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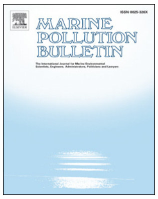

Do microplastics affect marine ecosystem productivity?

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ABSTRACT

Marine and coastal ecosystems are among the largest contributors to the Earth's productivity. Experimental studies have shown negative impacts of microplastics on individual algae or zooplankton organisms. Consequently, primary and secondary productivity may be negatively affected as well. In this study we attempted to estimate the impacts on productivity at ecosystem level based on reported laboratory findings with a modelling approach, using our biogeochemical model for the North Sea (Delft3D-GEM). Although the model predicted that microplastics do not affect the total primary or secondary production of the North Sea as a whole, the spatial patterns of secondary production were altered, showing local changes of ± 10%. However, relevant field data on microplastics are scarce, and strong assumptions were required to include the plastic concentrations and their impacts under field conditions into the model. These assumptions reveal the main knowledge gaps that have to be resolved to improve the first estimate above.

1. Introduction

Marine and coastal ecosystems are among the largest contributors to the Earth's biomass generating capability (Nichols et al., 2010), also known as ‘productivity’. We owe this productivity to algae (mainly phytoplankton), which take up dissolved inorganic carbon and turn it into organic carbon. This autotrophic capability makes them the primary producers of the ecosystem and places them at the base of the marine food web. Heterotrophic organisms feeding on algae (e.g. zooplankton) are the secondary producers and form the link between the lower and higher parts of the food web, including fish, birds and marine mammals. In the North Sea, for instance, the larval stages of the wide majority of fish species rely on copepods as feed (Daewel et al., 2014).

Microplastics potentially pose a threat to this important source of the world's biomass. With continuous growth for > 50 years, global plastic production in 2014 rose to 311 million tonnes (PlasticsEurope, 2015). Yet it has been estimated that annually 6 to 10% of the global plastic production ends up in the marine environment; without improvement in waste management infrastructure, the plastic waste will vastly increase by 2025 (Jambeck et al., 2015).

As plastic debris degrades very slowly, it is of little surprise that this material is now a pervasive and persistent contaminant of the marine environment. An important part of these released plastics may reach microscopic scales, thus forming what is termed ‘microplastics’, i.e. plastic particles with a maximum size of 5 mm down to the nanometer scale (Arthur and Baker, 2009). The microplastic component of the marine litter is of special interest as its small size makes it available for ingestion by a wide range of marine biota (Ivar do Sul and Costa, 2014; GESAMP, 2016). Experimental results indicate that microplastics negatively affect marine algal productivity (e.g. Bhattacharya et al., 2010; Sjollema et al., 2016) and zooplankton health and function, resulting in significantly decreased algal feeding (e.g. Cole et al., 2013).

When experimental results indicate negative impacts of microplastics on the health and fitness of individual organisms or laboratory cultures of algae and zooplankton species, it is difficult to predict how these impacts would manifest themselves at the ecosystem level. An ecosystem can be described as a complex set of interactions among organisms, nutrients and the abiotic environment through which energy flows and nutrients are cycled. Laboratory toxicity experiments typically only focus on a tiny fraction of the organisms and toxic substances involved, which makes it a challenge to scale up their results to the ecosystem level. Another major problem is to understand the ecosystem level impact that results from potentially large spatial and temporal variations in microplastic concentrations and environmental conditions under which the ecosystem operates. Moreover, these variable environments do not exist in isolation, but food or organisms may be diluted or resupplied/recolonised from adjacent water volumes. Marine ecosystem models help to address these issues by capturing

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essential parts of the complexity necessary to predict impacts at the ecosystem level. The model used in this study includes a simplified but integral food web (i.e. nutrients, four algal species, and zooplankton) as well as full spatial and temporal variability.

The objective of this study was to estimate the impact of microplastics on ecosystem-level productivity. For this we extended the Delft3D-GEM ecosystem model (Los et al., 2008; Blauw et al., 2009) for the North Sea to include zooplankton on the basis of Dynamic Energy Budget (DEB) theory. DEB-theory is a modelling framework based on first principles and simple physiology-based rules that describe the uptake and use of energy and nutrients and the consequences for physiological organisation throughout an organism's lifecycle (Kooijman, 2010). Microplastic concentrations in the Southern North Sea were included by means of a forcing function resulting from a previous modelling study of the transport of microplastics in the North Sea (van Der Meulen et al., 2014, 2016; Stuparu et al., 2015; Pope, 2015; also see Section 2.2). Impacts of microplastics on relevant process parameters of algae (respiration rate) and zooplankton (caloric ingestion rate) were calibrated based on data from literature and were implemented in the model. With this modified model set-up, various runs were performed and resulting productivities in the Southern North Sea were compared to those of the base model without microplastics. Model set-up and the modifications mentioned above are described in the methods section below. Note that we focus on pelagic productivity only and do not look into benthic productivity.

2. Methods

2.1. Delft3D-GEM for the North Sea

The biogeochemical transport model Delft3D-GEM is an open-source generic ecological modelling instrument that can be applied to any water system (fresh, transitional or coastal water) to calculate nutrient concentrations (nitrate, ammonium, phosphate, silica), dissolved oxygen and salinity, phytoplankton, and detritus. The Delft3D-GEM as applied to the North Sea is described in Los et al. (2008) and Blauw et al. (2009). It includes nutrients (carbon, nitrogen, phosphorous, silica and oxygen), detritus, four groups of phytoplankton (diatoms, flagellates, dinoflagellates and *Phaeocystis*) and was extended with a zooplankton compartment in this study. Furthermore, it includes all relevant biogeochemical processes (Fig. 1). The most relevant inputs and processes for this study are described below.

2.1.1. Model grid

The modelling grid used in the Delft3D-GEM for the North Sea is called the ZUNO-grid (Fig. 2). This grid covers the southern North Sea and the eastern English Channel but we refer to its domain only as the former. The model grid consists of 4350 grid cells in the horizontal and 12 topography-following vertical layers. The grid is curvilinear, with a resolution ranging from 1 × 1 km at the continental coast to 20 × 20 km at the North-western boundary. In addition to the 12 layers in the water column, a single (and relatively thin) sediment layer is taken into account without an explicit benthic community. Validation exercises showed that this single-layer approach for the bottom is capable of capturing the dynamics of the eutrophication-related variables in the Southern North Sea (see Section 3.1).

2.1.2. Hydrodynamics

Hydrodynamic transports underlying Delft3D-GEM are calculated using Delft3D-FLOW (http://oss.deltares.nl/web/opendelft3d), a multi-dimensional 3D hydrodynamic model that calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing, under the Boussinesq approximation, on a rectilinear or a curvilinear boundary-fitted grid. Hydrodynamic process details are described in Deltares (2017), and its set-up for the North Sea Delft3D-GEM is described in Los et al. (2008). Meteorology is included as forcing functions based on measurements. Silt concentrations are included as a forcing function based on a climatology combined with short-term wind-dependent variation.

2.1.3. Nutrient inputs and boundary conditions

Nutrients enter the North Sea system via 85 rivers, 2 open boundaries (the Atlantic Ocean and Channel), and via atmospheric deposition. In the model, each river discharges into one coastal grid cell in the surface layer. Discharges and nutrient concentrations for all rivers are based on a database that was set up and maintained by Cefas (pers comm S. van Leeuwen, Centre for Environment, Fisheries and Aquaculture). The Atlantic boundary consists of all segments located on the Northern model interface, the Channel boundary of all segments on the South-western North Sea model interface. Boundary concentrations are included as forcing functions based on in-situ measurements (Channel boundary: Bentley et al., 1999; Bot et al., 1996; Brion et al., 2004; Laane et al., 1993, 1996a; Radach et al., 1996; Atlantic boundary: Bot et al., 1996; Brockmann and Topcu, 2002; Laane et al., 1996b; NERC, 1991; Pätch and Radach, 1997; Radach et al., 1996). Atmospheric deposition of nitrogen takes place over the whole surface layer and is included as a spatially and temporally explicit forcing function. This atmospheric function was based on data in the year 2002 kindly provided by EMEP (European Monitoring and Evaluation Programme under the Convention on Long-range Transboundary Air Pollution). These data are based on results from the Unified EMEP model as reported by Bartnicki and Valiyaveetil (2008).

2.1.4. Phytoplankton module

The phytoplankton module (BLOOM) in Delft3D-GEM simulates primary production, respiration and mortality of phytoplankton. This module allows for the modelling of species competition and adaptation of phytoplankton to limiting nutrients or light (Los, 2005; Los and Bokhorst, 1997; Los and Brinkman, 1988; Los et al., 1994; Van der Molen et al., 1994). For the simulation of species competition, several species (groups) are predefined in BLOOM, four of which are included in the GEM for the North Sea: diatoms, flagellates, dinoflagellates and *Phaeocystis*. Within each of these groups, three phenotypes are defined to account for adaptation to changing environmental conditions. Growth-related processes are combined with an optimisation technique (linear programming) to determine the algal species and phenotypes composition that are best adapted to prevailing environmental conditions.

2.1.5. Zooplankton module

Zooplankton can be defined as the heterotrophic marine planktons, including both herbivorous and omnivorous species. In the North Sea, *Pseudocalanus* sp. and *Calanus finmarchicus* and to a smaller extent *Paracalanus parvus*, *Temora longicornus*, *Acartia* spp., and *Centropages typicus* copepod species are reported to be dominant regarding zooplankton biomass (Daewel et al., 2014). In its standard set-up for the North Sea, the model does not explicitly include grazing of phytoplankton, but this is implicitly accounted for by constantly elevated mortality rates. In this study we extended the model by including an explicit zooplankton compartment (see Fig. 1) and by reducing the algal mortality rate correspondingly.

Zooplankton biomass was modelled using the grazer module 'DEBGRZ', which is available in the Delft3D water quality process library. The module is based on the Dynamic Energy Budget (DEB) theory (Kooijman, 2010) and consists of the standard set of DEB equations adjusted to include filter-feeding and spawning-related processes (as were previously used and described in Bacher and Gangnery, 2006; Pouvreau et al., 2006; Rosland et al., 2009; Wijsman et al., 2009; Troost et al., 2010). Although the DEB approach may seem relatively complex, it provides several advantages such as genericity and flexibility, and its adherence to thermodynamic principles. Also, its mechanistic description of physiological mechanisms allows for linking of