3.30	3.60	4.09	4.58	4.84
Main, Nahe, Lahn	5.96	5.79	5.35	4.71	4.22	3.90	3.74	3.84	4.22	4.86	5.52	5.89
Mosel	6.33	6.14	5.67	4.98	4.45	4.12	3.93	4.04	4.45	5.15	5.88	6.27
Wied, Sieg, Wupper, Erft	6.83	6.62	6.13	5.37	4.79	4.44	4.18	4.32	4.77	5.56	6.41	6.82
Ruhr, Emscher, Lippe	7.57	7.32	6.79	5.90	5.21	4.84	4.48	4.66	5.18	6.11	7.16	7.62
North Sea	10.43	9.92	9.03	7.44	6.16	5.66	4.98	5.35	6.14	7.72	9.79	10.65

Table S11: Results for the effect factor for the sections where a tributary enters the Aare or Rhine for all 12 months.

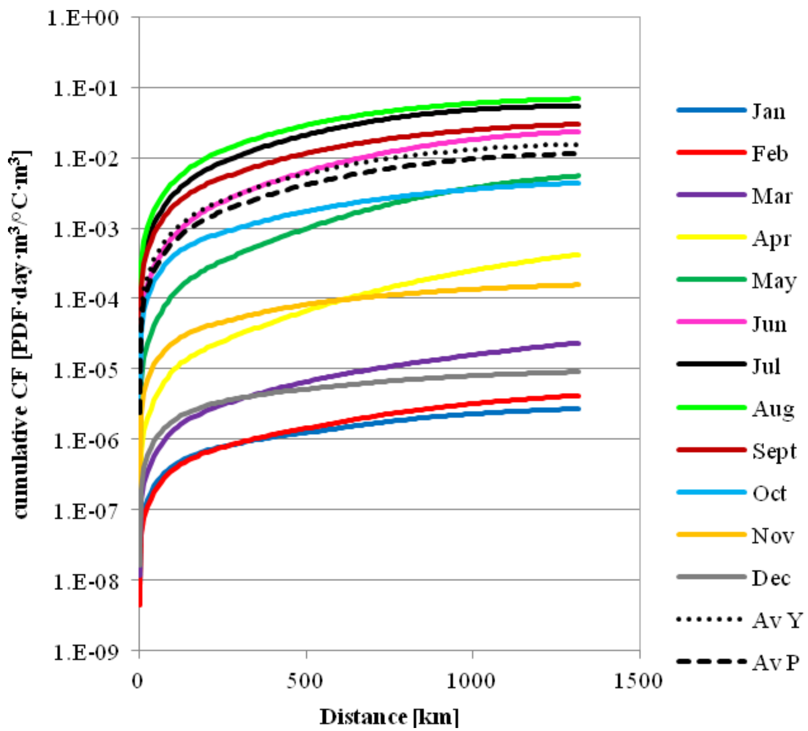
River/source	EF per section [PDF/°C]											
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Aare (headwater)	4.54E-07	4.17E-07	9.54E-07	4.16E-06	4.99E-05	3.69E-04	1.46E-03	2.31E-03	9.42E-04	1.96E-04	1.61E-05	1.60E-06
Saane	2.39E-07	2.10E-07	6.79E-07	4.20E-06	4.75E-05	3.41E-04	1.39E-03	2.21E-03	9.35E-04	1.85E-04	1.25E-05	9.63E-07
Bielersee out	2.97E-07	2.24E-07	6.91E-07	4.87E-06	6.29E-05	4.47E-04	1.82E-03	2.75E-03	1.24E-03	2.52E-04	1.65E-05	1.36E-06
Murg, Wigger, Dünnern	2.51E-07	2.45E-07	1.04E-06	9.65E-06	1.40E-04	9.59E-04	3.60E-03	4.92E-03	2.07E-03	3.35E-04	1.66E-05	1.17E-06
Reuss	2.54E-07	2.70E-07	1.16E-06	1.01E-05	1.71E-04	1.39E-03	5.00E-03	6.91E-03	2.44E-03	3.32E-04	1.51E-05	1.11E-06
Limmat	2.54E-07	2.70E-07	1.16E-06	1.01E-05	1.71E-04	1.39E-03	5.00E-03	6.91E-03	2.44E-03	3.32E-04	1.51E-05	1.11E-06
Rhine	2.19E-07	2.30E-07	9.79E-07	9.41E-06	1.71E-04	1.47E-03	5.41E-03	7.88E-03	2.65E-03	3.26E-04	1.49E-05	9.97E-07
Birs, Ergolz	2.09E-07	2.47E-07	1.25E-06	1.29E-05	2.24E-04	1.79E-03	6.35E-03	8.91E-03	2.97E-03	3.52E-04	1.45E-05	9.15E-07
Elz, Ill, Moder, Murg	2.18E-07	2.98E-07	1.53E-06	1.93E-05	3.33E-04	2.41E-03	8.64E-03	1.14E-02	3.97E-03	4.82E-04	1.79E-05	7.99E-07
Neckar	2.05E-07	3.19E-07	1.82E-06	2.79E-05	4.89E-04	3.13E-03	1.06E-02	1.37E-02	4.85E-03	5.38E-04	1.77E-05	7.22E-07
Main, Nahe, Lahn	2.91E-07	4.73E-07	2.47E-06	4.67E-05	8.28E-04	4.48E-03	1.49E-02	1.68E-02	6.03E-03	6.52E-04	1.76E-05	8.26E-07
Mosel	4.11E-07	6.17E-07	2.63E-06	5.53E-05	1.02E-03	5.00E-03	1.76E-02	1.81E-02	6.64E-03	7.38E-04	1.84E-05	1.01E-06
Wied, Sieg, Wupper, Erft	3.94E-07	6.36E-07	3.00E-06	6.93E-05	1.32E-03	6.19E-03	2.06E-02	2.02E-02	7.38E-03	7.85E-04	1.77E-05	9.51E-07
Ruhr, Emscher, Lippe	3.85E-07	6.74E-07	3.53E-06	9.22E-05	1.84E-03	8.07E-03	2.52E-02	2.31E-02	8.43E-03	8.55E-04	1.70E-05	9.02E-07
North Sea	2.13E-07	6.55E-07	7.45E-06	2.92E-04	5.63E-03	2.03E-02	4.16E-02	3.53E-02	1.25E-02	1.01E-03	1.30E-05	5.13E-07

Table S12: Results for the cumulative characterization factor for sections where tributaries enter for all 12 months. The arithmetic average over the year (AV Y) as well as the average based on production levels of Muehleberg (Av P) are given as well.

River/source	CF summed over distance [PDF·day·m^3/(°C·m^3)]													
	January	February	March	April	May	June	July	August	September	October	November	December	Av Y	Av P
Aare (headwater)	4.84E-09	4.43E-09	1.18E-08	3.81E-08	3.92E-07	2.70E-06	1.08E-05	1.77E-05	8.08E-06	1.91E-06	1.62E-07	1.67E-08	3.49E-06	2.39E-06
Saane	5.03E-08	4.41E-08	1.39E-07	6.64E-07	6.75E-06	4.62E-05	1.93E-04	3.17E-04	1.46E-04	3.22E-05	2.30E-06	1.95E-07	6.20E-05	4.24E-05
Bielersee out	9.59E-08	7.84E-08	2.41E-07	1.31E-06	1.46E-05	1.00E-04	4.17E-04	6.72E-04	3.14E-04	6.82E-05	4.73E-06	3.99E-07	1.33E-04	9.11E-05
Murg, Wigger, Dünnern	4.31E-07	3.83E-07	1.38E-06	9.81E-06	1.18E-04	7.81E-04	3.06E-03	4.59E-03	2.09E-03	4.07E-04	2.42E-05	1.89E-06	9.24E-04	6.41E-04
Reuss	5.26E-07	4.79E-07	1.78E-06	1.31E-05	1.64E-04	1.09E-03	4.19E-03	6.19E-03	2.77E-03	5.19E-04	3.00E-05	2.31E-06	1.25E-03	8.67E-04
Limmat	5.26E-07	4.79E-07	1.78E-06	1.31E-05	1.64E-04	1.09E-03	4.19E-03	6.19E-03	2.77E-03	5.19E-04	3.00E-05	2.31E-06	1.25E-03	8.67E-04
Rhine	5.82E-07	5.38E-07	2.02E-06	1.51E-05	1.94E-04	1.31E-03	4.97E-03	7.33E-03	3.20E-03	5.85E-04	3.33E-05	2.55E-06	1.47E-03	1.02E-03
Birs, Ergolz	7.21E-07	6.94E-07	2.69E-06	2.11E-05	2.86E-04	1.98E-03	7.28E-03	1.07E-02	4.47E-03	7.64E-04	4.21E-05	3.16E-06	2.13E-03	1.48E-03
Elz, Ill, Moder, Murg	9.60E-07	9.97E-07	4.18E-06	3.59E-05	5.10E-04	3.50E-03	1.23E-02	1.77E-02	7.11E-03	1.13E-03	5.86E-05	4.12E-06	3.53E-03	2.46E-03
Neckar	1.13E-06	1.24E-06	5.45E-06	5.10E-05	7.39E-04	4.94E-03	1.69E-02	2.36E-02	9.44E-03	1.46E-03	7.19E-05	4.74E-06	4.77E-03	3.34E-03
Main, Nahe, Lahn	1.33E-06	1.56E-06	7.36E-06	7.85E-05	1.16E-03	7.27E-03	2.36E-02	3.20E-02	1.28E-02	1.90E-03	8.80E-05	5.44E-06	6.57E-03	4.64E-03
Mosel	1.44E-06	1.73E-06	8.20E-06	9.27E-05	1.38E-03	8.36E-03	2.66E-02	3.54E-02	1.42E-02	2.09E-03	9.43E-05	5.76E-06	7.36E-03	5.23E-03
Wied, Sieg, Wupper, Erft	1.63E-06	2.03E-06	9.52E-06	1.17E-04	1.78E-03	1.02E-02	3.15E-02	4.08E-02	1.65E-02	2.40E-03	1.04E-04	6.29E-06	8.62E-03	6.17E-03
Ruhr, Emscher, Lippe	1.91E-06	2.48E-06	1.17E-05	1.61E-04	2.46E-03	1.31E-02	3.84E-02	4.84E-02	1.97E-02	2.85E-03	1.17E-04	7.00E-06	1.04E-02	7.54E-03
North Sea	2.73E-06	4.20E-06	2.35E-05	4.22E-04	5.47E-03	2.32E-02	5.38E-02	6.77E-02	2.96E-02	4.34E-03	1.56E-04	9.08E-06	1.54E-02	1.14E-02



A)



B)

Figure S10: Results of A) effect factor and B) characterization for the whole distance. “Av Y” is the arithmetic mean over all 12 months, while “Av P” symbolizes the average that is based on the percentage of monthly electricity production of the NPP Muehleberg. The values of EF and CF are each displayed on a logarithmic scale.

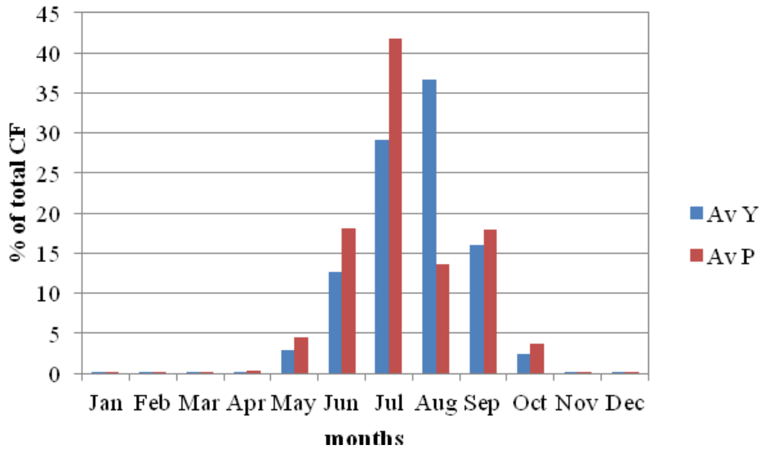


Figure S11: Contribution of each month at the total annual arithmetic characterization factor (Av Y) and the production-averaged yearly characterization factor (Av P).

1. Sensitivity analysis

In the following tables (Table S13 to Table S18) the sensitivity of the characterization factors to parameter changes in the model QUAL2Kw are shown. The sensitivities of the CFs were calculated following three different alternatives:

a) CF sensitivities with varied fate factor only,
b) CF sensitivities with varied effect factor only,
c) CF sensitivities with both EF and FF adapted.

The sensitivities were calculated for the months of August and December, because they represent two extreme months in the characterization factor results. Each model parameter tested was varied twice, once adding and once subtracting a certain percentage (indicated in the tables) of its original mean value.

The river water temperature was varied ±30%. The average annual standard deviation of the temperature is almost 50% among all tributaries. However, if a 50% change is applied in the months August and December this alteration leads to partially unrealistic temperature values, for instance to a water temperature below 0°C. Also, lakes buffer the water temperature and are thus narrowing the temperature variability. Therefore river water temperature changes were assessed by a variation of ±30%.

For the variation of the Manning roughness coefficient two additional values for the Manning coefficient were estimated. The first estimate describes a “rough” river flow with coarser gravel, larger irregularities and more vegetation growth. The second estimate outlines a “fine” river flow with fine gravel, very few irregularities and no vegetation growth. These estimations resulted in changes in the Manning value of +70% and -50% for sensitivity testing.

The standard deviation of the river width, the river flow and the air temperature was calculated from the inter-annual variations (for flow and temperature) and the difference along the rover itself, respectively. The obtained standard deviations are 40% for river width, 35% for river flow and 80% for air temperature. These variations have been applied to test the sensitivity.

For the bottom slope a variability of ±40% was employed. For the model an average slope was applied. The slope in Switzerland and the slope in Germany and the Netherlands were calculated separately, resulting in a steeper slope in the first case and a flatter slope in the latter case. The difference of these two cases to the average case was in both cases around 40% and therefore we applied this value for sensitivity testing. For shade and cloud cover the baseline of the original values was set to zero. In the sensitivity analysis, the shade parameter was determined as 10% shade and for cloud cover overcast (100% cloud cover) was chosen.

Table S13: Sensitivity [%] of the CF with adapted effect factor only to changes of river parameters for the month of August. Qriver stands for river flow, Triver and Tair for river water temperature and air temperature, respectively.

River/source	Width		Qriver		Triver		Wind		Manning		Bottom slope		Tair		Cloud cover	Shade
	+40%	-40%	+35%	-35%	+30%	-30%	+100%	-100%	+70%	-50%	+40%	-40%	+80%	-80%	+100%	+10%
Aare (headwater)	-0.19	0.21	0.13	-0.28	-709.22	95.19	0.16	-0.05	0.00	0.05	0.00	0.00	-0.20	0.20	0.45	0.07
Saane	-2.95	2.96	1.93	-4.07	-686.13	94.84	2.25	-0.78	0.00	0.09	0.00	0.00	-2.95	2.87	6.26	0.99
Bielersee out	-4.29	4.23	2.76	-5.88	-657.56	94.68	3.37	-1.17	0.00	0.09	0.00	0.00	-4.32	4.14	8.98	1.44
Murg, Wigger, Dünnern	-15.43	14.06	9.28	-21.17	-512.44	92.80	12.91	-5.06	0.00	0.08	0.00	0.00	-16.58	14.25	28.89	5.12
Reuss	-16.67	15.18	10.02	-22.85	-483.97	92.46	14.38	-5.74	0.00	0.07	0.00	0.00	-18.24	15.52	31.29	5.60
Limmat	-16.67	15.18	10.02	-22.85	-483.97	92.46	14.38	-5.74	0.00	0.07	0.00	0.00	-18.24	15.52	31.29	5.60
Rhine	-15.78	14.50	9.55	-21.59	-473.74	92.56	14.03	-5.58	0.00	0.06	0.00	0.00	-17.40	14.92	30.19	5.37
Birs, Ergolz	-14.09	13.19	8.66	-19.21	-448.62	92.70	13.93	-5.52	0.00	0.05	0.00	0.00	-16.04	13.95	28.49	5.00
Elz, Ill, Moder, Murg	-14.38	13.68	8.96	-19.54	-401.82	92.14	17.03	-6.93	0.00	0.03	0.00	0.00	-17.67	15.35	31.27	5.50
Neckar	-15.56	14.91	9.75	-21.08	-366.75	91.26	20.45	-8.68	0.00	0.03	0.00	0.00	-20.35	17.41	35.05	6.28
Main, Nahe, Lahn	-17.09	16.58	10.84	-23.08	-326.25	89.76	24.99	-11.28	0.00	0.03	0.00	0.00	-24.15	20.23	40.05	7.35
Mosel	-17.56	17.16	11.20	-23.68	-312.05	89.12	26.66	-12.31	0.00	0.02	0.00	0.00	-25.54	21.26	41.84	7.75
Wied, Sieg, Wupper, Erft	-18.08	17.89	11.66	-24.31	-292.62	88.11	29.01	-13.83	0.00	0.02	0.00	0.00	-27.44	22.68	44.29	8.29
Ruhr, Emscher, Lippe	-18.70	18.88	12.26	-25.04	-268.14	86.38	32.27	-16.13	0.00	0.02	0.00	0.00	-30.12	24.68	47.64	9.07
North Sea	-19.12	20.77	13.33	-25.28	-216.19	79.82	40.08	-22.53	0.58	-0.01	0.00	0.05	-36.11	29.55	55.37	10.95

Table S14: Sensitivity [%] of the CF with adapted effect factor only to changes of river parameters for the month of December. Qriver stands for river flow, Triver and Tair for river water temperature and air temperature, respectively.

River/source	Width		Qriver		Triver		Wind		Manning		Bottom slope		Tair		Cloud cover	Shade
	+40%	-40%	+35%	-35%	+30%	-30%	+100%	-100%	+70%	-50%	+40%	-40%	+80%	-80%	+100%	+10%
Aare (headwater)	0.29	-0.23	-0.15	0.36	-424.43	83.40	1.11	-0.38	0.00	0.89	0.00	0.00	0.00	-0.01	0.40	0.06
Saane	2.02	-2.10	-1.33	2.62	-375.51	81.29	10.04	-3.71	-0.06	-0.33	0.01	-0.02	0.02	-0.02	4.13	0.67
Bielersee out	2.30	-2.44	-1.56	3.08	-387.32	81.85	11.62	-4.33	-0.03	-0.36	0.01	-0.01	0.02	-0.02	4.74	0.76
Murg, Wigger, Dünnern	6.84	-7.86	-4.97	9.08	-368.13	81.06	30.01	-14.22	-0.01	-0.37	0.00	0.00	0.07	-0.07	13.52	2.29
Reuss	7.45	-8.75	-5.52	9.97	-364.53	80.91	32.53	-15.88	-0.01	-0.34	0.00	0.00	0.08	-0.08	14.89	2.54
Limmat	7.45	-8.75	-5.52	9.97	-364.53	80.91	32.53	-15.88	-0.01	-0.34	0.00	0.00	0.08	-0.08	14.89	2.54
Rhine	7.22	-8.77	-5.54	9.99	-363.37	80.85	32.67	-15.94	0.00	-0.32	0.00	0.00	0.08	-0.08	14.96	2.55
Birs, Ergolz	6.64	-8.90	-5.61	10.12	-359.09	80.63	33.24	-16.21	0.00	-0.28	0.00	0.00	0.08	-0.08	15.29	2.60
Elz, Ill, Moder, Murg	7.02	-9.92	-6.24	11.10	-349.82	80.15	36.22	-18.34	0.00	-0.23	0.00	0.00	0.09	-0.09	17.08	2.93
Neckar	7.38	-10.75	-6.75	11.85	-343.28	79.79	38.37	-20.13	0.00	-0.21	0.00	0.00	0.10	-0.10	18.47	3.20
Main, Nahe, Lahn	8.02	-12.01	-7.50	12.92	-334.98	79.30	41.20	-22.94	0.00	-0.19	0.00	0.00	0.11	-0.11	20.46	3.59
Mosel	8.21	-12.39	-7.73	13.22	-333.13	79.20	42.08	-23.80	0.00	-0.18	0.00	0.00	0.11	-0.11	21.10	3.72
Wied, Sieg, Wupper, Erft	8.45	-12.84	-8.01	13.60	-331.72	79.14	43.16	-24.83	0.00	-0.16	0.00	0.00	0.12	-0.12	21.88	3.87
Ruhr, Emscher, Lippe	9.00	-13.77	-8.56	14.34	-328.41	78.96	45.01	-26.86	0.00	-0.15	0.00	0.00	0.13	-0.13	23.23	4.14
North Sea	11.57	-18.45	-11.26	17.48	-311.08	77.83	51.60	-37.60	-0.45	-0.11	0.00	-0.06	0.17	-0.17	28.69	5.38

Table S15: Sensitivity [%] of the CF with adapted fate factor only to changes of river parameters for the month of August. Qriver stands for river flow, Triver and Tair for river water temperature and air temperature, respectively.

River/source	Width		Qriver		Triver		Wind		Manning		Bottom slope		Tair		Cloud cover	Shade
	+40%	-40%	+35%	-35%	+30%	-30%	+100%	-100%	+70%	-50%	+40%	-40%	+80%	-80%	+100%	+10%
Aare (headwater)	-1.37	11.82	6.85	-20.77	-3.73	-3.71	-3.65	-3.74	-44.38	45.32	6.54	-21.56	-3.68	-3.74	-3.78	0.00
Saane	-0.38	11.18	6.95	-18.80	-3.73	-2.41	-2.13	-3.38	-43.70	45.63	7.16	-20.88	-2.66	-3.46	-3.95	-0.12
Bielersee out	0.38	10.73	6.87	-17.78	-3.26	-2.40	-1.36	-3.32	-43.45	45.97	7.39	-20.63	-2.22	-3.42	-4.17	-0.20
Murg, Wigger, Dünnern	5.75	6.56	4.32	-10.75	-4.02	-1.34	2.88	-4.54	-43.23	46.87	7.61	-20.40	0.09	-5.30	-8.59	-0.90
Reuss	7.29	5.56	3.73	-8.76	-3.36	-1.60	4.69	-4.96	-42.94	47.28	7.78	-20.18	0.69	-5.52	-9.33	-1.04
Limmat	7.29	5.56	3.73	-8.76	-3.36	-1.60	4.69	-4.96	-42.94	47.28	7.78	-20.18	0.69	-5.52	-9.33	-1.04
Rhine	7.97	5.47	3.67	-7.87	-1.97	-2.45	6.27	-5.24	-42.52	47.65	7.98	-19.86	0.87	-5.22	-8.95	-1.02
Birs, Ergolz	9.74	4.96	3.39	-5.60	0.93	-4.24	9.75	-5.92	-41.63	48.49	8.39	-19.21	1.35	-4.72	-8.41	-1.01
Elz, Ill, Moder, Murg	13.29	2.65	1.99	-1.09	2.80	-5.34	13.65	-7.00	-40.95	49.57	8.77	-18.66	2.71	-5.21	-10.07	-1.34
Neckar	16.41	0.48	0.47	2.84	2.93	-5.29	15.86	-7.77	-40.49	50.28	8.91	-18.37	4.19	-6.31	-12.75	-1.77
Main, Nahe, Lahn	20.91	-3.22	-2.08	8.42	2.23	-4.58	18.30	-8.81	-40.10	51.26	9.02	-18.13	6.50	-8.38	-17.56	-2.52
Mosel	22.83	-4.94	-3.25	10.75	1.86	-4.23	19.25	-9.25	-39.97	51.68	9.05	-18.04	7.52	-9.33	-19.77	-2.86
Wied, Sieg, Wupper, Erft	25.86	-7.85	-5.18	14.39	1.22	-3.61	20.71	-9.95	-39.80	52.37	9.09	-17.94	9.18	-10.92	-23.45	-3.41
Ruhr, Emscher, Lippe	30.59	-12.86	-8.43	19.93	-0.68	-1.81	22.21	-10.74	-39.56	53.50	9.14	-17.82	12.13	-13.86	-30.22	-4.42
North Sea	53.96	-42.22	-26.50	46.74	-18.91	16.71	20.98	-8.74	-0.22	59.10	8.62	-7.74	29.87	-32.99	-75.14	-10.79

Table S16: Sensitivity [%] of the CF with adapted fate factor only to changes of river parameters for the month of December. Qriver stands for river flow, Triver and Tair for river water temperature and air temperature, respectively.

River/source	Width		Qriver		Triver		Wind		Manning		Bottom slope		Tair		Cloud cover	Shade
	+40%	-40%	+35%	-35%	+30%	-30%	+100%	-100%	+70%	-50%	+40%	-40%	+80%	-80%	+100%	+10%
Aare (headwater)	-6.76	7.75	0.09	-19.79	-10.50	-10.47	-10.40	-10.51	-52.97	57.41	0.36	-29.18	-10.48	-10.48	-10.52	0.00
Saane	-11.68	9.48	3.15	-16.53	-8.15	-6.15	-6.18	-7.48	-48.67	57.65	3.42	-25.39	-7.16	-7.16	-7.48	-0.05
Bielersee out	-9.79	10.18	4.75	-14.59	-6.04	-4.72	-3.80	-5.92	-46.46	58.63	5.06	-23.41	-5.38	-5.38	-5.75	-0.06
Murg, Wigger, Dünnern	-6.92	9.45	5.17	-11.27	-4.69	-3.28	0.17	-5.43	-44.73	59.13	6.35	-21.86	-3.99	-3.98	-5.18	-0.18
Reuss	-5.18	9.18	5.12	-10.38	-4.42	-3.04	1.40	-5.53	-44.38	59.20	6.58	-21.57	-3.74	-3.73	-5.07	-0.20
Limmat	-5.18	9.18	5.12	-10.38	-4.42	-3.04	1.40	-5.53	-44.38	59.20	6.58	-21.57	-3.74	-3.73	-5.07	-0.20
Rhine	-2.88	9.19	5.18	-9.79	-4.17	-2.84	2.33	-5.58	-44.01	59.25	6.77	-21.29	-3.52	-3.51	-4.85	-0.20
Birs, Ergolz	-1.95	9.11	5.24	-8.41	-3.67	-2.36	4.48	-5.74	-43.23	59.32	7.19	-20.68	-3.03	-3.02	-4.39	-0.21
Elz, Ill, Moder, Murg	-0.81	8.56	5.06	-6.45	-3.19	-1.80	7.24	-6.14	-42.46	59.35	7.64	-20.06	-2.52	-2.51	-4.06	-0.23
Neckar	-0.31	8.19	4.85	-5.27	-2.99	-1.51	8.84	-6.47	-42.05	59.33	7.84	-19.75	-2.28	-2.27	-3.98	-0.26
Main, Nahe, Lahn	0.47	7.64	4.50	-3.89	-2.84	-1.21	10.61	-6.94	-41.66	59.27	8.03	-19.46	-2.07	-2.05	-4.02	-0.30
Mosel	0.95	7.31	4.29	-3.19	-2.72	-1.15	11.55	-7.24	-41.49	59.29	8.11	-19.34	-1.97	-1.95	-4.01	-0.32
Wied, Sieg, Wupper, Erft	1.63	6.73	3.93	-2.01	-2.47	-1.11	13.12	-7.76	-41.25	59.35	8.22	-19.16	-1.83	-1.81	-3.99	-0.33
Ruhr, Emscher, Lippe	2.41	5.95	3.43	-0.58	-2.24	-1.03	14.94	-8.42	-40.90	59.38	8.35	-18.96	-1.68	-1.66	-4.06	-0.37
North Sea	5.80	3.25	1.64	5.52	-2.06	-0.56	19.05	-10.17	-26.67	59.18	8.41	-15.38	-1.37	-1.34	-4.80	-0.54

Table S17: Sensitivity [%] of the CF with adapted effect and fate factor to changes of river parameters for the month of August. Qriver stands for river flow, Triver and Tair for river water temperature and air temperature, respectively.

River/source	Width		Qriver		Triver		Wind		Manning		Bottom slope		Tair		Cloud cover	Shade
	+40%	-40%	+35%	-35%	+30%	-30%	+100%	-100%	+70%	-50%	+40%	-40%	+80%	-80%	+100%	+10%
Aare (headwater)	-1.56	12.00	6.98	-21.11	-739.42	95.01	-3.48	-3.80	-44.38	45.35	6.54	-21.56	-3.90	-3.53	-3.31	0.07
Saane	-3.34	13.82	8.74	-23.63	-715.41	94.72	0.17	-4.18	-43.70	45.68	7.16	-20.88	-5.69	-0.50	2.56	0.87
Bielersee out	-3.88	14.52	9.44	-24.68	-682.40	94.55	2.05	-4.53	-43.45	46.02	7.39	-20.63	-6.62	0.86	5.19	1.24
Murg, Wigger, Dünnern	-8.57	19.85	13.26	-33.79	-536.60	92.71	15.27	-9.85	-43.23	46.91	7.61	-20.40	-16.37	9.78	23.10	4.28
Reuss	-7.94	20.07	13.44	-33.20	-503.66	92.35	18.24	-11.00	-42.95	47.32	7.78	-20.18	-17.30	10.94	25.22	4.63
Limmat	-7.94	20.07	13.44	-33.20	-503.66	92.35	18.24	-11.00	-42.95	47.32	7.78	-20.18	-17.30	10.94	25.22	4.63
Rhine	-6.39	19.31	12.93	-30.87	-485.81	92.40	19.32	-11.14	-42.52	47.68	7.98	-19.86	-16.29	10.56	24.28	4.42
Birs, Ergolz	-2.93	17.57	11.79	-25.81	-445.62	92.40	22.26	-11.78	-41.64	48.52	8.39	-19.21	-14.42	9.96	22.74	4.04
Elz, Ill, Moder, Murg	0.87	16.05	10.81	-20.75	-390.35	91.72	28.12	-14.45	-40.95	49.59	8.77	-18.66	-14.40	11.00	24.60	4.25
Neckar	3.55	15.45	10.24	-17.40	-355.10	90.80	32.66	-17.20	-40.49	50.30	8.91	-18.37	-15.12	12.31	27.28	4.64
Main, Nahe, Lahn	7.71	14.19	9.11	-12.20	-317.37	89.33	38.11	-21.21	-40.10	51.27	9.02	-18.13	-15.69	13.80	30.60	5.05
Mosel	9.64	13.42	8.47	-9.79	-304.47	88.71	40.08	-22.86	-39.98	51.69	9.06	-18.04	-15.62	14.24	31.69	5.16
Wied, Sieg, Wupper, Erft	12.88	11.89	7.27	-5.76	-287.07	87.77	42.88	-25.37	-39.80	52.38	9.09	-17.94	-15.12	14.67	33.00	5.22
Ruhr, Emscher, Lippe	18.13	9.09	5.14	0.66	-267.43	86.38	46.35	-28.87	-39.56	53.50	9.14	-17.82	-13.37	14.93	34.56	5.14
North Sea	45.53	-10.77	-8.97	33.56	-246.91	87.69	52.39	-32.92	-1.72	59.10	8.62	-7.80	8.16	9.51	33.74	1.76

Table S18: Sensitivity [%] of the CF with adapted effect and fate factor to changes of river parameters for the month of December. Qriver stands for river flow, Triver and Tair for river water temperature and air temperature, respectively.

River/source	Width		Qriver		Triver		Wind		Manning		Bottom slope		Tair		Cloud cover	Shade
	+40%	-40%	+35%	-35%	+30%	-30%	+100%	-100%	+70%	-50%	+40%	-40%	+80%	-80%	+100%	+10%
Aare (headwater)	-6.45	7.54	-0.05	-19.36	-479.47	81.66	-9.17	-10.93	-52.97	57.78	0.36	-29.18	-10.48	-10.49	-10.07	0.06
Saane	-9.42	7.59	1.87	-13.49	-414.51	80.15	4.42	-11.45	-48.77	57.51	3.43	-25.41	-7.13	-7.17	-3.06	0.62
Bielersee out	-7.27	7.99	3.27	-11.07	-416.62	81.00	8.20	-10.48	-46.50	58.48	5.07	-23.42	-5.35	-5.40	-0.76	0.71
Murg, Wigger, Dünnern	0.33	2.30	0.45	-1.26	-390.10	80.45	29.80	-20.42	-44.74	58.98	6.35	-21.86	-3.92	-4.05	9.04	2.12
Reuss	2.60	1.20	-0.12	0.52	-385.11	80.33	33.09	-22.31	-44.38	59.06	6.58	-21.57	-3.66	0.01	10.57	2.34
Limmat	2.60	1.20	-0.12	0.52	-385.11	80.33	33.09	-22.31	-44.38	59.06	6.58	-21.57	-3.66	-3.81	10.57	2.34
Rhine	4.56	1.18	-0.08	1.08	-382.79	80.31	33.88	-22.42	-44.02	59.12	6.77	-21.29	-3.44	-3.59	10.84	2.35
Birs, Ergolz	4.85	0.99	-0.09	2.48	-376.07	80.19	35.89	-22.89	-43.24	59.20	7.19	-20.68	-2.95	-3.10	11.57	2.40
Elz, Ill, Moder, Murg	6.28	-0.55	-0.88	5.24	-364.43	79.81	40.31	-25.64	-42.46	59.26	7.64	-20.06	-2.43	-2.60	13.69	2.70
Neckar	7.10	-1.74	-1.59	7.04	-356.85	79.50	43.12	-27.98	-42.05	59.24	7.84	-19.75	-2.19	-2.36	15.20	2.95
Main, Nahe, Lahn	8.42	-3.55	-2.70	9.28	-347.69	79.08	46.50	-31.63	-41.66	59.20	8.03	-19.46	-1.95	-2.16	17.25	3.30
Mosel	9.04	-4.28	-3.14	10.19	-345.27	78.99	47.74	-32.95	-41.50	59.21	8.11	-19.34	-1.86	-2.06	17.91	3.42
Wied, Sieg, Wupper, Erft	9.89	-5.39	-3.81	11.57	-342.76	78.93	49.49	-34.75	-41.25	59.28	8.22	-19.16	-1.72	-1.93	18.74	3.55
Ruhr, Emscher, Lippe	11.10	-7.20	-4.90	13.49	-338.42	78.77	51.92	-37.87	-40.91	59.32	8.35	-18.96	-1.56	-1.79	20.10	3.79
North Sea	16.28	-15.23	-9.67	21.01	-319.90	77.74	58.90	-52.51	-26.81	59.13	8.42	-15.42	-1.20	-1.51	25.42	4.88

The most sensitive parameter for the CF with adapted EF is the river temperature, where a 30% change in the input values leads to changes in the result of up to 311 %, depending on the month and the location. This result underlines the EFs strong dependency on the river water temperature. For the CF with adapted FF the most sensitive parameter for both August and December is the Manning value, resulting in a change of up to 59% in the results. The CF inherits these sensitivities to a large part due to the multiplication of EF and FF, as is shown in Table S17 and Table S18 where both EF and FF are adapted. Since the river temperature indicates such high sensitivities, it is important for the modeling to use the monthly temporal resolution and whenever possible representative data for the river systems and climatic zones under study.

The sensitivity of the fate and characterization factors to varying amounts of heat released from cooling systems was evaluated (Table S19 and Table S20). The released heat amount is varied by 10%. In order to account for the changed release of heat energy, the released surplus temperature and alternatively the released volume of the cooling water can be adjusted. Thus for each change in released heat two analyses are carried out: once with adjusted surplus temperature and once with adjusted cooling water volume. The effect factor does not change since the ambient river water temperatures are not influenced by cooling water discharges.

The sensitivity of FF and CF towards changes in released heat is in most months small. The CF shows larger sensitivities than the FF. Adapting the cooling water surplus temperature to the changed heat release instead of the cooling water volume leads to slightly larger sensitivity values. These results indicate that reporting discharged heat energy and associated cooling water volume are sufficient since temperature values can be calculated from this information.

Table S19: Sensitivity of the CF to changes in released heat amount (variation by ±10%) expressed in [%] of the original CF value. The surplus temperature of the discharge is adjusted, while the volume of the cooling water stays constant. Av Y and Av P show the sensitivity in the results of the yearly and the production-based average.

		Months													
River/source	**change (Temp.)**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Av Y**	**Av P**
Aare (headwater)	**+10%**	0.00	0.00	16.66	-0.01	-0.01	-0.01	-0.02	-0.01	0.00	0.00	0.00	0.01	0.00	0.00
	-10%	-0.01	0.00	16.67	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.02
Saane	**+10%**	0.33	0.35	8.65	-0.02	0.04	0.06	0.03	0.05	0.00	0.05	0.17	0.28	0.04	0.03
	-10%	-0.41	-0.42	8.26	0.01	-0.03	-0.09	-0.06	-0.05	-0.01	-0.06	-0.21	-0.35	-0.04	-0.04
Bielersee outflow	**+10%**	0.31	0.37	5.09	-0.07	-0.10	-0.09	-0.13	-0.09	-0.17	-0.11	0.08	0.20	-0.12	-0.13
	-10%	-0.38	-0.45	4.67	0.08	0.12	0.10	0.16	0.13	0.21	0.13	-0.09	-0.24	0.15	0.16
Murg, Wigger, Dünnern	**+10%**	0.36	0.37	0.89	-0.47	-0.64	-0.67	-0.77	-0.64	-0.63	-0.35	0.04	0.22	-0.66	-0.68
	-10%	-0.44	-0.44	0.82	0.58	0.79	0.82	0.94	0.79	0.78	0.44	-0.04	-0.27	0.82	0.83
Reuss	**+10%**	0.37	0.36	0.66	-0.55	-0.80	-0.90	-1.02	-0.88	-0.78	-0.40	0.04	0.23	-0.88	-0.89
	-10%	-0.45	-0.43	0.67	0.68	0.99	1.11	1.24	1.08	0.96	0.50	-0.04	-0.28	1.08	1.09
Limmat	**+10%**	0.37	0.36	0.66	-0.55	-0.80	-0.90	-1.02	-0.88	-0.78	-0.40	0.04	0.23	-0.88	-0.89
	-10%	-0.45	-0.43	0.67	0.68	0.99	1.11	1.24	1.08	0.96	0.50	-0.04	-0.28	1.08	1.09
Rhine	**+10%**	0.38	0.35	0.57	-0.57	-0.89	-1.07	-1.21	-1.08	-0.88	-0.42	0.04	0.24	-1.05	-1.04
	-10%	-0.46	-0.42	0.61	0.71	1.09	1.31	1.47	1.32	1.07	0.52	-0.05	-0.29	1.28	1.28
Birs, Ergolz	**+10%**	0.41	0.35	0.40	-0.66	-1.10	-1.43	-1.62	-1.52	-1.11	-0.47	0.06	0.27	-1.43	-1.40
	-10%	-0.50	-0.43	0.49	0.82	1.34	1.77	1.97	1.89	1.35	0.56	-0.06	-0.33	1.76	1.72
Elz, Ill, Moder, Murg	**+10%**	0.44	0.33	0.13	-0.92	-1.54	-1.98	-2.28	-2.17	-1.50	-0.60	0.05	0.32	-2.02	-1.97
	-10%	-0.53	-0.40	0.47	1.15	1.87	2.43	2.78	2.67	1.84	0.72	-0.06	-0.38	2.48	2.41
Neckar	**+10%**	0.46	0.30	-0.03	-1.20	-1.95	-2.42	-2.83	-2.66	-1.84	-0.74	0.03	0.35	-2.49	-2.44
	-10%	-0.55	-0.36	0.52	1.47	2.37	2.98	3.44	3.27	2.26	0.91	-0.03	-0.43	3.05	2.99
Main, Nahe, Lahn	**+10%**	0.47	0.25	-0.23	-1.68	-2.70	-3.12	-3.62	-3.36	-2.34	-0.92	0.02	0.40	-3.18	-3.13
	-10%	-0.57	-0.31	0.64	2.06	3.32	3.86	4.44	4.12	2.86	1.13	-0.01	-0.48	3.90	3.84
Mosel	**+10%**	0.45	0.20	-0.31	-1.91	-3.11	-3.46	-4.08	-3.67	-2.56	-1.02	0.01	0.40	-3.52	-3.49
	-10%	-0.55	-0.24	0.70	2.35	3.82	4.28	5.01	4.49	3.13	1.25	0.00	-0.48	4.31	4.29
Wied, Sieg, Wupper, Erft	**+10%**	0.38	0.09	-0.43	-2.31	-3.82	-4.03	-4.95	-4.16	-2.93	-1.18	0.00	0.40	-4.11	-4.14
	-10%	-0.47	-0.10	0.78	2.81	4.70	4.95	6.08	5.10	3.58	1.45	0.01	-0.48	5.04	5.08
Ruhr, Emscher, Lippe	**+10%**	0.32	-0.03	-0.62	-2.91	-5.02	-5.06	-6.38	-4.94	-3.48	-1.40	-0.01	0.40	-5.08	-5.20
	-10%	-0.40	0.05	0.95	3.56	6.17	6.21	7.81	6.06	4.25	1.70	0.02	-0.48	6.22	6.37
North Sea	**+10%**	0.30	-0.29	-1.47	-6.31	-13.15	-12.99	-15.05	-9.17	-5.90	-2.06	0.04	0.47	-10.77	-11.36
	-10%	-0.36	0.37	1.91	7.71	16.09	15.85	17.00	11.22	7.20	2.49	-0.04	-0.57	12.76	13.63

Table S20: Sensitivity of the CF to changes in released heat amount (variation by ±10%) expressed in [%] of the original CF value. The volume of the discharge is adjusted, while the surplus temperature of the cooling water stays constant. Av Y and Av P show the sensitivity in the results of the yearly and of the production-based average.

		Months													
River/source	**change (Vol.)**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Av Y**	**Av P**
Aare (headwater)	**+10%**	1.64	1.62	17.88	4.29	-0.37	0.52	0.53	0.59	0.82	1.21	1.36	1.53	0.65	0.66
	-10%	-1.70	-1.67	15.42	2.35	-1.64	-0.52	-0.55	-0.59	-0.83	-1.23	-1.39	-1.58	-0.66	-0.68
Saane	**+10%**	1.13	1.09	9.34	3.98	-0.52	0.40	0.44	0.49	0.64	0.87	0.93	1.07	0.51	0.52
	-10%	-1.16	-1.11	7.59	2.68	-1.48	-0.40	-0.44	-0.48	-0.65	-0.88	-0.95	-1.10	-0.52	-0.54
Bielersee out	**+10%**	0.86	0.85	5.61	3.88	-0.60	0.36	0.39	0.45	0.56	0.70	0.74	0.81	0.45	0.45
	-10%	-0.88	-0.86	4.17	2.82	-1.43	-0.37	-0.40	-0.44	-0.56	-0.72	-0.75	-0.82	-0.47	-0.48
Murg, Wigger, Dünnern	**+10%**	0.61	0.58	1.37	3.91	-0.72	0.32	0.34	0.39	0.46	0.54	0.56	0.58	0.38	0.37
	-10%	-0.61	-0.58	0.33	3.10	-1.42	-0.32	-0.34	-0.39	-0.46	-0.55	-0.57	-0.59	-0.40	-0.40
Reuss	**+10%**	0.56	0.53	1.13	3.90	-0.77	0.29	0.31	0.35	0.42	0.49	0.52	0.54	0.34	0.34
	-10%	-0.56	-0.53	0.19	3.17	-1.41	-0.29	-0.31	-0.35	-0.42	-0.50	-0.52	-0.54	-0.36	-0.37
Limmat	**+10%**	0.56	0.53	1.13	3.90	-0.77	0.29	0.31	0.35	0.42	0.49	0.52	0.54	0.34	0.34
	-10%	-0.56	-0.53	0.19	3.17	-1.41	-0.29	-0.31	-0.35	-0.42	-0.50	-0.52	-0.54	-0.36	-0.37
Rhine	**+10%**	0.52	0.49	1.02	3.88	-0.82	0.25	0.27	0.31	0.37	0.45	0.48	0.50	0.30	0.29
	-10%	-0.53	-0.49	0.15	3.21	-1.39	-0.25	-0.28	-0.31	-0.38	-0.46	-0.48	-0.51	-0.32	-0.33
Birs, Ergolz	**+10%**	0.44	0.39	0.78	3.83	-0.92	0.18	0.19	0.23	0.27	0.35	0.39	0.42	0.22	0.21
	-10%	-0.44	-0.40	0.09	3.32	-1.34	-0.18	-0.21	-0.22	-0.28	-0.37	-0.40	-0.42	-0.24	-0.24
Elz, Ill, Moder, Murg	**+10%**	0.34	0.29	0.52	3.85	-1.04	0.11	0.11	0.14	0.18	0.25	0.30	0.33	0.13	0.12
	-10%	-0.34	-0.29	0.04	3.50	-1.31	-0.11	-0.13	-0.14	-0.18	-0.25	-0.30	-0.33	-0.16	-0.16
Neckar	**+10%**	0.29	0.23	0.40	3.90	-1.12	0.09	0.08	0.12	0.14	0.19	0.24	0.29	0.10	0.09
	-10%	-0.29	-0.23	0.03	3.65	-1.32	-0.08	-0.09	-0.10	-0.12	-0.19	-0.24	-0.29	-0.11	-0.12
Main, Nahe, Lahn	**+10%**	0.24	0.18	0.29	4.02	-1.22	0.08	0.06	0.07	0.09	0.14	0.20	0.25	0.06	0.05
	-10%	-0.25	-0.18	0.03	3.87	-1.36	-0.04	-0.07	-0.07	-0.07	-0.14	-0.20	-0.25	-0.08	-0.09
Mosel	**+10%**	0.22	0.16	0.26	4.10	-1.28	0.07	0.05	0.06	0.07	0.12	0.18	0.24	0.05	0.04
	-10%	-0.23	-0.16	0.03	3.98	-1.39	-0.02	-0.05	-0.06	-0.06	-0.12	-0.18	-0.24	-0.07	-0.08
Wied, Sieg, Wupper, Erft	**+10%**	0.18	0.13	0.22	4.22	-1.38	0.05	0.05	0.04	0.05	0.09	0.16	0.22	0.03	0.02
	-10%	-0.20	-0.12	0.02	4.13	-1.46	-0.03	-0.04	-0.04	-0.03	-0.09	-0.16	-0.21	-0.06	-0.07
Ruhr, Emscher, Lippe	**+10%**	0.14	0.10	0.15	4.42	-1.52	0.03	0.02	0.03	0.03	0.05	0.14	0.18	0.00	-0.01
	-10%	-0.16	-0.09	0.02	4.39	-1.57	0.00	-0.02	-0.03	-0.01	-0.07	-0.13	-0.18	-0.05	-0.06
North Sea	**+10%**	0.08	0.02	0.04	5.57	-2.49	-0.04	-0.10	-0.04	-0.09	-0.05	0.07	0.13	-0.12	-0.16
	-10%	-0.08	-0.01	0.06	5.69	-2.38	0.03	0.04	0.04	0.05	0.02	-0.07	-0.12	-0.02	-0.05

2. Relevance of cooling water emissions compared to other environmental impacts

In order to evaluate the relevance of cooling water emissions, two different types of cooling systems operated at NPPs were compared, a once-through cooling system (as operated at the Muehleberg NPP) and a cooling tower. It is assumed that both power plants are situated at the location of the Muehleberg NPP and that both plants run boiling water reactors, as in the case of the Muehleberg NPP. We used the ReCiPe impact assessment method (Goedkoop et al., 2009) (hierarchist perspective) to assess the importance of cooling water emissions in the categories freshwater ecosystem quality (encompassing freshwater eutrophication and freshwater ecotoxicity), total ecosystem quality, and the total ReCiPe score (including the damage categories Human Health, Ecosystem Quality and Resources). ReCiPe is a method that was established with the aim of integrating two existing prominent LCIA methodologies, namely Eco-Indicator 99 (Goedkoop and Spriensma, 1999) and CML (Guinée et al., 2002) into one new methodology, while at the same time improving the underlying impact assessment methods. The endpoint categories employed in ReCiPe are the same as those of Eco-Indicator 99; however some different impact categories and cause-effect chains are established.

The life cycle inventories for 1 kWh of electricity produced in boiling water reactors in Switzerland operating different cooling systems were taken from the ecoinvent database (ecoinvent, 2010). The applied inventories provide data for waste heat emitted as cooling water and cooling water volumes used. Employing the heat capacity of water, these data allowed calculating the released surplus temperature of the cooling water discharged. For the impact assessment of the cooling water emissions we applied the production-averaged characterization factor. Damage factors were calculated and transformed to the ReCiPE-specific "species·year" damage-unit (Goedkoop et al., 2009).

For the evaluation of cooling water from a once-through cooling system a cooling water volume of 140 l per 1kWh of electricity produced was estimated from the average cooling water need (11.6 m^3/s) and the yearly electricity production of the Muehleberg NPP. Other studies report cooling water requirements of 95-230 l in once-through cooling systems for the generation of 1 kWh (NETL, 2009; EPRI, 2002), which indicates the high variability of cooling water use. The cooling water data contained in the ecoinvent datasets applied cannot be used since these datasets represent plants with cooling towers and the specified cooling water volume of 4.73 l/kWh substantially underestimates the cooling water amount of once-through cooling systems. For cooling water discharged from cooling towers the data available in the respective ecoinvent dataset was adopted to calculate the excess temperature and the impact assessment results.

Table S21 shows the ReCiPe impact assessment results for nuclear electricity production differentiated by impact categories. The impacts of thermal emissions are listed separately. The ecosystem damage from thermal emissions from the nuclear facility with a once-through cooling system results in $4.3 \cdot 10^{-14}$ species·yr and in $2.2 \cdot 10^{-17}$ species·yr for a NPP with a cooling tower, respectively. Table S22 compares the size of the impact of thermal emissions with impacts provided by ReCiPe for freshwater ecosystem quality, ecosystem quality and the total impact.

Table S21: Impact assessment results for 1 kWh electricity produced in a NPP with a once-through cooling system and a cooling tower, respectively, evaluated with the ReCiPe method (unit: eco-points (Pts)). Note that thermal emissions are listed separately.

IMPACT CATEGORIES		Once-through cooling ReCiPe result [Pts]	Cooling tower ReCiPe result [Pts]
Human health	climate change Human Health	2.97E-04	2.97E-04
	ozone depletion	2.39E-06	2.39E-06
	human toxicity	4.39E-05	4.39E-05
	photochemical oxidant formation	3.70E-08	3.70E-08
	particulate matter formation	1.23E-04	1.23E-04
	ionising radiation	5.03E-04	5.03E-04
Resources	water depletion	-	-
	metal depletion	2.64E-06	2.64E-06
	fossil depletion	3.13E-04	3.13E-04
Ecosytem quality	climate change Ecosystems	1.95E-04	1.95E-04
	terrestrial acidification	8.83E-07	8.83E-07
	marine eutrophication	0.00E+00	0.00E+00
	terrestrial ecotoxicity	2.64E-07	2.64E-07
	marine ecotoxicity	1.65E-10	1.65E-10
	agricultural land occupation	1.15E-05	1.15E-05
	urban land occupation	1.13E-05	1.13E-05
	natural land transformation	7.48E-06	7.48E-06
	freshwater eutrophication	5.04E-08	5.04E-08
	freshwater ecotoxicity	5.12E-08	5.12E-08
	thermal emissions (contributing to the freshwater ecosystem quality damage)	9.73E-08	5.00E-11
	total	1.5E-03	1.5E-03

Table S22: Importance of thermal emissions from a nuclear power plant with once-through cooling system and a cooling tower in comparison to the ReCiPe impact categories. Indicated are the impact contributions of thermal emissions to 100% of impact in the respective category. For freshwater ecosystem quality and total ecosystem quality the comparison is done on the damage level expressed in species·yr, while for the total damage the single-score values in eco-points are compared.

	Once-through cooling system		Cooling tower	
	Thermal pollution share [%]	**RECIPE share [%]**	**Thermal pollution share [%]**	**RECIPE share [%]**
Freshwater ecosystem quality damage	48.9	51.1	0.05	99.95
Total ecosystem quality damage	0.04	99.96	0.00	100.00
Total aggregated damage (inc. Resource and human health)	0.01	99.99	0.00	100.00

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Chapter 5

Characterization factors for water consumption and greenhouse gas emissions based on freshwater fish species extinction

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Abstract

Human-induced changes in water consumption and global warming are likely to reduce the species richness of freshwater ecosystems. So far, these impacts have not been addressed in the context of life cycle assessment (LCA). Here, we derived characterization factors for water consumption and global warming based on freshwater fish species loss. Calculation of characterization factors for potential freshwater fish losses from water consumption were estimated using a generic species-river discharge curve for 214 global river basins. We also derived characterization factors for potential freshwater fish species losses per unit of greenhouse gas emission. Based on five global climate scenarios, characterization factors for 63 greenhouse gas emissions were calculated. Depending on the river considered, characterization factors for water consumption can differ up to 3 orders of magnitude. Characterization factors for greenhouse gas emissions can vary up to 5 orders of magnitude, depending on the atmospheric residence time and radiative forcing efficiency of greenhouse gas emissions. An emission of 1 ton of CO_2 is expected to cause the same impact on potential fish species disappearance as the water consumption of 10-1000 m^3, depending on the river basin considered. Our results make it possible to compare the impact of water consumption with greenhouse gas emissions.

Keywords: water consumption; global warming; life cycle assessment; freshwater ecosystems

1. Introduction

Life cycle assessment (LCA) is a technique used to assess the environmental impacts associated with a product, process or service (ISO, 2006). This paper focuses on life cycle impact assessment (LCIA), the phase where inventory data are assessed in terms of environmental impacts. Impact categories in LCIA can be associated with areas of protection (AoPs), such as natural resources, ecosystem quality and human health (Udo de Haes et al., 2002). The relationship between inventory data and the magnitude of impacts on the AoPs in LCIA are expressed in terms of characterization factors (Pennington et al., 2004).

Global freshwater biodiversity is one of the AoPs which has experienced large adverse effects (Dudgeon et al., 2006). Although freshwater fish species losses due to anthropogenic impacts have been addressed in earlier studies (Reist et al., 2006; Wrona et al., 2006a; Buisson et al., 2008), less attention has been paid to assessing these impacts in an LCA perspective (Koehler, 2008). At present, freshwater-related studies using LCA techniques have mostly focused on toxicological effects (Pennington et al., 2004; Pennington et al., 2006; Van de Meent and Huijbregts, 2005; Larsen and Hauschild, 2007a). The study of environmental impacts of water consumption on terrestrial ecosystems has only recently been conducted by Pfister et al. (2009). Impacts of water consumption and greenhouse gas emissions in relation to freshwater biodiversity have so far not been addressed in LCA context.

Global warming and increases in water consumption can significantly affect freshwater ecosystems (Vorosmarty et al., 2000; Xenopoulos et al., 2005). For example, reduced river discharge (the volume of water flowing through a river per unit time) due to water consumption and greenhouse gas emissions could lead to freshwater fish species losses (Xenopoulos and Lodge, 2006). In lotic freshwater ecosystems, river discharge can be used as a surrogate of habitat space to generate species-discharge relationships similar to terrestrial species-area curves (Xenopoulos and Lodge, 2006; Oberdorff et al., 1995; Poff et al., 2001). Because climate warming and water consumption is expected to reduce river discharge in many parts of the world (Postel, 2000), these species-discharge relationships have been used to forecast species diversity losses associated with reductions in freshwater. In addition, river discharge reduction can, for instance, lead to a higher concentration of nutrients and pollutants in freshwater (Xenopoulos and Lodge, 2006) thus compounding the negative effects of water quantity reductions alone on biodiversity. Changes in temperature and precipitation associated with global warming can also adversely affect water availability. It is expected that river discharge reduction due to global warming can negatively influence the distribution and occurrence of many fish species (Figure 1) (Buisson et al., 2008; Mohseni et al., 2003; Chu et al., 2005).

The aim of this paper is to derive characterization factors related to freshwater ecosystem damage for water consumption and greenhouse gas emissions. The present study focuses on the occurrence of freshwater native fish species in global rivers. In order to put our results into LCA perspective, we also calculate normalization factors for water consumption and global warming as input for overall normalization factors that represent biodiversity impacts in freshwater. Normalization factors provide information about the relative importance of each impact category considered, such as impacts on freshwater biodiversity.

2. Methods

2.1 Framework

Figure 1 gives an overview of the cause-effect chain regarding the disappearance of freshwater fish species caused by greenhouse gas emissions and water consumption. In this study, water consumption refers to water used for human activities, (e.g. communal, agricultural and industrial) that is not returned to the river. The influence of reduced flow rates on fish species numbers can be quantified with the global species-discharge model, an index of habitat space, feeding and reproductive opportunities. This model was developed on the basis of information on native fish species and river discharges in various river basins (Xenopoulos et al., 2005). This model assumes a positive correlation between the number of freshwater fish species and average river discharges at the mouth of river basins.

$$R = 4.2 \cdot Q_{mouth,i}^{0.4} \qquad (1)$$

where R is the freshwater fish species richness and Q_{mouth} is the annual average river discharge at the river mouth of basin i ($m^3.s^{-1}$).

The species-discharge relationship can be used as a basis to calculate characterization factors for water consumption that specify freshwater fish species extinction per unit of reduced river discharge for river basins in different regions of the world (Xenopoulos et al., 2005). This has been done in a river basin-specific way. Using the data provided in Xenopoulos et al. (2005) information of the average river discharge for 326 river basins was considered. These 326 rivers include well-known river basins in the world, representing a wide geographical distribution of rivers around the various continents. However, we excluded 83 river basins which are located at latitudes higher than 42^{o}, because these river basins were recently (in geological time) glaciated, i.e. covered by ice. As such, these rivers have not had enough time to evolve to their maximum species richness potential. It follows that the species-discharge relationship for these river basins is weak as they have much fewer species per unit discharge than the rivers below 42^{o}. This indicates that most of the world's river basins located in the high latitudes including Northern Europe, Northern America and Canada were not taken into account. In addition, due to data limitations in the river volume and length calculations, 29 river basins were also excluded. Thus, a total of 214 river basins were used in our final models.

The species-discharge relationship can also be used to derive characterization factors that quantify the potential extinction of freshwater fish species per unit of greenhouse gas emission. The endpoint modelling for global warming further includes the influence of greenhouse gas emissions on global mean temperature and subsequent effects on river water discharge (see Figure 1). The calculation of the characterization factors for water consumption and global warming is explained below.

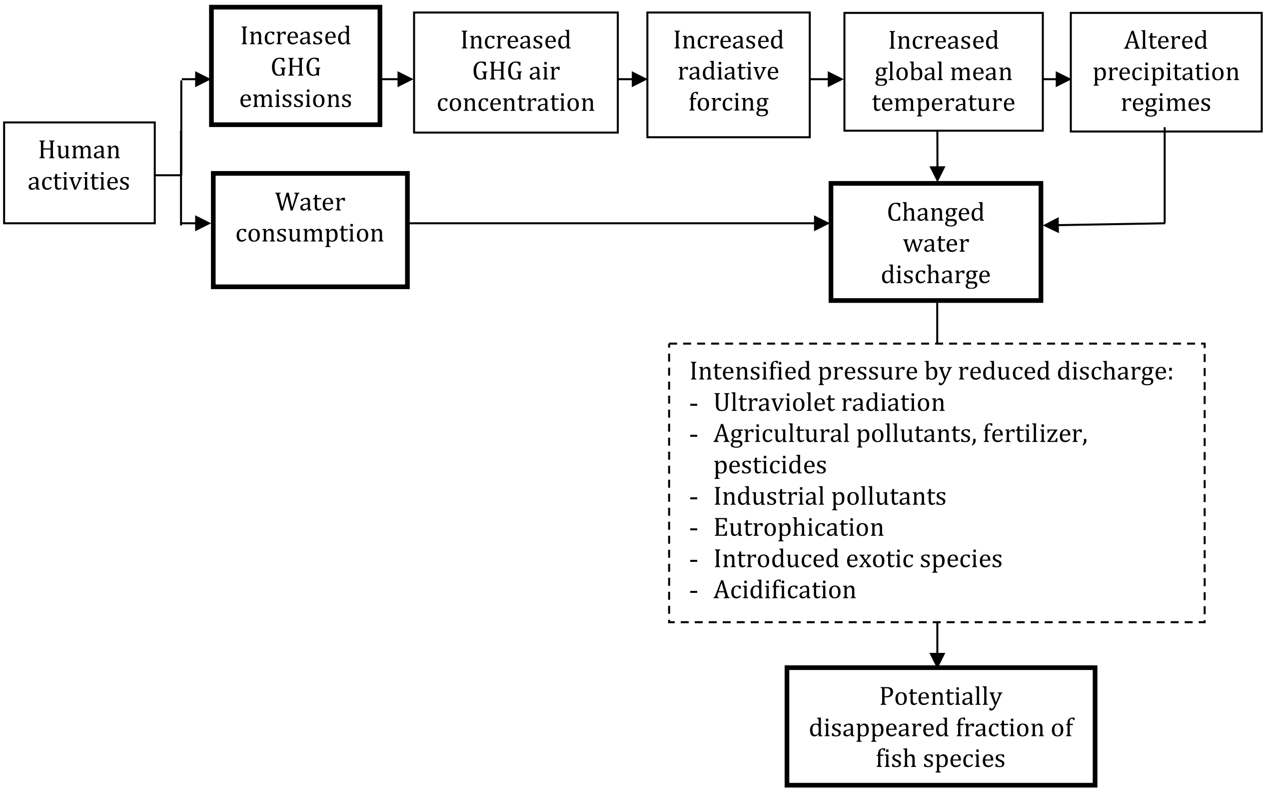


Figure 1: Cause-effect chain for impact of greenhouse gas emissions and water consumption on freshwater fish species (Xenopoulos et al., 2005; Xenopoulos and Lodge, 2006).

2.2 Water Consumption

Characterization factors for water consumption reflect the impact of water use due to human activities on freshwater fish species richness, expressed in units of PDF·m^3·yr·m^{-3}. The river basin-specific characterization factors for water consumption ($CF_{wc,i}$) were calculated by:

$$CF_{wc,i} = FF_i \cdot EF_i = \underbrace{\frac{dQ_{mouth,i}}{dW_i}}_{fate} \cdot \underbrace{\left(\frac{dPDF_i}{dQ_{mouth,i}} \cdot V_i \right)}_{effect} \tag{2}$$

where FF_i is the fate factor of river basin i, EF_i is the effect factor of river basin i (PDF·m^3·yr·m^{-3}), $dQ_{mouth,i}$ is the marginal change in water discharge at the river mouth in basin i (m^3·yr^{-1}), dW_i is the marginal change in water consumption by human activities in river basin i (m^3·yr^{-1}), $dPDF_i$ is the marginal change in the potentially disappeared fraction of the freshwater fish species due to the marginal river discharge change $dQ_{mouth,i}$ and V_i is the volume of river basin i (m^3). The $dQ_{mouth,i}/dW_i$ was assumed to be equal to one, indicating that a change in water consumption (m^3·yr^{-1}) is fully reflected in a change in water discharge at the mouth for that river basin (m^3·yr^{-1}).

The effect factor for each river basin was calculated by:

$$\frac{dPDF_i}{dQ_{mouth,i}} = \frac{dR_i}{R_i \cdot dQ_{mouth,i}} = \frac{4.2 \cdot 0.4 \cdot Q_{mouth,i}^{0.4-1}}{4.2 \cdot Q_{mouth,i}^{0.4}} = \frac{0.4}{Q_{mouth,i}} \tag{3}$$

where $dPDF_i$ is the marginal change in the potentially disappeared fraction of the freshwater fish species for river basin i, d$Q_{mouth,i}$ is the marginal discharge change at the river mouth in basin i (m^3·yr^{-1}) and dR_i is the marginal change of the freshwater fish species richness in river basin i. River basin-specific discharges at the river mouth $Q_{mouth,i}$ were derived from the WaterGap model (Alcamo et al., 2003a).

The river volumes (m^3) for all river basins were calculated by:

$$V_i = \frac{Q_{mouth,i}}{2} \cdot \tau_i \tag{4}$$

where V_i is the water volume in river basin i (m^3), $Q_{mouth,i}$ is the discharge at the river mouth in basin i, and τ_i is the average residence time of water in river basin i (s). Assuming a linear increase of river flow over the distance, we estimated that the average river discharge was half of the discharge at the river mouth. Derivation of the river volume was based on data from various sources (Xenopoulos et al., 2005; Alcamo et al., 2003a; Hugueny, 1989; Fekete et al., 2000; Doll et al., 2003; EarthTrends Watershed of the World, 2007). Further details of the derivation of the river volume can be found in the Supporting Information (estimation of river volumes).

2.3 Greenhouse Gas Emissions

Characterization factors for greenhouse gas emissions quantify the fraction of freshwater fish species that potentially disappear due to a change in emission of greenhouse gases. The characterization factors for 63 greenhouse gas emissions (in PDF·m^3·yr·kg^{-1}) were calculated by:

$$CF_{ghg,x} = FF_x \cdot EF = \underbrace{\frac{dTEMP}{dGHG_x}}_{fate} \cdot \underbrace{\left(\sum_i \frac{dQ_{mouth,i}}{dTEMP} \cdot \frac{dPDF_i}{dQ_{mouth,i}} \cdot V_i \right)}_{effect} \tag{5}$$

Where FF_x is the fate factor for greenhouse gas emission x (^oC·yr·kg^{-1}), EF is the effect factor (PDF·m^3·$^oC^{-1}$), $dGHG_x$ is the change in greenhouse gas emission x (kg·$year^{-1}$), $dTEMP$ is the change in global mean temperature (^oC), $dQ_{mouth,i}$ is the change in water discharge at the river mouth in basin i (m^3·yr^{-1}), $dPDF_i$ is the marginal change in the potentially disappeared fraction of freshwater fish species in river basin i and V_i is the volume of river basin i (m^3).

Temperature factors were taken from De Schryver et al. (2009) and consist of three calculation steps. The first step resembles the change in air concentration of greenhouse gases due to a change in emission and reflects the atmosphere life time of a greenhouse gas. The second step represents the change in radiative forcing due to a concentration change. The third step reflects the change in global mean temperature due to the change in radiative forcing. The climate sensitivity and heat absorption rate by the oceans determine the relation of global mean temperature change and radiative forcing change (Randall et al., 2007). A time horizon of 100-year was applied in the present study. The indirect cooling effect of ozone depleting substances was not included in the greenhouse gas calculations due to the high uncertainties involved (see De Schryver et al., 2009).

Freshwater effect factors related to climate change require river basin-specific information on the change in PDF due to a change in global mean temperature. The effect factor was derived by:

$$EF = \sum_i \frac{dQ_{mouth,i}}{dTEMP} \cdot \frac{dPDF_i}{dQ_{mouth,i}} \cdot V_i \approx \sum_i \frac{\Delta Q_{mouth,i}}{\Delta TEMP} \cdot \frac{0.4}{Q_{mouth,i}} \cdot V_i \tag{6}$$

where $dQ_{mouth,i}$ is the change in the water discharge at the river mouth in basin i ($m^3 \cdot yr^{-1}$) and $dTEMP$ is the change in global mean temperature (^oC). It is not possible to derive $dQ_{mouth,i}/dTEMP$ analytically, thus, data from IPCC (2001) and Millennium Ecosystem Assessment (2005) as described in Xenopoulos et al. (2005) and Sala et al. (2005) were used for the derivation of $\Delta Q_{mouth,i}/\Delta TEMP$ for five global climate scenarios in the year 2100. For every scenario, we divided the modelled change in river discharge from the WaterGap model (Alcamo et al., 2003a) by the predicted temperature change for the year 2100. Further information on the five global climate scenarios can be found in the Supporting Information (Table S1).

River discharge is predicted to increase in some areas of the world due to increased precipitation[31]. Without human accidental or intentional fish introductions, it is unlikely that increasing river discharge will have a positive effect on fish species richness, particularly at the current time scale as related to local scale and isolated river basins (Xenopoulos et al., 2005). Therefore, river basins with increased discharge were excluded in the calculation of the effect factor for global warming.

2.4 Normalization

Normalization factors provide information about the relative importance of each impact category and were expressed as the potentially disappeared fraction of species over a certain river volume per capita. Normalization factors for water consumption refer to the year 1995 (Alcamo et al., 2003a; Alcamo et al., 2003b; Shiklomanov, 1999), while normalization factors for global warming were based on greenhouse gas emissions in year 2000 (Sleeswijk et al., 2008). The population numbers were taken from the U.S. Census Bureau (2010). Due to lack of data, we were only able to derive the normalization factors for water consumption and global warming for 112 river basins and 21 greenhouse gas emissions, respectively.

3. Results

3.1 Water Consumption

River basin-specific characterization factors for water consumption differs 3 orders of magnitude (Figure 2). Most of the river basins (57%) have characterization factors for water consumption between 10^{-4} – 10^{-3} PDF·m^3·yr·m^{-3}. The characterization factors for the largest river basins in the world, such as the Nile, the Amazon and the Yangtze Rivers are between 10^{-3} – 10^{-2} PDF·m^3·yr·m^{-3}. Characterization factors for all 214 river basins can be found in the Supporting Information (Table S4).

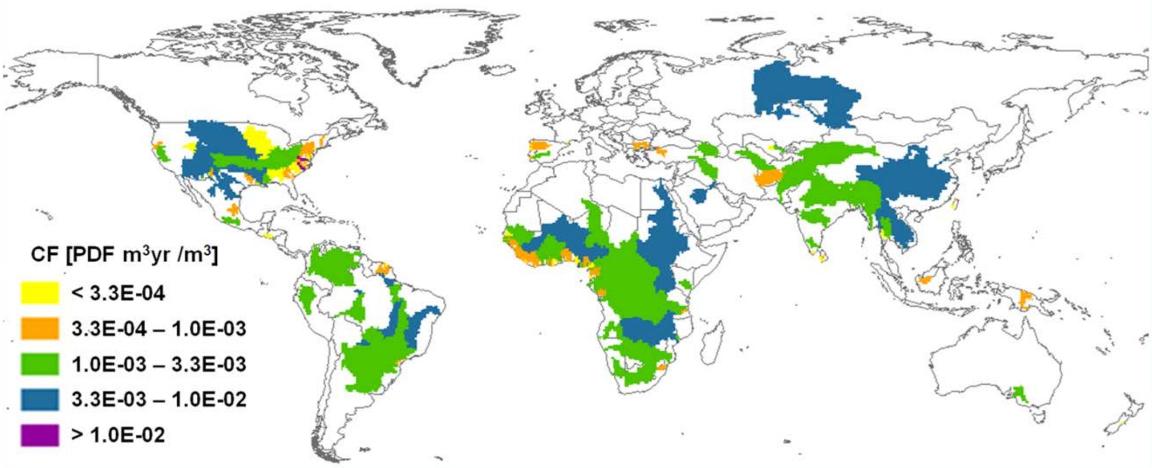


Figure 2: Characterization factors for water consumption (PDF·m^3·yr·m^{-3}).

3.2 Greenhouse Gas Emissions

Characterization factors for CO_2, CH_4, N_2O, CFC-11, SF6 and HFC-125 emissions are shown in Figure 3 (ranges from $8.5 \cdot 10^{-5}$ to 2.1 PDF·m^3·yr·kg^{-1}). The largest characterization factor is found for SF6 (around 4 orders of magnitude larger than CO_2). The differences between the greenhouse gases are determined by the differences in atmospheric residence time and radiative forcing efficiency. The rivers with the largest contribution to the characterization factors for global warming are the Amazon, Madeira, Orinoco, Purus and Brahmaputra. These rivers explain together 65% of the freshwater ecosystem impact per unit of greenhouse gas emission. The river basin-specific effect factors and the characterization factors of 63 greenhouse gases are listed in the Supporting Information (Tables S2 and S5 respectively).

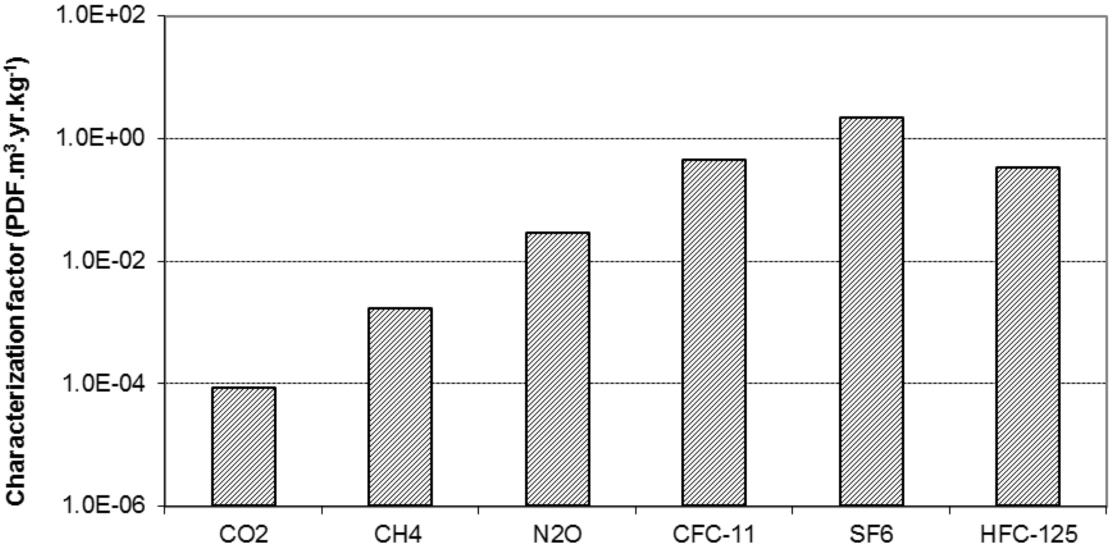
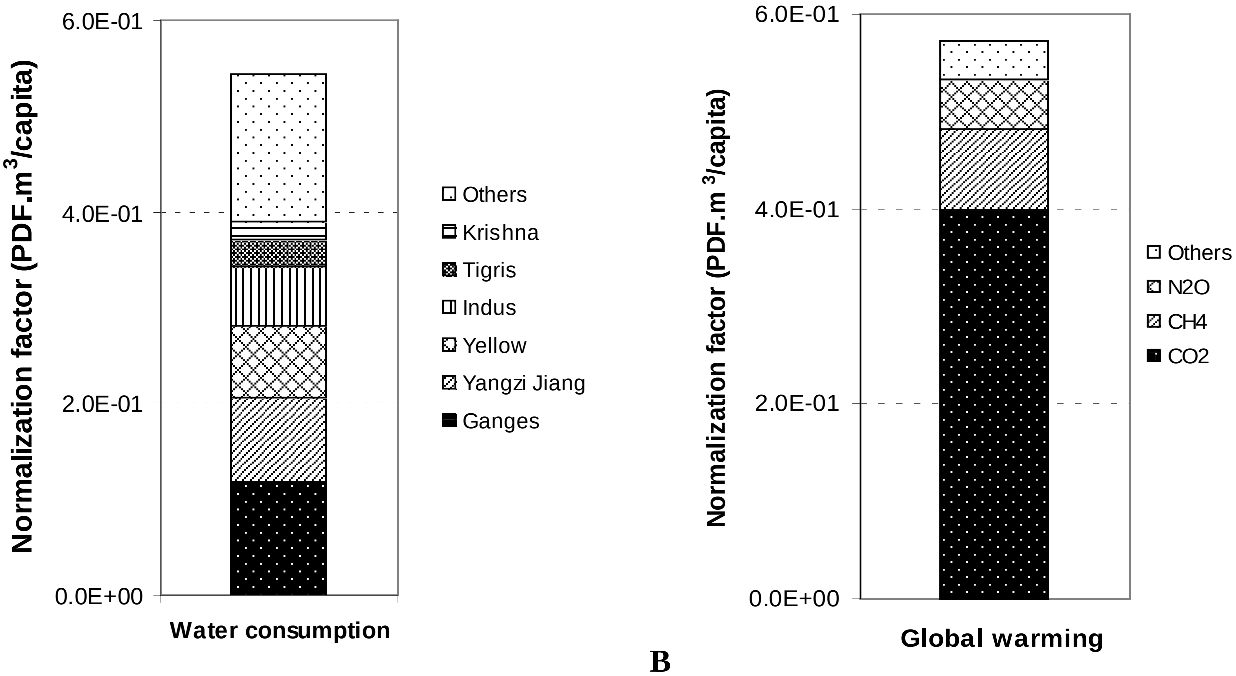


Figure 3: Characterization factors of six greenhouse gas emissions (PDF·m^3·yr·kg^{-1}) from a 100-year time horizon.

3.3 Normalization

The normalization factors per capita for water consumption and global warming are approximately equal (respectively 0.54 and 0.57 PDF·m^3/capita). For water consumption, the highest normalization factor is found for the Ganges River, which constitutes 22% impact of the river basins considered (Figure 4A). The normalization factor based on emissions in year 2000 shows that CO_2 contributes most to global warming, with 70% of the total greenhouse gas emissions included (Figure 4B). Normalization factors for river basin-specific water consumption and greenhouse gas emissions are given in the Supporting Information (Tables S4 and S5 respectively).



A **B**

Figure 4: River basin-specific normalization factors (PDF·m^3/capita) for water consumption in year 1995 (4A) and normalization factors for global warming based on emissions in year 2000 (4B).

4. Discussion

We were able to derive characterization factors for water consumption and global warming based on information of potential freshwater fish species disappearance for 214 river basins worldwide. Below we discuss the uncertainties related to our calculations and provide the implications of our study.

4.1 Fate factors

The estimation of river volumes, based on the average river discharge and the average water residence time in river, affects both the fate factors for water consumption and greenhouse gas emissions. We assumed as a first approximation that the average river discharge was half of the discharge at the river mouth and that the average travel time was half of the total length of river. Furthermore, integration of data from multiple data sources in the water volume calculation of the rivers will lower the degree of data consistency. A complete data for worldwide river characteristics is however, not available. Therefore, we had to combine heterogeneous data sources for deriving river volumes (see Table S2 in the Supporting Information).

Second, an uncertainty specifically related to the calculation of fate factors for global warming, is the arbitrary selection of a 100-year time horizon. For a number of greenhouse gases, particularly with a relative long lifetime in the atmosphere such as SF6, the results are sensitive to the choice of time horizon (De Schryver et al., 2009; Levasseur et al., 2010). For instance, the characterization factor of SF6 will increase with about 2 orders of magnitude if an infinite time horizon is chosen instead.

Finally, we excluded in our global warming calculations the indirect influence of ozone depleting chemicals, such as cholorofluorocarbons and halons, on radiative forcing. The indirect effects of ozone depleting chemicals can result in net negative radiative forcing and therefore negative fate factors (De Schryver et al., 2009; Brakkee et al., 2008).

4.2 Effect factors

A number of uncertainties are also related to the effect factor calculations of water consumption and global warming. First, due to recent geological glaciation, we had to exclude river basins in the effect factor calculations that are located at the latitude higher than 42^{o}. Applying the current species-discharge curve would lead to overestimation of effect factors for water consumption and global warming in these rivers, as the rivers above 42^{o} have much fewer species per unit discharge. In order to consider river basins above 42^{o}, a specific species-discharge curve need to be built for these river basins. For global warming we conducted a sensitivity analysis by including other river basins (> 42^{o}) as well in the calculation of the characterization factors. As shown in the Supporting Information (Figure S1), including all river basins (297 river basins in total) in the calculation of the characterization factors for global warming increases the effect factor by 1.5%. This uncertainty is considered low compared to the uncertainties in the calculation from emission to global mean temperature increase (see De Schryver et al., 2009).

Second, we used a global fish species-discharge model as opposed to basin-specific fish species-discharge curves which may be more accurate (Xenopoulos et al., 2005). However, global data sets of fish species are often not available to build watershed-specific species-discharge models.

Third, the modification of the flow regime at a range of spatial scales that affects fish species may also affect the associations between aquatic macroinvertebrates and their habitat

(Bunn and Arthington, 2002; Dewson et al., 2007; Poff and Zimmerman, 2010). However, other aquatic freshwater taxonomic groups could not be included in this study because of insufficient data on the global scale. This implies that our characterization factors do not fully represent all the lotic aquatic ecosystems.

Fourth, the influence from building dams and abstractions was not considered in the study (see Xenopoulos et al., 2005). The absence of dams allowed us to model more accurate species-discharge curves without any human influences, as dams are known to reduce the average downstream river discharge (Rosenberg et al., 2000; Magilligan and Nislow, 2005. In future research, the species-discharge curve as employed in this paper, could also be used to provide river-specific characterization factors for the construction of dams to produce hydropower.

Fifth, we estimated the river basin specific dQ/dTEMP for global warming based on five future scenarios. Uncertainty in the calculation of dQ/dTEMP is associated with the future scenario chosen. Future climate change projection is difficult and uncertain to define because changes in the future economic growth, technology and policy-making processes concerning human actions are unknown (Trenberth et al., 2000). In the present study, the dQ/dTEMP can be a factor of 2 higher or lower, depending on the scenario chosen. This uncertainty can particularly influence the relative importance of impacts of greenhouse gas emissions compared to other stressors.

Finally, we compared our effect factors for global warming with effect factors reported in a previous study on direct temperature effects towards aquatic organisms (Verones et al., 2010). Our volume-weighted effect factor for the impact of climate change on fish species is typically $7 \cdot 10^{-3}$ and ranges between $3 \cdot 10^{-3}$ and $2 \cdot 10^{-2}$ PDF·$^{o}C^{-1}$. This implies that an increase in global mean temperature of $1^{o}C$ would typically result in 0.7% (0.3-2%) fish species loss. Verones et al. (2010) calculated effect factors for freshwater ecosystems due to direct water temperature increase of cooling water discharge in the river Rhine. They found that the effect factor is significantly higher in summer than in winter time (5 orders of magnitude), with a yearly average effect factor of around 1% species loss per ^{o}C increase and a highest monthly effect factor of 4% species loss per ^{o}C increase. The results from Verones et al. (2010) imply that including direct temperature effects on freshwater species occurrence could significantly increase the characterization factors for greenhouse gas emissions. The river basin specific information, required to calculate the effect factors according to Verones et al. (2010) in a meaningful way, is, however, currently not available. For generalization, river-specific data for the ambient water temperature over the seasons, key river characteristics for heat exchanges and information on species pools, based on the susceptibility of species in different climatic zones, should be gathered.

4.3 Implications

We developed regionalized characterization factors for water consumption and generic characterization factors for global warming related to freshwater ecosystem impacts on the global scale. Regionalized inventory data of water consumption is required to apply the new characterization factors in practice. With this information, comparison between the new characterization factors of water consumption and greenhouse gas emissions with other stressors for freshwater biodiversity are now possible.

Acknowledgements

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Supporting Information

1. Estimation of river volumes

Estimation of the river volume was based on data from Xenopoulos et al. (2005), Alcamo et al. (2003a), Hugueny (1989), Fekete et al. (2000), Doll et al. (2003), and EarthTrends Watersheds of the World (2007). The water volume of a river can be calculated by:

$$V_i = Q_i \cdot \tau_i \tag{S1}$$

where V_i is the water volume of river i (m^3), Q_i is the average discharge of river i ($m^3 \cdot s^{-1}$) and τ_i is the average residence time of the water in river i (s).
The average river discharge was calculated by:

$$Q_i = \frac{Q_{mouth,i}}{2} \tag{S2}$$

where $Q_{mouth,i}$ is the discharge at the mouth of river i ($m^3 \cdot s^{-1}$) available from WaterGap (2003a). The average distance travelled by each raindrop will depend on the river network pattern. By dividing $Q_{mouth,i}$ by 2 to estimate the spatially averaged discharge, we assume that the average distance travelled is half of the river's total length.
The average residence time (in s) was obtained from the river's total length and the average river water velocity:

$$\tau_i = \frac{L_i/2}{v_i} \tag{S3}$$

where L_i is the length of river i (m) and v_i is the average velocity of river i ($m \cdot s^{-1}$). Again, we assumed that the average distance travelled of the water is half of the river's total length.

Based on Allen et al. (1994), a typical river velocity can be derived from river discharge data via:

$$v_i = 1.067 \cdot Q_i^{0.1035} \tag{S4}$$

where v_i is the river velocity ($m \cdot s^{-1}$) and Q_i is the average river discharge in river basin i ($m^3 \cdot s^{-1}$).

Feeding equation 4 into 3, and equations 2 and 3 into equation 1 reveals that:

$$V_i = \frac{Q_{mouth,i}}{2} \cdot \frac{L_i/2}{1.067 \cdot \left(\frac{Q_{mouth,i}}{2}\right)^{0.1035}} = 0.47 \cdot \left(\frac{Q_{mouth,i}}{2}\right)^{0.90} \cdot L_i \qquad \text{(S5)}$$

2. Derivation of $dQ_{mouth,i}/dTEMP$

The derivation of $dQ_{mouth,i}/dTEMP$ for all the 214 river basins was taken as a starting point in the calculation of the effect factor for global warming, using year 2100 as a future reference year. The river basin-specific $dQ_{mouth,i}/dTEMP$ was calculated by dividing the discharge at the mouth of each river basin with the global mean temperature change in 2100. As reported in IPCC (2001) and MA (2005), global mean temperature changes are projected within the range of 1.9 to 4.4 by the year 2100, depending on the scenario chosen (see Table S1). The effect factors were calculated for five global climate scenarios to project freshwater fish species loss for the year 2100 by multiplying $dQ_{mouth,i}/dTEMP$ with $dPDF_i/dQ_{mouth,i}$ over all river basins included.

Table S1: Summary of the five global climate scenarios considered in the present study (IPCC, 2001; MA, 2005).

Scenario	Summary	Global mean temperature change in 2100 (^oC)
A2	A heterogeneous world with continuously increasing population growth rate. Regionalized and fragmented economic growth and slow technological change.	4.4
B2	A world with intermediate levels of economic and population growth, and emphasize on local solutions to economic, social, and environmental sustainability. Technological change is faster than A2.	3.2
FW	Regionalized and fragmented world. Reactive approach to the global environmental problems. High population growth with low economic development and technological change. The gap between rich and poor countries increases over time.	3.3
GO	Strong global action with emphasis on trade and economic growth. Offer an equal access on public goods and services. Reduce poverty by improving human well-being. Reactive approach to the global environmental problems.	3.5
TG	Strong global action, with emphasis on green technology. High economic growth. Proactive approach to the global environmental problems using technology and market-oriented institutional reform. Focusing on economic, education and human well-being. Symbiotic benefits for both the environment and economy.	1.9

3. Influence of including river basins located above 42^o

3.1 Greenhouse gas emissions

Figure S1 shows the effect factors for greenhouse gases for five global scenarios in 214 and 297 river basins. The average effect factor for 214 river basins included is $2.04 \cdot 10^9$ PDF·.m^{3}·$^oC^{-1}$. When including other river basins that located at the higher latitude (> 42^o), the average effect factor increases to $2.07 \cdot 10^9$ PDF·m^{3}·$^oC^{-1}$. A relatively high potential freshwater fish species loss is reported in B2 scenario per degree of temperature increase compared to the other future scenarios. This finding can be explained by the fact that in the B2 scenario the decrease in water discharge is predicted is due to the low water discharge in this scenario compared to other scenarios in rivers with the highest effect factors, i.e. the rivers below 42 degrees latitude with the highest river length. This results in a relatively high value for *dPDF/dQ* in the B2 scenario.

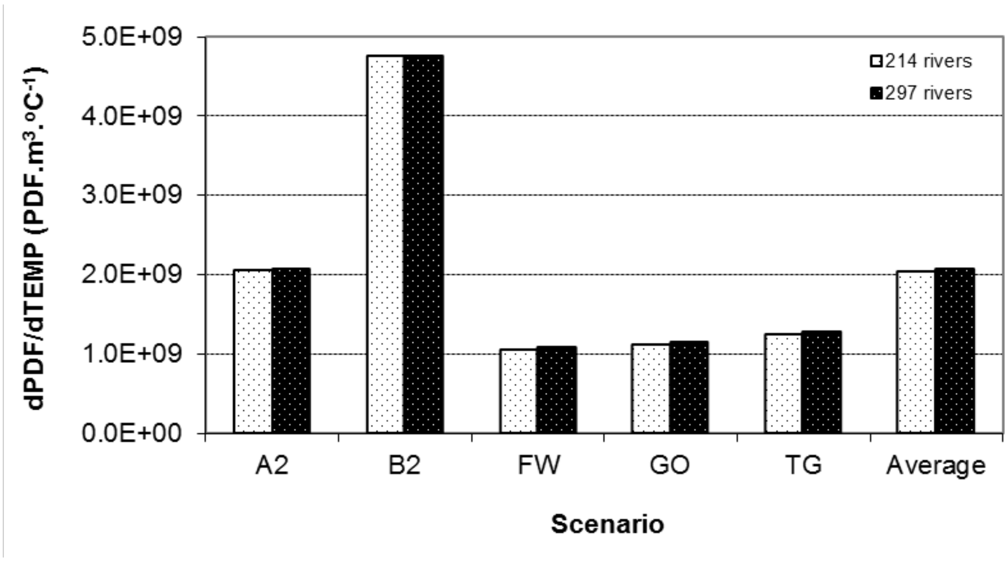

Figure S1: The effect factors for greenhouse gas emissions (PDF·m^{3}·°C^{-1}) based on IPCC and MA scenarios for 214 and 297 river basins, respectively.

4. Normalization factors

Characterization factors, water consumption in year 1995 and normalization factors for water consumption for 112 river basins were included. Due to lack of data, we were not able to derive normalization factors for all river basins considered in this study. To derive normalization factors for water consumption, we started with water withdrawal data for households, irrigation, industry, and livestock sectors representative for year 1995 from the WaterGap model (2003a; 2003b). We converted water withdrawal to water consumption by using continent-specific water withdrawal-consumption ratios derived from Shiklomanov (1999), i.e. for Europe = 43%, North America = 34%, Africa = 72%, Asia = 62%, South America = 53% and Australia = 58%. The total population for the 112 river basins included is $2.65 \cdot 10^{9}$. Normalization factors were expressed in unit of the potentially disappeared fraction of fish species for river-specific water consumption (PDF·m^3/capita). The total normalization factor for direct water consumption (NF_{wc}) was calculated by:

$$NF_{wc} = \frac{\sum_i W_i \cdot CF_i}{\sum_i N_i} \tag{S6}$$

where W_i is the water consumption in river basin i ($m^3 \cdot yr^{-1}$), CF_i is the characterization factor for river basin i ($PDF \cdot m^3 \cdot yr \cdot m^{-3}$) and N_i is the number of capita in river basin i (capita).

The normalization factors for global warming were based on the global greenhouse gas emissions for year 2000. The total population numbers in the world in 2000 is $6.1 \cdot 10^9$ (U.S. Cencus Bureau, 2010). Normalization factors were expressed in unit of the potentially disappeared fraction of fish species over a certain river volume due to global greenhouse gas emissions in 2000 ($PDF \cdot m^3$/capita). The total normalization factor for greenhouse gas emissions (NF_{ghg}) was calculated by:

$$NF_{ghg} = \frac{\sum_x M_x \cdot CF_x}{N_{world}} \tag{S7}$$

where M_x is the emitted quantity of a substance x (kg), CF_x is the characterization factor for substance x ($PDF \cdot m^3 \cdot yr \cdot kg^{-1}$) and N_{world} is the total number of capita in the world in year 2000 (capita).

Table S2: River characteristics for 214 river basins below 42 degrees latitude (Xenopoulos et al., 2005; Alcamo et al., 2003a; Hugueny, 1989; Fekete et al., 2000; Doll et al., 2003; EarthTrends Watersheds of the World, 2007) and river-specific effect factor for global warming. Due to increased precipitation, the river discharge rate is predicted to increase in some areas (Rosenzweig et al., 2007). River basins with increased discharge were excluded in the calculation of the effect factor for global warming.

* - River basins with increased discharge.

River basins below 42 degrees latitude	River length (km)	Average river discharge at the mouth ($km^3 \cdot yr^{-1}$)	Calculated river volume (m^3)	Effect factor for global warming ($PDF \cdot m^{3} \cdot {}^{o}C^{-1}$)
Nil (Af., int.)	5909	75.87	1.60E+09	*
Senegal (Guinée-Sénégal)	1680	9.94	7.34E+07	6.12E+06
Gambia (Guinée-Gambie)	745	6.76	2.31E+07	1.29E+06
Tominé ou Rio Corubal (Guinée-Guineé Bissau)	463	17.82	3.42E+07	9.67E+05
Konkouré (Guinée)	303	13.08	1.69E+07	2.70E+05
Kolenté (Guinée, Great Scarcies)	240	28.05	2.66E+07	4.07E+05
Jong (Sierra Leone)	249	17.85	1.84E+07	1.09E+05
Sewa (Sierra Leone)	240	17.41	1.73E+07	1.24E+05
Moa (Guinée-Sierra Leone)	425	26.14	4.42E+07	2.52E+05
Mano (Libéria)	276	10.79	1.30E+07	2.66E+04
Loffa (Guinée-Libéria)	349	15.81	2.31E+07	4.37E+04
St Paul (Libéria)	410	36.46	5.75E+07	2.26E+04
Nipoué (Cess, Libéria-RCI)	332	16.94	2.34E+07	*
Cavally (Libéria-RCI)	379	25.70	3.88E+07	*
Dodo (aka Déo) (RCI)	89	19.35	7.04E+06	*
San Pédro (RCI)	193	2.55	2.49E+06	*
Sassandra (RCI)	569	30.61	6.82E+07	*

N'Zo (a. Sassandra) (RCI)	243	3.25	3.91E+06	*
Boubo (RCI)	130	2.69	1.76E+06	*
Bandama (RCI)	692	23.26	6.48E+07	*
Yani (s.a. Bandama) (RCI)	167	23.26	1.56E+07	*
Marahoué (a. Bandama) (RCI)	249	12.76	1.36E+07	*
N'Zi (a. Bandama) (RCI)	472	6.86	1.48E+07	*
Kan (s.a. Bandama) (RCI)	629	23.26	5.89E+07	*
Agnébi (RCI)	281	2.76	3.89E+06	*
Comoé (RCI-Burkina)	750	5.92	2.06E+07	*
Bia (RCI-Ghana)	260	4.32	5.38E+06	5.53E+03
Volta (Ghana-Burkina)	1301	32.76	1.66E+08	*
Black Volta (Burkina-Ghana) (a. Volta)	1352	8.11	4.93E+07	*
Nasia (a. White Volta) (Ghana)	219	8.52	8.33E+06	3.00E+04
Daka (a. Volta) (Ghana)	106	21.45	9.23E+06	*
Mono (Togo)	412	3.47	7.01E+06	*
Ouémé (Bénin)	480	6.22	1.38E+07	*
Ogun (Nigéria)	410	5.81	1.11E+07	*
Niger (Afr. Int.)	4200	147.43	2.06E+09	*
Niandan (Guinée) (a. Niger)	344	18.69	2.65E+07	4.59E+05
Bénoué (Nigéria-Cameroun) (a. Niger)	1400	68.68	3.46E+08	*
Sokoto (a. Niger) (Nigeria)	275	29.01	3.14E+07	5.24E+04
Cross (Nigéria-Cameroun)	480	59.93	1.05E+08	*
Mungo (Cameroun)	13	8.27	4.82E+05	3.29E+02
Dibamba (Cameroun)	150	18.78	1.16E+07	1.48E+04
Wouri (Cameroun)	160	18.78	1.24E+07	1.58E+04
Sanaga (Cameroun)	803	63.81	1.86E+08	3.69E+05
Nyong (Cameroun)	402	22.14	3.60E+07	8.34E+04
Lokoundjé (Cameroun)	185	3.12	2.87E+06	2.85E+03
Kribi ou Kienké (Cameroun)	100	3.12	1.55E+06	1.54E+03

Lobé (Cameroun)	80	3.12	1.24E+06	1.23E+03
Ntem (Cameroun-Gabon-Guinée équat.)	356	19.21	2.81E+07	1.50E+04
Ogôoué (Gabon)	815	155.06	4.18E+08	9.00E+05
Niari-Kouilou (Congo)	481	28.35	5.38E+07	6.76E+05
Zaïre (Afr., Int.)	4339	1348.39	1.55E+10	5.11E+06
Cunene ou Kunene (Namibie-Angola)	828	8.80	3.24E+07	6.18E+05
Kasaï (a. Zaïre) (Zaïre-Angola)	2153	573.15	3.57E+09	*
Chari (Lac Tchad)	1733	25.45	1.76E+08	*
Ubangi (a. Zaïre) (Congo-RCA)	2300	177.98	1.34E+09	*
Zambezi (Mozambique-Zambie-Angola)	2693	120.36	1.10E+09	6.78E+07
Tana (Kénya)	671	7.31	2.23E+07	1.13E+05
Rufiji (Tanzanie)	809	30.49	9.66E+07	2.33E+05
Limpopo (Botswana-Mozamb.-Rhodésie-RSA)	1800	9.12	7.28E+07	3.45E+06
Pongolo ou Maputo (RCA-Mozambique)	347	4.73	7.80E+06	1.42E+05
Shire (a.) (Malawi-Mozambique)	1200	119.70	4.88E+08	3.00E+07
Kafue (a. Zambèze) (Zambie)	960	17.84	7.09E+07	3.80E+06
Ruaha (a. Rufiji) (Tanzanie)	475	30.49	5.67E+07	1.37E+05
Evros-Mariça (Grèce-Turquie-Bulgarie)	415	11.01	1.99E+07	5.58E+05
Nesta-Nestos (Grèce-Bulgarie)	230	1.91	2.29E+06	1.08E+05
Strymon-Strouma (Grèce-Bulgarie)	389	3.40	6.50E+06	2.45E+05
Agly (France)	82	1.38	6.12E+05	4.48E+03
Minho (Portugal-Espagne)	350	11.20	1.70E+07	1.20E+04
Lima (Portugal)	108	3.23	1.72E+06	1.63E+03
Cavado (Portugal)	135	3.23	2.15E+06	2.04E+03
Douro (Portugal-Esp.)	555	23.10	5.17E+07	5.06E+05
Vouga (Portugal)	148	1.67	1.31E+06	2.13E+03
Mondego (Portugal)	234	2.78	3.27E+06	7.06E+03
Sado (Portugal)	175	1.28	1.22E+06	1.22E+04
Mira (Portugal)	145	0.33	3.01E+05	2.74E+03

Guadiana (Portugal-Esp.)	766	7.86	2.71E+07	4.20E+05
Raisin (Canada)	217	178.89	1.27E+08	1.05E+05
Sydenham (Canada)	165	162.07	8.81E+07	7.69E+04
Grand river (Canada)	280	196.50	1.78E+08	1.28E+05
Thames (Canada)	270	4.90	6.26E+06	*
Mississipi (USA)	4185	530.64	6.47E+09	8.21E+06
Rio Grande (USA-Mexique)	2219	8.00	7.98E+07	2.10E+05
Pecos (a. Rio Grande)	1490	6.55	4.48E+07	*
Canadian (s. a. Mississipi) (USA)	1223	4.59	2.67E+07	3.05E+05
Colorado (USA-Mexique)	1750	1.35	1.28E+07	3.03E+04
San Juan (a. Colorado) (USA)	375	15.72	2.47E+07	7.52E+03
Zuni (s. a. Colorado) (a. Little Colorado)	145	15.05	9.19E+06	3.42E+03
San Francisco (a. Gila) (USA)	2212	0.04	7.17E+05	*
Gila (a. Colorado)	1044	0.68	4.13E+06	*
Ohio river (a. Mississipi)	2102	240.85	1.60E+09	*
Scioto (a. Ohio)	372	83.41	1.09E+08	*
Big Darby Creek (s. a. Ohio) (a. Scioto)	135	3.89	2.55E+06	6.29E+02
Wabash (a. Ohio)	764	147.34	3.75E+08	*
Little Wabash (a. Wabash)	320	147.34	1.57E+08	*
Embarras (a. Wabash)	298	12.70	1.62E+07	1.93E+04
St Joseph (s.a. Wabash)	160	2.84	2.27E+06	6.79E+03
Elk (s. a. Ohio) (a. Kanawha)	277	9.56	1.17E+07	*
Cumberland (a. Ohio)	1106	93.04	3.59E+08	*
Green (a. Ohio)	1175	118.14	4.73E+08	*
Kanawha (a. Ohio)	156	65.60	3.70E+07	*
Tennessee (a. Ohio)	1049	240.85	7.99E+08	*
Muskingum (s.a. Ohio) (a. Allegheny)	179	36.46	2.51E+07	*
Allegheny (a. Ohio)	523	10.61	2.42E+07	*
Little Miami (a. Ohio)	170	93.83	5.56E+07	*

Hocking (a. Ohio)	153	47.46	2.72E+07	*
Kinniconick (a. Ohio)	159325	85.56	4.80E+10	*
Licking (a. Ohio)	65	93.83	2.13E+07	*
Little Scioto (a. Ohio)	65	2.60	8.54E+05	8.11E+01
Ohio Brush Creek (a. Ohio)	102	83.41	3.00E+07	*
Olentangy (a. Little Scioto)	98	1.91	9.78E+05	2.24E+02
Paint Creek (a. Scioto river)	153	6.97	4.85E+06	*
Scioto Brush Creek (a. Scioto)	57936	83.41	1.71E+10	*
Symmes (a. Ohio)	97	67.74	2.37E+07	*
Tygart Creek (a. Ohio)	257	2.72	3.52E+06	*
Bear Creek	46	1.17	2.94E+05	*
Apalachicola (USA)	180	24.24	1.75E+07	1.07E+04
Klamath (USA)	318	19.77	2.57E+07	2.26E+05
Mobile (USA)	72	60.65	1.59E+07	*
Potomac (USA)	297	11.02	1.42E+07	*
Sabine (USA)	564	12.92	3.12E+07	5.05E+05
Sacramento (USA)	927	36.79	1.31E+08	1.81E+06
Savannah (USA)	457	11.18	2.22E+07	*
Susquehanna (USA)	514	33.01	6.59E+07	*
Connecticut (USA)	497	17.64	3.63E+07	*
Missouri (USA)	3767	192.83	2.35E+09	8.42E+06
Arkansas (USA)	2364	547.14	3.76E+09	3.28E+06
Red (USA)	2188	522.08	3.33E+09	4.00E+06
Altamaha (USA)	449	13.33	2.55E+07	9.55E+03
Balsas (Mexico)	706	24.85	7.02E+07	1.34E+06
Panuco (Mexico)	490	17.15	3.49E+07	6.76E+05
Sucio (a. Lempa) (San Salvador)	25	13.42	1.43E+06	7.85E+04
Paz (San Salvador)	134	4.47	2.86E+06	1.52E+05
San Tiguel (ou Miguel) San Salvador)	145	1.30	1.02E+06	1.07E+05

Paraguay (Brésil-Arg.-Paraguay) (a. Parana)	2549	539.87	4.00E+09	*
Uruguay (Brésil-Arg.-Uruguay)	1424	181.85	8.43E+08	*
Magdalena (Colombie)	1271	218.38	8.87E+08	9.30E+06
Rio Negro (a. Amazone) (Colomb.-Venez.-Brésil)	1112	4067.95	1.07E+10	8.24E+07
Parnaiba (Brésil)	1192	26.62	1.26E+08	5.25E+06
Madeira (a. Amazone) (Brésil-Bolivie)	3239	5010.21	3.75E+10	2.93E+08
Orinoco (Vénézuela-Colombie)	1970	1096.40	5.84E+09	1.85E+08
Parana (Brésil-Paraguay-Argentine)	2748	601.89	4.76E+09	*
Tibagi (Bresil)	550	11.51	2.74E+07	1.69E+04
Amazon (Br. Mère Maranon) (Pérou-Brésil)	4327	6394.15	6.23E+10	6.17E+08
Maroni (Guyane-Surinam)	445	57.17	9.34E+07	6.07E+06
Oyapock (Guyane-Brésil)	291	40.17	4.45E+07	2.28E+06
Approuague	270	10.68	1.26E+07	5.98E+05
Sinnamary (Guyane)	250	12.16	1.31E+07	6.78E+05
Kourou (Guyane)	112	6.90	3.53E+06	1.75E+05
Vakhsh ou Vachs (fSU) (a. Amu Darya)	1976	51.29	3.76E+08	*
Surkhandarya ou Surchandarya (fSU)	175	54.58	3.52E+07	*
Zeravshan (a. Syr Darya) (fSU)	1615	59.28	3.50E+08	*
Naryn (a. Syr Darya) (fSU)	807	16.27	5.49E+07	*
Tarim (Chine)	1227	2.23	1.40E+07	*
Murgab ou Murghab ou Mourbab (fSU-Afghanistan) Endo	850	2.78	1.19E+07	3.62E+04
Kabul (a. Indus) (Afghanistan-Inde)	700	84.80	2.09E+08	*
Salween (Tibet-Chine-Birmanie-Thaï)	2576	98.52	8.80E+08	*
Mae Khlong (Thaïlande)	145	21.06	1.24E+07	*
Chao Phrya (Menam) (Thaïlande)	710	27.48	7.72E+07	*
Mekong (Asie Sud-Est, Int.)	3977	421.80	5.01E+09	*
Kelani Ganga(Sri Lanka)	145	3.85	2.71E+06	6.55E+03
Kalu Ganga (Sri Lanka)	129	3.85	2.41E+06	5.82E+03
Gin Ganga (Sri Lanka)	116	2.38	1.41E+06	*

Nilwala Ganga (Sri Lanka)	72	4.32	1.49E+06	3.10E+03
Mahaweli Ganga (Sri Lanka)	335	3.44	5.66E+06	7.77E+04
Brahmapoutre ou Tsangpo (Inde-Bengladesh-Tibet)	2897	1186.94	9.22E+09	1.06E+08
Indus (Tibet-Inde-Pakistan)	2382	121.17	9.80E+08	2.34E+06
Gange (Inde)	2221	397.83	2.65E+09	9.78E+07
Ob (fSU)	3977	413.18	4.91E+09	*
Yangzi Jiang (Tibet-Chine)	6380	955.40	1.67E+10	*
Gandaki (a. Gange) (nepal)	630	1186.94	2.00E+09	3.87E+07
Sakaria (Turkey)	506	7.78	1.78E+07	4.82E+05
Rakaïa (New-Zealand)	150	4.74	3.38E+06	*
Fly (Nlle-Guinée)	678	135.37	3.08E+08	4.34E+06
Sepik-Ramu (Nlle-Guinée)	285	100.67	9.93E+07	1.76E+06
Kapuas (Bornéo)	569	174.16	3.24E+08	*
Murray-Darling (Australie)	1767	11.14	8.55E+07	2.83E+06
Yellow (Huang He, Huang Ho, China)	4168	56.53	8.66E+08	*
Yangtze (Chang Jiang, Yangtze Kiang, China)	4734	955.94	1.24E+10	*
Xi Jiang (Pearl, Chu Chiang, Zhu, Southeast China)	1696	270.52	1.43E+09	*
Tsengwen (Southwestern Taiwan)	130	1.29	9.12E+05	1.42E+03
Tigris (Southeast Turkey and Iraq)	1950	34.43	2.60E+08	4.97E+06
Tanshui (Northern Taiwan)	328	2.47	4.12E+06	*
Tano (West Africa)	400	4.52	8.63E+06	1.77E+04
Saloum (West Africa)	105	0.53	3.30E+05	2.48E+04
Saint John (West Africa)	616	25.02	6.16E+07	*
Rokel (Seli, West Africa)	386	13.16	2.17E+07	2.34E+05
Purus (Northwest central South America)	3379	2888.58	2.39E+10	1.14E+08
Pra (West Africa)	245	7.14	7.96E+06	2.38E+04
Pilcomayo (South central South America)	2500	86.50	7.60E+08	1.14E+06
Pará-Tocantins (Brazil)	2234	376.40	2.54E+09	4.67E+07
Orange (South Africa)	1840	8.44	6.95E+07	3.40E+06

Ombrone (Tuscany, Western Italy)	130	1.56	1.08E+06	5.20E+03
Okavango (Southwest central Africa)	1600	23.78	1.53E+08	6.29E+06
Marañon (Peru)	1415	5.37	3.56E+07	1.09E+05
Little Scarcies (West Africa)	280	14.87	1.76E+07	2.53E+05
Kwando (Southwest Africa/Namibia)	731	34.09	9.65E+07	8.25E+06
Kura (Russia and Turkey)	796	22.00	7.09E+07	4.63E+05
Krishna (Karnataka, India)	1091	107.26	4.02E+08	3.44E+06
Kogon (Guinea, West Africa)	256	10.75	1.22E+07	2.01E+05
Kaoping (Southern Taiwan)	171	4.29	3.52E+06	1.28E+04
Irrawaddy (Irawadi, Central Myanmar Burma)	1781	564.35	2.91E+09	*
Godavari (Central India)	950	107.26	3.50E+08	2.99E+06
Géba (Guinea Bissau, West Africa)	547	3.95	1.04E+07	4.04E+05
Ganges (Ganga, North and northeast Indian subcontinent)	2221	1045.01	6.30E+09	8.31E+07
Fatala (West Africa)	205	13.09	1.15E+07	1.83E+05
Euphrates (Firat Nehri, Al-Furat, Southwest Asia)	2289	19.60	1.84E+08	4.42E+06
Erhjen (Southern)	36	4.29	7.40E+05	5.34E+03
Chobe (Southwest Africa/Namibia)	1500	34.09	1.98E+08	1.69E+07
Chittar (Tamil Nadu, India)	80	0.00	2.13E+03	6.22E+01
Cauvery (Karnataka, India)	627	7.59	2.15E+07	1.31E+06
Casamance (West Africa)	320	3.49	5.47E+06	2.83E+05
Brahmaputra (Dyardanes, Oedanes, Tsangpo, Zangbo, Tibet, China, NE India and Bangladesh)	2948	1045.48	8.37E+09	1.10E+08
Araguaia (Araguaya, Central Brazil)	2627	183.47	1.57E+09	2.32E+07
Athi-Galana-Sabaki (Kenya, from Nairobi eastward to Mombasa)	962	3.99	1.85E+07	3.18E+04

Table S3: River characteristics for 83 river basins above 42 degrees latitude (Xenopoulos et al., 2005; Alcamo et al., 2003a; Hugueny, 1989; Fekete et al., 2000; Doll et al., 2003; EarthTrends Watersheds of the World, 2007) and river-specific effect factor for global warming.

* - River basins with increased discharge.

River basin above 42 degrees latitude	River length (km)	Average river discharge at the mouth ($km^3 \cdot yr^{-1}$)	Calculated river volume (m^3)	Effect factor for global warming ($PDF \cdot m^3 \cdot {}^oC^{-1}$)
Scorff (a. Blavet) (France)	75	1.9098	7.47E+05	*
Seine (France)	451	17.124	3.21E+07	*
Lot (a. Garonne) (France)	481	19.359	3.82E+07	2.33E+05
Garonne (France-Espagne)	484	21.098	4.15E+07	2.72E+05
Dordogne (a. Garonne)	483	30.929	5.84E+07	3.26E+05
Po (Italie)	500	52.048	9.64E+07	3.71E+05
Rhin (Suisse-All.-Neth.)	1018	79.748	2.88E+08	1.97E+05
Meuse (France-Belg.-NL)	565	12.816	3.10E+07	*
Nida (a. Vistule) (Pol.)	151	35.927	2.09E+07	9.02E+03
Pilica (a. Vistule) (Pol.)	319	18.886	2.48E+07	6.36E+04
Warta (a. Oder) (Pol.)	808	19.755	6.54E+07	9.21E+04
Lyna ou Lava (Pol.)	264	4.599	5.78E+06	*
Bzura (a. Vistule) (Pol.)	166	30.83229	2.00E+07	1.37E+04
Raba (Pol.)	137.4	7.484	4.66E+06	2.28E+04
Vistula (Pol.)	1014	35.927	1.40E+08	6.06E+04
Morava (a. Danube) (Tch.-Autriche)	354	65.878	8.43E+07	2.13E+05
Volga (fSU)	2785	234.33	2.07E+09	1.50E+06
Danube (Int.)	2222	218.517	1.55E+09	1.65E+07
Loire (France)	839	31.714	1.04E+08	*
Yèrres (a. Seine)	6	8.385	2.25E+05	*

River basin above 42 degrees latitude	River length (km)	Average river discharge at the mouth ($km^3 \cdot yr^{-1}$)	Calculated river volume (m^3)	Effect factor for global warming ($PDF \cdot m^3 \cdot {}^oC^{-1}$)
Yonne (a. Seine) (France)	292	4.605	6.40E+06	*
Touques (France)	104	1.4128	7.91E+05	*
Dives (France)	105	2.02	1.10E+06	*
Vire (France)	128	0.5467	4.16E+05	*
Doubs (s.a. Rhône) (a. Saône) (France)	453	14.108	2.71E+07	1.17E+04
Gudena (Danemark)	158	1.4956	1.26E+06	2.33E+04
Wye (Severn estuary) (Wales)	297	5.679	7.86E+06	*
Tees (Britain)	132	2.223	1.51E+06	*
Glama (Norvège)	490	21.935	4.36E+07	*
Dunajec (a. Vistule) (Pologne-Slovaquie)	251	7.484	8.51E+06	4.17E+04
Hérault (France)	148	3.154	2.31E+06	5.76E+03
Orb (France)	136	3.154	2.12E+06	5.29E+03
Tarn (a. Garonne)	381	4.106	7.54E+06	2.18E+04
Allier (a. Loire) (France)	421	9.768	1.81E+07	7.43E+03
Ain (a. Rhône)	190	15.143	1.21E+07	3.21E+04
Isère (a. Rhône)	286	45.661	4.91E+07	9.82E+04
Sorgues (s. a. Rhône)	46.4	48.389	8.38E+06	1.56E+04
Ardèche (a. Rhône)	125	48.389	2.26E+07	4.21E+04
Cèze (a. Rhône)	128	48.389	2.31E+07	4.31E+04
Gard (a. Rhône)	133	54.374	2.67E+07	5.50E+04
Rhône (France-Suisse)	637	54.3377	1.28E+08	2.65E+05
Saône (a. Rhône)	473	32.608	6.00E+07	8.81E+04
Durance (a. Rhône)	324	54.374	6.50E+07	1.34E+05
Arve (a. Rhône)	102	9.282	4.19E+06	2.08E+04
Fier (a. Rhône)	71.9	11.742	3.65E+06	1.24E+04
Bourbre (a. Rhône)	72.2	15.143	4.60E+06	1.22E+04

River basin above 42 degrees latitude	River length (km)	Average river discharge at the mouth ($km^3 \cdot yr^{-1}$)	Calculated river volume (m^3)	Effect factor for global warming ($PDF \cdot m^3 \cdot {}^oC^{-1}$)
Eyrieux (a. Rhône)	83	45.661	1.42E+07	2.85E+04
Drôme (a. Rhône)	110	45.661	1.89E+07	3.78E+04
Willamette (a. Columbia) (USA)	301	216.664	2.08E+08	*
St Laurent (Canada)	3175	366.784	3.53E+09	*
Moisie (Canada)	343	14.071	2.05E+07	*
Ganaraska (Canada)	49.6740093	200.547	3.21E+07	2.60E+04
Humber (Canada)	100	1.826	9.57E+05	*
Credit (Canada)	1500	1.164	9.59E+06	*
Au Sable (Canada)	240	0.8954	1.21E+06	*
Maitland (Canada)	150	2.083	1.62E+06	*
Saugeen (Canada)	160	2.927	2.34E+06	*
South Nation (Canada)	175	53.092	3.44E+07	*
Mackenzie (Canada)	3679	267.295	3.08E+09	*
Yukon (Canada-U.S.A.)	2716	187.187	1.65E+09	*
Amu Darya (fSU)	1976	50.257	3.69E+08	*
Syr Darya (fSU)	1615	21.326	1.40E+08	*
Talas (fSU)	661	3.938	1.26E+07	*
Chu ou Tchou (fSU)	1067	3.995	2.06E+07	*
Ili (Chine-fSU) (Lac Balkhach)	1400	4.1855	2.82E+07	*
Léna (fSU)	4387	540.007	6.89E+09	*
Amour (fSU-Chine)	5061	330.454	5.12E+09	*
Dvina (ex-fSU)	1441	101.23877	5.05E+08	*
Neva (ex-fSU)	911	3.38614	1.52E+07	*
Dniepr (ex-fSU)	1544	48.18512	2.78E+08	2.42E+06
Don (ex-fSU)	1401	29.6661	1.63E+08	2.27E+05
Anadir (ex-fSU)	1150	32.17743	1.44E+08	*

River basin above 42 degrees latitude	River length (km)	Average river discharge at the mouth ($km^3 \cdot yr^{-1}$)	Calculated river volume (m^3)	Effect factor for global warming ($PDF \cdot m^3 \cdot {}^oC^{-1}$)
Kamtchatka (ex-fSU)	626	28.88501	7.12E+07	*
Yukon	2716	187.20142	1.65E+09	*
Yenisei-Angara (Yenisey, Enisei, Russia)	4803	597.30829	8.26E+09	*
Ural (Russia)	1411	9.509	5.93E+07	7.15E+04
Ob-Irtysh	3977	413.183	4.91E+09	*
Nelson-Saskatchewan	2045	78.713	5.71E+08	*
Lena (East central Russia)	4387	539.918	6.89E+09	*
Kolyma (Russia)	2091	115.24	8.22E+08	*
Dneper (West and southwest Russia)	1544	48.185	2.78E+08	2.42E+06
Amur (Hei-lung chiang, Northeast Asia	5061	330.454	5.12E+09	*
Amudar'ya (Oxus, Jayhun, Amy; Amyderya; Dar'yoi Amu; Jaihun, Central and west Asia)	1976	50.257	3.69E+08	*

Table S4: Characterization factors, water consumption and normalization factors for water consumption. Characterization factors were calculated for 214 river basins. The data for water consumption, representative for the year 1995, were available for 112 river basins (Alcamo et al., 2003a; Alcamo et al., 2003b; Shiklomanov, 1999).

River basin	Characterization factor ($PDF \cdot m^3 \cdot yr \cdot m^{-3}$)	Water consumption 1995 ($m^3 \cdot yr^{-1}$)	Normalization factor ($PDF \cdot m^3$)
Nil (Af., int.)	8.42E-03	5.41E+09	4.56E+07
Senegal (Guinée-Sénégal)	2.96E-03	4.34E+08	1.28E+06
Gambia (Guinée-Gambie)	1.36E-03	1.46E+08	1.99E+05
Tominé ou Rio Corubal (Guinée-Guineé Bissau)	7.67E-04	7.75E+07	5.94E+04
Konkouré (Guinée)	5.18E-04	3.34E+07	1.73E+04
Kolenté (Guinée, Great Scarcies)	3.79E-04		
Jong (Sierra Leone)	4.12E-04		
Sewa (Sierra Leone)	3.98E-04	1.01E+07	4.04E+03
Moa (Guinée-Sierra Leone)	6.76E-04	2.80E+07	1.89E+04
Mano (Libéria)	4.82E-04	5.43E+06	2.61E+03
Loffa (Guinée-Libéria)	5.85E-04	3.47E+06	2.03E+03
St Paul (Libéria)	6.30E-04	3.52E+07	2.22E+04
Nipoué (Cess, Libéria-RCI)	5.53E-04		
Cavally (Libéria-RCI)	6.04E-04	1.24E+07	7.48E+03
Dodo (aka Déo) (RCI)	1.46E-04		
San Pédro (RCI)	3.91E-04	2.39E+06	9.33E+02
Sassandra (RCI)	8.91E-04	6.58E+07	5.86E+04
N'Zo (a. Sassandra) (RCI)	4.81E-04		
Boubo (RCI)	2.62E-04		
Bandama (RCI)	1.11E-03	8.88E+07	9.90E+04
Yani (s.a. Bandama) (RCI)	2.68E-04		
Marahoué (a. Bandama) (RCI)	4.27E-04		
N'Zi (a. Bandama) (RCI)	8.63E-04		
Kan (s.a. Bandama) (RCI)	1.01E-03		
Agnébi (RCI)	5.64E-04		
Comoé (RCI-Burkina)	1.39E-03	6.84E+07	9.53E+04
Bia (RCI-Ghana)	4.99E-04	1.76E+07	8.76E+03
Volta (Ghana-Burkina)	2.02E-03	4.34E+08	8.79E+05
Black Volta (Burkina-Ghana) (a. Volta)	2.43E-03		
Nasia (a. White Volta) (Ghana)	3.91E-04		
Daka (a. Volta) (Ghana)	1.72E-04		
Mono (Togo)	8.08E-04	2.75E+07	2.22E+04
Ouémé (Bénin)	8.86E-04	6.19E+07	5.48E+04
Ogun (Nigéria)	7.62E-04	1.17E+08	8.89E+04
Niger (Afr. Int.)	5.59E-03	7.84E+08	4.38E+06
Niandan (Guinée) (a. Niger)	5.66E-04		

River basin	Characterization factor (PDF·m^3·yr·m^{-3})	Water consumption 1995 (m^3·yr^{-1})	Normalization factor (PDF·m^3)
Bénoué (Nigéria-Cameroun) (a. Niger)	2.02E-03		
Sokoto (a. Niger) (Nigeria)	4.33E-04		
Cross (Nigéria-Cameroun)	7.01E-04	1.73E+08	1.21E+05
Mungo (Cameroun)	2.33E-05	1.13E+07	2.63E+02
Dibamba (Cameroun)	2.47E-04		
Wouri (Cameroun)	2.64E-04	2.47E+07	6.52E+03
Sanaga (Cameroun)	1.17E-03	1.33E+08	1.55E+05
Nyong (Cameroun)	6.51E-04	2.66E+07	1.73E+04
Lokoundjé (Cameroun)	3.67E-04	4.34E+05	1.59E+02
Kribi ou Kienké (Cameroun)	1.98E-04		
Lobé (Cameroun)	1.59E-04		
Ntem (Cameroun-Gabon-Guinée équat.)	5.85E-04	9.48E+06	5.54E+03
Ogôoué (Gabon)	1.08E-03	4.33E+07	4.68E+04
Niari-Kouilou (Congo)	7.59E-04	4.20E+06	3.19E+03
Zaïre (Afr., Int.)	4.59E-03		
Cunene ou Kunene (Namibie-Angola)	1.48E-03	7.81E+07	1.15E+05
Kasaï (a. Zaïre) (Zaïre-Angola)	2.49E-03	5.55E+07	1.38E+05
Chari (Lac Tchad)	2.77E-03	5.09E+08	1.41E+06
Ubangi (a. Zaïre) (Congo-RCA)	3.00E-03		
Zambezi (Mozambique-Zambie-Angola)	3.66E-03	8.00E+08	2.93E+06
Tana (Kénya)	1.22E-03	2.46E+08	3.00E+05
Rufiji (Tanzanie)	1.27E-03	6.84E+07	8.67E+04
Limpopo (Botswana-Mozamb.-Rhodésie-RSA)	3.20E-03	2.82E+09	9.02E+06
Pongolo ou Maputo (RCA-Mozambique)	6.59E-04	1.77E+08	1.17E+05
Shire (a.) (Malawi-Mozambique)	1.63E-03		
Kafue (a. Zambèze) (Zambie)	1.59E-03		
Ruaha (a. Rufiji) (Tanzanie)	7.44E-04		
Evros-Mariça (Grèce-Turquie-Bulgarie)	7.22E-04	2.83E+09	2.04E+06
Nesta-Nestos (Grèce-Bulgarie)	4.80E-04	2.03E+08	9.72E+04
Strymon-Strouma (Grèce-Bulgarie)	7.65E-04	8.20E+08	6.27E+05
Agly (France)	1.77E-04		
Minho (Portugal-Espagne)	6.08E-04	2.86E+08	1.74E+05
Lima (Portugal)	2.13E-04		
Cavado (Portugal)	2.67E-04	8.89E+07	2.37E+04
Douro (Portugal-Esp.)	8.95E-04	3.47E+09	3.11E+06
Vouga (Portugal)	3.13E-04	6.10E+07	1.91E+04
Mondego (Portugal)	4.70E-04	1.45E+08	6.83E+04
Sado (Portugal)	3.81E-04	1.23E+08	4.70E+04
Mira (Portugal)	3.63E-04	9.74E+06	3.53E+03
Guadiana (Portugal-Esp.)	1.38E-03	1.97E+09	2.72E+06
Raisin (Canada)	2.83E-04		
Sydenham (Canada)	2.17E-04		

River basin	Characterization factor ($PDF \cdot m^3 \cdot yr \cdot m^{-3}$)	Water consumption 1995 ($m^3 \cdot yr^{-1}$)	Normalization factor ($PDF \cdot m^3$)
Grand (Canada)	3.62E-04		
Thames (Canada)	5.11E-04		
Mississipi (USA)	4.88E-03	3.92E+09	1.91E+07
Rio Grande (USA-Mexique)	3.99E-03	5.28E+09	2.11E+07
Pecos (a. Rio Grande)	2.74E-03		
Canadian (s. a. Mississipi) (USA)	2.33E-03		
Colorado (USA-Mexique)	3.79E-03	4.08E+09	1.54E+07
San Juan (a. Colorado) (USA)	6.29E-04		
Zuni (s. a. Colorado) (a. Little Colorado)	2.44E-04		
San Francisco (a. Gila) (USA)	6.85E-03	1.68E+09	1.15E+07
Gila (a. Colorado)	2.42E-03		
Ohio (a. Mississipi)	2.66E-03	9.77E+09	2.60E+07
Scioto (a. Ohio)	5.25E-04		
Big Darby Creek (s. a. Ohio) (a. Scioto)	2.62E-04		
Wabash (a. Ohio)	1.02E-03		
Little Wabash (a. Wabash)	4.26E-04		
Embarras (a. Wabash)	5.11E-04		
St Joseph (s.a. Wabash)	3.20E-04		
Elk (s. a. Ohio) (a. Kanawha)	4.89E-04		
Cumberland (a. Ohio)	1.54E-03		
Green (a. Ohio)	1.60E-03		
Kanawha (a. Ohio)	2.26E-04		
Tennessee (a. Ohio)	1.33E-03		
Muskingum (s.a. Ohio) (a. Allegheny)	2.75E-04		
Allegheny (a. Ohio)	9.14E-04		
Little Miami (a. Ohio)	2.37E-04		
Hocking (a. Ohio)	2.29E-04		
Kinniconick (a. Ohio)	2.24E-01		
Licking (a. Ohio)	9.06E-05		
Little Scioto (a. Ohio)	1.31E-04		
Ohio Brush Creek (a. Ohio)	1.44E-04		
Olentangy (a. Little Scioto)	2.05E-04		
Paint Creek (a. Scioto)	2.78E-04		
Scioto Brush Creek (a. Scioto)	8.18E-02		
Symmes (a. Ohio)	1.40E-04		
Tygart Creek (a. Ohio)	5.17E-04		
Bear Creek	1.01E-04	1.43E+09	1.44E+05
Apalachicola (USA)	2.89E-04	1.48E+09	4.28E+05
Klamath (USA)	5.21E-04	3.18E+08	1.65E+05
Mobile (USA)	1.05E-04	1.18E+09	1.24E+05
Potomac (USA)	5.17E-04	1.56E+09	8.06E+05
Sabine (USA)	9.66E-04	3.24E+08	3.13E+05

River basin	Characterization factor (PDF·m³·yr·m⁻³)	Water consumption 1995 (m³·yr⁻¹)	Normalization factor (PDF·m³)
Sacramento (USA)	1.42E-03	1.08E+10	1.54E+07
Savannah (USA)	7.94E-04	4.31E+08	3.42E+05
Susquehanna (USA)	7.99E-04	1.94E+09	1.55E+06
Connecticut (USA)	8.24E-04	1.11E+09	9.11E+05
Missouri (USA)	4.88E-03	4.73E+09	2.31E+07
Arkansas (USA)	2.75E-03		
Red (USA)	2.55E-03		
Altamaha (USA)	7.66E-04	4.33E+08	3.32E+05
Balsas (Mexico)	1.13E-03	1.37E+09	1.55E+06
Panuco (Mexico)	8.15E-04	1.04E+09	8.51E+05
Sucio (a. Lempa) (San Salvador)	4.26E-05	4.51E+07	1.92E+03
Paz (San Salvador)	2.56E-04	6.20E+06	1.59E+03
San Tiguel (ou Miguel) San Salvador)	3.15E-04	9.00E+06	2.83E+03
Paraguay (Brésil-Arg.-Paraguay) (a. Parana)	2.97E-03	2.43E+09	7.22E+06
Uruguay (Brésil-Arg.-Uruguay)	1.85E-03	1.49E+09	2.77E+06
Magdalena (Colombie)	1.62E-03	1.84E+09	2.98E+06
Rio Negro (a. Amazone) (Colomb.-Venez.-Brésil)	1.05E-03	3.38E+06	3.54E+03
Parnaiba (Brésil)	1.89E-03		
Madeira (a. Amazone) (Brésil-Bolivie)	2.99E-03	3.84E+07	1.15E+05
Orinoco (Vénézuela-Colombie)	2.13E-03	1.12E+09	2.40E+06
Parana (Brésil-Paraguay-Argentine)	3.16E-03	2.05E+09	6.50E+06
Tibagi (Bresil)	9.53E-04	1.30E+08	1.23E+05
Amazon (Br. Mère Maranon) (Pérou-Brésil)	3.90E-03	5.43E+06	2.12E+04
Maroni (Guyane-Surinam)	6.53E-04	6.49E+06	4.24E+03
Oyapock (Guyane-Brésil)	4.43E-04	1.16E+06	5.14E+02
Approuague	4.71E-04	1.00E+06	4.72E+02
Sinnamary (Guyane)	4.31E-04	6.86E+05	2.95E+02
Kourou (Guyane)	2.05E-04	4.22E+05	8.63E+01
Vakhsh ou Vachs (fSU) (a. Amu Darya)	2.93E-03		
Surkhandarya ou Surchandarya (fSU)	2.58E-04		
Zeravshan (a. Syr Darya) (fSU)	2.36E-03		
Naryn (a. Syr Darya) (fSU)	1.35E-03		
Tarim (Chine)	2.52E-03	1.33E+10	3.36E+07
Murgab ou Murghab ou Mourbab (fSU-Afghanistan) Endo	1.71E-03	1.06E+10	1.81E+07
Kabul (a. Indus) (Afghanistan-Inde)	9.86E-04		
Salween (Tibet-Chine-Birmanie-Thaï)	3.57E-03	1.63E+09	5.83E+06
Mae Khlong (Thaïlande)	2.36E-04	3.03E+08	7.16E+04
Chao Phrya (Menam) (Thaïlande)	1.12E-03	4.51E+09	5.07E+06
Mekong (Asie Sud-Est, Int.)	4.75E-03	8.70E+09	4.13E+07
Kelani Ganga(Sri Lanka)	2.81E-04		
Kalu Ganga (Sri Lanka)	2.50E-04		

River basin	Characterization factor ($PDF·m^3·yr·m^{-3}$)	Water consumption 1995 ($m^3·yr^{-1}$)	Normalization factor ($PDF·m^3$)
Gin Ganga (Sri Lanka)	2.37E-04		
Nilwala Ganga (Sri Lanka)	1.38E-04		
Mahaweli Ganga (Sri Lanka)	6.58E-04	1.26E+09	8.31E+05
Brahmapoutre ou Tsangpo (Inde-Bengladesh-Tibet)	3.11E-03		
Indus (Tibet-Inde-Pakistan)	3.23E-03	4.95E+10	1.60E+08
Gange (Inde)	2.67E-03		
Ob (fSU)	4.76E-03	2.01E+09	9.57E+06
Yangzi Jiang (Tibet-Chine)	7.00E-03	3.38E+10	2.37E+08
Gandaki (a. Gange) (nepal)	6.76E-04		
Sakaria (Turkey)	9.13E-04	1.90E+09	1.74E+06
Rakaïa (New-Zealand)	2.85E-04	5.86E+07	1.67E+04
Fly (Nlle-Guinée)	9.10E-04	5.88E+06	5.35E+03
Sepik-Ramu (Nlle-Guinée)	3.95E-04	7.36E+06	2.90E+03
Kapuas (Bornéo)	7.44E-04	3.97E+07	2.96E+04
Murray-Darling (Australie)	3.07E-03	5.21E+09	1.60E+07
Yellow (Huang He, Huang Ho, China)	6.13E-03	3.25E+10	1.99E+08
Yangtze (Chang Jiang, Yangtze Kiang, China)	5.19E-03		
Xi Jiang (Pearl, Chu Chiang, Zhu, Southeast China)	2.12E-03		
Tsengwen (Southwestern Taiwan)	2.82E-04		
Tigris (Southeast Turkey and Iraq)	3.02E-03	2.48E+10	7.47E+07
Tanshui (Northern Taiwan)	6.66E-04		
Tano (West Africa)	7.63E-04		
Saloum (West Africa)	2.50E-04		
Saint John (West Africa)	9.85E-04	1.24E+07	1.22E+04
Rokel (Seli, West Africa)	6.60E-04		
Purus (Northwest central South America)	3.30E-03		
Pra (West Africa)	4.46E-04		
Pilcomayo (South central South America)	3.52E-03		
Pará-Tocantins (Brazil)	2.70E-03		
Orange (South Africa)	3.29E-03	2.24E+09	7.38E+06
Ombrone (Tuscany, Western Italy)	2.77E-04		
Okavango (Southwest central Africa)	2.57E-03	8.30E+07	2.14E+05
Marañon (Peru)	2.65E-03		
Little Scarcies (West Africa)	4.72E-04		
Kwando (Southwest Africa/Namibia)	1.13E-03		
Kura (Russia and Turkey)	1.29E-03		
Krishna (Karnataka, India)	1.50E-03	3.50E+10	5.25E+07
Kogon (Guinea, West Africa)	4.53E-04		
Kaoping (Southern Taiwan)	3.28E-04		
Irrawaddy (Irawadi, Central Myanmar Burma)	2.06E-03	9.58E+08	1.98E+06
Godavari (Central India)	1.31E-03		
Géba (Guinea Bissau, West Africa)	1.06E-03		

River basin	Characterization factor ($PDF \cdot m^3 \cdot yr \cdot m^{-3}$)	Water consumption 1995 ($m^3 \cdot yr^{-1}$)	Normalization factor ($PDF \cdot m^3$)
Ganges (Ganga, North and northeast Indian subcontinent)	2.41E-03	1.29E+11	3.11E+08
Fatala (West Africa)	3.51E-04		
Euphrates (Firat Nehri, Al-Furat, Southwest Asia)	3.75E-03		
Erhjen (Southern River)	6.90E-05		
Chobe (Southwest Africa/Namibia)	2.32E-03		
Chittar (Tamil Nadu, India)	3.31E-04		
Cauvery (Karnataka, India)	1.13E-03		
Casamance (West Africa)	6.27E-04		
Brahmaputra (Dyardanes, Oedanes, Tsangpo, Zangbo, Tibet, China, NE India and Bangladesh)	3.20E-03	8.47E+09	2.71E+07
Araguaia (Araguaya, Central Brazil)	3.42E-03	1.83E+08	6.26E+05
Athi-Galana-Sabaki (Kenya, from Nairobi eastward to Mombasa)	1.86E-03		

Table S5: Characterization factors, emissions in year 2000 and normalization factors for 63 greenhouse gas emissions, based on 100-year time horizon. The emissions in year 2000 were taken from Sleeswijk et al. (2008). Due to the data availability, we provide the normalization factors for 21 greenhouse gas emissions.

Substance	Characterization factor ($PDF \cdot m^3 \cdot yr \cdot kg^{-1}$)	Emission in year 2000 (kg)	Normalization factor ($PDF \cdot m^3$)
CO_2	8.53E-05	2.85E+13	2.43E+09
CH_4	1.69E-03	2.99E+11	5.04E+08
N_2O	2.78E-02	1.15E+10	3.19E+08
CFC-11	4.43E-01	4.06E+07	1.80E+07
CFC-12	1.02E+00	1.01E+08	1.02E+08
CFC-13	1.35E+00		
CFC-113	5.72E-01	3.86E+06	2.21E+06
CFC-114	9.37E-01	2.07E+06	1.94E+06
CFC-115	6.87E-01	8.73E+05	6.00E+05
Carbon tetrachloride	1.31E-01	4.17E+05	5.44E+04
Methyl bromide	4.48E-04		
Methyl chloroform	1.37E-02	3.57E+05	4.87E+03
HCFC-22	1.69E-01	3.00E+08	5.06E+07
HCFC-123	7.23E-03		
HCFC-124	5.68E-02	3.93E+06	2.23E+05
HCFC-141b	6.76E-02	1.66E+08	1.12E+07
HCFC-142b	2.16E-01	5.09E+07	1.10E+07
HCFC-225ca	1.14E-02		
HCFC-225cb	5.55E-02		
Halon-1211	1.76E-01	4.82E+06	8.48E+05
Halon-1301	6.66E-01	9.26E+05	6.17E+05
Halon-2402	1.53E-01	2.96E+05	4.54E+04
HFC-23	1.38E+00		
HFC-32	6.29E-02		
HFC-43-10mee	1.53E-01		
HFC-125	3.27E-01	7.40E+06	2.42E+06
HFC-134a	1.33E-01	1.30E+08	1.73E+07
HFC-143a	4.17E-01	5.40E+06	2.25E+06
HFC-227ea	3.01E-01		
HFC-245fa	9.65E-02		
HFC-152a	1.16E-02		
HFC-236fa	9.15E-01		
HFC-365mfc	7.41E-02		
Sulphur hexafluoride	2.13E+00	5.22E+06	1.11E+07

Substance	Characterization factor ($PDF \cdot m^3 \cdot yr \cdot kg^{-1}$)	Emission in year 2000 (kg)	Normalization factor ($PDF \cdot m^3$)
Nitrogen trifluoride	1.68E+00		
PFC-14	6.90E-01		
PFC-116	1.14E+00		
PFC-218	8.24E-01		
PFC-318	9.57E-01		
PFC-3-1-10	8.26E-01		
PFC-4-1-12	8.54E-01		
PFC-5-1-14	8.67E-01		
PFC-9-1-18	7.01E-01		
Trifluoromethyl sulphur pentafluoride	1.66E+00		
HFE-125	1.39E+00		
HFE-134	5.89E-01		
HFE-143a	7.05E-02		
HCFE-235da2	3.25E-02		
HFE-245cb2	7.51E-02		
HFE-245fa2	6.15E-02		
HFE-254cb2	3.68E-02		
HFE-347mcc3	5.37E-02		
HFE-347pcf2	5.39E-02		
HFE-356pcc3	1.02E-02		
HFE-449sl	2.86E-02		
HFE-569sf2	5.31E-03		
HFE-43-10pccc124	1.75E-01		
HFE-236ca12	2.64E-01		
HFE-338pcc13	1.40E-01		
PFPMIE	9.61E-01		
Dimethylether	3.96E-05		
Methylene chloride	8.15E-04		
Methyl chloride	1.20E-03		

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Chapter 6

Including the introduction of exotic species in life cycle impact assessment: the case of inland shipping

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Submitted

Abstract

The ecological impact of anthropogenically introduced exotic species is generally not accounted for in the environmental life cycle assessment (LCA) of products, while it is considered one of the major treats for anthropogenic stressors nowadays. Here, we propose a framework to include exotic species introduction in an LCA context. As an example, we derived characterization factors for exotic fish species introduction, expressed as the potentially disappeared fraction of native freshwater species in the rivers Rhine and Danube integrated over space and time, related to transport of goods across the Rhine-Main-Danube canal. We also quantified the relative importance of exotic fish species introduction compared to other anthropogenic stressors in the freshwater environment. We found that the relative importance of introduction of exotic fish species is 20 - 34% of the total freshwater ecosystem impact, depending on the transport distance of goods (3000 km vs. 1500 km, respectively). Our analysis showed that it is relevant and feasible to include the introduction of exotic species in an LCA framework. The framework proposed can be further extended by including impacts of other exotic species groups, types of water bodies and pathways for introduction.

Keywords: invasive species; endpoint assessment; characterization factor; fish freshwater ecosystems; non-native species

1. Introduction

The introduction of exotic species has significantly increased globally and has proven to affect biodiversity and to change ecosystem functioning (Wilcove et al., 1998; Mack et al., 2000; Sala et al., 2000; Bax et al., 2001; Lodge, 2001; Rahel, 2002; Clavero and García-Berthou, 2005; Millennium Ecosystem Assessment, 2006; Xu et al., 2006; Byrnes et al., 2007). An exotic species is defined as an anthropogenically introduced species into areas outside their natural range. According to Elliott (2003) and Arbačiauskas et al. (2008), exotic species can be considered as bio-contamination due to their high impact on aquatic ecosystems. They are often characterized by high tolerance to environmental conditions, high dispersal ability, wide geographical range, rapid production, high reproductive capacity and strong competitive ability (Ricciardi and Rasmussen, 1998; Lockwood, 1999; Richardson et al., 2000; Leuven et al., 2009, 2011; Verbrugge et al., 2012). Invasive exotic species have many ecological consequences, including displacement of native species, changes in habitat conditions, alteration of community structure and disruption of food webs (Moyle and Light, 1996a; Rahel, 2002; Vila-Gispert et al., 2005). These species not only led to a profound modification of ecosystems, but also cause economic damage (Pimentel et al., 2000; Jeschke and Strayer, 2005; Pysˇek and Richardson, 2006; Galil et al., 2007; Shine et al., 2008) and pose risks to public health (Mack et al., 2000).

Exotic species can be introduced intentionally (e.g. via livestock feed, pest management and pet industry) or accidently through transporting goods, lifting dispersal barriers between rivers basins by construction of canals and human travel (Hanson et al. 2003; Niimi, 2004). The transport of goods and development of inland waterway networks of rivers and canals are regarded as one of the main factors causing spread of exotic species in aquatic environments (Leuven et al., 2009). The accelerating introduction of exotic species via interbasin and intercontinental shipping has become an emerging issue of environmental concern. The spread of exotic species continue to rapidly increase with increasing continental and intercontinental exchange and transportation (Chen and Xu, 2001).

Although exotic species are one of the key threats to native biodiversity and their ecosystems (Butchart et al., 2010), impacts of bio-contamination are not yet taken into account in the context of life cycle impact assessment (LCIA) of products. LCIA is the phase where the results of the inventory data are analyzed and interpreted into their potential environmental impact. Including the introduction of exotic species in the current LCIA framework will give a more complete picture of the environmental impacts related to product life cycles.

The goal of this paper was to develop a method for assessing impacts of exotic freshwater species introduction in the LCIA framework. By focusing on exotic freshwater fish species related to transport of goods via the Rhine-Main-Danube (RMD) waterway, we derived new characterization factors in terms of the potential disappearance of native freshwater fish species integrated over time per amount of transported goods. A case study of shipping related transported goods was performed to demonstrate the applicability of the new characterization factors and to assess the relative importance of introduction of exotic fish species compared to other environmental stressors in freshwater ecosystems.

2. Methods

2.1. Framework

Figure 1 illustrates the cause-effect pathway for the potentially disappeared fraction (PDF) of native freshwater species caused by the introduction of exotic species. Depending on the size and nature, transportation of goods (raw materials, resources and end products) may take place via land (road or rail), air or water pathways. This study focuses on exotic species that are transferred into new environments via water transport. For freshwater ecosystems, shipping activities have been recognized as a source for exotic species introduction. Vectors that relate to shipping include ship hull fouling, ballast water and lifting of dispersal barriers by connection of river basins via canals. Shipping related transport include many different types of cargo vessels such as container, bulk carrier and tanker ships. The introduced exotic species may pose threats to freshwater biodiversity and human health. In freshwater ecosystems, fish, macroinvertebrates (e.g. mollusc and crustacean), algae and aquatic plants (e.g. macrophytes and diatoms) are the most common invasive exotic species (Leuven et al., 2009; 2011; Puijenbroek et al., 2009). The introduction of exotic species can influence freshwater biodiversity loss by disturbing ecosystem function through predation, competition with native species for food and habitat, alteration of the gene pool and disruption of food webs structure (Lodge, 1993; Townsend, 2003).

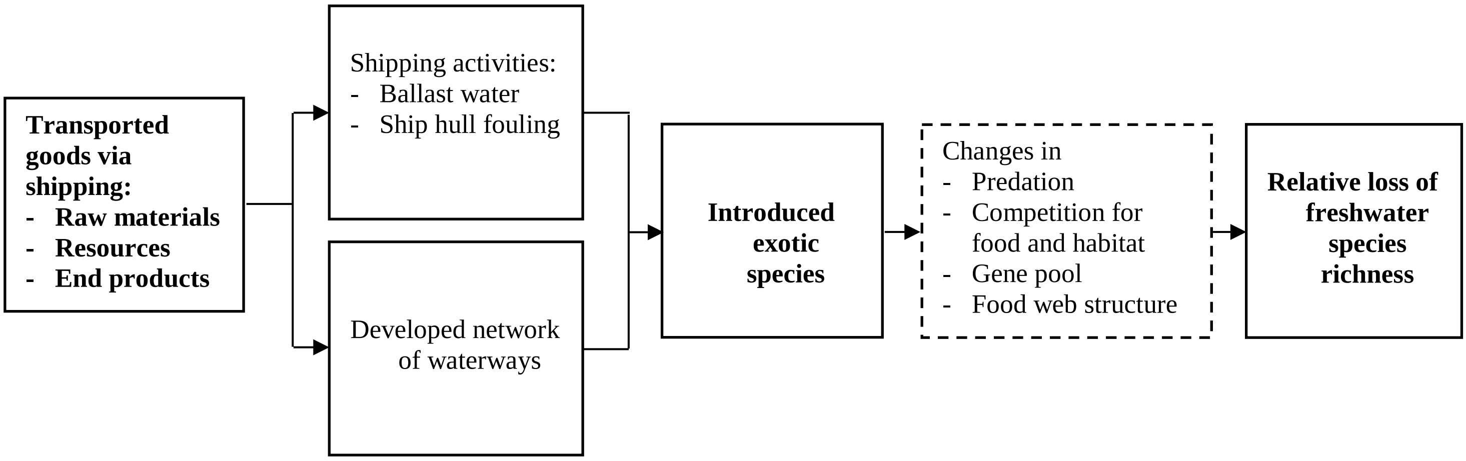

Figure 2.1: Cause-effect pathway for impact of exotic species introduction on freshwater native species via shipping-related transport.

Here, we focus on the impact of exotic freshwater fish species introduction. Effect factors for exotic fish species introduction were calculated using the percentage of fish species threatened by exotic fish species in rivers worldwide (Leprieur et al., 2008). Three categories of threatened native fish species (i.e. vulnerable, endangered and critically endangered), identified by the World Conservation Union (IUCN) Red List (IUCN, 2006), are assumed to represent the PDF of native fish species in our study. Figure 2 shows the relationship between the percentage of exotic species (ES) and the PDF of native species, as derived from Leprieur et al. (2008). We derived a log-linear regression to explain the stressor-response relationship between the percentage of exotic species and PDF of native species (eq. 1). The intercept was forced through the origin, implying no impact in cases where exotic species are not introduced.

$$PDF = a \cdot \ln(\%ES + 1) \tag{1}$$

The slope a obtained with the regression analysis was 0.02 (0.01-0.03 as 95% confidence interval) with a p value of 0.02.

The relationship between native fish species disappearance and exotic fish species introduction can also be used to derive characterization factors that quantify the potential extinction of freshwater fish species per unit of transported goods. The modeling further includes the influence of transported goods on percentage of exotic species introduction. The calculation of the characterization factors for exotic species introduction is explained below.

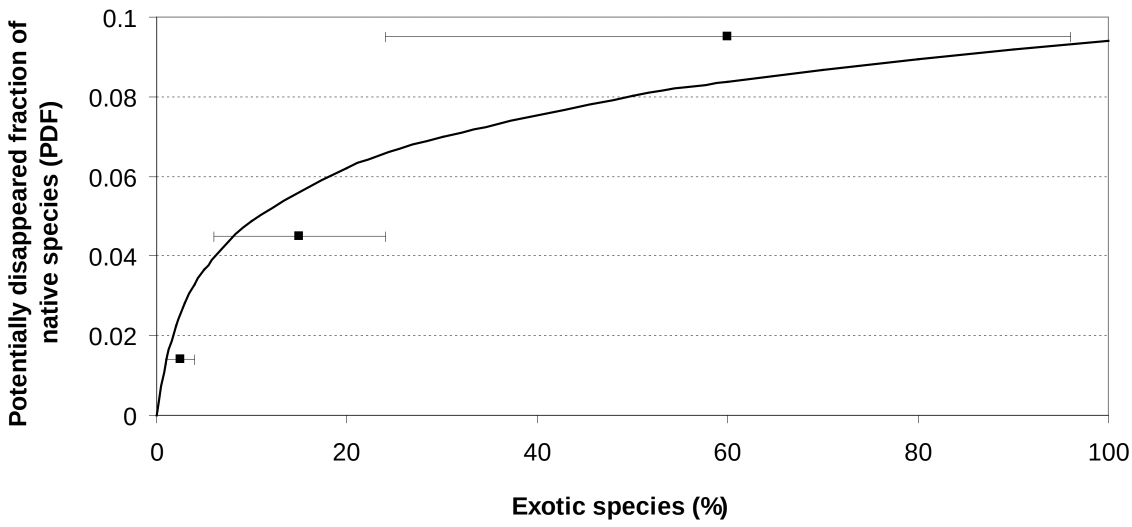

Figure 2.2: Potentially disappeared fraction (PDF), represented by the sum of vulnerable, endangered and critically endangered fish species fraction in relation to the percentage of exotic fish species introduction. The error bars refer to the minimum and maximum percentage of exotic fish species introduction reported per PDF data point (based on data of Leprieur et al., 2008).

2.2. Characterization Factor

Characterization factors that express freshwater ecosystem damage due to introduction of exotic species were derived for transported goods by inland shipping. Characterization factors for aquatic exotic species quantify the fraction of freshwater native species that potentially disappear aggregated over time and water volume due to shipping related transport, expressed in units of PDF·m^3·yr per kg of transported goods. The characterization factors for transport-related introduction of exotic species were obtained by multiplying a river basin specific fate factor with a river basin specific effect factor summed over all affected river basins:

$$CF = \sum_i FF_i \cdot EF_i = \sum_i \underbrace{\frac{\partial \%ES_i}{\partial TR}}_{fate} \cdot \underbrace{\frac{\partial PDF_i}{\partial \%ES_i} \cdot V_i}_{effect} \qquad (2)$$

where CF is the characterization factor for transported goods (PDF·m^3·yr·kg^{-1}), FF_i is the fate factor of river basin i (% exotic species·yr·kg^{-1}), EF_i is the effect factor of river basin i (PDF·m^3·yr·% exotic species^{-1}), $\partial\%ES_i$ is the marginal change of percentage of exotic freshwater species as part of the total species pool establishment in river basin i (% exotic species), ∂TR is the marginal change in yearly transport of goods (kg·yr^{-1}), ∂PDF_i is the marginal change in the potentially disappeared fraction of the freshwater native species in river basin i and V_i is the volume of river basin i (m^3).

2.3. Fate factor

The fate factor was defined as the time integrated change in % exotic species due to a change in transportation of goods. The fate factor (FF_i) for river basin i, expressed in units of % exotic species·year·kg^{-1} can be approximated with empirical data on the change in exotic species occurrence specifically caused by transport-related activities relative to the total species pool in a specific period ($\Delta\%ES_i$) and the yearly average amount of transported goods ($\overline{\Delta TR}$) in that time period:

$$FF_i = \frac{\partial \%ES_i}{\partial TR} \approx \frac{\Delta \%ES_i}{\overline{\Delta TR}} \quad (3)$$

2.4. Effect factor

The effect factor reflects the impact of exotic fish species on native freshwater fish species richness (in PDF·m^3·% exotic species^{-1}). In this study, we explored two options to calculate the effect factor for fish species disappearance.

The first and most common option is to directly use the derivative of equation 1 multiplied with the water volume as the marginal effect factor for river basin i:

$$EF_i = \frac{\partial PDF_i}{\partial \%ES_i} \cdot V_i = \frac{0.02}{\%ES_i + 1} \cdot V_i \quad (4)$$

The second option is to directly link the effect factor calculation to the empirical change in % exotic species introduction in river basin i to the relative change in native freshwater species richness via equation 1:

$$EF = \frac{\Delta PDF_i}{\Delta \%ES_i} \cdot V_i \quad (5)$$

2.5. RMD waterway

To demonstrate how to calculate characterization factors of exotic species introduction by shipping activities, we derived characterization factors for transported goods via the Rhine-Main-Danube (RMD) waterway. The Main-Danube canal was constructed in 1992 to make possible shipping transport between western, central and south-eastern Europe via the rivers Rhine, Main and Danube. The RMD waterway is an important corridor for dispersal of exotic species between Western Europe and the Ponto-Caspian area (i.e. southern corridor; Bij de Vaate et al., 2002; Arbačiauskas et al., 2008; Leuven et al., 2009).

The rivers Rhine and Danube are among the largest rivers of Europe and are regarded as important economic pathways for shipping transport between various European regions (WWF, 2002; ICPDR, 2005; Sommerwerk et al., 2009; Uehlinger et al., 2009). The river Rhine runs for over 1,320 km from its sources in Switzerland and Austria to its estuary in the Netherlands (Uehlinger et al., 2009). The river Danube is located in Central Europe and has a length of 2,780 km (Sommerwerk et al., 2009).

For the calculation of the characterization factor, we obtained data on (1) the yearly average of transported goods over the period 1992 - 2009 through the RMD waterway, (2) the change in percentage of exotic species introduced via passive dispersal with inland ships or active dispersal using the RMD waterway in both the rivers Rhine and Danube, and (3) their water volumes. The average yearly amount of transported goods via the RMD waterway over the period 1992 - 2009 was 6.45 Megaton·year^{-1} (Water and Navigation Administration of the Federation Germany, 2011). The data on the cumulative number of exotic fish species introduced via passive dispersal with inland ships or active dispersal using the RMD waterway was obtained from various references (Lenders, 1993; Bischoff et al., 1998; Soes, 2005; Pollux and Korosi, 2006; Van Beek, 2006; Kottelat and Freyhof, 2007; Soes et al., 2007; Stemmer, 2008; Harka and Szepesi, 2009; Sommerwerk et al., 2009; Uehlinger et al., 2009; Van Kessel et al., 2009; Borcherding et al., 2011a; Leuven et al., 2011; Working group on Exotic Species, 2010). A total of 81 fish species was found in river Rhine (45 native and 36 exotic) (Uehlinger et al., 2009). For the river Danube, a total of 132 fish species were recorded (115 native and 17 exotic) (Sommerwerk et al., 2009). Over the period 1992 - 2009, a total of 9 exotic fish species dispersed from the river Danube to the river Rhine and 1 exotic fish species from the river Rhine to the river Danube. The water volume of the rivers Rhine and Danube ($2.88 \cdot 10^8$ and $1.55 \cdot 10^9$ m^3, respectively) were taken from Hanafiah et al. (2011). A list of exotic fish species related to shipping activities and the yearly average amount of transported goods through RMD waterway can be found in the Supporting Information (Tables S1 and S2, respectively).

2.6. Case study

The relative importance of exotic species introduction in LCIA freshwater damage calculations was evaluated with a case study on transported goods from the port of Rotterdam to Budapest (+/- 1500 km transport distance) and the Black sea (+/- 3000 km transport distance) or vice versa via the RMD waterway. We calculated the freshwater ecosystem damage (in PDF·m^3·yr) of 1 ton transported goods from Rotterdam to Budapest and the Black sea per barge, respectively. The impact categories included were exotic species introduction, water consumption, and emissions of greenhouse gases, toxic pollutants and nutrients. Inventory data were taken from the ecoinvent database v.2.0 (Frischknecht et al., 2007). Characterization factors for greenhouse gas emissions and water consumption were taken from Hanafiah et al. (2011), for ecotoxicity from Van Zelm et al. (2009) and (Goedkoop et al., 2009) and for eutrophication from Helmes et al. (2012). Further information on inventory data and characterization factors can be found in the Supporting Information (Table S3).

3. Results

3.1. Characterization factors

Table 1 shows the fate, effect and characterization factors for transport of goods through the RMD waterway. Based on an average approach, the characterization factor of the river Rhine is a factor of 1.5 higher compared to that of the river Danube. The fate factor of the river Rhine is a factor of 16 higher compared to that of the river Danube, while the effect factor is about a factor of 11 higher for the river Danube than for the river Rhine. This can be explained by the fact that ΔPDF/Δ%ES and river volume were larger for the river Danube compared to the river Rhine (a factor of 2 and 5, respectively).

In the present study, we conducted a sensitivity analysis by calculating the effect and characterization factors using a marginal and average approach. The differences between both approaches are small (a factor of 1.05), implying that the choice between a marginal or average approach does not influence the effect factors for exotic species introduction in this specific case.

Table 3.1: Characterization factors for shipping related transport of goods of rivers Rhine and Danube ($PDF \cdot m^3 \cdot yr \cdot kg^{-1}$).

	Unit	River Rhine	River Danube	Total
Fate factor	% exotic species·yr·kg^{-1}	$1.7 \cdot 10^{-9}$	$1.1 \cdot 10^{-10}$	n.a.
Marginal effect factor	PDF·m^3·% exotic species^{-1}	$1.3 \cdot 10^{5}$	$1.5 \cdot 10^{6}$	n.a.
Average effect factor	PDF·m^3·% exotic species^{-1}	1.4·105	1.5·106	n.a.
Marginal characterization factor	PDF·m^3·yr.kg^{-1}	$2.2 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	$3.8 \cdot 10^{-4}$
Average characterization factor	PDF·m^3·yr.kg^{-1}	$2.4 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	$4.0 \cdot 10^{-4}$

3.2. Case study

Figure 3 shows the relative contribution of five impact categories (exotic species introduction, eutrophication, ecotoxicity, greenhouse gases and water consumption) to the freshwater ecosystem damage caused by transport of 1 ton goods by shipping from the port of Rotterdam via the RMD waterway to Budapest or the Black sea. The average characterization factor for exotic fish species introduction was used in the calculations. For the 1500 km and 3000 km shipping of 1 ton goods, the introduction of exotic species contributes 34% and 20% to the total impact, respectively. The highest relative contribution is found for the eutrophication, which constitutes 51% and 62% of the total environmental impact for the 1500 km and 3000 km, respectively. The relative contribution of the stressors changes with the transport distance due to the fact that the impact of exotic species introduction only scales with the amount of goods transported, while the impacts of the other impacts both scale with amount of goods transported and with travel distance.

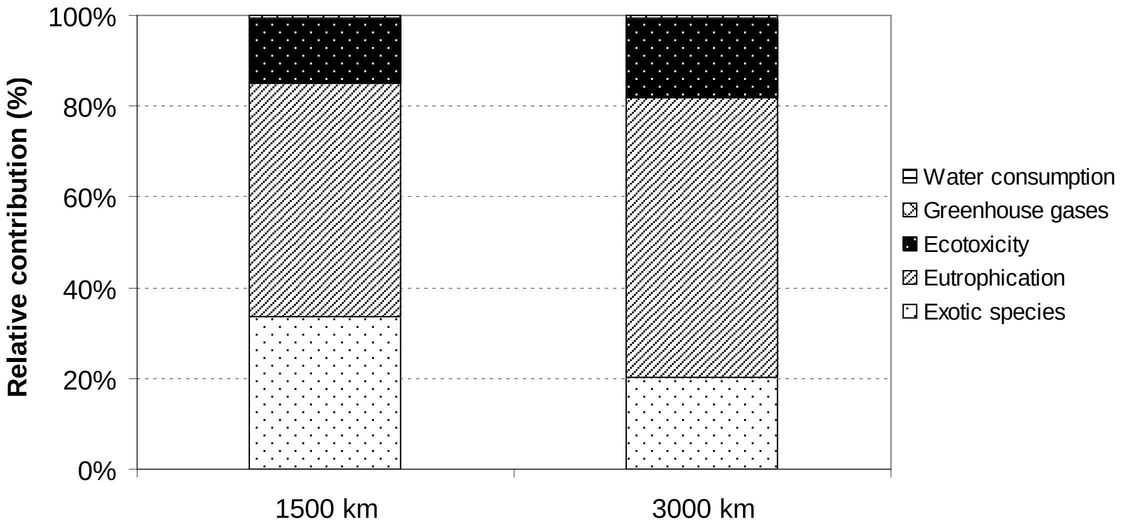

Figure 3.1: The relative contribution of five impact categories (exotic species introduction, eutrophication, ecotoxicity, greenhouse gases and water consumption) to the freshwater ecosystem damage by transport of 1 ton of goods from Rotterdam to respectively Budapest (1500 km) and the Black Sea (3000 km).

4. Discussion

The development and application of a framework to evaluate the relative change in freshwater species richness per unit of transported goods by introduction of exotic species will be further discussed below. We also provide the implications of our results for application within the context of LCIA.

4.1 Fate factor

We found that a relatively low number of exotic species directly or indirectly introduced by shipping via the RMD waterway was found in river Danube (1 exotic fish species) compared to the river Rhine (9 exotic fish species). The difference in shipping related species introductions of both rivers may be explained by two factors: 1) the difference in biotic resistance and open niches, and 2) the dominant water flow in the RMD waterway. The river Danube harbors a higher native fish species richness than the river Rhine, i.e. 115 versus 45 species (Sommerwerk et al., 2009). On the one hand, a higher species richness is associated with a higher biotic resistance or ability of native species to reduce the success of exotic species introductions (Torchin, 2010). On the other hand, a river with a low species richness may have more open niches and a higher success of exotic species introductions. Apart from differences in biotic resistance and open niches, the water in- and outlet regime of the staircase locks in the RMD waterway may also contribute to the higher dispersal of exotic species from Danube to the Rhine than vice versa. The water inlet of the RMD waterway is dominated by water originating from the river Danube (Van der Weijden et al., 2007).

Uncertainty in the fate factors can emerge from the lack of completeness and accuracy in the information on exotic species introduction. In this study, information on exotic species introduction was based on various data sources. Combination of data from multiple data sources can decrease the data consistency and underestimate the calculation of fate factors. Exotic species can be introduced into new areas from multiple pathways and vectors. Therefore, it is important to carefully determine via which vectors and dispersal corridors exotic species are introduced and to include only shipping transport-related species introductions.

One of the important factors affecting establishment and spread of exotic species in a new environment is the lag period. Time lags can be found between i) opening of the canal and dispersal of species, ii) dispersal of species and date of first record and iii) date of first record, establishment of viable populations and impact on native species. Dispersal and population establishment of exotic species may take time to achieve. Considering different lag periods could also affect the number of native species that are available because it could lead to species pool saturation and exotic-native species turnover in both rivers. This implies that excluding the lag period can particularly influence the fate factors.

4.2 Effect factor

In the present study, we developed a relationship between the percentage of exotic fish species and the potentially disappeared fraction of native species, without explicit consideration of the individual steps that cause this disappearance (see Figure 1). For instance, the step from exotic species to invasive species is not explicitly included, as it is very difficult to predict whether a species will become invasive (Verbrugge et al., 2012). Exotic species are considered to be invasive when their introduction causes harm to ecosystems, human health or economy (National Invasive Species Council, 2001). Although not all introduced species become invasive, but once a viable population of exotic species is established, it may spread and can dominate freshwater native species. Factors enabling successful invasion, establishment and spread of exotic species include complex invasion processes, such as the number and frequency of introductions of exotic species into a new area (propagule pressure), minimum viable population size, delay between the introduction of exotic species and its successful spread in a new region (lag period) (Grevstad, 1999; Kolar and Lodge, 2001). If sufficient information on the concept of species invasiveness is available, it is recommended to include these individual steps in the LCIA framework. Considering the complex invasive processes is subject to further research because it will provide a more complete picture of the consequences of exotic species on aquatic ecosystems.

The impacts of exotic species on native biodiversity differ widely in kind and magnitude. Besides negative effects, some exotic species can potentially have positive effects, e.g. increase of the local or regional number of aquatic species (Davis et al., 2011) or predate on other exotic species and control their population size. Whether these effects are considered to be positive or negative, however, is a subjective value judgement (Brown and Sax, 2005). In this study, we only considered effects of exotic fish species introduction on extinction of native fish species.

Uncertainty in the effect factor arises from uncertainties in the stressor-response model that links exotic fish introduction with threatened native species. The response curve for deriving the PDF was based on a limited number of data points with a large range between the minimum and maximum values. Information on the exotic species-native species disappearance relationship of individual rivers was, however, not readily available up to now. Furthermore, the number of threatened native species was based on the IUCN Red List (IUCN, 2006) and this extinction status of species is still incomplete and can lead to underestimation of the percentages of three categories of threatened fish species. It also remains uncertain whether species in these three categories of threatened species will certainly become extinct.

The scope of the study was limited to freshwater exotic fish species. Exotic fish not only displace native fish species but also affect other freshwater taxonomic groups (e.g. macroinvertebrates and plankton) and ecosystem functioning (Bradford et al., 1998). However, effects on other aquatic freshwater taxonomic groups and ecosystem functioning could not be included due to lack of data. In addition, shipping transport and development of the European network of waterways also result in the introduction of exotic species that belong to other taxonomical groups than fish, e.g. macroinvertebrates (Leuven et al., 2009). Including the impacts of introduction of other taxonomical groups is recommended for future study, as several macroinvertebrate species may also cause local and regional species extinction (Leuven et al., 2009; Van der Velde et al., 2009).

4.3 Implications

The method developed in this paper makes it possible to compare the relative importance of exotic species introduction with other stressors for freshwater biodiversity. We have shown for transport of goods through the RMD waterway that introduction of exotic species has an important share (> 20%) to freshwater ecosystem damage (i.e. PDF of biodiversity). This implies that neglecting exotic species introduction in current life cycle impact assessments of shipping transport-related activities can substantially underestimate the overall damage to freshwater ecosystems. The focus in our study was on the introduction influence of other interbasin connections and intercontinental transport related introduction of exotic species was not dealt with in this study. Native freshwater species in freshwater bodies are increasingly affected by exotic species that are introduced from other continents by ballast water or via other inland dispersal corridors (Leuven et al., 2009). Including impacts caused by exotic species introduction via other interbasin or continental routes is a next step to be taken in LCIA. This will provide a more complete picture of the consequences of exotic species on freshwater ecosystems in an LCA context.

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Supporting Information

Fate factor

Table S1 shows the exotic species introduced in the river Rhine and river Danube via Rhine-Main-Danube (RMD) waterway. The total amount of transported goods per year via RMD waterway can be found in Table S2.

Table S1: Exotic fish species related to shipping activities from1990 until 2009 in river Rhine and river Danube.

Species	Origin	First arrival	Reference
River Rhine			
Pseudorasbora parva	Southeast Asia	1992	Lenders (1993); Pollux and Korosi (2006)
Proterorhinus semilunaris/ Proterorhinus marmoratus	Ponto-Caspian	1999	Kottelat and Freyhof (2007); http://www.werkgroepexoten.nl/soorten.php (2011)
Ballerus sapa/ Abramis sapa	Black Sea, Caspian Sea	2000	http://www.werkgroepexoten.nl/soorten.php (2011); Bischoff et al. (1998)
Romanogobio belingi	Danube basin	1998	Soes et al. (2005)
Micropogonias undulatus	North and South America	2004	Stevens et al. (2004)
Neogobius melanostomus	North America	2004	Van Beek (2006); Borcherding et al. (2011); Van Kessel et al. (2009)
Neogobius kessleri	Ponto-Caspian	1999	Soes et al. (2007); Borcherding et al. (2011)
Neogobius fluviatilis	Ponto-Caspian	2008	Stemmer (2008); Van Kessel et al. (2009); Borcherding et al. (2011)
Babka gymnotrachelus	Ponto-Caspian	2010	Borcherding et al. (2011)
River Danube			
Gasterosteus gymnurus	Western Europe	<2010	Harka & Szepesi (2009)

Table S2: Amount of goods transported via RMD waterway from 1992 until 2009 (Water and naviation administration of the federation Germany, 2011)

Year	**Total Kg/yr**
1992	3.0E+09
1993	5.1E+09
1994	6.2E+09
1995	6.7E+09
1996	6.1E+09
1997	5.5E+09
1998	6.8E+09
1999	7.6E+09
2000	8.5E+09
2001	7.7E+09
2002	7.6E+09
2003	6.1E+09
2004	7.0E+09
2005	7.6E+09
2006	6.2E+09
2007	6.6E+09
2008	6.1E+09
2009	5.7E+09
Average	**6.4E+09**

Case study

Table S3 shows the inventory data that were used in the case study for calculating relative contribution of respectively, phosphorus emission to water (eutrophication), metal emissions to water (ecotoxicity), exotic species introduction, greenhouse gas emissions and water consumption. These inventory data were obtained from the ecoinvent database (Frischknecht et al., 2007). The characterization factors of five impact categories were taken from various sources (Helmes et al., 2012; Struijs et al., 2011; Van Zelm et al., 2009; Goedkoop et al., 2009; Hanafiah et al., 2011).

Table S3: Inventory data of five impact categories (exotic species introduction, eutrophication, ecotoxicity, greenhouse gases and water consumption) to the freshwater ecosystem damage in relation to the distance of shipping transport.

Impact category	**Impact category**		**Characterization factor**	**Reference**
	1500 km	**3000 km**		
Exotic species	$1.00\cdot10^{3}$ kg	$1.00\cdot10^{3}$ kg	$4.00\cdot10^{-4}$ PDF·m^3·yr/kg	This study
Eutrophication				
- Phosphate	$2.63\cdot10^{-2}$ kg	$5.25\cdot10^{-2}$ kg	$2.32\cdot10^{1}$ PDF·m^3·yr/kg	Helmes et al. (2012); Struijs et al. (2011)
- Phosphorus	$8.37\cdot10^{-6}$ kg	$1.67\cdot10^{-5}$ kg	$7.12\cdot10^{1}$ PDF·m^3·yr/kg	Helmes et al. (2012); Struijs et al. (2011)
Ecotoxicity				
- Antimony	$8.68\cdot10^{-6}$ kg	$1.74\cdot10^{-5}$ kg	$1.52\cdot10^{1}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Arsenic, ion	$4.91\cdot10^{-5}$ kg	$9.82\cdot10^{-5}$ kg	$1.55\cdot10^{1}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Barium	$1.22\cdot10^{-3}$ kg	$2.43\cdot10^{-3}$ kg	2.66 PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Beryllium	$1.14\cdot10^{-5}$ kg	$2.27\cdot10^{-5}$ kg	$4.31\cdot10^{2}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Cadmium, ion	$1.14\cdot10^{-5}$ kg	$2.29\cdot10^{-5}$ kg	8.96 PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Chromium, VI	$3.51\cdot10^{-4}$ kg	$7.03\cdot10^{-4}$ kg	$8.93\cdot10^{-1}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Chromium, ion	$4.19\cdot10^{-6}$ kg	$8.38\cdot10^{-6}$ kg	$8.93\cdot10^{-1}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Cobalt	$1.88\cdot10^{-4}$ kg	$3.76\cdot10^{-4}$ kg	$3.26\cdot10^{1}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Copper, ion	$1.65\cdot10^{-4}$ kg	$3.30\cdot10^{-4}$ kg	$1.17\cdot10^{2}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Lead	$3.37\cdot10^{-5}$ kg	$6.73\cdot10^{-5}$ kg	$4.10\cdot10^{-1}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Manganese	$6.23\cdot10^{-3}$ kg	$1.25\cdot10^{-2}$ kg	4.37 PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Mercury	$2.44\cdot10^{-6}$ kg	$4.89\cdot10^{-6}$ kg	$9.21\cdot10^{1}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Molybdenum	$4.32\cdot10^{-5}$ kg	$8.64\cdot10^{-5}$ kg	1.79 PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Nickel, ion	$8.76\cdot10^{-4}$ kg	$1.75\cdot10^{-3}$ kg	$9.75\cdot10^{1}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Selenium	$2.69\cdot10^{-5}$ kg	$5.37\cdot10^{-5}$ kg	$8.45\cdot10^{1}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Silver, ion	$1.41\cdot10^{-6}$ kg	$2.81\cdot10^{-6}$ kg	$3.93\cdot10^{2}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Thallium	$1.16\cdot10^{-6}$ kg	$2.32\cdot10^{-6}$ kg	$6.62\cdot10^{1}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Tin, ion	$8.65\cdot10^{-}$ kg	$1.73\cdot10^{-5}$ kg	$9.26\cdot10^{-1}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Vanadium, ion	$1.25\cdot10^{-4}$ kg	$2.49\cdot10^{-4}$ kg	$9.46\cdot10^{1}$ PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
- Zinc, ion	$1.31\cdot10^{-3}$ kg	$2.61\cdot10^{-3}$ kg	7.44 PDF·m^3·yr/kg	Van Zelm et al. (2009); Goedkoop et al. (2009)
Greenhouse gases				
- Carbon dioxide	$6.66\cdot10^{1}$ kg	$1.33\cdot10^{2}$ kg	$8.53\cdot10^{-5}$ PDF·m^3·yr/kg	Hanafiah et al. (2011)
- Dinitrogen monoxide	$5.07\cdot10^{-3}$ kg	$1.01\cdot10^{-2}$ kg	$2.78\cdot10^{-2}$ PDF·m^3·yr/kg	Hanafiah et al. (2011)
- Methane	$5.08\cdot10^{-2}$ kg	$1.02\cdot10\text{-}^{1}$ kg	$1.69\cdot10^{-3}$ PDF·m^3·yr/kg	Hanafiah et al. (2011)

Water consumption				
- Water, lake	$1.52 \cdot 10^{-3}$ m^3	$3.04 \cdot 10^{-3}$ m^3	$7.66 \cdot 10^{-4}$ PDF·m^3·yr/m^3	Hanafiah et al. (2011)
- Water, river	$6.57 \cdot 10^{-2}$ m^3	$1.31 \cdot 10^{-1}$ m^3	$7.66 \cdot 10^{-4}$ PDF·m^3·yr/m^3	Hanafiah et al. (2011)
- Water, unspecified	$1.44 \cdot 10^{-1}$ m^3	$2.87 \cdot 10^{-1}$ m^3	$7.66 \cdot 10^{-4}$ PDF·m^3·yr/m^3	Hanafiah et al. (2011)

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Chapter 7

Synthesis

This PhD thesis aims to address several stressors and endpoints not accounted for in ecological footprint and life cycle impact assessment calculations. The first aim was to assess the prospects for inclusion of non-CO_2 greenhouse gases and nutrients and impacts on biodiversity in ecological footprint (EF) method. In addition, new frameworks and methods for life cycle impact assessment (LCIA) were developed in the next part of this thesis. The synthesis chapter first reviews the major findings. The implications of the studies on the terrestrial environment using EF analysis are discussed in Section 7.1. Subsequently, a framework for fate and effect modelling for several impact categories (thermal pollution, climate change, water consumption and introduction of exotic species) for the freshwater environment is outlined (Section 7.2). The synthesis will be concluded with several recommendations for future research in LCIA modelling.

1.1 Terrestrial environment

The influence of including non-CO_2 greenhouse gases, nutrients and impacts on biodiversity in the original ecological footprint method was evaluated in chapters 2 and 3. Table 1.1 shows the fate factors and effect factors included in modeling of bioproductivity and biodiversity footprints.

Table 1.1: Fate factors and effect factors in bioproductivity and biodiversity footprints.

Impact category	Bioproductivity footprint		Biodiversity footprint	
	Fate factor	Effect factor	Fate factor	Effect factor
CO_2 emissions	Fraction of CO_2 absorbed by oceans, sequestration rate of CO_2 by biomass	Equivalence factor of forests	Global mean temperature increase due to CO_2 emissions	Relative loss of species richness due to temperature increase
Direct land use	Not applicable	Equivalence factor of land use type	Not applicable	Mean species abundance of land use type
Non-CO_2 emissions	Fraction of CO_2 absorbed by oceans, sequestration rate of CO_2 by biomass, global warming potentials of greenhouse gas	Equivalence factor of forests	Not evaluated	Not evaluated
Nutrients	Uptake rate of P and N by crops, denitrification rate of N in agricultural soils	Equivalence factor of agricultural soils	Not evaluated	Not evaluated

The ratio for the original EF and modified EF (including non-CO_2 greenhouse gases and nutrients) appears to give different results for various human activities from those obtained for the bioproductivity-biodiversity ratio (except for agricultural products). Agricultural products are influenced either by adding extra stressors (non-CO_2 greenhouse gases and nutrients) or focusing on different endpoint (biodiversity). Figure 1.1A indicates that the contribution of nutrients and non-CO_2 greenhouse gases is relatively high for a number of processes within biomass energy, metals, chemicals and agricultural products. Bio-based products (i.e. biomass energy, agricultural products, and paper and cardboards), dominated by direct land use, have a relatively high biodiversity footprint (BF) compared to the EF (figure 1.1B). This is due to the fact that direct land use is the most relevant driver of biodiversity loss compared to global warming for a 100 year time horizon within these three product categories. However, the relative importance of different drivers can change with the time horizon considered (chapter 2). This is particularly true in the case of CO_2 emissions that remain in the atmosphere for quite a long time (IPCC, 2001). Note that non-CO_2 greenhouse gases and nutrients were not included in the BF. Therefore, it was not possible to directly compare the results of the biodiversity footprint with that of the modified EF (including nutrients and non-CO_2 greenhouse gases).

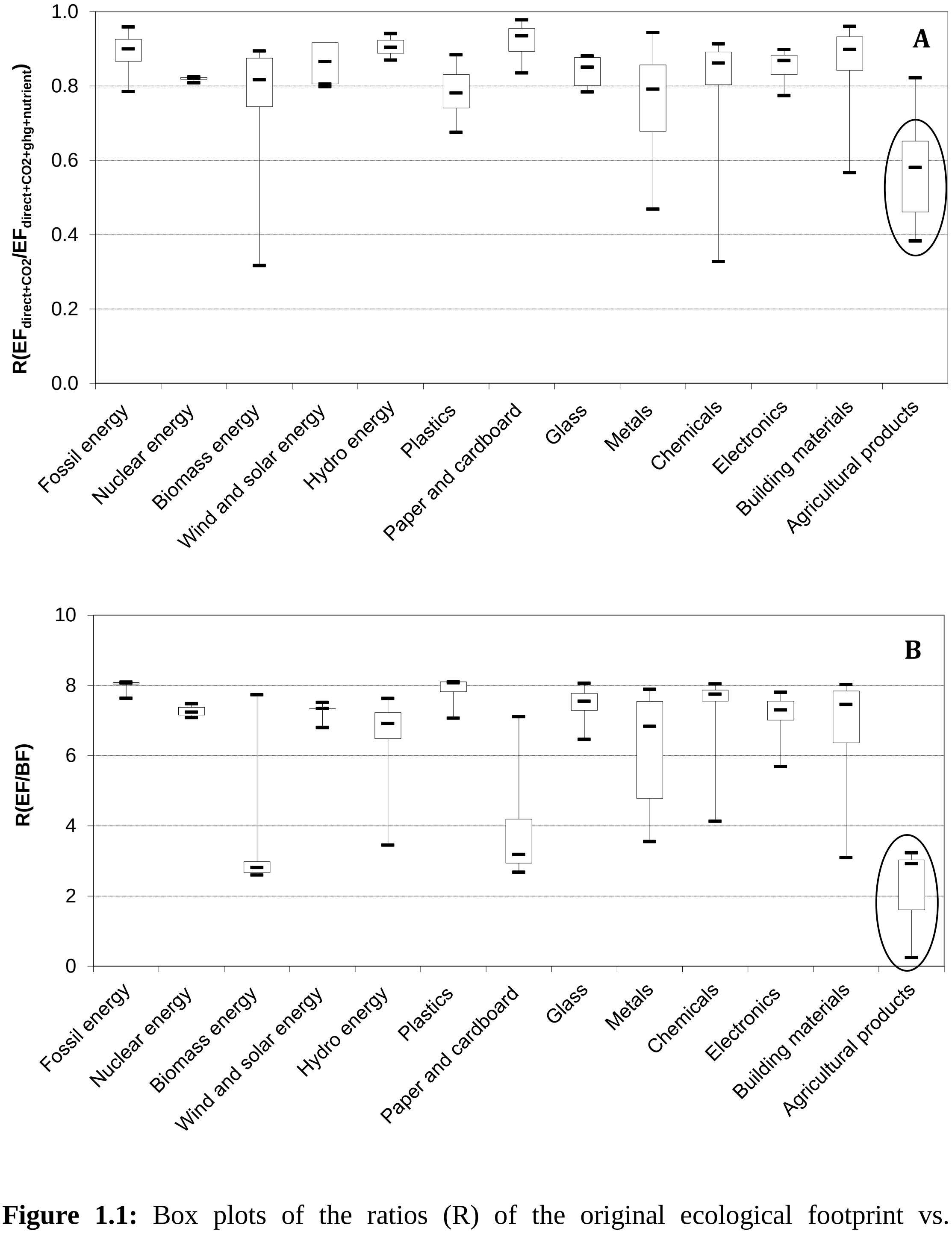

Figure 1.1: Box plots of the ratios (R) of the original ecological footprint vs. modified ecological footprint (A) and ecological footprint vs. biodiversity footprint (B) scores for 13 product groups based on a 100-year time horizon. The centre of the box represents the median value, the edges of the box indicate the 25th and 75th percentiles and the whiskers represent the 5th and 95th percentiles of the distributions (chapters 2 and 3).

1.2 Freshwater environment

Chapters 4, 5 and 6 provide new methods for assessing impacts of thermal pollution, climate change, water consumption and exotic species introduction on freshwater ecosystem damage in LCIA. Freshwater ecosystem damage was calculated using the damage indicator called potentially disappeared fraction (PDF) of aquatic species. The advantage of this endpoint approach is that it enables one to quantify the damage to areas of protection, providing more meaningful results compared to midpoint approach. The endpoint approach that is defined at the end of the cause-effect chain make it possible to aggregate and rank the different impact categories with different modes of action related to a single area of protection (Bare et al., 2000; Jolliet et al., 2004; Bare and Gloria, 2006; 2008). Table 1.2 illustrates the fate and effect modeling of impact categories addressed in this PhD thesis. For reasons of data availability, different models and data were used to arrive at the endpoint impact scores. The reasons of the application of the various models for fate and effect factors are further discussed below.

Table 1.2: An overview of fate and effect modeling of impact categories in the life cycle impact assessment implemented in this PhD thesis.

<table>
<tr><th>Impact category</th><th>Fate modeling</th><th>Effect modeling</th><th>Endpoint</th></tr>
<tr><td>Thermal pollution</td><td>Residence time of heat emissions in the river was simulated using QUAL2Kw model</td><td>SSD: temperature induced mortality due to a change in ambient temperature</td><td rowspan="4">PDF of freshwater species</td></tr>
<tr><td>Climate change</td><td>The change in global mean temperature and subsequent water discharge due to the change in GHG emissions</td><td rowspan="2">SSD: Species-discharge curve based on the information on native fish species and river discharges</td></tr>
<tr><td>Water scarcity</td><td>The change in water discharge due to the change in water consumption was set to 1</td></tr>
<tr><td>Exotic species introduction</td><td>Introduction of % exotic species per amount of transported goods</td><td>SSD: % of exotic-native species curve, where PDF represents the sum of threatened native fish species (i.e. vulnerable, endangered and critically endangered)</td></tr>
</table>

SSD: Species sensitivity distribution; GHG: Greenhouse gas; PDF: Potentially disappeared fraction.

1.2.1 Fate factor modeling

The QUAL2Kw model was applied to quantify the change in ambient river temperature due to a change in thermal discharges in the rivers Aare and Rhine (chapter 4). The one-dimensional QUAL2Kw model simulates the transport and fate of non-toxic pollutants and calculates steady-state hydraulics systems (Pelletier et al., 2006; Pelletier and Chapra, 2008). This model takes into account components of surface heat exchange (i.e. shortwave solar radiation, longwave atmospheric radiation, back longwave radiation from water, heat convection/conduction between air, water and sediment and heat loss due to evaporation) (Edinger et al., 2007). Most impact assessment methods currently used in LCIA take into account the global environmental effects, such as global warming. However, generalization of the fate factors of thermal pollution to other water systems on a global scale has not been done in this PhD thesis. The emission location is regarded an important factor for this type of location-specific impacts that often occur as regional or local impacts. To apply this site-specific approach with QUAL2Kw model requires a large amount of input parameters, such as river water temperatures, ambient water temperature, river flow over time and space and distance to the sea. A more generic model could be used in the calculation of fate factor for thermal pollution. Instead of using a complex model, a relative simple model for water temperature, such as the rTemp model could serve as an alternative approach to assess the fate of heat emissions. rTemp is a response temperature model used to examine the variation in water temperature over time. Although information relating to hydraulics still needs to be added to such a stagnant model, this hydraulics information is readily available from other study (e.g. Helmes et al., 2012) that deals with freshwater eutrophication on a global scale.

For greenhouse gas (GHG) emissions, the fate factor reflects the change in water discharge due to a change in GHG emission (chapter 5). The fate factor for climate change has spatially explicit component because the link between global mean temperature change and the change in water discharge is river basin specific.

The fate factor for water consumption was set equal to one, based on the assumption that the change in water discharge at the river mouth is equal to the change in water consumption by human activities (chapter 5).

The fate factor for exotic species introduction refers to the change in % exotic species due to a change in transportation of goods (chapter 6). Lack of completeness and accuracy in the information on the introduction of exotic species serve as the main limitation in the fate factors. In this chapter 6, data on the cumulative number of exotic species introduction in the rivers Rhine and Danube was gathered from various data sources.

1.2.2 Effect factor modeling

The relative species richness was taken as a starting point in the effect modeling of thermal pollution, water consumption, climate change and exotic species introduction. The effect factors were modeled consistently using species sensitivity distributions (SSD) throughout chapters 4 to 6. SSDs were introduced in life cycle impact assessment to address the relative importance of individual chemical exposure towards impacts on ecosystems (Huijbregts et al., 2002; Van de Meent and Huijbregts, 2005). In this PhD thesis, the SSD method was used to predict impacts of non-toxic stressors, i.e. thermal pollution, water consumption, climate change and introduction of exotic species. The effects were quantified in terms of the PDF of freshwater aquatic species per unit of exposure.

The SSD method is increasingly applied in ecological risk assessment. An SSD is usually estimated by assuming that the data are from a random sample of species from a lognormal distribution and constructed using sensitivity data from an adequate number of species (Grist et al., 2006). However, these assumptions are difficult to be attained for the majority of toxicants (Newman et al., 2000; Wheeler et al., 2002). The development of tests with new species is very time-consuming and complicated with most species due to their rarity or conservation status and limited information about their biological aspects (Kefford et al., 2005). The SSD modeling does not consider interactions between species and all species in a community are treated as equally important and non-dependent on each other. Furthermore, SSD modeling does not indicate which species are lost or what will be the ecological consequences of the species loss.

For temperature-induced mortality, a normal temperature-response function of the acclimation temperature of potentially affected fraction (PAF) of species derived in their study has been taken as a starting point (De Vries et al., 2008). In this study, we assumed the PAF to be equal to the PDF of freshwater aquatic species. The SSD for thermal pollution that based on acute LT50 data was derived from laboratory tests. The tests were carried-out to determine the range by which the temperature can increase above the background river temperature without killing more than 50% of the species population (LT50). The log-normal stressor-response curve was obtained through analysis of 36 freshwater species, including fish, molluscs, crustacean, annelida and hydrozoa from temperate regions. This spatially explicit study that based on empirical data has shown that the effect factor strongly depends on the river water temperature. This study was specifically focused on the cooling water discharges from the nuclear power plant Muehleberg (NPPM) in Switzerland for the rivers Aare and Rhine. In the case of thermal pollution, the location of emissions, such as temperate versus tropical zone appears to be important when dealing with heat emissions.

An SSD was constructed to examine the sensitivity of freshwater species to changes in the water discharges, where it describes the fraction of freshwater species that potentially disappeared due to climate change and water consumption based on marginal changes approach (chapter 5). The complex effects of climate change on water discharge were modeled using empirical data. The change in the water discharge due to the change in global mean temperature was empirically derived based on data from IPCC (2001) and Millennium Ecosystem Assessment (2005). The modeled change in river discharge from the WaterGap model (Alcamo et al., 2003) was related to the predicted temperature change for the year 2100.

The effect factor for surface water consumption relates the influence of reduced flow rates to fish species richness with an empirical global species-discharge model. The effect factors for climate change and water consumption were only calculated based on the information on the occurrence of freshwater native fish species in global rivers. Using field data, the SSD curve for changes in fish species richness due to water discharge changes was generated based on a log-linear distribution.

An empirically-based PDF of native species in rivers due to the percentage of exotic species introduced was used to derive the effect factor for the introduction of exotic species related to shipping transport of goods via the Rhine-Main-Danube (RMD) waterway (chapter 6). This study focused on freshwater fish species only and other aquatic species groups were not included. A field-based SSD curve was constructed to quantify the fraction of freshwater native species that potentially disappeared due to the exotic species introduction. A log-linear regression was derived to explain the stressor-response relationship between the percentage of exotic species and PDF of native species. Invasibility of ecosystems, invasiveness of exotic species and impacts of species introduction are highly dependent on the local or regional environmental circumstances. In order to have a better perception of this emerging issue that can adversely affect aquatic ecosystems, deriving impact factors for different spatial scale should be conducted. A simpler method using the high impact invader (HII) factor developed by Ricciardi and Kipp (2008) could be applied as an alternative for the effect factor calculations. It can be done by multiplying the number of exotic species by the HII for specific pathways and ecosystem types. The HII refers to exotic species that can cause severe declines in native species. According to Ricciardi and Kipp (2008), not all exotic species will become invasive (on average circa 10% of exotic species cause a negative effect on native species populations). However, the percentage of HII factor varies for different ecosystems.

1.3 Conclusions and recommendations

The research outlined in this PhD thesis contributes to improvements in both ecological footprint and life cycle impact assessment methods. It has been concluded that:

- Depending on the product group, including non-CO_2 greenhouse gases and nutrient emissions, as well as the impacts on biodiversity in ecological footprint analysis change the interpretation of the results (chapter 2 and 3). Therefore, the incorporation of these additional drivers and applying another environmental endpoint in the ecological footprint analysis is required.
- A common framework for assessing effects of thermal pollution (chapter 4), greenhouse gas emissions (chapter 5), water use (chapter 5) and introduction of exotic species on biodiversity (chapter 6) was developed and applied. It appears that both relevant and feasible to include these stressors in an LCA framework.

The findings of this PhD thesis also provide the following recommendations for further research:

- Impacts of non-CO_2 greenhouse gases and nutrients were not yet assessed in the biodiversity footprint for the terrestrial environment (chapter 3). In order to arrive at a comprehensive evaluation of opportunities to improve the biodiversity footprint, these stressors should also be included in the biodiversity footprint for the terrestrial environment.
- Simplified models for fate and effect modeling that do not require detailed data could be used to close data gaps. It is also expected that this may reduce uncertainties in the calculation of characterization factors. For instance, in

chapter 4 the fate factor for heat emissions was simulated using a complex heat discharge model called QUAL2Kw. It would be interesting to compare the results obtained in QUAL2Kw (that models the response temperature over distance) with that of a more simple model, rTemp (that models the response temperature over time).

- To date, no characterization factors have been derived to address impacts of thermal pollution and introduction of exotic species on a global scale (chapter 4, 6). Future research in this area should focus on developing archetypes (according to e.g. climate zones) for different areas worldwide. The derivation of globally applicable characterization factors is regarded as the next step in the sophistication of these impact categories.
- the analysis of the effects of exotic species introductions on biodiversity in the rivers Rhine and Danube was restricted to the construction of the Rhine-Main-Danube Canal for shipping transport between western and central-/eastern Europe and was focused on fish diversity only (chapter 6). To give a more complete picture of the consequences of exotic species introduction on native species, macro-invertebrate species and other taxonomic groups should be included in assessments. Furthermore, it is recommended to derive fate and effect factors covering other relevant impact pathways for the introduction of exotic species (such as ship hull fouling, ballast water and aquaculture).
- The newly developed methods in this PhD thesis should be applied in practice in a number of LCA case studies, where the relative importance of these indicators can be compared across impact categories, at an endpoint level.

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Summary

Life Cycle Assessment (LCA) is a tool to evaluate and model the environmental impacts and resources associated with a product, process or service throughout its life cycle (i.e., from raw material acquisition, via production and use phases and to disposal). This PhD thesis focuses on the life cycle impact assessment (LCIA), the phase where potential environmental impacts associated with identified inputs and releases are modelled and expressed in terms of characterization factors (CFs).

Although the characterization factors to assess impacts associated with terrestrial ecosystems in the LCIA methodology are available for a wide range of stressors, evaluation on how the results for terrestrial ecosystems would be when a simple method such as ecological footprint (EF) is applied still remains unknown. For the assessment of effects on freshwater ecosystem quality, this part is still lacking in the LCA framework. While few freshwater-related impacts are currently included in LCA at the level of effects on biodiversity, other relevant impacts due to thermal emissions, global warming, water use and exotic species have so far not been included in the LCIA.

The overall aim of this PhD thesis is two-fold:

1. To include impacts of other stressors (nutrients and non-CO_2 greenhouse gases) on terrestrial ecosystems in the ecological footprint methods and to compare the common bioproductivity-based with a newly developed biodiversity-based ecological footprint.
2. To develop life cycle impact assessment methods to assess damages towards freshwater ecosystems related to thermal emissions, climate change, water use and introduction of exotic species.

Chapter 2 investigates the influence of nutrients and non-CO_2 greenhouse gases in the ecological footprint (EF) calculations. It was found that for most of the products included in the study, the influence of the addition of emissions of nutrients and non-CO_2 greenhouse gases was typically smaller than 20%. The EF was generally dominated by CO_2 emissions or direct land use. However, for goods and services within specific product categories, i.e., waste treatment processes, bio-based energy,

agricultural products and chemicals, adding non-CO_2 greenhouse gas emissions to air and nutrient emissions to water can have a dominant influence on the EF. Our findings suggest that in specific cases, the inclusion of non-CO_2 greenhouse gases and nutrient emissions can indeed change the interpretation of the EF results.

Chapter 3 analyzed the ecological footprint (EFs) of products comparing biodiversity-based impacts with bioproductivity-based impacts. Impact on biodiversity was quantified with the mean species abundance indicator, while impact on bioproductivity was based on the common ecological footprint calculations. In the analysis we used a data set of 1340 product systems, subdivided into 13 product groups. The product groups include various types of energy generation and material production. We found that the ranking of production processes can change by the selection of biodiversity-based EF instead of the common bioproductivity-based EF. This is particularly the case if the EFs of bio-based products, dominated by direct land use, are compared with the EFs of fossil-based products, dominated by CO_2 emissions. The results also show that the relative importance of different drivers can change over time within the biodiversity perspective. The relative importance of climate change is expected to increase significantly, particularly when projected for a longer time horizon. As the interpretation of the biodiversity-based EFs can differ from the bioproductivity-based EFs, the inclusion of impacts on biodiversity should be considered in the EF calculation.

Chapter 4 develops and implements a model framework to assess the impact of thermal pollution on freshwater ecosystem. A method to derive characterization factors for the impact of cooling water discharges on aquatic ecosystems was developed which uses space and time explicit integration of fate and effects of water temperature changes. The fate factor is calculated with a 1-dimensional steady-state model and reflects the residence time of heat emissions in the river. The effect factor specifies the loss of species diversity per unit of temperature increase and is based on a species sensitivity distribution of temperature tolerance intervals for various aquatic species. As an example, time explicit characterization factors were calculated for the cooling water discharge of a nuclear power plant in Switzerland, quantifying the impact on aquatic ecosystems of the rivers Aare and Rhine. The relevance of thermal emissions constitutes 0.01% of the total environmental impact. For freshwater ecosystem quality, thermal emissions contribute 49% of the whole freshwater impact in the case of a once-through cooling system.

In **chapter 5**, an operational method is developed to derive characterization factors for direct water consumption and global warming based on freshwater ecosystem damages. We derived characterization factors for water consumption and global warming based on freshwater fish species loss. Calculation of characterization factors for potential freshwater fish losses from water consumption were estimated using a generic species-river discharge curve for 214 global river basins. We also derived characterization factors for potential freshwater fish species losses per unit of greenhouse gas emission. Based on five global climate scenarios, characterization factors for 63 greenhouse gas emissions were calculated. The study shows that depending on the river considered, characterization factors for water consumption can differ up to 3 orders of magnitude. Characterization factors for greenhouse gas emissions can vary up to 5 orders of magnitude, depending on the atmospheric residence time and radiative forcing efficiency of greenhouse gas emissions. An emission of 1 ton of CO_2 is expected to cause the same impact on potential fish species disappearance as the water consumption of 10-1000 m^3, depending on the river basin considered.

Chapter 6 demonstrates the possibility of calculating the introduction of exotic species characterization factors for freshwater ecosystem. The ecological impact of anthropogenically introduced exotic species is generally not accounted for in the environmental life cycle assessment (LCA) of products, while it is considered one of the major treats for anthropogenic stressors nowadays. Here, we propose a framework to include exotic species introduction in an LCA context. As an example, we derived characterization factors for exotic fish species introduction, expressed as the potentially disappeared fraction of native freshwater species in the rivers Rhine and Danube integrated over space and time, related to transport of goods across the Rhine-Main-Danube canal. We also quantified the relative importance of exotic fish species introduction compared to other anthropogenic stressors in the freshwater environment. We found that the relative importance of introduction of exotic fish species is 20 - 34% of the total freshwater ecosystem impact, depending on the transport distance of goods (3000 km vs. 1500 km, respectively). Our analysis showed that it is relevant and feasible to include the introduction of exotic species in an LCA framework. The framework proposed can be further extended by including impacts of other exotic species groups, types of water bodies and pathways for introduction.

Chapter 7 provides an overview of the new approaches to the modelling of the terrestrial and freshwater ecosystems damage caused by several relevant impact categories. Limitations and uncertainties of the methods developed in this PhD thesis are also touched upon in the Chapter 7. Practical implications and recommendations for future research are given in the end of this chapter.

Samenvatting

Levenscyclusanalyse (LCA) is een wetenschappelijke methode voor het integraal evalueren en modelleren van milieueffecten en verbruik van natuurlijke hulpbronnen tijdens de gehele levenscyclus van producten, processen of diensten (dat wil zeggen van grondstofwinning, productie en gebruiksfase tot afvalverwijdering). Dit proefschrift is vooral gericht op de levenscyclus impactanalyse (LCIA) waarin de potentiële milieueffecten, die zijn gerelateerd aan de invoer van hulpbronnen en emissies van stoffen, worden gemodelleerd en uitgedrukt in zogenoemde karakterisatiefactoren.

Ondanks de beschikbaarheid van karakterisatiefactoren voor de analyse van effecten van een breed scala stressoren op terrestrische ecosystemen, was bij aanvang van dit promotieonderzoek niet bekend of de resultaten van relatief eenvoudige methoden, zoals de ecologische voetafdruk, veranderen indien deze karakterisatiefactoren daarin worden toegepast. Voorts ontbraken in LCIA karakterisatiefactoren voor een groot aantal stressoren op de kwaliteit van zoetwater ecosystemen. Hoewel analysemethoden voor de effecten van diverse stressoren op de biodiversiteit van zoetwater ecosystemen al in gangbare levenscyclusanalyses waren geïmplementeerd, zoals toxische stoffen en eutrofiëring, ontbraken dergelijke methoden voor thermische vervuiling, broeikasgasemissies, water gebruik en introductie van uitheemse soorten.

Het voorliggende proefschrift heeft een tweevoudige doelstelling:

1. De implementatie van effecten van andere stressoren (nutriënten en non-CO_2 broeikasgassen) op terrestrische ecosystemen in de ecologische voetafdruk methode en vergelijking van de resultaten van gangbare voetafdrukken die zijn gebaseerd op bioproductie met die van een nieuwe op biodiversiteit gebaseerde benadering.
2. De ontwikkeling van levenscyclus impactanalyse methoden voor de aantasting van zoetwater ecosystemen door thermische emissies, broeikasgasemissies, water gebruik en de introductie van uitheemse soorten.

Hoofdstuk 2 analyseert de invloed van nutriënten en andere broeikasgassen dan CO_2 in berekeningen van ecologische voetafdrukken. Voor de meeste producten die zijn doorgerekend is de invloed van het meenemen van de emissies van deze nutriënten en broeikasgassen minder dan 20%. De ecologische voetafdruk wordt immers sterk gedomineerd door CO_2 emissies en landgebruik. Het meerekenen van emissies van andere broeikasgasemissies in de lucht en nutriënten in water heeft echter een dominante invloed op de ecologische voetafdruk van goederen en diensten binnen specifieke productcategorieën, zoals afvalwaterzuivering, biobrandstoffen, landbouw producten en chemicaliën. De resultaten tonen dat in specifieke gevallen, het meerekenen van nutriënten en andere broeikasgassen dan CO_2 een aanmerkelijke invloed heeft op de uitkomsten van de ecologische voetafdrukmethode.

Hoofdstuk 3 analyseert ecologische voetafdrukken van producten die zijn gebaseerd op de biodiversiteit en bioproductiviteit benadering. De effecten op biodiversiteit zijn gekwantificeerd met een indicator voor de gemiddelde abundantie van een soort, terwijl de effecten op bioproductiviteit zijn gebaseerd op gangbare berekeningen van de ecologische voetafdruk. In de analyse is een data set van 1340 productsystemen onderverdeeld in 13 productgroepen. De productgroepen bevatten diverse productietypen voor energie en materialen. De rangorde van productieprocessen kan veranderen indien ecologische voetafdrukken worden gebaseerd op biodiversiteit of bioproductiviteit. Dit is het geval wanneer de ecologische voetafdruk voor producten worden vergeleken waarvoor biobrandstof of fossiele brandstof is gebruikt. De effecten van deze typen brandstoffen worden gedomineerd door respectievelijk landgebruik en CO_2 emissies. De resultaten tonen ook dat het relatieve belang van verschillende milieustressoren bij toepassing van de biodiversiteitbenadering kan veranderen over de tijd. Het relatieve belang van klimaatverandering neemt significant toe met de lengte van de tijdshorizon. De uitkomsten van de twee methodieken voor het berekenen van ecologische voetafdrukken verschillen. Daarom zouden ook effecten op biodiversiteit moeten worden meegenomen bij berekeningen van ecologische voetafdrukken.

H**oofdstuk 4** beschrijft de ontwikkeling en implementatie van een modelconcept voor de analyse van effecten van thermische emissies op zoetwater ecosysteem. De methode voor het afleiden van karakterisatiefactoren voor de effecten van koelwaterlozingen op aquatische ecosystemen is ruimte en tijd expliciet en integreert zowel het gedrag als de effecten van veranderingen in de water temperatuur. De ‘fate’-factor is berekend met een 1-dimensional stationair model en reflecteert de verblijftijd van warmte emissies in de rivier. De effectfactor specificeert het verlies van soortenrijkdom per eenheid temperatuurtoename en is gebaseerd op de gevoeligheidverdeling van soorten voor temperatuurtolerantie van verschillende aquatische soorten. Bij wijze van voorbeeld zijn tijd expliciete karakterisatiefactoren berekend voor koelwaterlozingen van een kerncentrale in Zwitserland en de effecten op aquatische ecosystemen van de rivieren Aare en Rijn gekwantificeerd. Voor zoetwater ecosysteemkwaliteit, dragen warmtelozingen zonder hergebruik van koelwater 49% bij aan het totale effect.

Hoofdstuk 5 beschrijft de ontwikkeling van een operationele methode voor het afleiden van karakterisatiefactoren voor de effecten van waterconsumptie en emissies van broeikasgassen op zoetwater ecosystemen. Deze karakterisatiefactoren zijn gebaseerd op het verdwijnen van zoetwater vissoorten. Bij de berekeningen van de karakterisatiefactoren voor het potentieel verlies van zoetwatervissoorten door water consumptie is gebruik gemaakt van een generieke mondiale soortenrijkdom – rivierafvoer curve voor 214 rivierstroomgebieden. Tevens zijn karakterisatiefactoren voor het potentieel verlies van zoetwater vissoorten afgeleid voor 63 broeikasgassen. De studie toont dat de karakterisatiefactoren voor water consumptie, afhankelijk van de betrokken rivier, tot drie ordegroottes kunnen verschillen. Karakterisatiefactoren voor broeikasgasemissies kunnen tot 5 ordegroottes verschillen, afhankelijk van de verblijftijd in de atmosfeer en de capaciteit om infra-rood straling te absorberen en terug te kaatsen van de verschillende broeikasgassen. Een uitstoot van 1 ton CO_2 veroorzaakt naar verwachting het zelfde effect op vissen, uitgedrukt als potentieel verdwijnende vissoorten, als de water consumptie van 10-1000 m^3, afhankelijk van de betrokken rivier.

Hoofdstuk 6 beschrijft een methode voor het afleiden van karakterisatiefactoren voor de introductie van uitheemse soorten in zoetwater ecosystemen in de context van de levenscyclusanalyse. De ecologische gevolgen van de introductie van uitheemse soorten door de mens worden momenteel beschouwd als een van de belangrijkste milieuproblemen. In de milieugerichte levenscyclusanalyse van producten wordt hiermee echter nog geen rekening gehouden. In een case studie zijn de karakterisatiefactoren voor de introductie van uitheemse vissoorten, uitgedrukt als potentieel aangetaste fractie van inheemse zoetwatervissoorten in de rivieren Rijn en Donau en geïntegreerd over ruimte en tijd, gerelateerd aan goederentransport via het Rijn-Main-Donau kanaal. Het relatieve belang van de effecten van de introductie van uitheemse soorten door scheepvaarttransport en aanleg van kanalen tussen rivieren is gekwantificeerd en vergeleken met de gevolgen van andere antropogene stressoren in het zoetwatermilieu. De relatieve bijdrage van introductie van uitheemse vissoorten is 20 - 34% van het totale effect van goederentransport op zoetwater ecosystemen, afhankelijk van de transportafstand van goederen (3000 km vs. 1500 km, respectievelijk). Deze analyse toont dat implementatie van effecten van de introductie van uitheemse soorten in levenscyclusanalyse haalbaar en relevant is. Het geschetste kader voor de effectanalyse kan verder worden uitgebreid door implementatie van karakterisatiefactoren voor andere groepen van uitheemse soorten, typen watersystemen en wijzen van introductie.

Voor diverse relevante effectcategorieën wordt in **hoofdstuk 7** een overzicht gegeven van de nieuw ontwikkelde methoden om de aantasting van terrestrische en zoetwater ecosystemen te modelleren. Daarnaast wordt ingegaan op de beperkingen en onzekerheden van deze methoden. Tenslotte worden implicaties voor de toepassing van deze methoden in de praktijk geschetst en diverse aanbevelingen gedaan voor verder onderzoek.

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Curriculum vitae

Marlia Mohd Hanafiah dilahirkan pada 5 September 1980 di Negeri Sembilan, Malaysia. Pada tahun 2003, beliau memperolehi Ijazah Sarjana Muda dalam bidang Sains Sekitaran dari Universiti Kebangsaan Malaysia (UKM). Seterusnya, pada tahun 2006 beliau mendapat Ijazah Sarjana dengan pengkhususan dalam bidang Penilaian Impak Alam Sekitar dari universiti yang sama. Beliau memulakan karier akademik sebagai Tutor di Fakulti Sains dan Teknologi, UKM pada Julai 2006. Pada April 2008, beliau melanjutkan pengajian peringkat Doktor Falsafah di dalam bidang Penilaian Kitar Hayat di Radboud University Nijmegen (RUN), The Netherlands. Fokus tesis kedoktoran beliau adalah menambahbaik metodologi sedia ada di dalam penilaian impak kitar hayat. Penyelidikan beliau turut melibatkan kerjasama beberapa institut penyelidikan luar termasuk ETH Zurich (Switzerland), Trent University (Canada) dan Washington State Department of Ecology (USA). Beliau juga menghadiri kursus-kursus yang di anjurkan oleh Pusat Penyelidikan SENSE. Kini beliau berkhidmat sebagai pensyarah di UKM dan meneruskan kajian penyelidikan di dalam bidang penilaian kitar hayat.

Marlia Mohd Hanafiah was born on September 5, 1980 in Negeri Sembilan, Malaysia. She obtained her B.Sc. in Environmental Science from the National University of Malaysia (UKM) in 2003. Subsequently, she earned a M.Sc. with a specialisation in Environmental Impact Assessment from the same university in 2006. After graduating, she started her academic career as a Tutor at the Faculty of Science and Technology, the National University of Malaysia in 2006. In April 2008, she furthered her Ph.D study at the Radboud University Nijmegen (RUN), The Netherlands in the field of Life Cycle Assessment. In her doctoral thesis, Marlia addressed the topic of methods improvement in life cycle impact assessment. Her research involved various research institutions including ETH Zurich (Switzerland), Trent University (Canada) and Washington State Department of Ecology (USA). During her Ph.D study, she also attended courses organized by the research school SENSE (Socio-economic and natural sciences of the environment). She is currently working as a lecturer at UKM and continuing her research in life cycle assessment.

List of Publications

- **Hanafiah, M.M.,** Leuven, R.S.E.W., Huijbregts, M.A.J. 2012. Including the introduction of exotic species in life cycle impact assessment: the case of inland shipping. Environ. Sci. Technol. submitted.

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