

## 8. Freshwater eutrophication

Ligia B. Azevedo<sup>1,2</sup>, Francesca Verones<sup>1,3\*</sup>, Andrew D. Henderson<sup>4,5</sup>, Rosalie van Zelm<sup>1</sup>, Olivier Jolliet<sup>4</sup>, Laura Scherer<sup>6</sup>, Mark A. J. Huijbregts<sup>1</sup>

<sup>1</sup> Department of Environmental Science, Institute for Water and Wetland Research, Radboud University Nijmegen, P.O. Box 9010, 6500 GL, Nijmegen, the Netherlands

<sup>2</sup> International Institute for Applied Systems Analysis, Ecosystem Services and Management Program, Schlossplatz 1, A-2361 Laxenburg, Austria

<sup>3</sup> Industrial Ecology Programme, Department for Energy and Process Technology, Norwegian University of Science and Technology, Trondheim, Norway

<sup>4</sup> Department of Environmental Health Sciences, School of Public Health, University of Michigan, 1415 Washington Heights, Ann Arbor, MI 48109, USA

<sup>5</sup> Division of Epidemiology, Human Genetics and Environmental Sciences, School of Public Health, The University of Texas Health Science Center at Houston, 1200 Herman Pressler, Houston, Texas 77030, USA

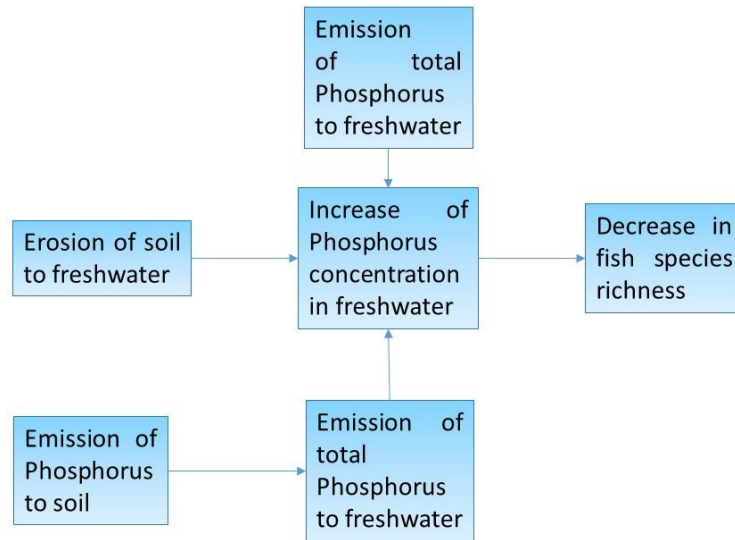
<sup>6</sup> Institute of Environmental Engineering, ETH Zurich, 8093 Zurich, Switzerland

\* [francesca.verones@ntnu.no](mailto:francesca.verones@ntnu.no)

**Based on:** Helmes *et al.* (2012), Azevedo *et al.* (2013a), Azevedo *et al.* (2013b), Azevedo (2014), and Scherer and Pfister (2015).

### 8.1. Areas of protection and environmental mechanisms covered

Freshwater eutrophication occurs due to the discharge of nutrients into soil or into freshwater bodies and the subsequent rise in nutrient levels (namely, of phosphorus and nitrogen). Environmental impacts related to freshwater eutrophication are numerous. They follow a sequence of ecological impacts offset by increasing nutrient emissions into freshwater, thereby increasing nutrient uptake by autotrophic organisms such as cyanobacteria and algae and, ultimately, potential losses to biodiversity. In this work, emission impacts to freshwater are based on the transfer of phosphorus from the soil to freshwater bodies, its residence time in freshwater systems and on the potentially disappeared fraction (PDF) following an increase in phosphorus concentrations in freshwater (Figure 8.1). The detailed sequence of impacts related with freshwater eutrophication is described next.



**Figure 8.1: Illustration of impact pathway represented in equations 8.1 and 8.2.**

Ecological impacts from freshwater eutrophication are initialized by the increase in primary productivity resulting from enhanced nutrient uptake by autotrophs, thereby prompting the increase in water turbidity, odor, and, subsequently, the decomposition of organic matter, water temperatures, and the depletion of dissolved oxygen. The latter is particularly detrimental to heterotrophic species. The depletion of sunlight caused by increased water turbidity also enhances competition for light by photosynthesizing organisms, which, in some cases, may lead to the synthesis of toxic substances (allelochemicals) by competing phytoplankton (Carpenter et al. 1998; Leflaive et al. 2007). Ultimately, they may prompt losses in biodiversity, e.g. decline in genera richness (Struijs et al. 2011b). In this report, we only include the environmental impact of emissions of phosphorus as increases in phosphorus levels in freshwaters seem to instigate primary production more than those of nitrogen (Schindler 2012).

The area of protection covered for this environmental mechanism is the ecosystem quality. The freshwater eutrophication impact is determined by the fraction of P emitted to soil or erosion of soil that reaches the freshwater compartment, the residence time of phosphorus (P) in freshwater (described by the fate factor) and by the sensitivity of the ecosystem to P levels (described by the effect factor). Here, the effect factor is based on a probabilistic model of a decline in richness of freshwater fish species with increasing emissions of P in freshwater systems. Note that, in cases where allelochemicals are released in the environment and these are also toxic to humans, there can be a direct impact to human health. However, this environmental mechanism is not taken into account in this chapter.

The geographical coverage of the endpoint characterization factor is global. The effect factor is based on a linear approach (see description of the effect factor below). The spatial resolution of the fate factor for direct emissions to water is  $0.5^\circ \times 0.5^\circ$ , the one for the fate factor for emissions to soil is 5 arc-minutes and the spatial resolution of the effect factor is biogeographical habitats (defined by the Freshwater Ecoregions of the World project, [www.feow.org](http://www.feow.org)). Here, we use a modified version of the ecoregion classification (Azevedo et al. 2013b), where freshwater habitats are divided into cold, temperate, (sub)tropical, and xeric systems. The spatial resolution for the endpoint characterization factors is  $0.5^\circ \times 0.5^\circ$ .

## 8.2. Calculation of the characterization factors at endpoint level

### Characterization factor

The characterization factor for freshwater eutrophication ( $\text{PDF}\cdot\text{yr}\cdot\text{kg}^{-1}$  or  $\text{PDF}\cdot\text{yr}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ ) caused by emissions of P to compartment e (agricultural soil or freshwater) or by erosion of soil to compartment e were calculated for every freshwater ecoregion in the world, denoted with subscript r (Abell et al. 2008). It is described as

$$CF_{FW,e,r} = \frac{1}{\sum_{i \in r} w_{i \in r}} \sum_{i \in r} w_{i \in r} \cdot CF_{FW,e,i \in r}$$

Equation 8.1

where

$CF_{FW,e,r}$  = the characterisation factor of freshwater eutrophication of P emitted to compartment e in ecoregion r ( $\text{PDF}\cdot\text{yr}\cdot\text{kg}^{-1}$  or  $\text{PDF}\cdot\text{yr}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$  for erosion)

$w_{i \in r}$  = the weighting factor of grid cell i situated in ecoregion r, which is phosphorus emissions for P emissions to freshwater and for P emissions to agricultural soil and cropland for erosion

$CF_{FW,e,i \in r}$  = the characterisation factor of freshwater eutrophication of P emitted to compartment e in grid cell i situated in ecoregion r ( $\text{PDF}\cdot\text{yr}\cdot\text{kg}^{-1}$  or  $\text{PDF}\cdot\text{yr}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$  for erosion)

The characterisation factor for a P emission in grid cell i is derived via

$$CF_{FW,e,i \in r} = \sum_{j \in r} FF_{e,i,j \in r} \cdot \overline{EF}_{j \in r}$$

Equation 8.2

where

$FF_{e,i,j \in r}$  = the partial fate factor of P emitted to compartment e in grid cell i that travels to grid cell j situated in ecoregion r ( $\text{year}$  or  $\text{kg}\cdot\text{yr}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ )

$\overline{EF}_{j \in r}$  = the average effect factor of grid cell j situated in ecoregion r ( $\text{PDF}/\text{kg}$ ).

Note that we did not derive CFs if the emitting cell i was entirely deprived of water.

### Fate factor

The partial fate factor of P emitted to compartment e (agricultural soil or freshwater) in grid cell i and transferred to grid cell j which are situated in ecoregion r.  $FF_{e,i \rightarrow j \in r}$  is described as

$$FF_{e,i \rightarrow j \in r} = f_{e \rightarrow i \in r} \cdot f_{i \rightarrow j \in r} \cdot \tau_{j \in r}$$

Equation 8.3

where

$f_{e \rightarrow i \in r}$  = the fraction of P transported from compartment e to cell i in ecoregion r (dimensionless). Note that this fraction is by definition 1 for an emission to freshwater. Note that the for erosion this fraction has unit  $\text{kg}/\text{m}^2$

$f_{i \rightarrow j \in r}$  = the fraction of P transported from cell i to j in ecoregion r (dimensionless),

$\tau_{j \in r}$  = the retention of P in grid cell j situated ecoregion r (year) (as derived by Helmes et al. 2012). The persistence of P is based on the rate at which P is removed from the freshwater compartment by three different processes, i.e. advection, water use, and retention (Figure 8.2a).

The fraction of P transferred from agricultural soil to freshwater was derived from a combination of two models. The Universal Soil Loss Equation (USLE) for the estimation of soil erosion was coupled with the

Swiss Agricultural Life Cycle Analysis (SALCA) model to determine the emissions from soil to the aquatic environment (Scherer and Pfister 2015). Two separate P transfer fractions from soil to freshwater are provided:

- i) for erosion as a result of land use ( $\text{kg P}_{\text{water}} / (\text{ha} \cdot \text{yr})$ ); and
  - ii) for runoff, drainage and groundwater leaching as a result of fertilizer application ( $\text{kg P}_{\text{water}} / \text{kg P}_{\text{fertilizer}}$ ).
- While the original grid-specific fraction transferred from soil to freshwater was crop specific (Scherer and Pfister 2015), here it is crop independent by using a generic crop factor  $C_1$  of 0.3 in the USLE.

#### Effect factor

The average effect factor of grid cell  $j$  as part of ecoregion  $r$  is averaged over the types of freshwater  $w$  (rivers or lakes), based on the fraction of their presence in that grid cell:

$$\overline{EF}_{j \in r} = \sum_w f_{w,j \in r} \cdot EF_{w,r}$$

**Equation 8.4**

where

$f_{w,j \in r}$  = the fraction of freshwater type  $w$  (river or lake) in grid cell  $j$  of ecoregion  $r$ ;

$EF_{w,r}$  = the effect factor of freshwater type  $w$  (river or lake) in ecoregion  $r$  (PDF/kg).

The effect factor for a specific water type in a specific ecoregion is described as

$$EF_{w,r} = \frac{FRD_r \cdot LEF_{w,r}}{FR_{global}}$$

**Equation 8.5**

where

$FRD_r$  = the fish richness density (species/l, see Figure 8.3 for illustration) in each ecoregion  $r$ ,

$LEF_{w,r}$  = the linear effect factor describing the increase in the potentially disappeared fraction (PDF) of heterotrophic species in freshwater type  $w$  due to an increase in the total P level ( $\text{PDF} \cdot \text{m}^3 \cdot \text{kg}^{-1}$ ), and

$FR$  = the total fish richness in the world (species).  $FR$  equals 15'000 and was determined by counting the total number of every “non-extinct” and “non-extinct in the wild” fish species living in streams and freshwater lakes listed by the International Union for Conservation of Nature (IUCN 2014).

Here, we assumed that the probabilistic model for heterotrophic species (including fishes and invertebrates) from which the LEF was derived is representative for the PDF of fish species. Also, we do not account for seasonal variation (e.g. summer versus winter) in the response of species to increasing P levels. We employ a linear effect model since P concentrations are unfrequently reported on a global scale and, as opposed to marginal and average effect factors, linear modelling does not require the environmental concentration of total P as an input variable.

The fish richness density (Figure 8.3) is described as

$$FRD_r = \frac{FSR_r}{\sum_{j \in r} V_{j,r}}$$

**Equation 8.6**

The fish species richness  $FSR_r$  in ecoregion  $r$  was obtained from data from Abell et al. (2008). The freshwater water volume in each ecoregion ( $V_{j,r}$ ) was obtained from the model derived by Helmes *et al.*

(2012) on a pixel basis and summed per ecoregion. We assumed no difference between FRD across the two freshwater types lakes and rivers in an ecoregion.

The linear effect factor is described as

$$LEF_{w,r} = \frac{0.5}{10^{\alpha_{w,r}}}$$

Equation 8.7

where

$\alpha_{w,r}$  = the total P level (log m<sup>3</sup>/kg) in water type w in ecoregion r at which the potentially not occurring fraction (PNOF) of heterotrophic species equals 50% in water type.

The effect factor is based on a probabilistic model of the cumulative PNOF as a logistic function of total P concentration (Azevedo et al. 2013a) and is illustrated in Figure 8.2b. In this work, we equate PNOF with PDF. The effect factor depends both on the climate type (warm, temperate or cold) and the water type (river vs. lake). The climate type per ecoregion was identified based on geographical location of each pixel and the respective effect factor was used. The effect factors for every climate-water type combination are given in Table 8.1. The parameter logistic function parameter  $\alpha$  was derived for four biogeographic regions, i.e. cold, temperate, (sub)tropical, and xeric, as well as for lakes and streams separately. The empirical data employed in the derivation of the logistic regressions consisted of the maximum tolerance total P concentration of each heterotrophic species subsisting in freshwater w in the biogeographic region occupied by cell *j* as described by the Freshwater Ecoregions of the World project, FEOW (<http://www.feow.org>). Species-specific data on maximum tolerable total P concentration were given by Azevedo *et al.* (2013b) and the  $\alpha$  coefficients for the four biogeographic regions and two freshwater types are shown in Figure 6. For xeric lakes as well as for cold and (sub)tropical streams, the  $\alpha$  coefficient could not be determined. In those cases, the  $\alpha$  parameters of (sub)tropical lakes and streams were employed as the  $\alpha$  for xeric lakes and streams, respectively, and the  $\alpha$  for temperate streams was employed as the  $\alpha$  for cold streams. Grid-specific CFs are shown in Figure 8.4. The global average CF is for emissions to water 1.81E-12 PDF·yr·kg<sup>-1</sup> and for emissions to soil and erosion 1.76E-13 PDF·yr·kg<sup>-1</sup> and 3.88E-12 PDF·yr/m<sup>2</sup>·yr. Country, continent, and world CFs were derived based on a emission-based or area-based average. For emission to water and fertilizer applications combined fertilizer and manure applications are used for weighting. For the factors related to erosion we used as a proxy for weighting the crop area (both fertilizer and cropland information from Scherer et al. (2015) )(see Excel file and Table 8.2 and 8.3).

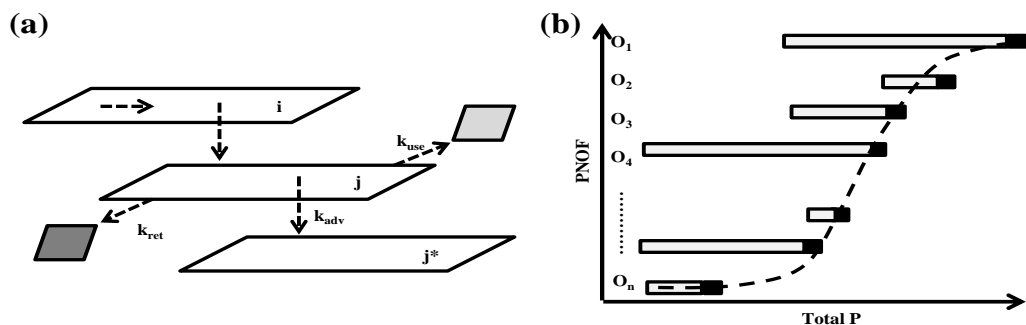


Figure 8.2: (a) fate transport, adapted from Helmes *et al.* (2012), and (b) the logistic regression originating the linear effect model, adapted from Azevedo (2014). (a) shows the flow of P from the soil compartment into the freshwater compartment within emitting cell  $i$  and from emitting cell  $i$  into  $j$  and the flow through three pathways of P removal from the freshwater compartment of, i.e. advection  $k_{adv}$  to cell  $j^*$  downstream of  $j$ , retention  $k_{ret}$  to the sediment (dark grey) compartment of  $j$  and water use  $k_{use}$  to the soil (light grey) compartment of  $j$ . In (b), the potentially not occurring fraction (PNOF) of species as a logistic function of total P is determined with the highest tolerable total P condition (illustrated as the black tip of the grey bar total P range) for individual species ( $O_i$ ) recorded in observational field studies.

Table 8.1: Linear effect factors for streams and lakes for the different climate zones. See also explanations in text.

	Lake [PDF·m <sup>3</sup> /kg]	Stream [PDF·m <sup>3</sup> /kg]
subtropical	13457.67	777.98
tropical	13457.67	777.98
temperate	1253.05	674.48
cold	18279.74	674.48
xeric	13457.67	777.98

### 8.3. Uncertainties

The transfer model of phosphorus from soils to freshwater bodies relies on multiple assumptions. As such, it was assumed that soil phosphorus is equally distributed between surface and sub-surface soil layers and that all phosphorus from fertilizers is bioavailable. However, we do not include phosphorus impacts to groundwater. Emissions caused by wind erosion (i.e., via dust uplift) were neglected. Furthermore, the crop factor  $C_1$  was here assigned to a fixed number whereas it actually varies according to the crops, chemical and physical soil properties, and agricultural management (including P inputs and soil conservation strategies) (Kleinmann *et al.* 2011; Vadas *et al.* 2010).

It is not possible to provide evidence of the actual phosphorus residence times unless P transport is measured in the field and then compared with the fate factors. Another option is the comparison with an independent phosphorus fate model. Helmes *et al.* (2012) compared their FF results with those reported by Struijs *et al.* (2011a) for Europe. This comparison may be skewed since P flows are not the same for both fate models. The fate model employed in this report is that of Helmes *et al.* (2012), who include water retention and use. However, Struijs *et al.* (2011a) do not include these two P transport pathways.

The level of robustness of the effects of freshwater eutrophication on fish species is high. The effect of increasing P levels on net primary productivity has been verified at multiple spatial scales, see meta-analyses by Wilson *et al.* (2006) and Elser *et al.* (2007) for laboratory and whole-field experiment examples, respectively. Additionally, the effect of a nutrient discharge to freshwater, particularly to lakes,

has been demonstrated for short term response (within days) (Schindler 1977) and long term response as well (decades) (Marsden 1989). Our method is based on field surveys consisting of records whereby a freshwater species is observed and the concentration of total P is measured at the same location and at the same time (Azevedo et al. 2013b). Although the presence of the species at a specific P level and at a certain P range is confirmed, the absence of that species at levels below or above that specified range is less certain. (The species may indeed be present beyond the registered P levels but it may go unrecorded.)

The failure to record the species at a specific P level may be human related, such as (1) an incomplete survey of the existing species or of the existing P levels, but also due to natural causes, such as that (2) the species may be rare and difficult to spot, (3) extreme P levels may be tolerated by the species but it may not be found under natural conditions, or (4) the level of P is tolerated by the species but the species absence is due to another stressor. For a detailed description of the downsides of observational field data for conducting impact assessments, see Azevedo (2014). Because of the possible underestimation of the maximum P level tolerated by the species, the uncertainty of the effect model specifically employed here is considered high.

Nearly 50% of the variance in CF results is attributed to the difference in freshwater types. This difference is determined by the residence time of P in the water (i.e. the fate factor) (Azevedo et al. 2013a). In turn, the fate factors are primarily dependent upon water advection and, to a lower extent, to water use (Helmets et al. 2012).

#### 8.4. Value Choices

The time horizon for this impact category is not relevant since it is assumed that the impact occurs at the moment of emitting phosphorus to freshwater bodies. No choices are thus modelled for fate and effect factors for freshwater eutrophication. The level of robustness for the CFs is considered to be high, since the effects on freshwater fish are certain.

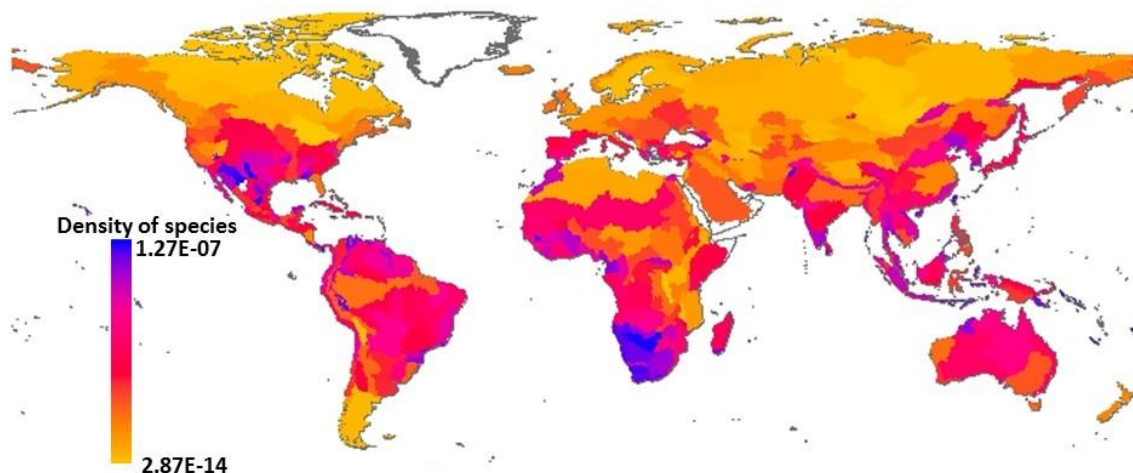


Figure 8.3: Freshwater fish density (species·m<sup>-3</sup>) based on data from Abell et al. (2008) and freshwater volumes of Helmes et al. (2012).

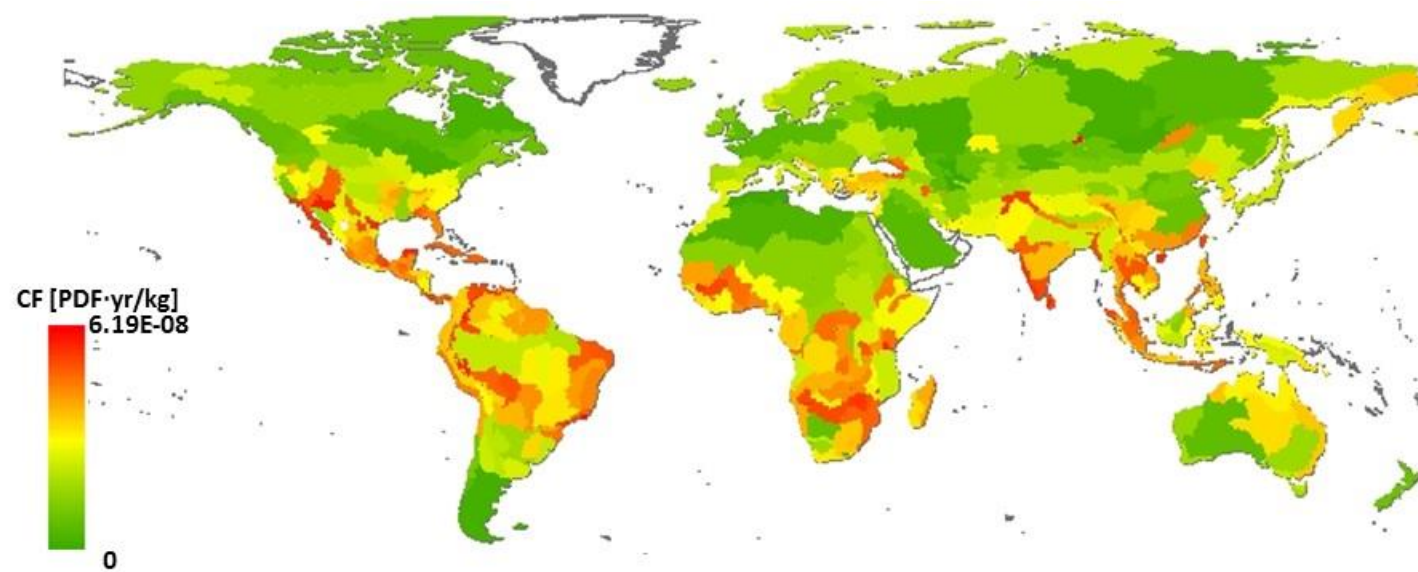


Figure 8.4: Endpoint characterization factors for emissions of P to freshwater ( $\text{CF}_{\text{freshwater}}$ ,  $\text{PDF}\cdot\text{yr}\cdot\text{kg}^{-1}$ ) based on fish richness.



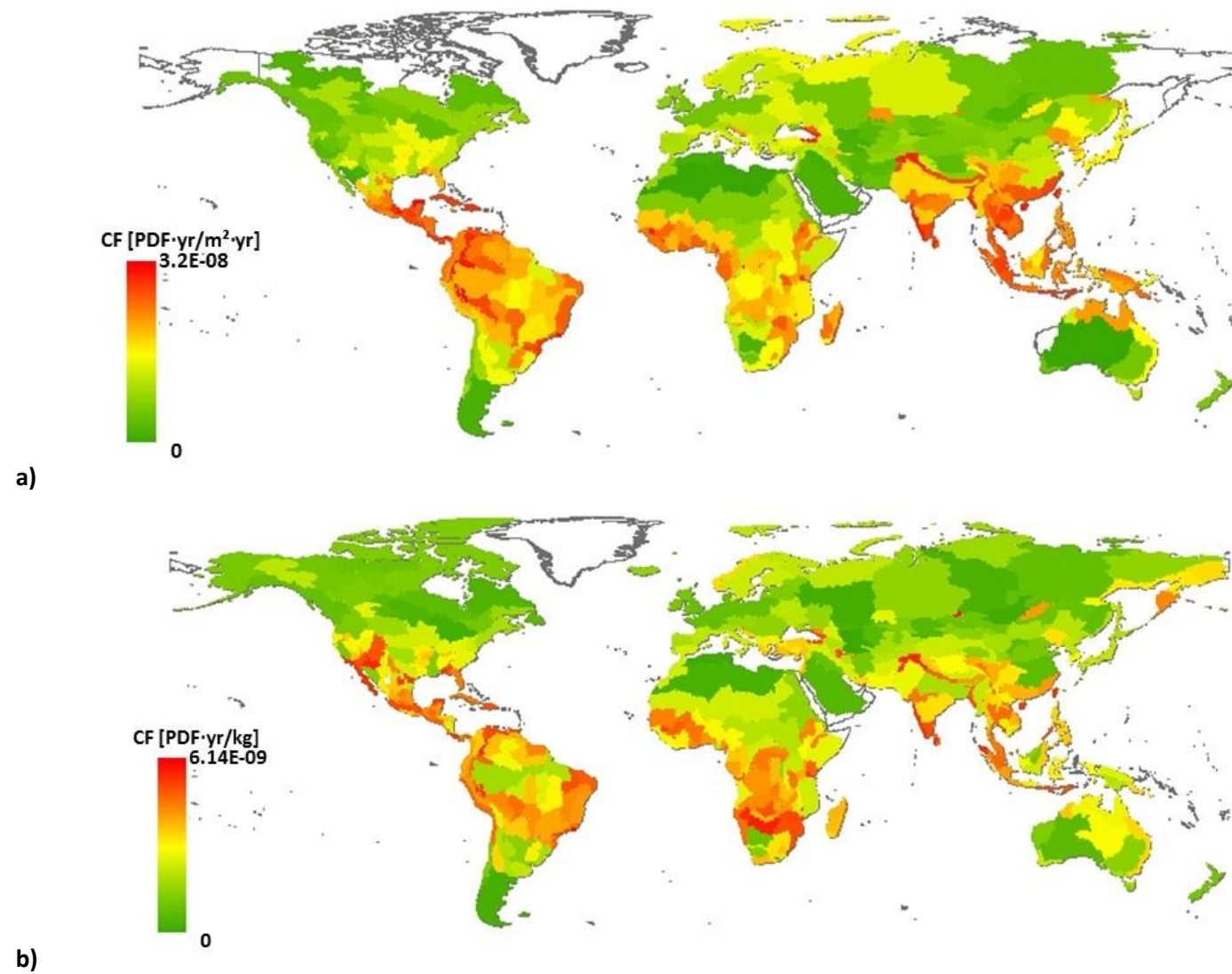


Figure 8.5: Endpoint characterization factors for emissions of P to soil and erosion based on fish richness. A) for P from erosion and B) for P from fertilizer application.

**Table 8.1: Global endpoint characterization factors for emissions to freshwater ( $CF_{\text{freshwater}}$ ,  $\text{PDF}\cdot\text{yr}\cdot\text{kg}^{-1}$ ), for emissions to soil ( $CF_{\text{soil}}$ ,  $\text{PDF}\cdot\text{yr}\cdot\text{kg}^{-1}$ ) and for impacts from erosion ( $CF_{\text{erosion}}$ ,  $\text{PDF}\cdot\text{yr}/\text{m}^2\cdot\text{yr}$ ) on a country level, based on fish richness. This is the CF for total phosphorus, reported as P. The emissions all go to the freshwater compartment.**

Country	$CF_{\text{freshwater}}$ [ $\text{PDF}\cdot\text{yr}/\text{kg}$ ]	$CF_{\text{soil}}$ [ $\text{PDF}\cdot\text{yr}/\text{kg}$ ]	$CF_{\text{erosion}}$ [ $\text{PDF}\cdot\text{yr}/\text{m}^2\cdot\text{yr}$ ]
Afghanistan	7.66E-12	1.06E-12	6.27E-12
Albania	5.20E-13	7.51E-14	1.38E-12
Algeria	6.36E-15	6.44E-16	6.58E-16
Andorra	3.37E-13	3.11E-14	2.16E-13
Angola	4.73E-12	9.04E-13	1.96E-12
Argentina	5.61E-13	4.18E-14	7.22E-13
Armenia	2.15E-13	3.29E-14	3.53E-13
Australia	7.05E-13	4.97E-14	1.13E-13
Austria	2.33E-13	2.18E-14	3.17E-13
Azerbaijan	2.61E-13	3.74E-14	3.85E-13
Bahrain	3.45E-14	1.92E-15	2.95E-15
Bangladesh	1.16E-12	7.35E-14	4.36E-12
Belgium	3.56E-14	5.43E-15	2.58E-14
Belize	4.24E-12	3.64E-13	1.26E-11
Benin	3.40E-12	2.78E-13	9.30E-12
Bhutan	2.16E-12	3.02E-13	5.43E-11
Bolivia	5.57E-12	3.94E-13	7.89E-12
Bosnia and Herzegovina	9.69E-13	9.19E-14	1.90E-12
Botswana	2.13E-11	3.79E-12	3.29E-12
Brazil	3.18E-12	3.47E-13	6.69E-12
Brunei	2.49E-13	1.72E-14	1.41E-12
Bulgaria	7.58E-13	7.13E-14	2.94E-13
Burkina Faso	4.63E-12	4.18E-13	3.99E-12
Burundi	2.02E-12	1.42E-13	2.06E-12
Belarus	2.91E-13	2.60E-14	4.08E-13
Cambodia	3.11E-12	2.07E-13	1.57E-11
Cameroon	1.45E-12	1.62E-13	2.23E-12
Canada	2.46E-13	1.88E-14	6.81E-14
Central African Republic	9.12E-13	1.62E-13	5.62E-13
Chad	1.93E-13	4.37E-14	2.45E-13
Chile	1.78E-13	2.13E-14	3.75E-13
China	1.18E-12	8.96E-14	2.89E-12
Colombia	6.02E-12	7.69E-13	1.85E-11
Congo	3.26E-12	8.44E-13	8.18E-12
Costa Rica	6.56E-12	8.01E-13	3.23E-11
Croatia	7.50E-13	7.19E-14	1.97E-12
Cuba	7.01E-12	4.83E-13	2.76E-11
Czech Republic	1.02E-13	1.13E-14	1.23E-13
Denmark	5.86E-14	9.44E-15	8.91E-14
Djibouti	3.11E-13	3.37E-14	3.16E-14
Dominican Republic	7.24E-12	9.67E-13	3.98E-11
Ecuador	2.59E-12	3.12E-13	1.39E-11
Egypt	1.79E-13	1.16E-14	6.53E-14
El Salvador	4.07E-12	7.89E-13	1.97E-11
Equatorial Guinea	1.97E-12	1.80E-13	8.43E-12
Eritrea	9.30E-13	7.94E-14	1.70E-12
Estonia	1.46E-13	1.21E-14	4.62E-13
Ethiopia	3.39E-12	3.01E-13	6.61E-12
Finland	2.87E-13	4.86E-14	3.38E-13
France	1.15E-13	1.53E-14	1.17E-13
French Guiana	3.48E-12	4.17E-13	2.63E-12
Gabon	2.03E-12	2.63E-13	1.08E-11
Gambia, The	3.33E-12	4.71E-13	2.39E-12
Gaza Strip	9.55E-13	7.96E-14	3.36E-13
Georgia	3.61E-12	4.56E-13	1.58E-11
Germany	6.52E-14	7.88E-15	6.38E-14
Ghana	6.17E-12	5.62E-13	6.71E-12
Greece	1.15E-12	1.28E-13	4.42E-13

Guatemala	4.82E-12	5.93E-13	1.98E-11
Guinea	1.14E-11	9.45E-13	2.16E-11
Guinea-Bissau	2.75E-12	3.54E-13	4.44E-12
Guyana	2.86E-12	2.54E-13	3.50E-12
Haiti	7.25E-12	9.69E-13	3.88E-11
Honduras	2.78E-12	4.14E-13	1.36E-11
Hungary	2.26E-13	2.07E-14	2.90E-13
Iceland	1.86E-13	1.64E-14	0.00E+00
India	3.15E-12	2.68E-13	8.61E-12
Indonesia	2.88E-12	3.51E-13	1.20E-11
Iran	9.74E-13	1.46E-13	3.59E-13
Iraq	1.90E-13	2.20E-14	9.38E-14
Ireland	1.46E-13	9.91E-15	6.22E-14
Israel	1.05E-12	1.18E-13	2.12E-13
Italy	2.98E-13	3.57E-14	2.84E-13
Ivory Coast	3.00E-12	2.43E-13	4.46E-12
Japan	5.41E-13	4.51E-14	1.03E-12
Jordan	9.88E-13	1.58E-13	2.68E-14
Kazakhstan	1.90E-13	1.59E-14	4.30E-13
Kenya	2.76E-12	2.83E-13	2.68E-12
Kuwait	3.92E-14	3.15E-15	2.56E-15
Kyrgyzstan	1.89E-13	2.93E-14	9.18E-14
Laos	5.06E-12	3.51E-13	1.65E-11
Latvia	1.53E-13	1.26E-14	4.65E-13
Lebanon	1.29E-12	1.25E-13	2.39E-13
Lesotho	2.24E-12	2.15E-13	4.52E-12
Liberia	1.45E-12	1.02E-13	7.40E-12
Libya	2.38E-14	1.58E-15	0.00E+00
Liechtenstein	3.55E-14	5.44E-15	2.61E-14
Lithuania	7.07E-14	7.84E-15	1.88E-13
Luxembourg	3.62E-14	5.52E-15	2.73E-14
Macedonia	5.63E-13	7.72E-14	4.84E-13
Madagascar	2.25E-12	2.24E-13	5.88E-12
Malawi	1.80E-11	1.80E-12	6.48E-11
Malaysia	3.88E-12	3.28E-13	1.12E-11
Mali	6.24E-12	5.19E-13	4.33E-12
Mauritania	2.64E-12	3.68E-13	2.05E-12
Mexico	6.96E-12	8.73E-13	2.20E-11
Moldova	2.04E-13	1.86E-14	2.63E-13
Mongolia	2.65E-13	2.43E-14	2.60E-13
Montenegro	4.15E-13	4.52E-14	2.14E-12
Morocco	5.93E-13	4.64E-14	7.67E-14
Mozambique	8.45E-12	1.03E-12	1.69E-11
Myanmar (Burma)	2.95E-12	2.17E-13	6.91E-12
Namibia	9.28E-12	2.11E-12	1.42E-12
Nepal	3.20E-12	4.72E-13	1.52E-11
Netherlands	3.44E-14	5.25E-15	2.52E-14
New Zealand	6.25E-14	9.36E-15	3.31E-14
Nicaragua	1.59E-12	1.33E-13	1.43E-11
Niger	4.36E-13	6.60E-14	9.16E-13
Nigeria	1.14E-12	1.16E-13	3.32E-12
North Korea	5.64E-13	3.95E-14	2.66E-12
Norway	3.94E-13	8.36E-14	3.76E-13
Oman	1.58E-14	1.29E-15	1.27E-16
Pakistan	3.45E-12	4.06E-13	7.51E-12
Panama	1.26E-11	1.56E-12	4.71E-11
Papua New Guinea	8.21E-13	6.86E-14	5.75E-12
Paraguay	2.78E-12	2.66E-13	4.96E-12
Peru	5.53E-12	8.29E-13	1.88E-11
Philippines	2.35E-12	2.17E-13	6.58E-12
Poland	3.65E-14	5.55E-15	2.60E-14
Portugal	3.68E-13	3.36E-14	1.50E-13
Qatar	3.24E-14	2.64E-15	0.00E+00

Romania	2.04E-13	1.85E-14	2.64E-13
Russia	4.66E-13	5.10E-14	4.47E-13
Rwanda	7.45E-13	5.37E-14	9.57E-13
San Marino	1.60E-13	2.67E-14	1.58E-13
Saudi Arabia	3.01E-14	2.46E-15	2.23E-15
Senegal	3.22E-12	4.57E-13	2.39E-12
Serbia	2.35E-13	2.32E-14	3.15E-13
Sierra Leone	1.64E-12	1.13E-13	8.22E-12
Singapore	9.07E-12	6.17E-13	2.25E-11
Slovakia	2.26E-13	2.13E-14	2.98E-13
Slovenia	4.59E-13	5.91E-14	4.05E-13
Somalia	7.15E-13	5.04E-14	3.67E-13
South Africa	4.31E-12	3.83E-13	1.54E-12
South Korea	9.71E-13	6.71E-14	1.95E-12
Spain	4.68E-13	4.03E-14	1.78E-13
Sri Lanka	1.80E-11	1.50E-12	4.27E-11
Sudan	3.77E-13	3.46E-14	6.24E-13
Suriname	3.52E-12	4.22E-13	2.62E-12
Swaziland	5.40E-12	7.50E-13	3.26E-12
Sweden	2.83E-13	4.82E-14	3.42E-13
Switzerland	4.94E-14	7.46E-15	2.93E-14
Syria	7.24E-13	7.75E-14	1.43E-13
Taiwan	1.52E-11	2.45E-12	8.50E-11
Tajikistan	2.56E-13	3.41E-14	7.81E-14
Tanzania, United Republic of	5.00E-12	3.72E-13	7.11E-12
Thailand	8.52E-12	5.79E-13	2.28E-11
Togo	5.43E-12	4.45E-13	8.99E-12
Trinidad and Tobago	1.10E-11	1.08E-12	1.64E-11
Tunisia	4.77E-15	3.92E-16	6.57E-16
Turkey	2.15E-12	2.05E-13	2.67E-12
Turkmenistan	2.24E-13	2.38E-14	4.53E-14
Uganda	6.47E-13	4.61E-14	9.83E-13
Ukraine	3.76E-13	3.22E-14	4.88E-13
United Arab Emirates	5.84E-16	4.75E-17	0.00E+00
United Kingdom	8.74E-14	7.58E-15	3.50E-14
United States	1.27E-12	1.10E-13	4.75E-13
Uruguay	1.35E-12	9.02E-14	3.48E-12
Uzbekistan	2.02E-13	2.30E-14	5.58E-14
Venezuela	9.72E-12	9.98E-13	2.52E-11
Vietnam	2.16E-12	1.59E-13	1.26E-11
West Bank	1.25E-12	1.62E-13	1.90E-13
Western Sahara	5.50E-13	4.26E-14	0.00E+00
Yemen	3.32E-15	2.71E-16	1.11E-17
Zaire	3.69E-12	3.87E-13	2.12E-12
Zambia	4.08E-12	4.46E-13	2.51E-12
Zimbabwe	1.40E-11	1.22E-12	1.08E-11

**Table 8.2: Global endpoint characterization factors for emissions to freshwater ( $CF_{\text{freshwater}}$ , PDF·yr·kg<sup>-1</sup>), for emissions to soil ( $CF_{\text{soil}}$ , PDF·yr·kg<sup>-1</sup>) and for impacts from erosion ( $CF_{\text{erosion}}$ , PDF·yr/m<sup>2</sup>·yr) on a continental level based on fish richness.**

Continent	$CF_{\text{freshwater}}$ [PDF·yr/kg]	$CF_{\text{soil}}$ [PDF·yr/kg]	$CF_{\text{erosion}}$ [PDF·yr/m <sup>2</sup> ·yr]
Africa	2.75E-12	2.85E-13	3.67E-12
Asia	1.94E-12	1.71E-13	5.84E-12
Australia	7.05E-13	4.98E-14	1.13E-13
Europe	2.20E-13	2.28E-14	3.47E-13
North America	1.86E-12	1.95E-13	3.85E-12
Oceania	6.34E-14	9.50E-15	1.17E-13
South America	3.18E-12	3.47E-13	6.03E-12

## 8.5. References

- Abell, R., Thieme, M. L., Revenga, C., Bryer, M., Kottelat, M., Bogutskaya, N., Coad, B., Mandrak, N., Balderas, S. C., Bussing, W., Stiassny, M. L. J., Skelton, P., Allen, G. R., Unmack, P., Naseka, A., Ng, R., Sindorf, N., Robertson, J., Armijo, E., Higgins, J. V., Heibel, T. J., Wikramanayake, E., Olson, D., López, H. L., Reis, R. E., Lundberg, J. G., Sabaj Pérez, M. H. and Petry, P. (2008). "Freshwater Ecoregions of the World: A New Map of Biogeographic Units for Freshwater Biodiversity Conservation." *BioScience* **58**(5): 403-414.
- Azevedo, L. B. (2014). *Development and application of stressor – response relationships of nutrients*. Chapter 8. Ph.D. Dissertation, Radboud University Nijmegen, The Netherlands. <http://repository.ubn.ru.nl>.
- Azevedo, L. B., Henderson, A. D., van Zelm, R., Jolliet, O. and Huijbregts, M. A. J. (2013a). "Assessing the Importance of Spatial Variability versus Model Choices in Life Cycle Impact Assessment: The Case of Freshwater Eutrophication in Europe." *Environmental Science & Technology* **47**(23): 13565-13570.
- Azevedo, L. B., van Zelm, R., Elshout, P. M. F., Hendriks, A. J., Leuven, R. S. E. W., Struijs, J., de Zwart, D. and Huijbregts, M. A. J. (2013b). "Species richness–phosphorus relationships for lakes and streams worldwide." *Global Ecology and Biogeography* **22**(12): 1304-1314.
- Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N. and Smith, V. H. (1998). "Nonpoint pollution of surface waters with phosphorus and nitrogen." *Ecological Applications* **8**(3): 559-568.
- Elser, J. J., Bracken, M. E. S., Cleland, E. E., Gruner, D. S., Harpole, W. S., Hillebrand, H., Ngai, J. T., Seabloom, E. W., Shurin, J. B. and Smith, J. E. (2007). "Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems." *Ecology Letters* **10**(12): 1135-1142.
- Helmes, R. J. K., Huijbregts, M. A. J., Henderson, A. D. and Jolliet, O. (2012). "Spatially explicit fate factors of phosphorous emissions to freshwater at the global scale." *International Journal of Life Cycle Assessment* **17**(5): 646-654.
- IUCN (2014). International Union for Conservation of Nature. Red List of Threatened Species. Version 2010.1. Downloaded on 30 June 2014 at [www.iucnredlist.org](http://www.iucnredlist.org).
- Leflaive, J. and Ten-Hage, L. (2007). "Algal and cyanobacterial secondary metabolites in freshwaters: a comparison of allelopathic compounds and toxins." *Freshwater Biology* **52**(2): 199-214.
- Kleinman, P., Sharpley, A., Buda, A., McDowell, R., and Allen, A. (2011). *Soil controls of phosphorus in runoff: Management barriers and opportunities*. Canadian Journal of Soil Science. **91**(3): 329-338.
- Marsden, M. W. (1989). "Lake restoration by reducing external phosphorus loading: the influence of sediment phosphorus release." *Freshwater Biology* **21**(2): 139-162.
- Scherer, L. and Pfister, S. (2015). "Modelling spatially explicit impacts from phosphorus emissions in agriculture." *International Journal of Life Cycle Assessment* **20**(6): 785–795.
- Schindler, D. W. (1977). "Evolution of phosphorus limitation in lakes." *Science* **195**(4275): 260-262.
- Schindler, D. W. (2012). "The dilemma of controlling cultural eutrophication of lakes." *Proceedings of the Royal Society B: Biological Sciences*.
- Struijs, J., Beusen, A., de Zwart, D. and Huijbregts, M. (2011a). "Characterization factors for inland water eutrophication at the damage level in life cycle impact assessment." *International Journal of Life Cycle Assessment* **16**(1): 59-64.
- Struijs, J., De Zwart, D., Posthuma, L., Leuven, R. S. E. W. and Huijbregts, M. A. J. (2011b). "Field sensitivity distribution of macroinvertebrates for phosphorus in inland waters." *Integrated Environmental Assessment & Management* **7**(2): 280-286.
- Vadas, P.A. and J, W.M. (2010). *Validating soil phosphorus routines in the SWAT model*. Transactions of the ASABE **53**: 1469-1476.

Wilson, A. E., Sarnelle, O. and Tillmanns, A. R. (2006). "Effects of cyanobacterial toxicity and morphology on the population growth of freshwater zooplankton: Meta-analyses of laboratory experiments." *Limnology and Oceanography* **51**(4): 1915-1924.

## 8.6. Appendix

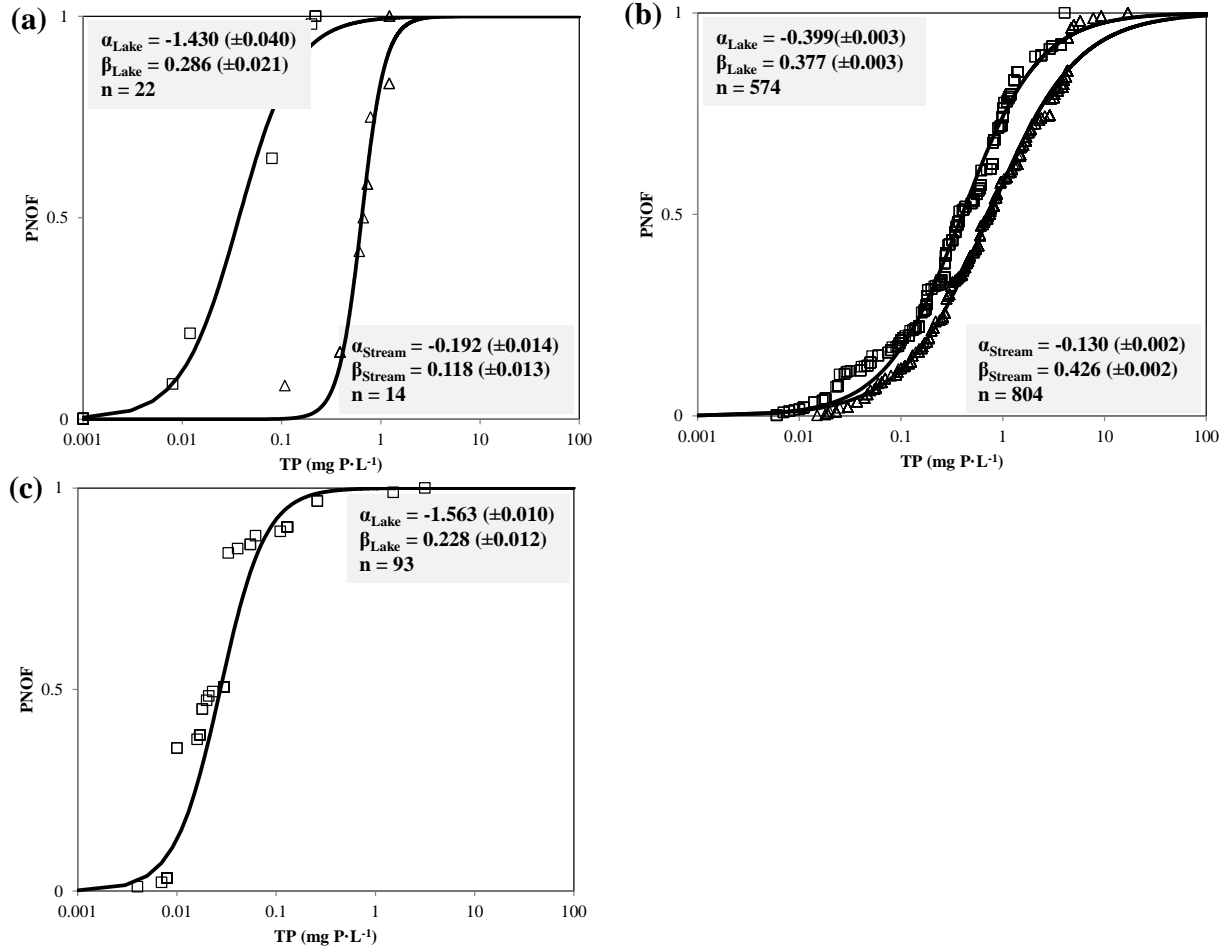


Figure 8.6: Coefficients  $\alpha$  and  $\beta$  of the potentially not occurring fraction (PNOF) of heterotrophic species in lake (squares) and streams (triangles) as a logistic function of total P (TP, mg P·L<sup>-1</sup>) in the (a) (sub)tropical, (b) temperate, and (c) cold. The PNOF is a logistic function of  $\alpha$ ,  $\beta$ , and TP, i.e.  $PNOF = \frac{1}{1 + e^{-\left(\frac{\log_{10} TP - \alpha}{\beta}\right)}}$ . Although  $\beta$  is not used in the derivation of effect factors in our work, it can later be employed in future LCAs in the derivation of average or marginal effect factors.