Modelling the Uptake and Exchange of Microplastics in Marine Ecosystems using a Novel Integrated System of High-Resolution Numerical Models

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1. Background

a) Microplastic

Review Paper

→Plastic particles < 5mm in size.
→Persistent and difficult to remove from natural water streams[1]
→May be transported far from their sources[2,3]
→Degrade into smaller particles[4]
→Available for ingestion by a wide range of organisms[5-7]

Review paper: Coyle et al (2020) DOI: 10.1016/j.cscee.2020.100010

⚠ EMERGING CONTAMINANT OF CONCERN ⚠

EU MSFD (2008/56/EC) key objective: Determination of the ecological harm caused by mPs

b) Knowledge gaps?

→Lack of consensus of mP transport processes[8]
→Potential for and significance of trophic transfer unclear[9,10]
→Lack of relevant data:
- Laboratory exposure studies use unrealistic mP concentrations[11]
- Plastic beads used in lab aren't analogous to plastic fibres that are found most commonly in the environment[12]

? How can numerical models be applied to understand microplastic uptake and exchange processes at Lower Trophic Levels in the Northwest European Continental Shelf?

c) Continental Shelf?

→Under pressure from anthropogenic stressors
→High primary productivity

⚠ Area of heightened risk as uptake since of mPs into the food chain depends on its co-occurrence with the organism in space and time[13]

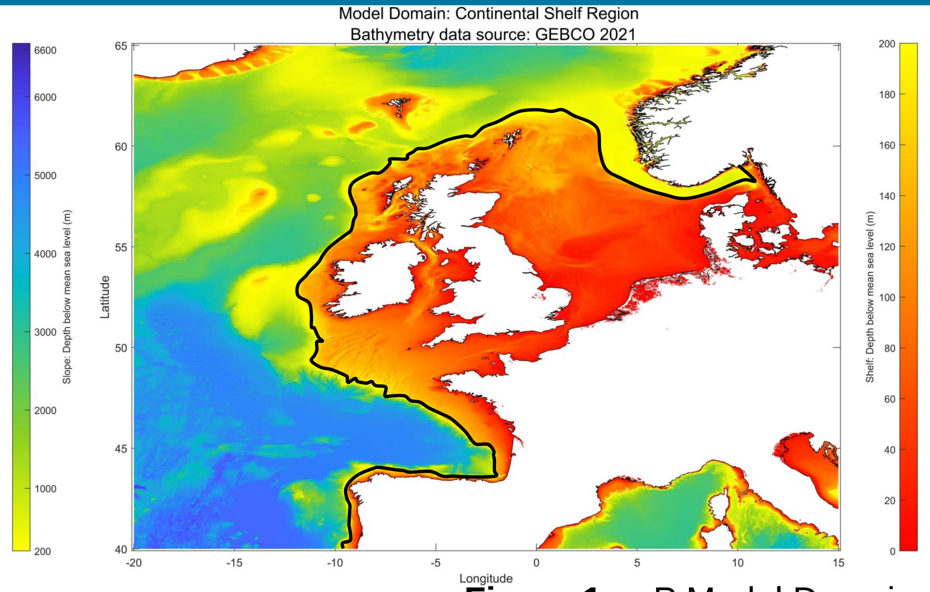


Figure 1: mP Model Domain

d) Lower trophic levels?

→A key component of nutrient cycling (Primary producers and consumers).
→Susceptible to the ingestion of mPs alongside natural prey[10]
→mPs cause adverse impacts at lower trophic levels:
- **E.g., Phytoplankton:** Reduced photosynthesis, hindered growth[14,15]
- **E.g, Zooplankton:** Decreased fecundity, increased mortality[16]

2. Proposed integrated system of numerical models:

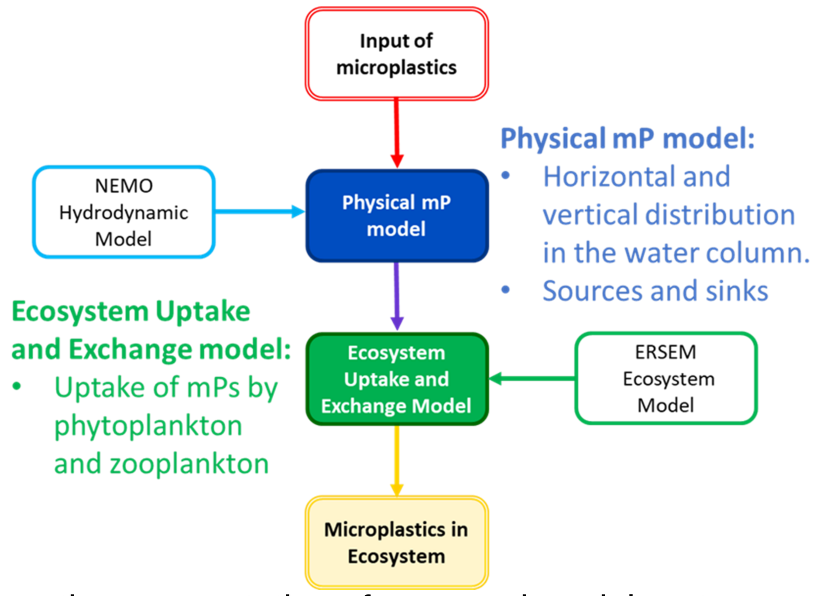
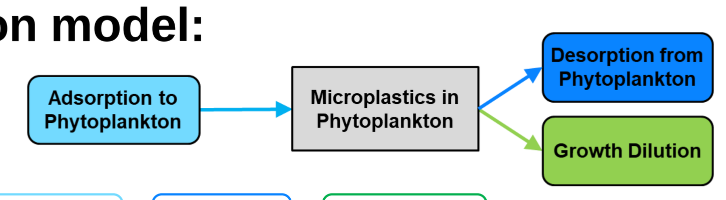


Figure 2: Schematic representation of proposed model system

Physical Transport Model:

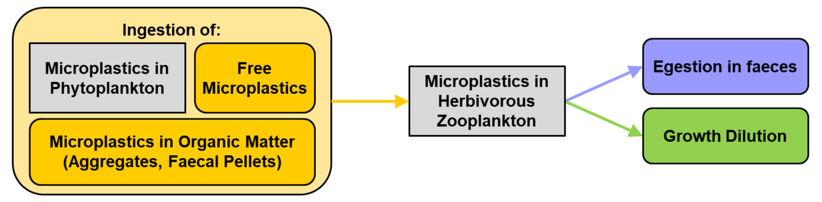
$$\frac{\partial C_{mp,W}}{\partial t} = \underbrace{-\left(\overrightarrow{u_H}\cdot\nabla_H C_{mp} + \frac{\partial (wC_{mp})}{\partial z}\right)}_{\text{Advection}} + \underbrace{\left(\kappa_H \nabla_H{}^2 C_{mp} + \kappa_w \frac{\partial^2 C_{mp}}{\partial z^2}\right)}_{\text{Diffusion}} \underbrace{- \frac{\partial w_s C_{mp}}{\partial z}}_{\text{Sinking}} + \underbrace{Q_c(t,x,y,z)}_{\text{Sources}} \underbrace{- R_c(t,x,y,z)}_{\text{Sinks}}$$

Phytoplankton model:



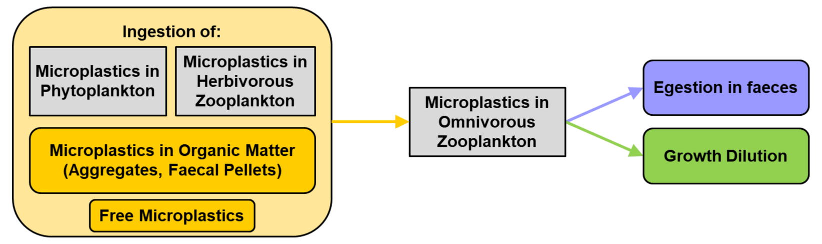
$$\frac{\partial C_{mp,Phy}}{\partial t} = \underbrace{k_{ads} C_{mp,W}}_{\text{Adsorption from water}} - \underbrace{k_{des} C_{mp,Phy}}_{\text{Desorption from phytoplankton}} - \underbrace{k_{G,Phy} C_{mp,Phy}}_{\text{Growth dilution}}$$

Herbivorous Zooplankton Model:



$$\frac{\partial C_{mp,HZ}}{\partial t} = \underbrace{k_{diet,HZ}\left(P_W C_{mp,W} + P_{Phy} C_{mp,Phy} + P_{OM} C_{mp,OM}\right)}_{\text{Uptake from diet}} - \underbrace{k_{eg,HZ} C_{mp,HZ}}_{\text{Egestion in faeces}} - \underbrace{k_{G,HZ} C_{mp,HZ}}_{\text{Growth Dilution}}$$

Omnivorous Zooplankton Model:



$$\frac{\partial C_{mp,OZ}}{\partial t} = \underbrace{k_{diet,OZ}\left(P_W C_{mp,W} + P_{Phy} C_{mp,Phy} + P_{OM} C_{mp,OM} + P_{HZ} C_{mp,HZ}\right)}_{\text{Uptake from diet}} - \underbrace{k_{eg,CZ} C_{mp,OZ}}_{\text{Egestion in faeces}} - \underbrace{k_{G,CZ} C_{mp,OZ}}_{\text{Growth Dilution}}$$

Nomenclature:
$C_{mP,\{W, Phy, HZ, OZ\}}$ = Concentration of microplastics in seawater/phytoplankton/herbivorous zooplankton/omnivorous zooplankton; t = Time; x, y, z = Spatial coordinate system; $\overrightarrow{u_H}$ = Horizontal component of current velocity; w = Vertical current velocity; $\kappa_{\{H,w\}}$ = Coefficient of diffusivity (Horizontal/Vertical); w_s = mP vertical settling velocity; Q_C = mP inputs; R_C = mP outputs; k_{ads} = Rate constant for adsorption of microplastics to phytoplankton, k_{des} = Rate constant for desorption of microplastics from phytoplankton, $k_{G,\{phy, HZ, OZ\}}$ = Growth rate constant for phytoplankton/herbivorous zooplankton/omnivorous zooplankton, $k_{diet,\{HZ, OZ\}}$ = Clearance rate constant for mP uptake via ingestion of food and water by herbivorous zooplankton/omnivorous zooplankton, $P_{\{w, phy, OM, HZ\}, \{HZ, OZ\}}$ = Fraction of herbivorous zooplankton/omnivorous zooplankton diet consisting of water/phytoplankton/organic matter/herbivorous zooplankton.

3. Refinements to physical transport model

Assessed the applicability of 7 models for the terminal settling velocity of regularly and irregularly shaped particles in the context of mP transport modelling:

- A, B and C predict the settling velocity of mPs to a high precision.
- An explicit model is the most appropriate for implementation in an mP model.

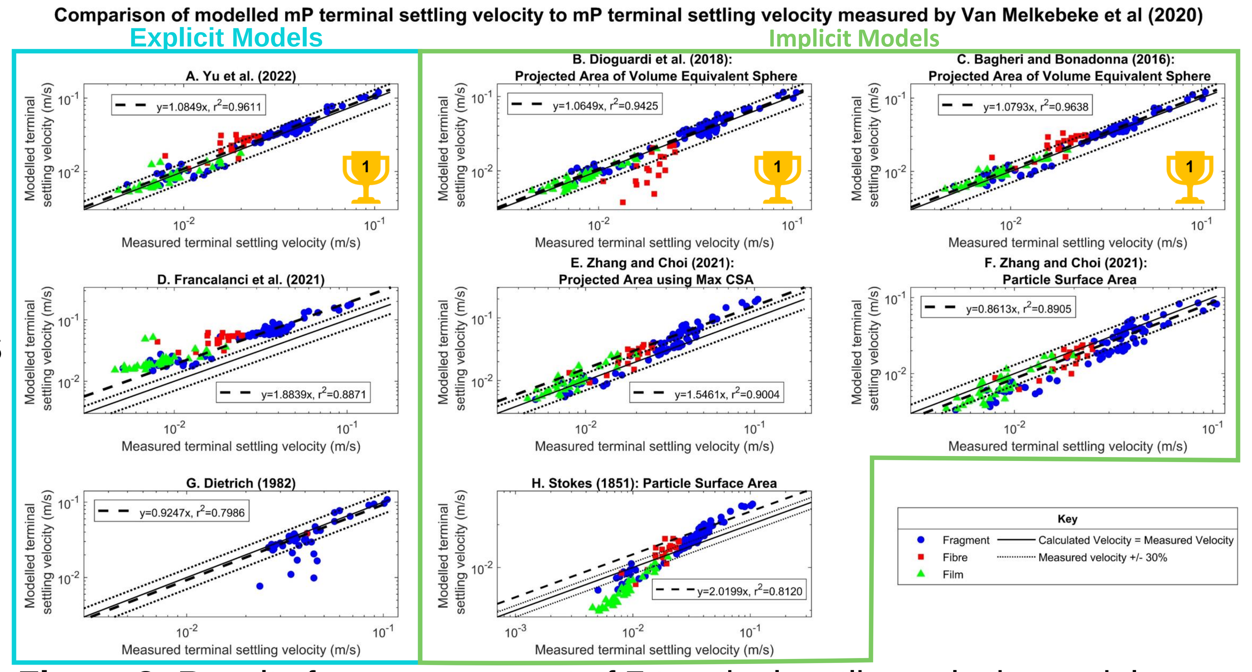


Figure 3: Results from assessment of 7 terminal settling velocity models

Other key results:
- Modelled terminal settling velocity does not vary significantly across the expected range of seawater density.
- The time taken to attain terminal settling velocity and therefore the distance travelled in this time is negligible.
- The specified initial velocity has negligible impact on the modelled terminal settling velocity

Full results

Results paper: Coyle *et al* (2023) DOI: 10.1021/acsestwater.2c00466

4. Challenges

Challenge: Difficulty compiling sufficient data to validate regional model of mP transport:

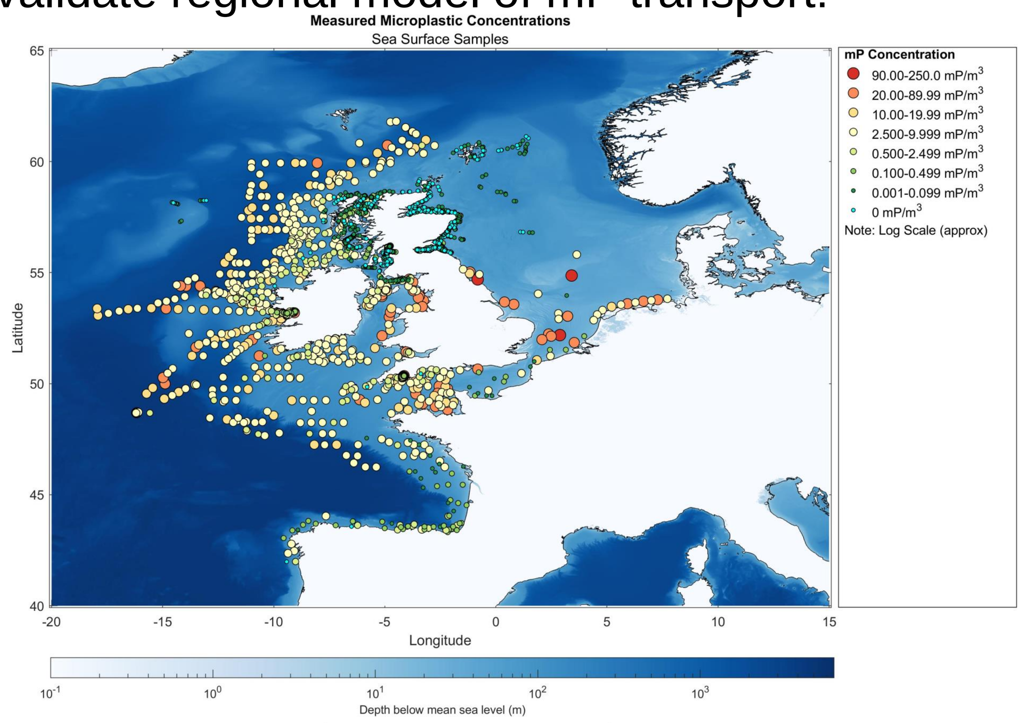


Figure 4: Location of measurements of mP concentration within mP model domain compiled from sampling studies in literature.

→Measurements of mP concentration generally one-off: **No continuous monitoring, cannot validate model's ability to predict temporal trends.**
→Most sampling conducted in surface waters: **Limited data available beyond the surface.**
→Sampling techniques used generally capture mPs **>333μm** whereas the relevant mP size for zooplankton and phytoplankton exchange is processes **<30μm.**

5. Significance of research

EU MSFD (2008/56/EC) key objective: The determination of the ecological harm caused by mPs. Numerical models contribute by improving our understanding of sources, transport, uptake and exchange processes.

Numerical models are useful tools to policy makers for:
➔Risk assessment of mP pollution.
➔Implementation of suitable mitigation measures.
➔Providing useful information on improvements to datasets and long term monitoring programs required to implement such a model.

Acknowledgement

This work was supported by NERC under the QUADRAT DTP (https://www.quadrat.ac.uk/)
We gratefully acknowledge the contribution of Dr. K.O'Driscoll to the project design and initial conceptualisation of the numerical model system.

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