9. Marine eutrophication

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9.1. Areas of protection and environmental mechanisms covered

Description of impact pathway

Marine eutrophication can be defined as a response of the marine ecosystem to the increased availability of a limiting nutrient in the euphotic zone of marine waters (Cloern 2013). The 'limiting nutrient' concept implies that it is the availability of the limiting nutrient that determines the extent of the primary production in the ecosystem. We assume nitrogen (N) as the limiting nutrient in marine waters. Studies and reviews have discussed the topic and support this assumption (e.g. Ryther and Dunstan 1971; Vitousek et al. 2002; Howarth and Marino 2006; Hood and Christian 2008), and we acknowledge that spatial and temporal limitation by phosphorus or silicon may occur (see e.g. Elser et al. 2007 or Turner et al. 1998). There may also be cases of co-limitation (Arrigo 2005) as different species may show different requirements (Finnveden and Potting 1999).

Globally, anthropogenic emissions of N to the environment have increased more than 10-fold in the last 150 years, mainly originating from agricultural runoff and leaching (waterborne N-emissions) and combustion processes (airborne N-emissions) (Galloway et al. 2004). The modelled impact pathway (Figure 9.1) is limited to waterborne (as total-N) loadings from human activities into coastal marine waters increasing its N-concentrations there (Vitousek et al 1997; Galloway et al. 2004). The emission routes can be direct discharge of N into rivers or coastal areas, as well as nitrogen applications to the soil. Airborne emissions are excluded. The N input to marine coastal waters is assimilated by primary producers (mainly phytoplankton), promoting the increase in planktonic biomass (Nixon et al. 1996; Rabalais 2002). The organic matter (OM) thus synthesized is eventually exported to bottom waters (Ducklow et al. 2001) where its aerobic respiration by heterotrophic bacteria results in consumption of dissolved oxygen (DO) (Cole et al. 1988; Diaz and Rosenberg 2008). If excessive amounts of organic carbon reach the benthic (bottom) layer, DO may drop to hypoxic or anoxic levels (Gray et al. 2002), which may then lead to loss of species diversity (NRC 1993; Socolow 1999; Vaquer-Sunyer and Duarte 2008; Levin et al. 2009; Vitousek et al. 2012). The overall model builds on the environmental fate of N-forms, the biological processes in the entire water column of coastal areas, and on the species response to the depletion of DO, assuming linearity of cause-effect relationships along the adopted impact pathway.

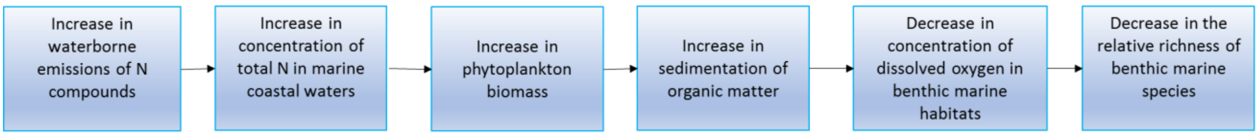

Figure 9.1: Impact pathway for marine eutrophication from anthropogenic emission of waterborne nitrogen into marine coastal waters to ecosystem damage.

Description of all related AoPs

The area of protection addressed by the model framework for marine eutrophication is that of ecosystem quality. The environmental mechanism of the impact of N emissions is described by combining *(i)* environmental fate of N, *(ii)* exposure of the coastal ecosystem to the nutrient enrichment, *(iii)* effect of oxygen depletion to exposed species, and *(iv)* upscaling to global level:

(i) N-fate modelling covers the loss processes that affect the N emitted to the environment. It considers waterborne emission routes (direct discharge into rivers and marine environment, application and subsequent run-off/drainage to waterways), accounting for runoff and advection of N into the freshwater compartment, or leaching to groundwater, and coastal marine water compartments. Loss processes in the marine compartment are also included;

(ii) Modelling the ecosystems exposure to N enrichment incorporating the biological processes that determine the nitrogen-to-oxygen conversion potential of each spatial unit among the ecosystems. The exposure model is based on nutrient-limited primary production, metazoan consumption, and aerobic bacterial respiration of this primary production;

(iii) Modelling the effects of oxygen depletion on biota using Species Sensitivity Distribution (SSD) curves per spatial unit. The ecological community's sensitivity is estimated from the statistical distribution of sensitivities of all tested species.

(iv) The local species losses are upscaled to potential global species loss by using a vulnerability score.

Methodological choice

The EF modelling based on SSD curves assumes a linear approach to calculate the EFs as no background dissolved oxygen concentrations are known. This assumption further reflects that (i) the temporal variation of the stress intensity and effects is not accounted and (ii) no threshold levels in the LMEs are considered in the EF estimation.

Spatial detail

The Large Marine Ecosystems (LME) biogeographical classification system (Sherman et al. 1993) was adopted to address the spatial variation of the modelled parameters among coastal ecosystems and to link the location of the emission sources to 66 spatial units of continental shelves. The CFs are presented for N emissions to soil and freshwater at the level of countries, continents and the world. The LME spatial units were deemed adequate and manageable both in size and number, easily linked to potentially N-emitting countries, and supported by readily available data on global depth-integrated primary production rates (Sea Around Us Project database, www.seaaroundus.org).

9.2. Calculation of the characterization factors at endpoint level

The endpoint characterization factor, CF_{end} [PDF·yr·kgN^{-1}], for emissions of nitrogen is estimated by Equation 9.1:

$$CF_{end,ijk} = \sum_{j} FF_{ijk} \times XF_j \times EF_j \times VS_j$$

Equation 9.1

where FF_{ijk} is the Fate Factor [yr] for emissions from country i to receiving marine ecosystem j by emission route k, XF_j is the exposure factor [kgO$_2$·kgN^{-1}] in receiving ecosystem j, and EF_j is the Effect

Factor [PDF·kgO_2^{-1}] in receiving ecosystem j. Emission routes (k) include, "N to surface freshwater", "N to groundwater" (from e.g. applications on agricultural fields), and "N to marine water" (waterborne as total-N). The receiving ecosystems j correspond to the 66 different Large Marine Ecosystems (LME).

The resulting CFs are reported at country, continental (Europe, Europe, Africa, Asia, North America, South America, and Oceania) and world resolution (Table 9.2), using spatially differentiated, total annual emissions of N fertilizers (Potter et al. 2010) as weighting factors in the calculation of a weighted average factor for the respective higher spatial aggregation for emissions to soil (groundwater) and freshwater. For emissions to marine waters we used the length of the coastline a country shares with a respective LME as a weighting factor.

Fate Factor (FF)

The FF_{ij} [yr] is obtained from equation 9.2:

$$FF_{i,j,k} = \frac{f_{\exp i,k}}{\lambda_j}$$

Equation 9.2

where $f_{\exp i,k}$ [dimensionless] is the fraction of N exported from country i to coastal marine waters calculated for each emission route k, and λ_j [yr^{-1}] is the N-loss rate in the receiving ecosystem *j.*

The FFs are estimated at a country-to-LME resolution per emission route, i.e. factors for a country emitting to a receiving LME, e.g. "*Canada to LME#2. Gulf of Alaska*" and "*Canada to LME#63. Hudson Bay Complex*" (for each of the three emission routes: "N to surface freshwater", "N to groundwater" and "N to marine water").

The fate model is composed of an inland-based component and a marine-based component. The first assesses the loss processes affecting N-forms from the direct discharge of water-borne N-compounds to surface freshwater, groundwater, and marine coastal waters. The second component assesses the N-losses due to denitrification and advection in the marine environment. The method and results are described in Cosme et al. (2017)

Estimation of N export to coastal marine waters ($f_{\exp k}$)

The estimation of the fraction of N exported to marine marine coastal waters ($f_{\exp k}$) for each of the emission routes (k) for N (inventory data, LCI), identified as "N to sfw", "N to gw", and "N to mw", is done as follows:

a) Accounting for N exported from point and non-point discharges to marine water via surface water 'sfw', is done in equation 9.3:

$$f_{\text{exp from "N to sfw"}} = 1\text{-}f_{\text{estuary retention}}$$

Equation 9.3

b) Accounting for N exported from non-point emissions to marine water via groundwater 'gw' (from e.g. agricultural fields), is done in equation 9.4:

$$f_{\text{exp from "N to gw"}} = (1\text{-}f_{\text{denitr in gw}}) * (1\text{-}f_{\text{estuary retention}})$$

Equation 9.4

c) Accounting for N exported as direct discharges to marine coastal waters ('mw'), is done in equation 9.5:

$$f_{\text{exp from "N to mw"}} = 1 \text{ (originated from direct N point source emissions to mw)}$$

Equation 9.5

where

$f_{\text{denitr in gw}}$ is the average denitrification rate in the fraction leaching to groundwater from agricultural soil, i.e. 64.6% (Bouwman et al. 2011b)

$f_{\text{estuary retention}}$ is the N-fraction lost due to denitrification, hydrography, and biological activity in surface freshwater, i.e. 52.7% (Wollheim et al. 2008)

Estimation of the nitrogen-loss rate coefficient (λ_j) in the marine compartment

The λ_j coefficient accounts for N-losses in marine coastal waters by denitrification, i.e. the reduction of oxidized forms of nitrogen (NO_3^-, NO_2^- and NO) into the biological unavailable forms N_2 and N_2O in a microbially-mediated process, and by advection, i.e. the transport of nitrogen forms from the considered spatial unit by the effect of local hydrodynamics (equivalent to flushing or the inverse of hydraulic residence time). The coefficient is obtained from equation 9.7:

$$\lambda_j = \lambda_{denitr} + \frac{1}{\tau_j}$$

Equation 9.7

where λ_{denitr} [yr^{-1}] is the loss coefficient due to denitrification (site-generic) and equal to 26% (Seitzinger et al. 2006), and τ_j [yr] is the residence time (LME-dependent) in receiving ecosystem j obtained from Table 9.4. The hydraulic residence times for some of the receiving LMEs were found in literature. For LMEs, for which no data was found or for which data was high variable, a classification was performed into four archetypes based on coastal exposure to currents and regional ocean circulation, depth, and coastal profile, High dynamics and exposure to regional currents: Residence time estimated of 3 months (archetype 1); Medium dynamics and exposure to local currents: estimated residence time of 2 years (archetype 2); Low dynamics: estimated residence time of 25 years (archetype 3); Very low dynamics or embayment: estimated residence time of 90 years (archetype 4).

Exposure Factor (XF)

The Exposure Factor (XF) [$kgO_2 \cdot kgN^{-1}$] delivers a nitrogen-to-oxygen conversion potential based on vertical carbon flux processes (Ducklow et al. 2001) and bacterial degradation (DelGiorgio and Cole 1998; Iversen and Ploug 2010). In short, the potential consumption of DO is estimated as a function of the production of organic material from the N-input, the vertical transport of the organic carbon to the bottom strata of coastal marine waters, and the degradation of organic carbon reaching these. Overall, the nitrogen assimilated by phytoplankton is converted into organic carbon (biomass) – the C:N ratio is obtained from the stoichiometry of the photosynthesis equation. The organic carbon export from the surface mixed layer is modelled in four distinct downward routes (see Figure 9.1): route 1, particulate organic carbon (POC) exported as algal aggregates (phytoplankton biomass); route 2, POC exported as faecal pellets (egestion from zooplankton after grazing); route 3, POC from non-predatory mortality of zooplankton (body parts and carcasses); and route 4, particulate and dissolved organic carbon (POC and DOC) exported by active vertical transport (zooplankton feeding on phytoplankton). Independent of the route all organic carbon reaching the bottom is aerobically respired there by heterotrophic bacteria and dissolved oxygen is consumed. The vertical carbon flux is further modulated (not shown for simplification) by consumption (grazing and bacterial respiration) of sinking POC from routes 1-3, leaching of DOC from faecal pellets in route 2, and bacterial respiration of POC and DOC from egestion and excretion, respectively, in route 4. Bacterial degradation in bottom waters and oxygen consumption are also added to the model – the O_2:C ratio is obtained from the stoichiometry of the aerobic respiration equation. The XF estimation method is fully described in Cosme et al. (2015)

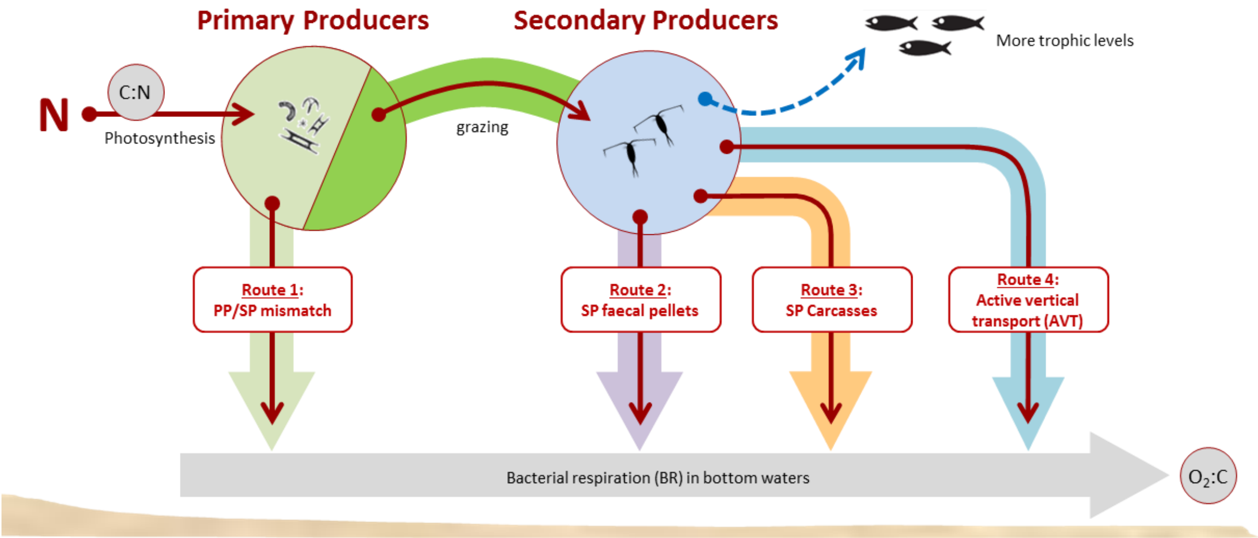

Figure 9.2: Vertical carbon flux model to estimate the ecosystems exposure factors converting nitrogen (N) inputs into consumption of dissolved oxygen (O_2). Identification of carbon (C) export routes via sinking of primary producers (PP) biomass (route 1), sinking particulate organic carbon from secondary producers (SP) as faecal pellets (route 2), sinking zooplankton carcasses (route 3), and active vertical transport (AVT) as dissolved and particulate organic carbon (route 4). Bottom horizontal arrow refers to bacterial respiration (BR) in benthic layer. Grey small circles represent the elemental conversions of C:N and O_2:C. Dashed blue arrow represents further flows outside the scope of the study (not modelled). Adapted from Cosme et al. (2015)

The simplified descriptive equation can be shown as (equation 9.8):

$$XF_j = PP_{Pot\ j} * (C:N) * \left(f_{sinkPP\ j} + f_{sinkFP\ j} + f_{SPcarc\ j} + f_{AVT\ j}\right) * f_{BR} * (O_2:C)$$

Equation 9.8

where

$PP_{Pot\ j}$ [dimensionless] is the normalised potential primary production for receiving ecosystem (LME) j, obtained from equation 9.9:

$$PP_{Pot\_LME} = PP_{LME}/PP_{Avg\_66LME}$$

Equation 9.9

$(C:N)$ and $(O_2:C)$ are the molar mass ratios of carbon to nitrogen [$kgC \cdot KgN^{-1}$] and di-oxygen to carbon [$kgO_2 \cdot kgC^{-1}$] respectively.

The fractions [dimensionless] of organic carbon sinking to bottom waters by the different routes are explained as sinking primary producer (phytoplankton) biomass (PP) as POC ($f_{sinkPP\ j}$), as zooplankton's faecal pellets (FP) as POC ($f_{sinkFP\ j}$), as secondary producer's (zooplankton) carcasses

(SP_{carc}) as POC ($f_{SPcarc\ j}$), and active vertical transport (AVT) as POC and DOC ($f_{AVT\ j}$) in receiving ecosystem j.

f_{BR} [dimensionless] is the fraction (site-generic) of organic carbon as POC and DOC aerobically respired by heterotrophic bacteria.

Exposure factors are reported per receiving ecosystem, i.e. for each of the 66 LMEs.

Effect Factor (EF)

The Effect Factor [PAF·kgO_2^{-1}] represents in a first step the average change in effect (ΔPAF) due to an increase of the stressor intensity (-Δ[O_2]), which corresponds to a decrease in [O_2], contrary to e.g. toxicity of chemicals, hence justifying the minus sign. The EF is calculated as shown in equation 9.10:

$$EF_j = \frac{\Delta PAF_j}{-\Delta[O_2]_j} = \frac{0.5}{-\left(HC50_{LOEL\,j} - O_2solub_j\right)}$$

Equation 9.10

where $HC50_{LOEL\,j}$ is the DO concentration [in kg/m^3] at which 50% of the species are affected above their lowest-observed-effect-level (LOEL) obtained by calculating:

$$HC50_{LOEL\,j} = 10^{\mathrm{avg}(logLOEL_j)}$$

Equation 9.11

equivalent to the geometric mean of the LOEL data, in accordance with the linear gradient approach as described by Pennington et al. (2004), for each receiving ecosystem j, and the O_2solub_j is the solubility of oxygen at 100 m depth (LME's average depth) in ecosystem j based on the average water temperature at the corresponding climate zone for which ecosystem j is assigned.

The LOEL data refers to the sensitivity of individual species to hypoxia. The used dataset is extracted from a comprehensive review of marine species responses to low DO concentrations (i.e. response to hypoxia) by Vaquer-Sunyer and Duarte (2008) and is limited to the data referring to benthic, demersal, or benthopelagic species. This dataset restricts the analysis to the species that live close or attached to the substrat or those whose feeding, reproduction, or hiding habits depend on bottom waters, and it includes 57 species of fish, crustaceans, molluscs, echinoderms, annelids, or cnidarians. The biological endpoints assessed include sublethal effects at behavioural and physiological level.

A species sensitivity distribution (SSD) method is used to estimate the sensitivity of the community based on the sensitivity of individual species by means of a probabilistic model, as described by Posthuma et al. (2002). The method delivers the $HC50_{LOEL}$, i.e. the concentration of DO (intensity of the stressor) affecting 50% of the species above their LOEL. The estimation of EFs is further detailed in Cosme et al. (2016).

We used an estimate of the volume of each LME (area multiplied with 100m depth, as done in USEtox), in order to arrive at effect factors that do not contain the volume of the LMEs.

The CFs are calculated as potentially affected fractions of species (PAF). A transformation from PAF to PDF is achieved by using factor of 0.5.

Vulnerability score (VS)

We calculated a VS based on IUCN data for lobsters, bony fish, cartilaginous fish and sea cucumbers, following the same procedure as in the water consumption or land use chapters and presented in the framework chapter.

9.3. Uncertainties

The fate modelling framework shows high uncertainty mainly caused by the assumption of generic loss rate coefficients for several of the parameters due to the need of a global fate model that includes both inland (soil and freshwater) and marine fate processes. In addition, for countries emitting to more than one receiving spatial unit, the calculation of country-specific CFs assumes an even split of that emission between all potentially receiving LMEs which is a rough approximation of the real emission profile that reduces the precision of the results. Regarding the sensitivity of the model to the different parameters, the estimated FFs are strongly correlated to the hydraulic residence time of the receiving marine spatial units.

The estimation of the exposure factor is built on biological processes described by accepted and transparent empirical mechanisms and models. Overall, it delivers spatially differentiated parameter fitting and results. The method adds ecological relevance to the exposure modelling and its sensitivity shows strong correlation to local primary productivity, expressed by a correlation coefficient of 94% between XFs and PP rates.

The effect estimation based on sensitivity to hypoxia is built on a limited dataset (57 species). The estimation of EFs for individual LMEs is not possible due to the low representativeness of such number of species for a total of 66 LMEs. The adoption of a 5 climate zones resolution is thus preferred delivering EFs that can then be assigned to the LMEs falling into those climate zones. Several other species may be occurring in the receiving ecosystems (LME or climate zones) for which no sensitivity data is available. The data available is clearly short when comparing to the potential total number of resident species but the level of representativeness is not assessed. However, compared to e.g. efect factor calculation in ecotoxicty (in many cases using information for 5-7 species), the data availability was high. See Cosme et al. (2016) for further details on EF estimation and significance of spatial differentiation between climate zones.

The adoption of the LME biogeographical classification system with 66 spatial units is a discrete choice in the modelling framework. The decision regarding any possible alternative zonation system falls on data availability for the driving parameter Primary Production rate (depth and area integrated). This fact also adds robustness and adaptability to the model proposed both in terms of size (and number) of spatial units adopted and extrapolation potential.

9.4. Value choices

Time horizon

An infinite time horizon is taken in the calculations. No choices are thus modelled for marine eutrophication.

Level of robustness

The robustness of the fate modelling is considered low as some of the modelled parameters adopt a site-generic coefficient which still gives a valuable global coverage but reduces spatial differentiation. In addition, the method used to assign the country emissions to multiple receiving ecosystems (where applicable) is both highly uncertain and greatly contributing to the model results.

The exposure and effects modelling are based on ecological and biological processes. All the relevant processes are covered and built on state-of-the-art empirical models, estimation methods, and relevant data. The results are meaningful and the most sensitive/driving parameters are not very uncertain with the applied level of spatial differentiation. The level of robustness for these model components is therefore considered high.

Overall, the robustness of the model for marine eutrophication impacts is considered moderate to high acknowledging that the lower robustness of the fate component has more influence in the CFs for countries with emissions to multiple receiving ecosystems (LMEs) than for the remaining countries.

Figures 9.3 to 9.5 below show the spatial distribution of the endpoint characterization factors (CF_{end}) for marine eutrophication impacts from nitrogen emissions on the three modelled emission routes. Tables 9.1 and 9.2 include the endpoint characterization factors (CF_{end}) for marine eutrophication impacts calculated for the three emissions routes per country of emission, and Table 9.3 includes the aggregated CFs for the continental regions and the global average for the same emission routes.

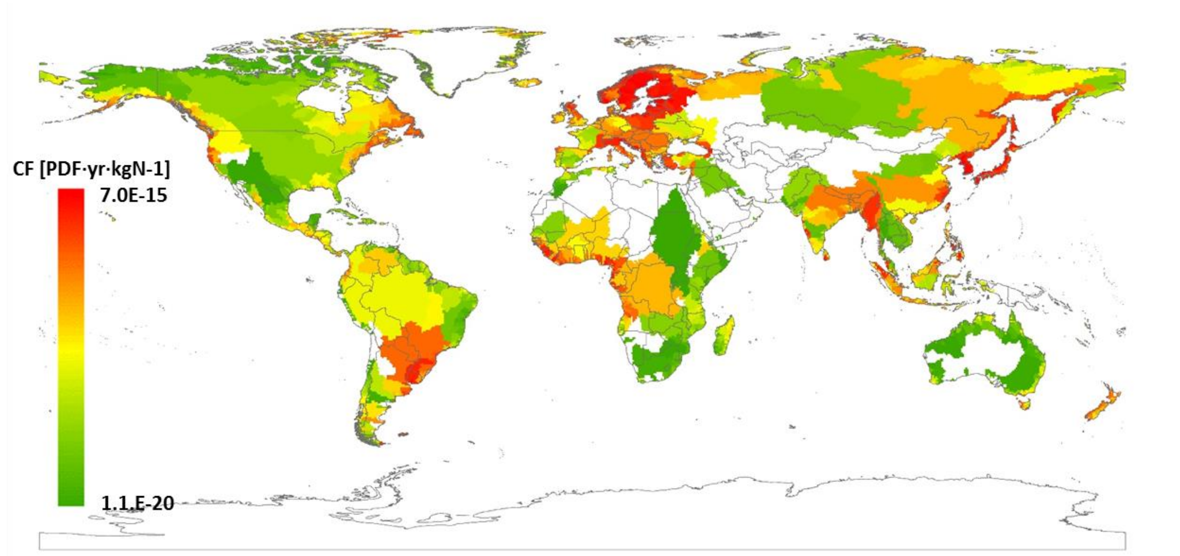

Figure 9.3: Endpoint characterization factors (CF_{end}) [PDF·yr·kg^{-1}] for marine eutrophication impacts from N emissions to groundwater.

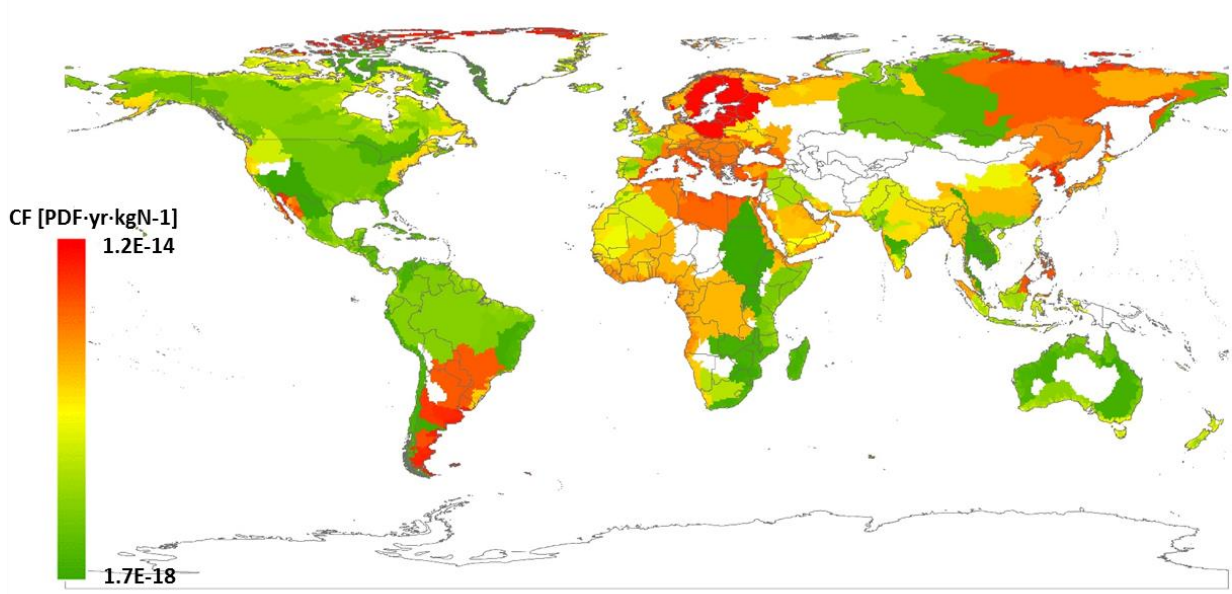

Figure 9.4: Endpoint characterization factors (CF_{end}) [PDF·yr·kg^{-1}]for marine eutrophication impacts from N emissions to freshwater.

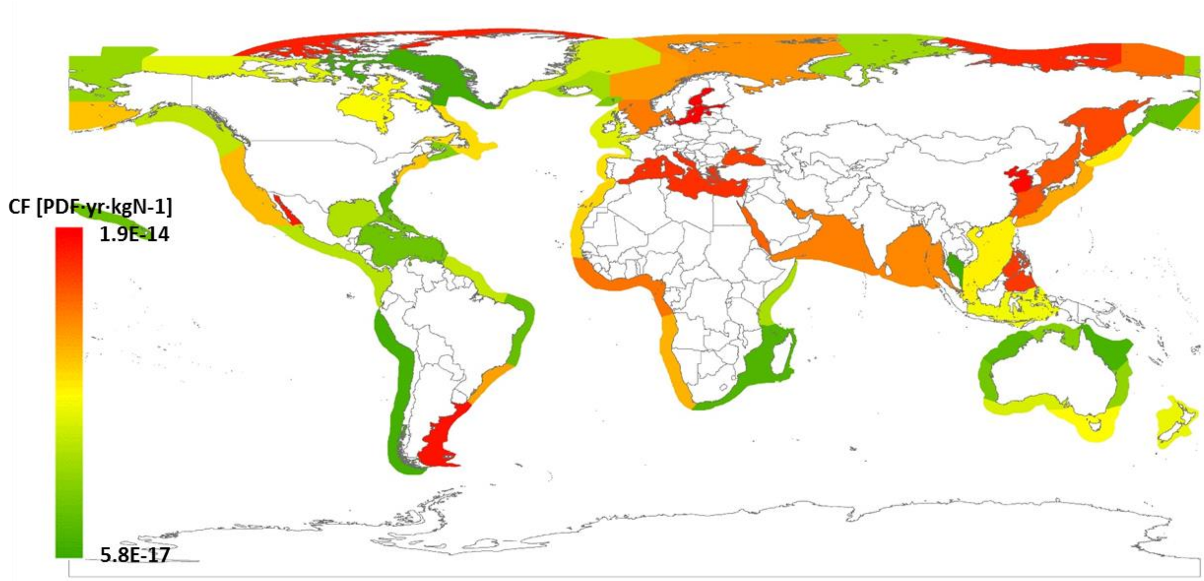

Figure 9.5: Endpoint characterization factors (CF_{end}) [PDF·yr·kg^{-1}] for marine eutrophication impacts from nitrogen emissions to marine waters.

Table 9.1: Endpoint characterization factors [PDF·yr·kg^{-1}] for marine eutrophication impacts from N emissions to surface water and to soil. Countries with no access to a coast or transport of water to a coastal regions can have a CF of zero.

Country	CF for N emission to soil [PDF*yr/kg]	CF for N emission to freshwater (river) [PDF*yr/kg]
Afghanistan	0.00E+00	2.64E-17
Albania	1.59E-15	2.65E-15
Algeria	9.12E-17	2.62E-15
Angola	2.27E-16	9.08E-16
Argentina	3.17E-16	2.38E-15
Australia	5.00E-16	6.94E-15
Austria	6.28E-17	2.49E-16
Bangladesh	1.99E-15	3.23E-15
Belgium	1.02E-15	4.16E-15
Belize	0.00E+00	3.55E-19
Benin	1.22E-17	7.35E-17
Bhutan	0.00E+00	0.00E+00
Bolivia	1.02E-16	4.47E-16
Bosnia and Herzegovina	1.59E-15	3.88E-15
Botswana	0.00E+00	1.16E-16
Brazil	1.16E-14	4.33E-14
Brunei	0.00E+00	0.00E+00
Bulgaria	1.00E-18	1.16E-17
Burkina Faso		
Burundi	0.00E+00	1.28E-17
Byelarus	1.32E-14	8.18E-14
Cambodia	0.00E+00	2.41E-16
Cameroon	1.67E-17	4.91E-17
Canada	1.98E-15	1.29E-14
Central African Republic	0.00E+00	0.00E+00
Chad	0.00E+00	2.99E-19
Chile	5.59E-14	3.46E-13
China	3.54E-13	1.80E-12
Colombia	1.42E-16	1.93E-16
Congo	1.40E-20	7.02E-20
Costa Rica	3.84E-17	5.44E-17
Croatia	6.54E-14	1.81E-13
Cuba	3.31E-17	1.66E-16
Czech Republic	1.16E-15	8.64E-15
Denmark	3.82E-15	1.86E-14
Djibouti	0.00E+00	0.00E+00
Dominican Republic	2.85E-18	1.90E-17
Ecuador		
Egypt	7.58E-18	2.48E-14
El Salvador	1.47E-16	1.98E-16
Equatorial Guinea	0.00E+00	0.00E+00
Eritrea	0.00E+00	1.22E-16
Estonia	5.37E-11	2.90E-10
Ethiopia	3.21E-16	2.43E-15
Finland	1.25E-14	7.09E-14
France	1.20E-14	3.88E-14
French Guiana	0.00E+00	0.00E+00
Gabon	0.00E+00	1.79E-19
Gambia, The	0.00E+00	1.20E-15
Georgia	1.80E-14	4.57E-14
Germany	1.00E-12	5.99E-12
Ghana	2.13E-17	1.17E-16
Greece	3.53E-17	1.95E-16
Guatemala	2.62E-15	3.08E-15
Guinea	1.59E-17	3.75E-17
Guinea-Bissau	2.69E-18	5.37E-18
Guyana	3.20E-17	3.20E-16
Haiti	5.27E-16	1.58E-15

Honduras	7.95E-16	1.28E-15
Hungary	1.92E-14	7.67E-14
Iceland	0.00E+00	0.00E+00
India	5.90E-15	1.30E-14
Indonesia		
Iran	6.63E-19	2.70E-17
Iraq	3.62E-18	6.78E-17
Ireland	1.11E-16	2.15E-16
Israel	2.13E-17	2.66E-16
Italy	1.31E-15	3.96E-15
Ivory Coast	2.67E-16	9.85E-16
Japan	4.78E-16	5.98E-16
Jordan	0.00E+00	1.64E-17
Kazakhstan	1.31E-18	1.64E-17
Kenya	1.14E-16	1.21E-15
Kuwait	2.50E-18	7.51E-18
Laos	6.25E-16	9.99E-18
Latvia	1.91E-14	3.19E-13
Lebanon	0.00E+00	8.57E-16
Lesotho	5.40E-18	2.70E-17
Liberia	5.00E-17	1.11E-17
Libya	5.89E-15	3.91E-15
Lithuania	1.21E-15	1.83E-13
Luxembourg	1.15E-14	2.78E-14
Macedonia	5.53E-17	9.56E-15
Madagascar	1.20E-17	2.99E-18
Malawi	2.24E-15	9.17E-17
Malaysia	4.34E-16	1.03E-13
Mali	0.00E+00	2.61E-16
Mauritania	2.89E-16	4.74E-18
Mexico	6.71E-17	3.04E-14
Moldova	6.62E-17	7.95E-16
Mongolia	3.99E-17	2.14E-18
Montenegro	4.57E-16	6.86E-15
Morocco	4.87E-17	1.47E-14
Mozambique	3.18E-15	4.50E-17
Myanmar (Burma)	0.00E+00	1.06E-15
Namibia	1.13E-15	0.00E+00
Nepal	8.93E-16	2.00E-16
Netherlands	2.34E-13	4.24E-12
New Zealand	1.60E-17	2.98E-16
Nicaragua	6.71E-19	1.01E-17
Niger	2.25E-16	1.83E-17
Nigeria	1.27E-14	4.25E-15
North Korea	3.17E-14	5.48E-14
Norway	0.00E+00	5.88E-15
Oman	3.65E-16	2.11E-17
Pakistan	1.07E-17	5.57E-15
Panama	0.00E+00	9.03E-16
Papua New Guinea	3.74E-18	0.00E+00
Paraguay	1.00E-15	4.12E-15
Peru	5.56E-15	1.81E-15
Philippines	4.39E-14	1.69E-14
Poland	4.70E-17	4.61E-14
Portugal	4.84E-16	1.79E-16
Qatar	1.20E-16	0.00E+00
Romania	0.00E+00	4.64E-15
Russia		
Rwanda	4.60E-18	0.00E+00
Saudi Arabia	9.17E-17	1.20E-16
Senegal	0.00E+00	3.04E-14
Serbia	2.02E-16	2.59E-15
Sierra Leone	2.13E-15	0.00E+00

Slovakia	0.00E+00	5.35E-16
Slovenia	6.25E-14	1.72E-12
Somalia	7.03E-15	2.87E-18
South Africa	4.21E-15	4.28E-15
South Korea	5.36E-14	6.73E-13
Spain	0.00E+00	3.67E-15
Sri Lanka	0.00E+00	5.14E-16
Sudan	0.00E+00	2.02E-19
Suriname	2.95E-15	1.19E-17
Swaziland	8.09E-16	8.70E-18
Sweden	2.07E-14	1.95E-12
Switzerland	7.72E-15	1.20E-14
Syria	4.95E-18	5.08E-16
Taiwan	2.08E-16	7.78E-16
Tanzania, United Republic of	1.33E-17	5.77E-17
Thailand	0.00E+00	6.49E-16
Togo	2.82E-16	1.00E-15
Trinidad and Tobago	1.42E-14	5.10E-17
Tunisia	0.00E+00	1.27E-16
Turkey	6.72E-15	2.42E-13
Uganda	0.00E+00	0.00E+00
Ukraine	8.14E-15	1.17E-14
United Arab Emirates	3.19E-16	1.45E-17
United Kingdom	4.46E-16	1.11E-14
United States	6.50E-15	7.70E-13
Uruguay	1.56E-16	2.90E-16
Venezuela	0.00E+00	2.09E-15
Vietnam	0.00E+00	1.46E-16
Western Sahara	0.00E+00	0.00E+00
Yemen	1.18E-17	2.43E-16
Zaire	2.57E-18	4.28E-19
Zambia	0.00E+00	1.35E-17
Zimbabwe	0.00E+00	1.38E-17

Table 9.2: Endpoint characterization factors [PDF·yr·kg^{-1}] for marine eutrophication for marine eutrophication impacts from emissions directly to marine coastal waters.

Country	CF for direct N emission to marine system [PDF*yr/kg]
Afghanistan	0.00E+00
Albania	4.94E-15
Algeria	4.94E-15
American Samoa	0.00E+00
Andorra	0.00E+00
Angola	1.73E-15
Anguilla	0.00E+00
Antarctica	0.00E+00
Antigua and Barbuda	5.23E-16
Argentina	6.72E-15
Armenia	0.00E+00
Aruba	3.68E-16
Australia	4.28E-16
Austria	0.00E+00
Azerbaijan	0.00E+00
Bahamas, The	6.74E-16
Bahrain	2.65E-15
Baker Island	0.00E+00
Bangladesh	1.47E-15
Barbados	3.58E-16
Belgium	2.69E-15
Belize	4.18E-16
Benin	1.72E-15

Bermuda	0.00E+00
Bhutan	0.00E+00
Bolivia	0.00E+00
Bosnia and Herzegovina	4.94E-15
Botswana	0.00E+00
Bouvet Island	0.00E+00
Brazil	8.07E-16
British Indian Ocean Territory	0.00E+00
British Virgin Islands	0.00E+00
Brunei	8.40E-16
Bulgaria	2.44E-15
Burkina Faso	0.00E+00
Burundi	0.00E+00
Byelarus	0.00E+00
Cambodia	5.87E-17
Cameroon	1.54E-15
Canada	1.09E-15
Cape Verde	0.00E+00
Cayman Islands	5.21E-16
Central African Republic	0.00E+00
Chad	0.00E+00
Chile	2.48E-16
China	5.02E-15
Christmas Island	0.00E+00
Cocos (Keeling) Islands	0.00E+00
Colombia	5.18E-16
Comoros	2.94E-16
Congo	1.55E-15
Cook Islands	0.00E+00
Costa Rica	5.50E-16
Croatia	4.94E-15
Cuba	6.40E-16
Cyprus	4.94E-15
Czech Republic	0.00E+00
Denmark	1.31E-14
Djibouti	2.76E-15
Dominica	7.42E-16
Dominican Republic	3.47E-16
Ecuador	6.57E-16
Egypt	4.21E-15
El Salvador	6.57E-16
Equatorial Guinea	1.45E-15
Eritrea	3.11E-15
Estonia	1.92E-14
Ethiopia	0.00E+00
Falkland Islands (Islas Malvinas)	8.10E-15
Faroe Islands	7.65E-16
Federated States of Micronesia	0.00E+00
Fiji	0.00E+00
Finland	1.92E-14
France	2.35E-15
French Guiana	6.97E-16
French Polynesia	0.00E+00
French Southern & Antarctic Lands	0.00E+00
Gabon	2.06E-15
Gambia, The	1.33E-15
Gaza Strip	4.94E-15
Georgia	4.07E-15
Germany	1.16E-14
Ghana	2.89E-15
Gibraltar	4.94E-15
Glorioso Islands	2.94E-16
Greece	4.94E-15

Greenland	9.49E-16
Grenada	5.43E-16
Guadeloupe	6.71E-16
Guam	0.00E+00
Guatemala	7.31E-16
Guernsey	8.26E-16
Guinea	2.57E-15
Guinea-Bissau	1.20E-15
Guyana	6.97E-16
Haiti	3.64E-16
Heard Island & McDonald Islands	0.00E+00
Honduras	5.84E-16
Howland Island	0.00E+00
Hungary	0.00E+00
Iceland	5.68E-16
India	2.10E-15
Indonesia	1.40E-15
Iran	2.65E-15
Iraq	2.65E-15
Ireland	7.71E-16
Israel	4.86E-15
Italy	4.94E-15
Ivory Coast	2.25E-15
Jamaica	3.37E-16
Jan Mayen	7.39E-16
Japan	2.59E-15
Jarvis Island	0.00E+00
Jersey	7.88E-16
Johnston Atoll	0.00E+00
Jordan	3.11E-15
Juan De Nova Island	2.94E-16
Kazakhstan	0.00E+00
Kenya	6.05E-16
Kiribati	0.00E+00
Kuwait	2.65E-15
Kyrgyzstan	0.00E+00
Laos	0.00E+00
Latvia	1.92E-14
Lebanon	4.94E-15
Lesotho	0.00E+00
Liberia	2.41E-15
Libya	4.94E-15
Liechtenstein	0.00E+00
Lithuania	1.92E-14
Macau	8.40E-16
Macedonia	0.00E+00
Madagascar	2.94E-16
Malawi	0.00E+00
Malaysia	9.12E-16
Maldives	2.65E-15
Mali	0.00E+00
Malta	4.94E-15
Man, Isle of	7.99E-16
Marshall Islands	0.00E+00
Martinique	3.75E-16
Mauritania	1.11E-15
Mauritius	0.00E+00
Mayotte	2.94E-16
Mexico	1.50E-15
Midway Islands	3.28E-16
Moldova	0.00E+00
Monaco	4.94E-15
Mongolia	0.00E+00

Montenegro	4.94E-15
Montserrat	3.82E-16
Morocco	4.90E-15
Mozambique	2.94E-16
Myanmar (Burma)	1.38E-15
Namibia	1.74E-15
Nauru	0.00E+00
Netherlands	2.69E-15
Netherlands Antilles	6.69E-16
New Caledonia	0.00E+00
New Zealand	7.67E-16
Nicaragua	6.76E-16
Niger	0.00E+00
Nigeria	2.12E-15
Niue	0.00E+00
Norfolk Island	0.00E+00
North Korea	6.71E-15
Northern Mariana Islands	0.00E+00
Norway	2.46E-15
Oman	2.65E-15
Pacific Islands (Palau)	0.00E+00
Pakistan	2.65E-15
Panama	5.84E-16
Papua New Guinea	0.00E+00
Paracel Islands	8.40E-16
Peru	6.57E-16
Philippines	3.49E-15
Pitcairn Islands	0.00E+00
Poland	1.92E-14
Portugal	1.09E-15
Puerto Rico	3.50E-16
Qatar	2.65E-15
Reunion	0.00E+00
Romania	3.55E-15
Russia	3.00E-15
Rwanda	0.00E+00
Sao Tome and Principe	1.03E-15
Saudi Arabia	2.98E-15
Senegal	1.40E-15
Seychelles	0.00E+00
Sierra Leone	1.58E-15
Singapore	8.40E-16
Slovakia	0.00E+00
Slovenia	4.94E-15
Solomon Islands	0.00E+00
Somalia	2.65E-15
South Africa	1.74E-15
South Georgia and the South Sandwich Is	0.00E+00
South Korea	1.99E-15
Spain	2.93E-15
Spratly Islands	8.40E-16
Sri Lanka	1.34E-15
St. Helena	0.00E+00
St. Kitts and Nevis	8.01E-16
St. Lucia	6.75E-16
St. Pierre and Miquelon	1.13E-15
St. Vincent and the Grenadines	7.97E-16
Sudan	3.11E-15
Suriname	6.97E-16
Svalbard	2.12E-15
Sweden	1.88E-14
Syria	4.94E-15
Taiwan	1.30E-15

Tajikistan	0.00E+00
Tanzania, United Republic of	6.05E-16
Thailand	8.03E-16
Togo	9.15E-16
Tokelau	0.00E+00
Tonga	0.00E+00
Trinidad and Tobago	7.06E-16
Tunisia	4.94E-15
Turkey	4.58E-15
Turkmenistan	0.00E+00
Turks and Caicos Islands	4.06E-16
Tuvalu	0.00E+00
Uganda	0.00E+00
Ukraine	4.33E-15
United Arab Emirates	2.65E-15
United Kingdom	1.64E-15
United States	8.66E-16
Uruguay	2.25E-15
Vanuatu	0.00E+00
Venezuela	4.90E-16
Vietnam	8.20E-16
Virgin Islands	3.69E-16
Wake Island	0.00E+00
Wallis and Futuna	0.00E+00
Western Sahara	1.29E-15
Western Samoa	0.00E+00
Yemen	2.68E-15
Zaire	1.52E-15
Zambia	0.00E+00

Table 9.3: Continental and global averages of the CFs.

CONTINENT	CF for N emission to soil [PDF*yr/kg]	CF for N emission to freshwater (river) [PDF*yr/kg]	CF for direct N emission to marine system [PDF*yr/kg]
Africa	4.697E-17	9.202E-16	2.191E-15
Asia	2.055E-16	7.483E-16	2.244E-15
Europe	3.751E-16	1.962E-15	3.869E-15
North America	4.444E-17	2.175E-16	1.000E-15
Oceania	3.028E-17	1.748E-16	5.123E-16
South America	2.699E-16	1.172E-15	1.284E-15
Global average	2.07E-16	9.16E-16	1.95E-15

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Supporting Information

Table 9.4: Hydraulic residence times on the receiving Large Marine ecosystems (LME) (data from sources or defined by archetype).

Large Marine Ecosystem	Hydraulic residence time		Source
#. name	archetype	[yr]	References *(see list below)
01. East Bering Sea	2	2.00	
02. Gulf of Alaska	1	0.25	
03. California Current	1	0.25	
04. Gulf of California		1.50	Lopez & Garcia (2003)
05. Gulf of Mexico	4	90.00	Turner & Rabalais (2009); USGS (2012); Rivas et al. (2005)
06. Southeast U.S. Continental Shelf	1	0.25	Alegria et al. (2000)
07. Northeast U.S. Continental Shelf	1	0.25	
08. Scotian Shelf	1	0.25	Smith et al. (2003)
09. Newfoundland-Labrador Shelf	1	0.25	
10. Insular Pacific-Hawaiian	1	0.25	
11. Pacific Central-American	1	0.25	
12. Caribbean Sea		0.21	Molinari et al. (1980)
13. Humboldt Current		0.03	Hall et al. (1996)
14. Patagonian Shelf	1	0.25	
15. South Brazil Shelf	1	0.25	
16. East Brazil Shelf	1	0.25	Attisano et al. (2008)
17. North Brazil Shelf	1	0.25	Limeburner et al. (1995)
18. Canadian Eastern Arctic - West Greenland	1	0.25	
19. East Greenland Shelf	1	0.25	
20. Barents Sea	2	2.00	
21. Norwegian Sea	2	2.00	
22. North Sea		2.00	Blaas et al. (2001)
23. Baltic Sea		25.00	Jansson B-O (1980); Matthäus & Schinke (1999)
24. Celtic-Biscay Shelf	2	2.00	
25. Iberian Coastal	1	0.25	
26. Mediterranean		90.00	Pinet PR (2008)
27. Canary Current	1	0.25	
28. Guinea Current		3.10	Hall et al. (1996)
29. Benguela Current	1	0.25	
30. Agulhas Current	2	2.00	
31. Somali Coastal Current	1	0.25	Naqvi (2012)
32. Arabian Sea		6.50	Sarma (2002)
33. Red Sea		40.00	Smeed (2010); Grasshoff (1969); Tomczak & Godfrey (2003)
34. Bay of Bengal		12.00	Sarma (2002)
35. Gulf of Thailand		0.04	Dulaiova et al. (2006)
36. South China Sea	3	25.00	
37. Sulu-Celebes Sea	3	25.00	Tessler (2012); Tessler et al. (2011).
38. Indonesian Sea		0.75	Ffield & Gordon (1992)
39. North Australian Shelf	1	0.25	
40. Northeast Australian Shelf	1	0.25	Choukroun et al. (2010)
41. East-Central Australian Shelf	1	0.25	
42. Southeast Australian Shelf	1	0.25	
43. Southwest Australian Shelf	1	0.25	
44. West-Central Australian Shelf	1	0.25	
45. Northwest Australian Shelf	1	0.25	
46. New Zealand Shelf	1	0.25	
47. East China Sea		1.90	Tsunogai et al. (1997); Tomczak & Godfrey (2003); Hall et al. (1996)
48. Yellow Sea		2.00	Tsunogai et al. (1997); Tomczak & Godfrey (2003)
49. Kuroshio Current		2.30	Matsuno et al. (2009)
50. Sea of Japan/East Sea	3	25.00	
51. Oyashio Current	1	0.25	
52. Sea of Okhotsk	2	2.00	Yamamoto et al. (2001)

53. West Bering Sea	1	0.25	
54. Northern Bering - Chukchi Seas		3.50	Schlosser et al. (1994)
55. Beaufort Sea		3.50	Schlosser et al. (1994)
56. East Siberian Sea		3.50	Schlosser et al. (1994)
57. Laptev Sea		3.50	Schlosser et al. (1994)
58. Kara Sea		3.50	Schlosser et al. (1994)
59. Iceland Shelf and Sea	1	0.25	
60. Faroe Plateau		0.25	Gaard (2000)
61. Antarctic		6.00	Jacobs et al. (1985)
62. Black Sea	4	90.00	Murray et al. (2007)
63. Hudson Bay Complex		6.60	Ingram & Prinsenberg (1998)
64. Central Arctic Ocean		11.00	Jahn et al. (2010)
65. Aleutian Islands	1	0.25	
66. Canadian High Arctic - North Greenland	2	2.00	

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