ŚRODKOWO-POMORSKIE TOWARZYSTWO NAUKOWE
OCHRONY ŚRODOWISKA
Rocznik Ochrona Środowiska
Tom 13. Rok 2011 ISSN 1506-218X 187-206

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Parameterisation of a zero-dimensional Pelagic Detritus Model, Gdańsk Deep, Baltic Sea

Karol Kuliński, Anna Maciejewska,
Lidia Dzierzbicka-Głowacka, Janusz Pempkowiak
Polish Academy of Sciences, Sopot, Poland

1. Introduction

This paper presents a zero-dimensional particulate detritus model (Figure 1) and a comprehensive description of parameterisation processes that influence the non-living organic matter (detritus) concentration in the whole water column. Mathematically, the particulate pelagic detritus concentration can be described as a variable dependent on the number of its sources and sinks. Temporal supplies in the pelagic detritus concentration are affected by the natural mortality of phytoplankton and zooplankton as well as by the faecal pellets that enter the detritus pool. On the other hand, sedimentation, grazing of detritus by zooplankton and mineralization of pelagic detritus act as sinks that reduce the detritus concentration in the water column.

The aim of this model study was to calibrate the detritus model under the environmental conditions typical of the Gdańsk Deep in the southern Baltic Sea. The combined effects of nutrient, temperature, phyto- and zooplankton, as well as other sources and sinks on the

dynamics of particulate dead organic matter concentration have not yet been established. This is a key statement, since it is the motivation and justification for the study.

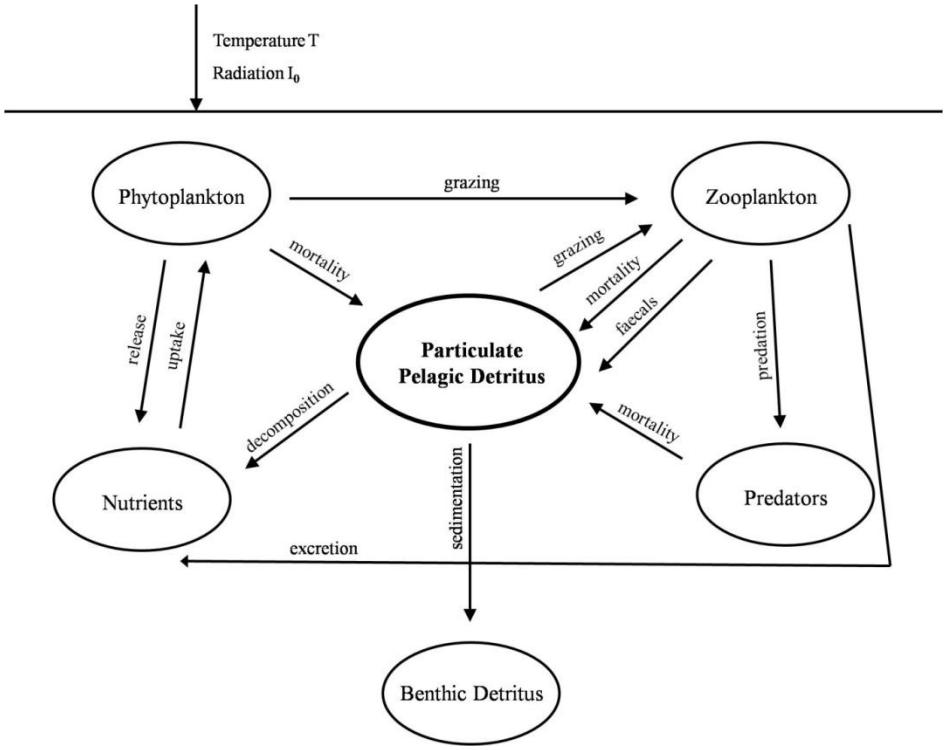

Fig. 1. Conceptual diagram of the Pelagic Detritus Model
Rys. 1. Schemat Modelu Detrytusu Pelagicznego

Accurate quantification of pelagic detritus concentration linked to both phyto- and zooplankton, all expressed in units of carbon concentration, is necessary for the further modelling of particulate organic carbon (POC), while the temporal and spatial dynamics of POC concentrations has potential for enriching marine carbon cycle models, which seldom deal with particulate carbon species as a complex biochemical factor.

2. Pelagic Detritus Model

The source/sink balance of detritus in the water column can be expressed mathematically as the following equilibrium:

$$\begin{aligned} &\textit{change in pelagic detritus} = \textit{phytoplankton mortality} + \\ &\quad \textit{zooplankton mortality} + \textit{predator mortality} + \\ &+ \textit{faeces} - \textit{grazing} - \textit{decomposition} - \textit{sedimentation} \end{aligned} \tag{1}$$

Through the production of faeces by zooplankton, as well as the natural mortality of autotrophs and zooplankton, the detritus pool is increased. Detritus is mineralised into CO_2, phosphates and ammonia in the water mass. Part of the ammonia is oxidised to nitrates. Zooplankton excreta contain ammonia and phosphate. During anoxic conditions, nitrates are lost from the system through pelagic denitrification.

In this model the limiting nutrient, light and temperature regulate phytoplankton primary production by the multiplicative approach. The light limitation of primary production is taken from Steele [1], and the temperature limitation is a modification of the expression suggested by Varela et al. [2]. The limiting nutrient is determined by the standard Michaelis-Menten expression following Dugdale [3]. Nutrients are represented by two components: inorganic nitrogen and phosphorus species.

Since it is a food component, detritus is ingested by zooplankton. Additionally, pelagic detritus particles undergo sedimentation in the water column; on reaching the sea floor, they are incorporated into the benthic detritus. The detritus pool is also diminished by pelagic biochemical degradation.

The mathematical terms representing the processes in Eq. (1) are given below. Table 1 lists all the parameters used in the numerical model. The zero-dimensional model for pelagic detritus (equation 1) was solved numerically using the second-order Runge-Kutta method, known as the midpoint method:

$$u^{n+1} = u^n + \Delta t f\left[t^n + \frac{\Delta t}{2}, u^n + \frac{\Delta t}{2} f\left(t^n, u^n\right) \right] \tag{2}$$

Table 1. Parameters used in the numerical model
Tabela 1. Wykaz parametrów użytych w modelu numerycznym PDM

Symbol	Value	Unit	Meaning
c_{dec}	0.15		temperature function coefficient
DEC	variable	mg C m^{-3} d^{-1}	decomposition
Detr	variable	mg C m^{-3}	detritus variability
d_{sink}	0.5		reduction of the detritus sinking velocity with respect to the vertical stratification of the water mass
el_i	$el_1 = 0.2$ $el_2 = 0.5$		part of phytoplankton lysis to pelagic detritus
FEC	variable		faecal production
f_{Pmaxi}	f_{Pmax1}=2.9 f_{Pmax2}=2.4	d^{-1}	maximum growth rate of phytoplankton
g_{max}	0.3		maximum zooplankton grazing per day
GRD	variable	mg C m^{-3} d^{-1}	grazing
I_{opti}	$I_{opt1} = 60$ $I_{opt2} = 200$	Wm^{-2}	optimum radiation for phytoplankton growth
I_{PAR}	variable	Wm^{-2}	active radiation
k_g	50	mg C m^{-3}	half-saturation constant for zooplankton grazing
k_{Ni}	$k_{N1} = 0.1$ $k_{N2} = 0.05$	mmol N m^{-3}	nitrogen half-saturation constant
k_{Pi}	$k_{P1} = 0.1$ $k_{P2} = 0.05$	mmol P m^{-3}	phosphorus half-saturation constant
k_z	1	mg C m^{-3}	half-saturation constant for carnivorous grazing
LYS	variable	mg C m^{-3} d^{-1}	phytoplankton lysis
m_d	0.3		natural mortality rate of predators
m_{dec}	0.002	d^{-1}	maximum decomposition rate of detritus
m_{Ni}	0.3		nutrient-dependent lysis rate
MOR	variable	mg C m^{-3} d^{-1}	phytoplankton mortality
MRD	variable	mg C m^{-3} d^{-1}	predator mortality
MRP	variable	mg C m^{-3} d^{-1}	particulate part of phytoplankton mortality
MRZ	variable	mg C m^{-3} d^{-1}	zooplankton mortality
m_z	0.01	d^{-1}	rate of zooplankton mortality
p_d	0.25		zooplankton preference for detritus
pgr_i	variable		potential growth rate
Phyt	variable	mg C m^{-3}	phytoplankton variability
p_{max}	0.1	d^{-1}	maximum predation rate
p_p	0.75		zooplankton preference for phytoplankton

Table 1. cont.
Tabela 1. cd.

Symbol	Value	Unit	Meaning
Q_z	1.07		temperature function coefficient
rs_d	variable		relative supply of detritus
rs_p	variable		relative supply of phytoplankton
SIN	variable	mg C m^{-3} d^{-1}	sedimentation
T	variable	°C	water temperature
T_m	10	°C	annual mean water temperature
ws_{det}	1.5	m d^{-1}	maximum detritus sinking velocity
Zoop	variable	mg C m^{-3}	zooplankton variability

2.1. Sources of detritus

The detritus pool increases as a result of the natural mortality of phytoplankton, zooplankton and predators, and of faecals production.

The phytoplanktonic organisms in this model are divided into two groups: diatoms (for i = 1) and non-diatoms (for i = 2). Individual growth conditions are used for both groups in the following equations.

Generally, mortality of phytoplankton is described by specific mortality rate m_p *e.g.* m_pP; [4]. In our study mortality is expressed as a function where part of the phytoplankton originating from the phytoplankton lysis rate is transferred to the pelagic detritus:

$$MOR = el\ LYS\ Phyt$$

Phytoplankton lysis rate is assumed to be proportional to the difference between the maximum and actual phytoplankton growth rate [2, 5].

$$LYS = m_{Ni}\, pgr_i (1 - f_{\min i}) \tag{3}$$

The potential growth rate, pgr_i, of phytoplankton may be limited by water temperature and light availability, following a fully synergistic multiplicative approach represented by

$$pgr_i = f_{P\max i}\, f_{PTi}\, f_{Ii} \tag{4}$$

Temperature affects the potential growth rate parameter through an exponential factor (f_{PT}), which is estimated according to Varela et al. [2]:

$$f_{PTi} = Q_P^{\,0,1(T-T_m)} \tag{5}$$

where the parameter Q_P corresponds to the physiological parameter Q_{10}; T is the water temperature and T_m is the mean annual temperature (set to 10°C in the model)

Phytoplankton growth in relation to the intensity of active radiation I_{PAR} (f_I) is given by

$$f_{Ii} = \frac{I_{PAR}}{I_{opt}} \exp\left(1 - \frac{I_{PAR}}{I_{opt}}\right) \tag{6}$$

The final actual growth rates are calculated. They include a composite nutrient limiting factor, estimated for the two main nutrient species (nitrogen and phosphorus) using the geometrical mean approach. These factors are expressed using the classical Michaelis-Menten equation [3]:

$$f_{Ni} = \frac{NutrN}{k_{Ni} + NutrN} \tag{7}$$

$$f_{Pi} = \frac{NutrP}{k_{Pi} + NutrP} \tag{8}$$

The combined nutrient limitation factor is given by:

$$f_{\min i} = \sqrt{f_{Ni} f_{Pi}} \tag{9}$$

Zooplankton as a source of detritus is covered by two terms: predation and other components. Predation (*PRED*) is the only cause of zooplankton mortality, which is taken into consideration separately in the model description [1]:

$$PRED = p_{\max} \frac{Zoop}{k_z + Zoop} Zoop \tag{11}$$

All other causes of mortality (MRZ) are lumped together in the temperature-dependent fractional loss [6]:

$$MRZ = m_z Q_z^{(T-20)} Zoop \tag{12}$$

We have adopted the standard geometric model with Q_{10} (in this model Q_z) = *2*.

We assume that a fixed proportion (*f*) of the ingested material (*GRZ*) is lost to faeces (*FEC*):

$$FEC = fGRZ \tag{13}$$

Material lost through the natural mortality of predators is transferred to the pelagic detritus; this process is represented by the following equation [7]:

$$MRD = m_d PRED \tag{14}$$

2.2. Losses from the detritus pool

The detritus pool decreases as a result of zooplankton grazing, decomposition and sedimentation.

The zooplankton variability (*Zoop*) represents the zooplankton in the first order. Zooplankton ingests both phytoplankton (*Phyt*) and detritus (*Detr*). The mathematical expressions describing the processes were given by [7]:

$$GRZ = GRPhyt + GRDetr \tag{15}$$

where

$$GRPhyt = g_{\max} rs_p \frac{Phyt^2}{k_g\left(p_p Phyt + p_d Detr\right) + p_p Phyt^2 + p_d Detr^2} Zoop \tag{16}$$

$$GRDetr = g_{\max} rs_d \frac{Detr^2}{k_g\left(p_p Phyt + p_d Detr\right) + p_p Phyt^2 + p_d Detr^2} Zoop \tag{17}$$

where rs_p and rs_d are the respective relative supplies of phytoplankton and detritus

$$rs_p = \frac{p_p Phyt}{p_p Phyt + p_d Detr} \tag{18}$$

$$rs_d = \frac{p_d Detr}{p_p Phyt + p_d Detr} \tag{19}$$

The biochemical degradation (mineralisation) of detritus is another important process decreasing the detritus pool in the water

column. Detritus mineralisation yields inorganic nutrients. In the model detrital degradation is expressed as an exponential temperature factor according to Savchuk and Wulff [8]:

$$DEC = m_{dec} \exp(c_{dec} T) Detr \tag{20}$$

The sedimentation of detritus is estimated according to SMHI [9]:

$$SIN = d_{sink} ws_{det} Detr \tag{21}$$

where d_{sink} is the reduction of the detritus sinking velocity with respect to the vertical stratification of the water mass. Here we assume a mean value of $d_{sink} = 0.5$.

3. Parameterisation results

All the numerical experiments were performed for a 30-day period with a time step of 300 s. The investigations were carried out for different values of variables: phytoplankton biomass (*Phyt*: 50, 100, 200, 300 mg C m^{-3}), zooplankton biomass (*Zoop*: 5, 10, 20, 30 mg C m^{-3}), nutrient concentrations (for $Nutr_N$: 0.6, 2, 4, 6 mmol N m^{-3} and for $Nutr_P$: 0.06, 0.2, 0.4, 0.6 mmol P m^{-3}), radiation (I_{PAR}: 50, 100, 150, 200 Wm^{-2}) and temperature (*T*: 5, 10, 15, 20°C). This section presents the results of numerical studies which the authors considered to be the most meaningful. Initial values of the model variables were selected for all the parameterisation calculations. If no additional information is given, the initial values of the parameters are as follows: *Phyt* = 100 mg C m^{-3}, *Zoop* = 10 mg C m^{-3}, *Detr* = 100 mg C m^{-3}, $Nutr_N$ = 0.6 mmol m^{-3}, $Nutr_P$ = 0.06 mmol m^{-3}, I_0=100 Wm^{-2}, *T* = 10ºC.

3.1. Phytoplankton

The initial phytoplankton concentration has a distinct impact on the evaluation of detritus concentration in time. This is true for both phytoplankton groups defined in this model, i.e. diatoms and non-diatoms (Figures 2 and 3). However, given the same environmental conditions, the influence of diatoms on the detritus concentration (Figure 2) is stronger than when the phytoplankton is defined as non-diatoms (Figure 3).

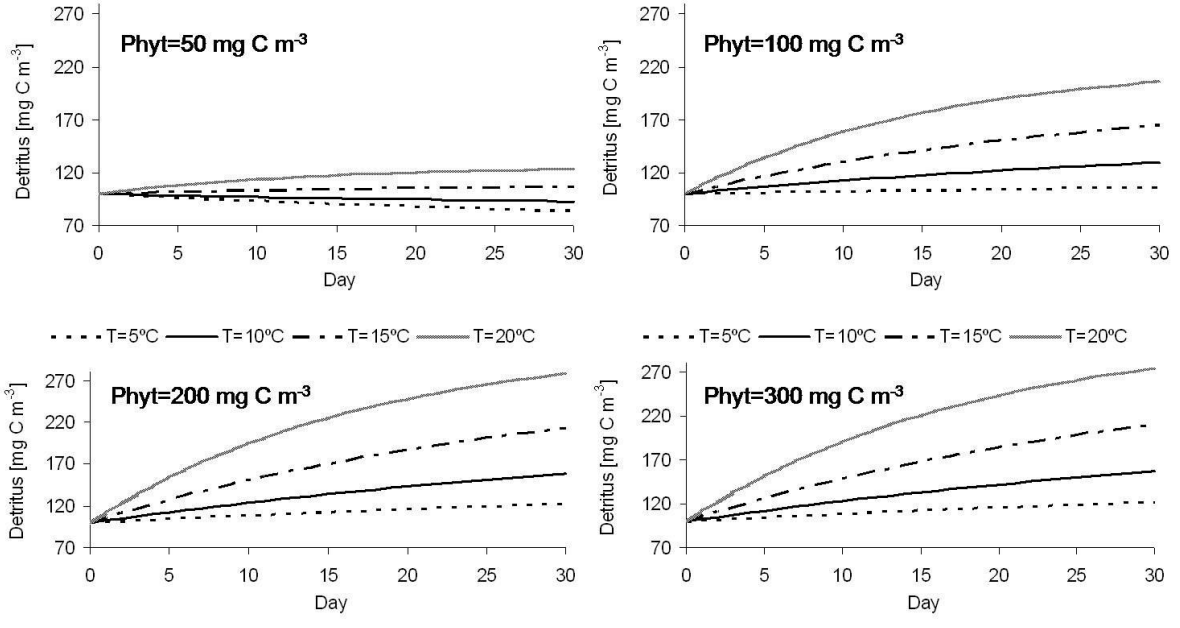

Fig. 2. Impact of diatoms concentrations on detritus concentration at different temperatures
Rys. 2. Wpływ biomasy okrzemek zależnie od temperatury na stężenie detrytusu pelagicznego

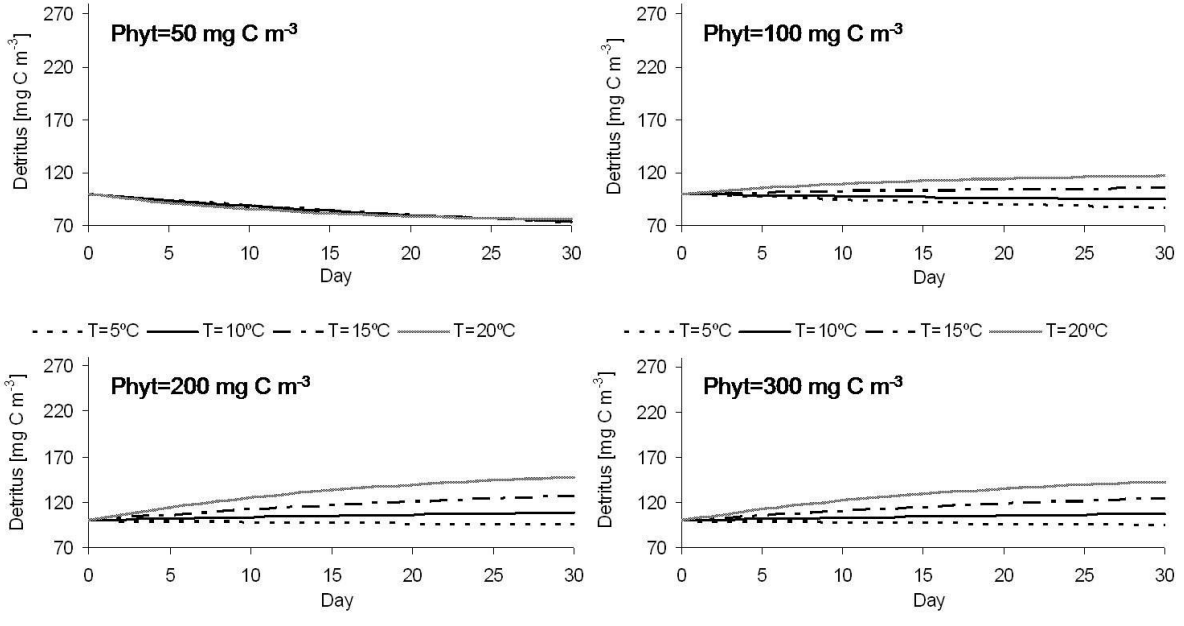

Fig. 3. Impact of non-diatoms concentrations on detritus concentration at different temperatures
Rys. 3. Wpływ biomasy fitoplanktonu nienależącego do okrzemek zależnie od temperatury na stężenie detrytusu pelagicznego

Furthermore, the increase in detritus concentration is directly proportional to temperature rise, irrespective of the phytoplankton group. With an initial phytoplankton (diatom) concentration of 50 mg C m^{-3}, there was a temporal decrease in detritus concentration at the two lowest temperatures (5 and 10ºC – see Figure 2). After 30 days at these two temperatures, initial detritus concentrations of 100 mg C m^{-3} dropped to respective final concentrations of c. 84 and 93 mg C m^{-3}. At the other two temperatures, the detritus concentration increased with time. The greatest detritus concentration increase occurred with initial phytoplankton concentrations of 200 mg C m^{-3}. However, the differences between the final detritus concentrations obtained with initial phytoplankton biomasses of 200 and 300 mg C m^{-3} were insignificant: the difference – c. 2% – was greatest at 20ºC.

For phytoplankton defined as non-diatoms, irrespective of its initial concentration, there was a temporal decrease in detritus concentration at a temperature of 5ºC, (Figure 3). The final detritus concentrations were also lower at all the temperatures where the initial phytoplankton concentration was 50 mg C m^{-3}. All the other results, except at 10ºC and an initial phytoplankton concentration of 100 mg C m^{-3}, were positively correlated with time, with final detritus concentrations exceeding the initial ones. Under these environmental conditions, as with the diatoms, the final detritus concentration was lowest at 5ºC and an initial phytoplankton concentration of 50 mg C m^{-3}. In this case, the detritus concentration fell to about 73.2 mg C m^{-3}. The largest final detritus concentration (147.7 mg C m^{-3}) was obtained when $Phyt$ = 200 mg C m^{-3} and T = 20°C.

3.2. Zooplankton

Analysis of the influence of initial zooplankton concentrations on the detritus concentrations (Figure 5) showed these parameters to be directly proportional to each other. However, the significance of zooplankton concentration diminished with temperature rise. At 5ºC, the difference between detritus concentrations after 30 days for the two extreme initial zooplankton concentrations was the largest at about 33.7 mg C m^{-3}. On the other hand, at a temperature of 20ºC, the initial zooplankton concentration – a mere 10 mg C m^{-3} – became much less significant.

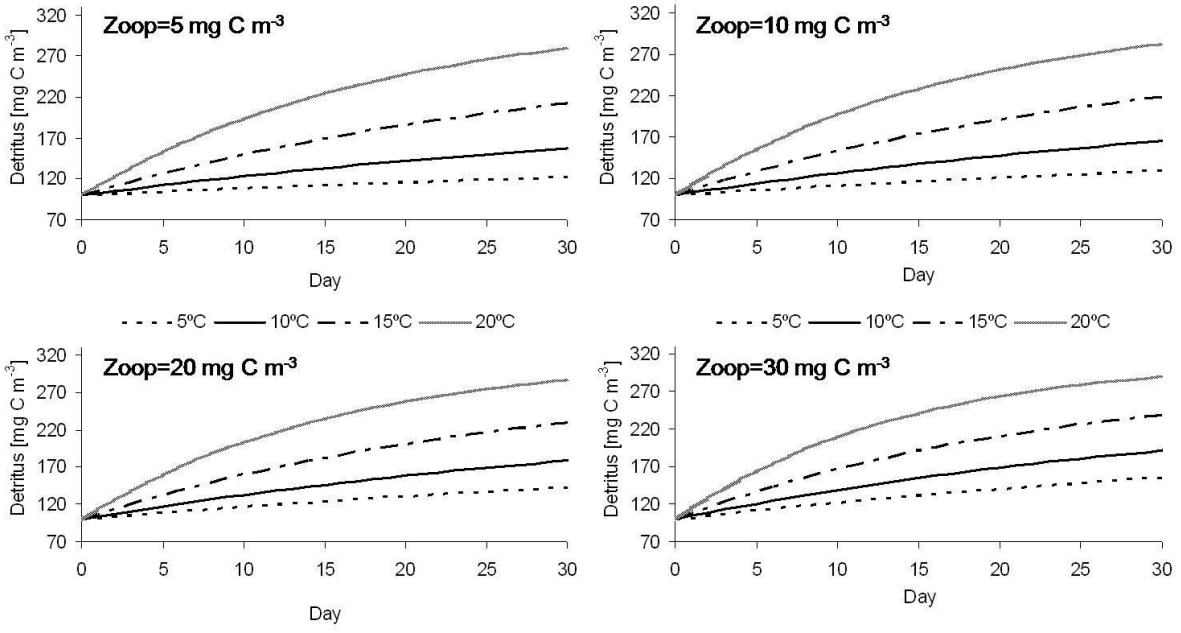

Fig. 4. Impact of zooplankton concentrations on detritus concentration at different temperatures
Rys. 4. Wpływ biomasy zooplanktonu zależnie od temperatury na stężenie detrytusu pelagicznego

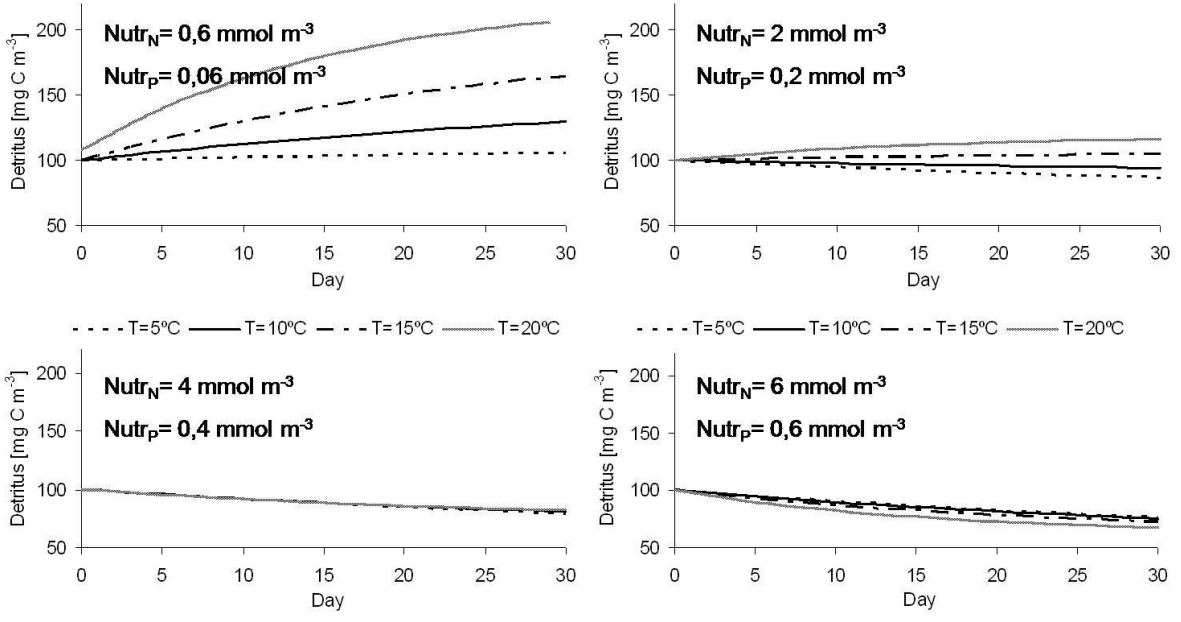

Fig. 5. Impact of nutrient concentrations on detritus concentration at different temperatures
Rys. 5. Wpływ stężenia związków biogennych zależnie od temperatury na stężenie detrytusu pelagicznego

3.3. Nutrients

Phytoplankton concentration was assumed constant in our study. Hence, nutrient concentrations influence detritus concentration only by the phytoplankton lysis rate (*MOR*). This impact was especially well exemplified at low nutrient concentrations (Figure 5). The detritus concentration increased with time irrespective of temperature. Nonetheless, temperature did have a very distinct impact – the difference between final detritus concentrations at 5 and 20ºC was about 100 mg C m^{-3} – but as nutrient concentrations increased, this impact became less important. We then had a situation where $Nutr_N$ = 4 mmol m^{-3} and $Nutr_P$ = 0.4 mmol m^{-3}, and where after 30 days there were no significant differences in detritus concentrations in this temperature range. At the highest nutrient concentrations, the impact of temperature was still low, but the two parameters were now inversely proportional to each other.

3.4. Radiation

The level of radiation is another important parameter directly proportional to the detritus concentration. Figures 6 and 7 present the impact of temperature on the detritus concentration at different levels of radiation, separately for diatoms and non-diatoms. Both dependences were tested using initial phytoplankton concentrations of 100 mg C m^{-3}. The impact of radiation varied in strength, depending on the phytoplankton group. When the phytoplankton consisted of diatoms, the final detritus concentrations were 10.5% and 0.5% lower respectively than the initial ones in two of the cases considered – when the radiation level was 50 Wm^{-2} and temperature 5 and 10ºC. All the other results indicate elevated detritus concentrations with time. The differences between final detritus concentrations are temperature-dependent; the largest (189.2 mg C m^{-3}) was recorded for a temperature of 20ºC.

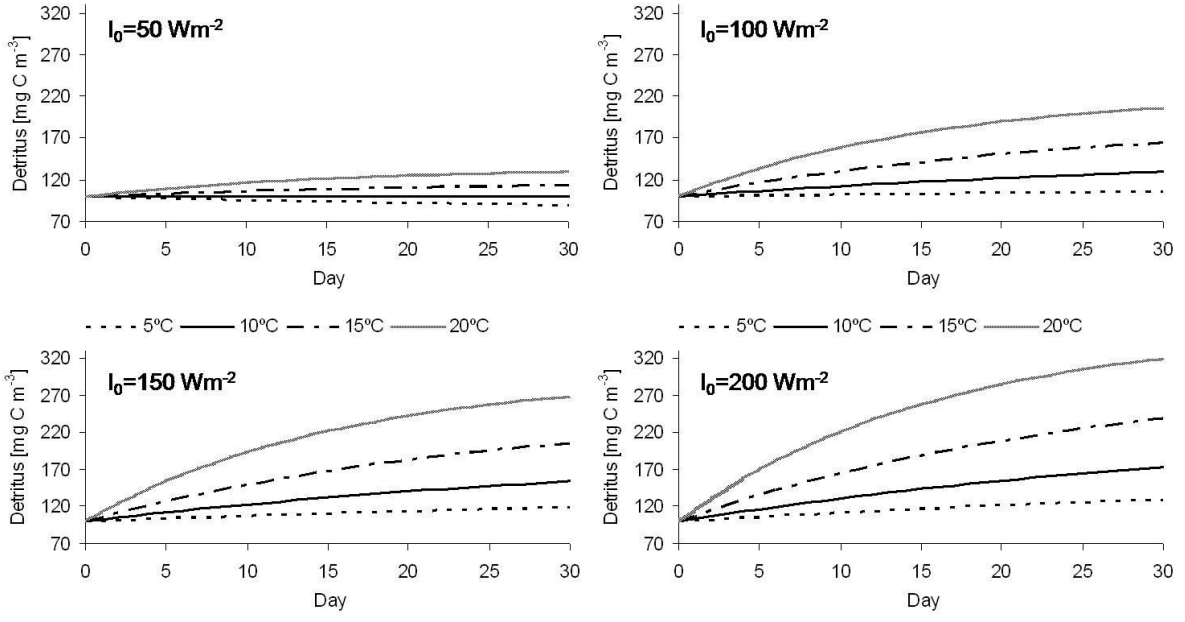

Fig. 6. Impact of radiation levels on detritus concentration at different temperatures and for diatom phytoplankton
Rys. 6. Wpływ nasłonecznienia zależnie od temperatury na stężenie detrytusu pelagicznego w przypadku, gdy fitoplankton stanowią gatunki należące do okrzemek

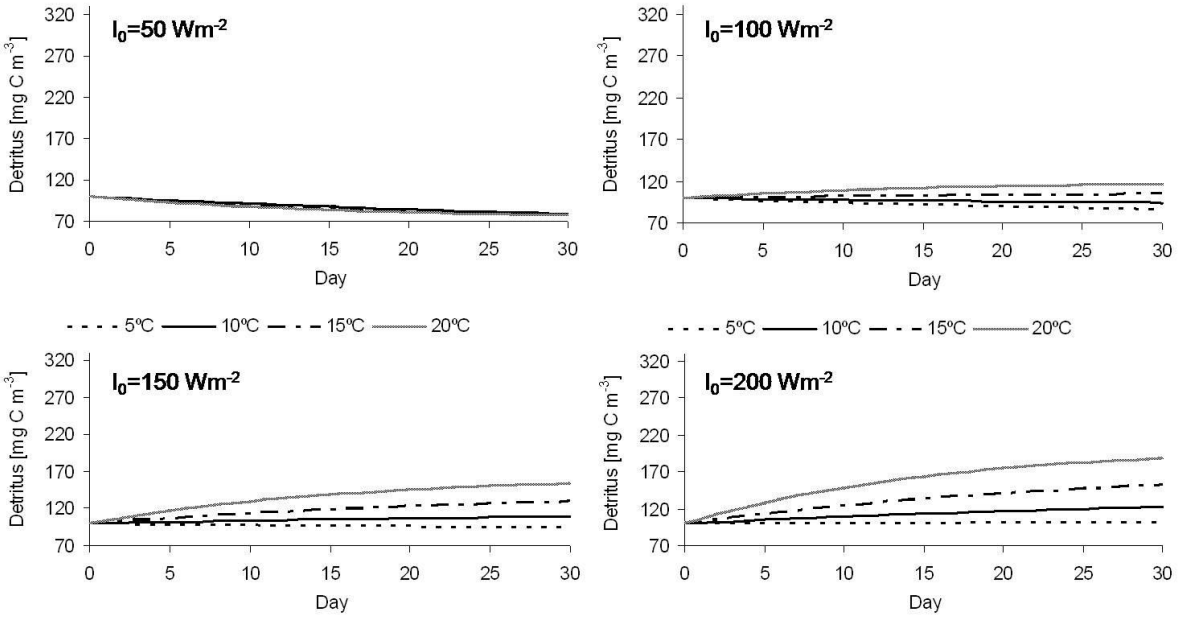

Fig. 7. Impact of radiation levels on detritus concentration at different temperatures and for non-diatom phytoplankton

Rys. 7. Wpływ nasłonecznienia zależnie od temperatury na stężenie detrytusu pelagicznego w przypadku, gdy fitoplankton stanowią gatunki nienależące do okrzemek

For non-diatom phytoplankton, the detritus concentration decreased with time at a radiation level of 50 Wm^{-2}. This decrease of c. 78 mg C m^{-3} was of roughly the same proportion as that for diatom phytoplankton, irrespective of temperature. Detritus concentrations decreased at 5 and 10ºC, when the radiation level was set to 100 Wm^{-2}, and also at 5ºC and 150 Wm^{-2}. In the remaining cases, the final detritus concentrations exceeded the initial ones. The differences between the final results become more distinct with increasing temperature, as was the case with diatom phytoplankton. Hence, the largest final detritus concentration was recorded for a radiation level of 200 Wm^{-2} and a temperature of 20ºC.

4. Discussion

The ranges of the initial values of the parameters evaluated were selected on the basis of environmental conditions typical of the Baltic Sea. In this model, the initial detritus concentration was 100 mg C m^{-3}; this result corresponded with the findings of Andersson and Rudehäll [10], who established detritus concentrations of 91 and 151 mg C m^{-3} for the offshore and nearshore zones, respectively. Both values were measured in the euphotic zone in winter. Those authors measured the highest detritus concentrations in spring – 168 and 375 mg C m^{-3} for the offshore and nearshore zones, respectively. In the present work, phytoplankton concentrations were defined in correspondence with the data published by Żmijewska et. al. [11] and Łotocka [12], and zooplankton concentrations were established according to Wiktor [13].

Phytoplankton, the group of organisms with the greatest biomass and a short lifespan in the sea, has a direct influence on detritus concentration. Changes in phytoplankton concentration in the pelagic detritus model parameterisation lead to distinct modifications of detritus concentrations: this is very well exemplified by the high temperatures and phytoplankton defined as diatoms (Figure 2). Diatoms are sensitive to low phosphorus concentrations, a situation governing the extent of diatom blooms in the early spring and autumn, when nutrient concentrations in the Baltic Sea are highest [14]. The low temperatures during these periods mean that diatom growth rate is strongly influenced by temperature, a feature well reflected in the detritus concentration pattern.

The impact on detritus concentrations is somewhat less when phytoplankton is defined as non-diatoms. This applies to the other nutrients and radiation conditions appropriate to the growth of phytoplankton species other than diatoms. This is evident from a comparison of detritus concentration changes with time under different radiation conditions (Figures 6 and 7). The threshold level of radiation enabling growth of non-diatoms and the consequent increase in detritus concentration is higher than that required by diatoms.

The detritus concentration in the marine environment is influenced by nutrient availability (Figure 5): in periods when nutrients are present in the highest concentrations, more detritus is lost than is produced. This state of affairs is confirmed by processes occurring in the environment. During autumn and winter, when nutrient levels are at their highest, detritus concentrations fall to their annual minimum. On the other hand, when nutrients are consumed by growing autotrophic organisms, the detritus pool is enriched by the dead phytoplankton cells accumulating in the pelagic zone.

That zooplankton has a marginal influence on detritus concentration is confirmed by the insignificant changes in detritus concentration between the successive zooplankton concentrations (Figure 4). This is due to the relatively low biomass and longer lifespan of zooplankton, when compared to phytoplankton [15].

The parameterisation results point to the significance of the major environmental variables influencing the detritus pool. In all of the tests carried out, detritus concentrations were stable in the range between 70 and 300 mg C m^{-3} over a period of 30 days. This corresponds well with the range found experimentally by Andersson and Rudehäll [10]. We therefore conclude that the PDM model is an appropriate tool for both evaluating the seasonal changes in the actual pelagic detritus concentration and simulating possible future scenarios. Since detritus, together with phyto- and zooplankton, is responsible for the level of particulate organic carbon (POC) in the sea, further organic carbon cycle modelling studies will require proper validation of initial POC concentrations in the water column. This will be the focus of the subsequent improvements to the pelagic detritus model.

Acknowledgements

This work was co-funded by the statutory activity of IOPAS, the Polish State Committee of Scientific Research (grant No N N305 111636) and the FP6 EU 'CarboOcean' programme.

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Parametryzacja Modelu Detrutusu Pelagicznego, Głębia Gdańska, Morze Bałtyckie

Streszczenie

Przedmiotem badań jest parametryzacja zerowymiarowego Modelu Detrytusu Pelagicznego (PDM). Stężenie detrytusu pelagicznego w wodzie morskiej jest determinowane równowagą ustaloną pomiędzy źródłami i ubytkami martwej, zawieszonej materii organicznej. Do źródeł zalicza się: śmiertelność fito- i zooplanktonu oraz odchody zooplanktonu. Wśród ubytków detrytusu wyróżnić można natomiast sedymentację, wyżeranie przez zooplankton oraz rozkład biochemiczny. Przedstawione badania opisują oddziaływanie temperatury, stężenia związków biogenicznych, nasłonecznienia oraz biomasy fito- i zooplanktonu na stężenie detrytusu pelagicznego w wodzie morskiej. Parametryzacja przeprowadzona została w typowych dla południowego rejonu Morza Bałtyckiego zakresach zmiennych. Detrytus pelagiczny razem z fito- i zooplanktonem są komponentami niezbędnymi do opisania zmienności stężeń zawieszonego węgla organicznego (POC) będącego istotnym składnikiem obiegu węgla w środowisku morskim. Prawidłowa parametryzacja PDM stanowi zatem podstawę dla numerycznego opisu aktualnej i przyszłej zmienności stężeń POC w wodzie Morza Bałtyckiego