

Supplementary material

The system of equations describing the dynamics of the model state variables is given by:

$$\frac{\partial C_i}{\partial t} + u \frac{\partial C_i}{\partial x} + \frac{\partial}{\partial z} (w_{C_i} C_i) - \frac{\partial}{\partial x} K_L \frac{\partial C_i}{\partial x} - \frac{\partial}{\partial z} K_z \frac{\partial C_i}{\partial z} + \tau^{-1} (C_i^* - C_i) = R_{C_i} \quad (1)$$

where u is the horizontal current velocity, w_{C_i} is the sinking rate, K_L is the horizontal turbulence coefficient, K_z is the vertical turbulence coefficient, τ is a relaxation time, R_{C_i} is the biogeochemical sources-minus-sinks term, C_i is the concentration of the i th model state variable, and C_i^* is the concentration in the array for relaxation (climatic data).

OxyDep parameterizations

The scheme of biogeochemical fluxes in OxyDep (Fig. 3), described by R_i functions (the “right-hand sides”) in a System of advection-diffusion equations (1) is defined as follows:

$$R_{PHY} = GrowthPhy - RespPhy - ExcrPhy - MortPhy - GrazPhy$$

$$R_{HET} = U_z (GrazPhy + GrazPOM) - MortHet - RespHet$$

$$R_{NUT} = -GrowthPhy + RespPhy + POM_{Decay\ O_2} + RespHet - N_{toN} (POM_{Decay\ denitr} + DOM_{Decay\ denitr})$$

$$R_{DOM} = ExcrPhy + Autolys - DOM_{Decay\ O_2} - DOM_{Decay\ denitr} + (GrazPhy + GrazPOM)(1 - U_z)Hz \quad (2)$$

$$R_{POM} = MortPhy + MortHet - Autolys - POM_{Decay\ O_2} - POM_{Decay\ denitr} + (GrazPhy + GrazPOM)(1 - U_z)(1 - Hz) - GrazPOM$$

$$R_{OXY} = -O_{toN} (POM_{decay\ O_2} + DOM_{decay\ O_2} - GrowthPhy + RespPhy) - (0.5 - 0.5 \tanh(OXY - O_{2\ AddMorPhy})) O_{toN} DOM_{decay\ O_2}$$

The biogeochemical fluxes between state variables were parameterized for specific processes as follows:

PHY

The specific growth rate of PHY:

$$GrowthPHY = Max_{uptake} Lim_{Light} Lim_T Lim_N PHY \quad (3)$$

which represents the function of temperature, light and NUT availability.

Light dependence:

$$Lim_{Light} = I_z / I_{opt} \exp(1 - I_z / I_{opt}) \quad (4)$$

describes also photoinhibition and considers optimal (I_{opt}) and given on a specific depth (I_z) light intensity.

Temperature effect:

$$Lim_T = q10^{(T - T_{UptMin})/10} - q10^{(T - T_{UptMax})/3} \quad (5)$$

is based on Q10 approach, where $q10$ is the coefficient of temperature dependence of nutrient uptake; T_{UptMin} and T_{UptMax} are the lower and upper limits of this dependence.

Nutrient limitation:

$$Lim_N = \frac{(NUT/PHY)^2}{(NUT/PHY)^2 + K_{NUT}} \quad (6)$$

describes nutrient availability for a unit of phytoplankton biomass as a squared saturation (sigmoid) function (cf. Fig. 2.3), where K_{NUT} is a half-saturation constant.

PHY respiration and corresponding changes of NUT concentration are calculated as:

$$RespPhy = R_{NUT}^{PHY} PHY \quad (7)$$

PHY metabolism and increase of DOM concentration is described by:

$$RespPhy = R_{DOM}^{PHY} PHY \quad (8)$$

The mortality rate of PHY and an increase of POM concentration is given by:

$$MortPhy = \left(R_{POM}^{PHY} + \left(0.5 - 0.5 \tanh(OXY - O_{2 \text{ AddMorPhy}}) \right) R_{PHY \text{ om anox}} \right) PHY, \quad (9)$$

where the second term in the parentheses is an augmentation of mortality rate in suboxic/anoxic conditions. The changes between the processes occurring in oxic and suboxic conditions were parameterized with “soft switches” based on hyperbolic tangents functions:

$$f_o(OXY) = 1 - 0.5(1 + \tanh(OXY - O_2^{bf})) \quad (10)$$

and

$$f_s(OXY) = 0.5(1 + \tanh(OXY - O_2^{bf})) \quad (11)$$

where O_2^{bf} is a threshold oxygen concentration at which the changes occur.

HET

The grazing of HET on PHY is described as:

$$GrazPhy = R_{HET}^{PHY} \frac{(PHY/HET)^2}{(PHY/HET)^2 + K_{PHY}} HET \quad (12)$$

The grazing of HET on POM is given by:

$$GrazPOM = R_{HET}^{POM} \frac{(POM/HET)^2}{(POM/HET)^2 + K_{POM}} HET \quad (13)$$

HET respiration and changes in NUT concentration are described as:

$$RespHet = R_{NUT}^{HET} HET \quad (14)$$

The mortality rate of HET and increase of POM concentration is given by:

$$MortHet = (R_{POM}^{HET} + (0.5 - 0.5 \tanh(OXY - O_{2 \text{ sub}})) R_{het \text{ POM anox}}) HET, \quad (15)$$

where the second term is an augmentation of mortality rate in suboxic/anoxic conditions.
POM

Autolysis, the formation of DOM from POM, is described as:

$$Autolys = R_{DOM}^{POM} POM \quad (16)$$

POM decomposition occurs due to the consumption of oxygen under aerobic conditions is given by:

$$POM_{decay \text{ ox}} = R_{POM \text{ NUT OXY}} f_{decay}^T DOM \quad (17)$$

with the temperature dependence:

$$f_{decay}^T = (1 + B_{da} \frac{T^2}{T^2 + T_{da}^2}) \quad (18)$$

where T is temperature, B_{da} and T_{da} are temperature dependence coefficients.

POM mineralization in hypoxic condition due to denitrification and anaerobic oxidation of ammonium depends on concentration of O_2 , NO_3 (+ NO_2), and temperature:

$$POM_{decay\ denitr} = R_{POM\ NUT\ NUT}^{POM} \cdot f_{subox}^{OXY} \cdot f_{subox}^{NUT} \quad (19)$$

where

$$f_{subox}^{OXY} = 0.5 - 0.5 \tanh(O_2^{subox} - OXY) \quad (20)$$

is a switch between processes occurring in oxic and suboxic conditions making possible denitrification at oxygen less than O_2^{bf} , while a switch allowing consumption of NUT at values higher than NUT^{bf} was given by:

$$f_{subox}^{NUT} = 0.5 - 0.5 \tanh(NUT^{bf} - NUT) \quad (21)$$

DOM

The decomposition of DOM occurs similar to POM due to the consumption of oxygen under aerobic conditions and denitrification under suboxic conditions. Mineralization of DOM under aerobic conditions, was described as:

$$DOM_{decay\ ox} = R_{DOM\ NUT\ OXY} f_{decay}^T DOM \quad (22)$$

DOM mineralization in hypoxic condition was described with the same expressions 18, 20, and 21:

$$DOM_{decay\ denitr} = R_{DOM\ NUT\ NUT}^{DOM} \cdot f_{subox}^{OXY} \cdot f_{subox}^{NUT} \quad (23)$$

NUT

Changes in NUT ($NO_3 + NO_2$) concentrations were described according to equation for R_{NUT} from the system of equations (2), where $NtoN$ is the stoichiometric constant for denitrification leading to the loss of NUT.

OXY

Changes in OXY concentration due to the production and destruction of organic matter was calculated according to equation for R_{OXY} in the System 2 using a stoichiometric Redfield constant $OtoN$ (Redfield et al., 1953). The last term in R_{OXY} describes the additional consumption of OXY for oxidizing the reduced forms of S (sulfur), Mn (manganese), Fe (iron) under conditions of oxygen deficiency, which is proportional to the oxygen consumption for the DOM destruction.

The names, values, units, and indices of the parameters used in OxyDep are given in Table 1.

Table S1. Description of OxyDep Parameters.

Index	Value	Units	Long name
Max_{Uptake}	0.68	d ⁻¹	Maximum nutrient uptake rate
K_{NUT}	0.7	d ⁻¹	The half-saturation constant for the uptake of biogenic elements by photoautotrophic organisms and for the NUT / PHY ration
q_{10}	2.0	-	The coefficient of dependence of the uptake intensity on T
T_{UptMin}	10.	-	Lower limit of dependence of the uptake intensity on T
T_{UptMax}	32.	-	Upper limit of dependence of the uptake intensity on T
b_m	0.12	°C ⁻¹	The coefficient of dependence of the uptake intensity on T
c_m	1.4	-	The coefficient of dependence of the uptake intensity on T

ir_{min}	25.	nd	Bioshading parameter
I_{opt}	25.	W/m ²	Optimal irradiance
R_{POM}^{PHY}	0.15	d ⁻¹	Specific mortality rate of PHY
R_{DOM}^{PHY}	0.17	d ⁻¹	Specific excretion rate of PHY
$R_{PHY\ om\ anox}$	0.4	d ⁻¹	Specific rate of additional mortality in suboxic/anoxic conditions
R_{NUT}^{PHY}	0.05	d ⁻¹	Specific respiration rate of PHY
$O_2\ AddMorPHY$	20.	μM	Threshold value of O ₂ concentration for additional mortality PHY
R_{HET}^{PHY}	0.5	d ⁻¹	Maximum specific consumption rate of PHY by HET
K_{PHY}	0.02	nd	Half-saturation coefficient of PHY consumption by HET for PHY/HET ratio
R_{HET}^{POM}	0.7	d ⁻¹	Maximum specific consumption rate of POM by HET
R_{POM}^{HET}	0.02	d ⁻¹	Specific mortality rate of HET
U_z	0.6	nd	HET assimilation
H_z	0.5	nd	The ratio between the suspended and dissolved forms of HET excretions
R_{DOM}^{POM}	0.15	d ⁻¹	Specific rate of autolysis
$R_{POM\ NUT\ OXY}$	0.010	d ⁻¹	Specific rate of POM decomposition under aerobic conditions
$R_{POM\ NUT\ NUT}$	0.001	d ⁻¹	Specific rate of POM denitrification
$R_{DOM\ NUT\ OXY}$	0.020	d ⁻¹	Specific rate of DOM decomposition under aerobic conditions
$R_{DOM\ NUT\ NUT}$	0.001	d ⁻¹	Specific rate of DOM denitrification
O_2^{subox}	30	μM	The threshold of O ₂ concentration for the transition from aerobic to oxygen deficiency conditions (and vice versa)
NUT^{bf}	0.01	μM	The threshold of NUT concentration for stop of denitrification
T_{da}	13.	-	Coefficient for dependence of mineralization on T
B_{da}	20.	-	Coefficient for dependence of mineralization on T
B_u	0.4	nd	Burial coefficient for lower boundary
T_{rel}	1.e6	s/m	Relaxation time of exchange with bottom sediments
b_{Ox}	0.	μM	OXY concentration in bottom sediments
$b_{Dom\ Ox}$	2.	μM	Organic matter in bottom sediments (aerobic conditions)
$b_{Dom\ Anox}$	10.	μM	Organic matter in bottom sediments (anoxic conditions)
b_{Nut}	0.	μM	NUT in bottom sediments
P_{vel}	5.	m/s	Wind speed
a_0	31.25	μM	Oxygen saturation parameter
a_1	14.603	nd	Oxygen saturation parameter
a_2	0.4025	1/°C ⁻¹	Oxygen saturation parameter
$OtoN$	8,625	μM(O)/μM(N)	Ratio O/N (138/16)
$NtoB$	0.016	mg m ⁻³	N[μM]/biomass ratio
$NtoN$	5.3	M(N)/μM(N)	Loss of nitrogen following Richards denitrification (84.8/16)
W_{PHY}	0.25	m/d	Vertical velocity of PHY (<0 for sinking)
W_{POM}	15.0	m/d	Vertical velocity of POM (<0 for sinking)
W_{HET}	0.4	m/d	Vertical velocity of HET (<0 for sinking)

BioPlast parameterization

The following system of equations describes the MP variables changes described by R_i functions in Equation 1:

$$\begin{aligned}
R_{MP\ free} &= Decay_{MP\ free} - free2biof + det2free - free2het + biof2free \\
R_{MP\ biof} &= Decay_{MP\ biof} + free2biof - biof2het + het2biof - biof2free \\
R_{MP\ het} &= Decay_{MP\ het} + free2het + biof2het + det2het - het2det - het2biof \\
R_{MP\ det} &= Decay_{MP\ det} + het2det - det2free - det2het \\
R_{MP\ tot} &= R_{MP\ free} + R_{MP\ biof} + R_{MP\ het} + R_{MP\ det}
\end{aligned} \tag{25}$$

Where $Decay_{MP_{free}}$, $Decay_{MP_{biof}}$, $Decay_{MP_{het}}$, $Decay_{MP_{det}}$ – the degradation rates of corresponding MP forms, $free2biof$, $free2het$, $biof2free$, $biof2het$, $het2biof$, $het2det$, $det2free$, $det2het$ – are fluxes between the MP state variables (Fig. 2.3).

Flux from MP_{free} to MP_{biof} depends on biofouling rate $MP_{freebiof}$ and phytoplankton growth, calculated in OxyDep:

$$free2biof = MP_{freebiof} \cdot GrowthPhy \quad (26)$$

Graphical representation of the dependence of the rate on concentration of MP_{free} is shown in the Figure 2.2. This is a saturation function reflecting small dependence in small concentration of the substrate, highest dependence near thr_{free} value with a consequent decrease of dependance. The same function was used for some other processes described below.

Reverse flow from MP_{biof} to MP_{free} is set to zero, which means that there is no defouling:

$$biof2free = 0$$

Flux from MP_{free} to MP_{het} (ingestion of free MP by zooplankton) is proportional to HET feeding and is calculated according to:

$$free2het = Max_{freehet} \cdot GrazPhy \cdot Uz \cdot \frac{MP_{free}^2}{MP_{free}^2 + thr_{free}} \quad (27)$$

$Max_{freehet}$ – maximum ingestion rate of MP_{free} by heterotrophs; Uz – food assimilation by heterotrophs.

Flux from MP_{biof} to MP_{het} is given by:

$$biof2het = Max_{biofhet} \cdot GrazPhy \cdot Uz \cdot \frac{MP_{free}^2}{MP_{biof}^2 + thr_{biof}} \quad (28)$$

$Max_{biofhet}$ – maximum ingestion rate of MP_{biof} by heterotrophs.

Flux from MP_{det} to MP_{het} is:

$$det2het = Max_{dethet} \cdot GrazPOM \cdot Uz \cdot \frac{MP_{det}^2}{MP_{det}^2 + thr_{det}} \quad (29)$$

thr_{biof} , thr_{det} – threshold values at which heterotrophs begin to ingest MP_{biof} and MP_{det} .

Flux from MP_{het} to MP_{det} is modelled as a sum of excretes and died zooplankton:

$$het2det = \frac{free2het + free2det + biof2het}{uz(1 - uz) \cdot (1 - hz)} + MP_{het} \cdot \frac{MortHet}{Het} \quad (30)$$

Flux from MP_{het} to MP_{biof} is:

$$het2biof = \frac{free2het + det2het + biof2het}{uz(1 - uz) \cdot hz} + MP_{het} \cdot \frac{RespHet}{Het} \quad (31)$$

Flux from MP_{det} to MP_{free} due to decomposition depends on the rates of POM decomposition in aerobic conditions, denitrification and autolysis:

$$det2free = MP_{det} \cdot \frac{R_{POM\ NUT\ OXY} + R_{POM\ NUT\ NUT} + Autolys}{POM} \quad (32)$$

Since the thermal degradation of plastic in the ocean is negligible, only photodegradation of MP_{free} depending on irradiation is considered:

$$Decay_{MP_{free}} = -MP_{free_{decay}} \cdot I_z \cdot MP_{free} \quad (33)$$

Degradation of MP_{biof} consists of photo- and biodegradation:

$$Decay_{MP_{biof}} = -\left(MP_{free_{decay}} \cdot I_z + MP_{biof_{decay}}\right) \cdot MP_{biof} \quad (34)$$

Degradation of MP_{het} and MP_{det} is modelled as a first-order kinetics:

$$\begin{aligned} Decay_{MP_{het}} &= MP_{het_{decay}} \cdot MP_{het} \\ Decay_{MP_{det}} &= MP_{det_{decay}} \cdot MP_{det} \end{aligned} \quad (35)$$

$MP_{free_{decay}}$, $MP_{biof_{decay}}$, $MP_{det_{decay}}$ - decay constants of the corresponding forms of MP.

Total concentration of MP in all forms is calculated as a sum of all considered MP forms:

$$MP_{TOT} = MP_{free} + MP_{het} + MP_{det} + MP_{biof} \quad (36)$$

in mg/m^3 and is converted into items/ m^3 with:

$$MP_{TOT \text{ items}} = MP_{TOT} \cdot N_{fib} \quad (37)$$

The names, values, units, and indices of the BioPlast parameters used in the model are presented in Table 2.

Table S2. The names, values, units, and indices of the BioPlast parameters.

Notation	Model value, units	Existing estimates	Title
$MP_{free_{decay}}$	0 d ⁻¹	7·10 ⁻⁵ d ⁻¹ (18 – 36 moths exposure time) (Andrady, 2011; Brandon et al., 2016)	maximum rate of photodegradation in seawater
$MP_{biof_{decay}}$	0 d ⁻¹	12·10 ⁻⁵ d ⁻¹ (for polyurethane) (Muthukumar et al., 2011)	mean rate of degradation (weight loss) due to biofouling
$MP_{det_{decay}}$	0 d ⁻¹		maximum rate of degradation of plastic in detritus
$MP_{free_{biof}}$	100 d ⁻¹		maximum rate of biofouling of MP_{free}
$Max_{free_{het}}$	1		maximum rate of ingestion of MP_{free} by HET
$Max_{biof_{het}}$	1		maximum rate of ingestion of MP_{biof} by HET
thr_{free}	0.01		threshold constant for ingestion of MP_{free} by HET
thr_{biof}	0.01		threshold constant for ingestion of MP_{biof} by HET
w_{free}	0 m/d, -0.5 m/d 20 m/d	518 – 7862 m/d (Kowalski, Reichardt, and Waniek 2016)	MP_{free} sinking rate
w_{biof}	0.25 m/d	860 – 2600 m/d (Kaiser, Kowalski, and Waniek 2017)	MP_{biof} sinking rate
w_{het}	0.4 m/d		MP_{het} sinking rate
w_{det}	15 m/d	25 – 75 m/d (Cole et al. 2016)	MP_{det} sinking rate
N_{fib}	2 · 10 ⁶ mg ⁻¹	Estimated from (Christian Vogelsang, p.c. 2020)	Conversion factor from fibres total weight to number

It is necessary to note that the experimental data on degradation, ingestion and excretion of MP is scarce. Besides this, there are large challenges in applying the experimental results to the complexity found in nature. For example, laboratory experiments of gravitational sinking usually give fairly high rates that contradicts with the observations, when even high-density MP can be found in the surface layer. (Irina Chubarenko et al. 2018) points out, that natural turbulence, water currents, complexity of the particle shape decrease theoretical sinking velocity, so typical settling velocity in real environmental conditions varies from about zero for floating particles to few cm/s. Here we model fibres with a morphology that allows them to be kept suspended in the water column due to turbulent mixing. In this work we considered 3 scenarios with the following rates of sinking: 0 m/d (neutral buoyancy), -0.5 m/d (floating), 20 m/d (sinking).