BONUS MICROPOLL PROJECT (1 July, 2017 – 30 September, 2020)

Deliverable 6.4 **Report on food web effects of MP in the Baltic to the task groups for Descriptor 4 (HELCOM HOLAS, HOLAS II) and presentations for HELCOM and OSPAR working groups**

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Work package 3: **Impacts of MP, associated contaminants, and biofilms on Baltic biota**

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Modeling body burden of microplastic in a simple food web: Predicting microplastic burden in the Baltic herring involved in trophic interactions

This deliverable is a contribution to Task 6.3 (WP6) *Recommendations for the assessment of biological effects of MP in the Baltic*.

The focus of Deliverable 6.4 is on the transfer of microplastic (MP) in a simplified pelagic food web. This report is based on the Diploma Thesis of Astrid Månsson (ACES, SU) that presented a mass-balance model evaluating trophic transfer of MP in a trophic guild *herring – invertebrate zooplanktivores – zooplankton*. This trophic guild is typical not only for the Baltic pelagic food webs, but virtually for any pelagic system, where a small zooplanktivorous fish and large predatory invertebrates (such as mysids, jellies, chaetognats, etc.) are sharing a same food source (herbivorous zooplankton). The results have been discussed at HELCOM indicator workshop in Copenhagen, 16-18 October, 2019.

Summary

Background. Microplastic hazard assessment in the marine environment requires quantification and understanding of MP transfer in the food web. However, gathering quantitative data on MP body burden in biota is difficult due the analytical challenges with material identification as well as unsettled sampling methodologies. A modeling approach is useful for this purpose, because it can help predicting body burden using data on microplastic occurrence in the environment and knowledge of the food web topography. A mass-balance model has recently been applied to predict microplastic body burden in the Baltic herring; the model is relatively simple and based on the microplastic abundance in the water and physiological rates of the food processing by the fish (Ogonowski et al. 2019). To add food-web complexity, a trophic guild structure was incorporated in this model; this was implemented in the Diploma Thesis project of A. Månsson (2019).

Study objectives. Microplastic particles enter aquatic consumers both directly (by ingestion of MP mistaken for food particles) and indirectly (through secondary consumption). Regardless of the ingestion route, possible negative effects on digestive functions, food intake and growth can occur. Using the revised model, we (1) evaluated how the mixed diet (zooplankton and mysids) affected the total MP body burden in the fish, and (2) calculated the relative contribution to the total MP burden in herring via secondary consumption.

Methods. To predict microplastic abundance in Baltic herring, a dynamic model using the Vensim PLE® software was developed and compared to the earlier model that simulates direct uptake of MP from the water by herring of 20 cm (ca 35 g). The revised model simulates uptake of microplastic by herring through two pathways: filtration associated with feeding on zooplankton (direct intake) and predation on mysids that are feeding on zooplankton in the waters contaminated with MP (indirect intake).

Main findings. The predicted MP burden in Baltic herring in the trophic guild was 2.7 MP ind^{-1}, which is in the range of the values reported from the field observations (0-20 MP ind^{-1}) and 30% lower compared to the model predictions for the fish with exclusively zooplanktivorous diet. Thus, for particles 1-5 mm, predation on mysids contribute negligibly to ingestion of MP, and direct ingestion of MP is the main source of MP intake by herring.

Conclusions. The modeled MP abundance in mysids was very low but reasonable considering that their ingestion of 1-mm MP ought to be extremely low at the ambient MP concentrations used in the model. The low uptake of MP by mysids leads to the negligible contribution to MP body burden in herring. As a result, the mysids represent MP-free food and “dilute” the MP body burden originated from the direct uptake. When modeling transfer of ≥microplastic particles of this size (1-5 mm), this would be also true for other invertebrate zooplanktivores in various trophic guilds, because they have a lower filtration efficiency than fish and thus a diluting effect on the MP body burden. However, these invertebrates, including mysids, commonly ingest smaller MP particles (<50 μm; Deliverable 3.2). Hence, to further develop the modeling approach for analysis of the food web transfer of MP, we need to focus on the smaller MP commonly found in invertebrates.

Stockholm University

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Astrid Månsson
Bachelor's thesis, 15 HE credits
Environmental Science, 2019

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Predicting microplastic burden in the Baltic herring involved in trophic interactions

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Abstract

Microplastic particles enter aquatic consumers by direct ingestion and indirectly through trophic transfer, with possible negative effects on digestive functions, food intake and growth. To predict microplastic abundance in Baltic herring, I created a dynamic model using the Vensim PLE® software. The model simulates uptake of microplastic by herring through filtration associated with zooplankton, and predation on mysids. Model outcomes predict MP burden in Baltic herring to be 2.7 MP ind^{-1}, which was close to mean MP burden values from reported field observations. Predation on mysids did not contribute to ingestion of MP by herring for particles 1-5 mm, which suggests that direct ingestion is the main source of MP intake for consumers. However, incorporating microplastic of a smaller size could help further develop this model and create a more realistic overview of microplastic transfer in the Baltic food web.

Keywords

Microplastic, Prediction model, Baltic herring, Baltic food web, Trophic interactions

Contents

1 Introduction

Microplastic are subject to extensive research due to large knowledge gaps and concerns regarding their ecosystem- and human health impacts. Introduction of plastic and other anthropogenic debris into the marine environment and food web has been recently highlighted (Romeo et al., 2015; SAPEA, 2019). Microplastic enter aquatic consumers by direct ingestion and indirectly through trophic transfer (Nelms et al., 2018), with possible negative effects on digestive functions, food intake and growth (Ogonowski et al., 2019). Further areas of concern include adhered toxic pollutants with possible impacts on biota due to bioaccumulation and magnification (Cole et al 2011). Current research initiatives aim to quantify microplastic ingestion by several fish species (Diepens & Koelmans, 2018); Ogonowski et al., 2019), but data describing predator-prey transfer of microplastic and associated contaminants is still insufficient for risk assessment (Carbery et al., 2018).

Several issues complicate microplastic risk assessment in the marine environment. Prognostic modelling is dependent on relevant and up-to-date observational data. However, gathering quantitative data is difficult due the large areas of the oceans, small size of plastic particles, analytical challenges with material identification, and unsettled sampling methodologies, along with spatial and temporal variabilities (Cole et al., 2011; Gouin et al., 2019). The Swedish Environmental Protection Agency (2016) reported that we currently have insufficient data for quantifying microplastic pathways and sources into the Swedish marine environment as well as for assessing biological and ecological impacts.

The need for increased knowledge on possible effects on environmental- and human health have resulted in projects such as *Towards quantifying impacts of microplastics on environmental and human health*, funded by the Swedish Environmental Protection Agency (Naturvårdsverket), and BONUS-MICROPOLL project. In both projects (and the risk assessment in general), an important part is quantification of microplastic burden in aquatic organisms used for human consumption, such as fish and shellfish, including transfer of microplastics in the Baltic Sea food webs. This thesis contributes to these projects, focusing on predicting microplastic abundance in Baltic Sea herring, *Clupea harengus membras*.

A modeling approach is highly useful for this purpose, because it can help predicting body burden from the microplastic occurrence in the environment. By comparing observed field data to expected amounts of microplastic particles in fish guts, we can calibrate and validate such models. A mass-balance model has recently been applied to predict microplastic body burden in Baltic herring based on the microplastic abundance in the water and physiological rates of the food processing by the fish (Ogonowski et al. 2019). To add food-web complexity to this model, I used the same approach and introduced another pathway related to trophic interactions between herring and its prey. Whereas Ogonowski and co-workers (2019) treated filtration as the only source of microplastic uptake by herring, I also considered an additional pathway of microplastic uptake via predation on mysids. These small crustaceans, commonly known as opossum shrimp, feed on zooplankton and make up an important part of the herring diet (Möllmann et al., 2004). Using literature data, I re-parameterized the model to include this interaction, thus creating a more realistic model. In a larger context, the model framework can be used as a tool for predicting microplastic abundance in indicator species and commercially important fish used for human consumption as well as for large-scale ecosystem assessment.

1.1 Research aim & objective

This project aims to: (1) model microplastic exposure in herring (*Clupea harengus membras*) feeding on plankton and mysids; (2) compare the accuracy of the model results to the field observations reported by Ogonowski et al. (2019); and (3) compare the results of the improved model to that of the original model described by Ogonowski et al. (2019) to evaluate how the implemented changes affected the model outcome.

2 Background

2.1 Microplastic in the Baltic Sea

2.1.1 Definition, sources & distribution

Plastic littering and release of microplastic into the environment have been identified as a serious environmental threat by the planetary boundary framework under the category *Introduction of novel entities* (Steffen et al., 2015). Along with other pollutants in this category, e.g. persistent organic pollutants and heavy metals, these contaminants are of concern because of their properties, such as persistency, ability to move over large spatial scales and potential to affect vital Earth system processes (Steffen et al., 2015).

Plastic waste is categorized as either macroplastic (larger debris) or microplastic (Cole et al., 2011). Primary microplastic are manufactured as small pellets and beads; they enter the environment through spills and wastewater from industrial and domestic sources. Secondary microplastic enter the environment as a result of degradation and fragmentation of macroplastic. Although the size categories for microplastic particles found in the environment are debatable (Cole et al., 2011), particles <5 mm are generally considered microplastic (Barnes et al., 2009).

Microplastic end up in the Swedish marine environment primarily through river runoff, stormwater, wastewater, atmospheric deposition, and direct discharge into the sea or beach areas (Magnusson et al., 2016). Microplastic particles have been found in surface water, in the water column, and in sediments; moreover, they are often concentrated in coastal waters (Auta et al., 2017). Their small size and density enables them to travel over large distances with ocean currents (Magnusson et al., 2016). In 2014, Eriksen et al. (2014) estimated that 5.25 trillion plastic particles weighing 269 million tonnes are distributed in the World's Oceans, not including litter polluted shorelines, seabeds or those ingested by biota. The abundances of these particles in the surface waters were found to be far less than expected from the plastic production and release, suggesting that sedimentation is an important removal pathway for these particles from surface waters. Other sinks and processes include bio- and UV degradation, as well as ingestion by biota.

2.1.2 Bioavailability & trophic transfer

As microplastic abundance in the marine environment increases, the bioavailability also increases (Auta et al., 2017). A central aspect of the microplastic discussion is the possible negative effects on biota, including humans. These include decreased food intake, compromised digestive functions, and growth (Setälä et al., 2018). Particle toxicity can be exerted by very small particles that can cross biological membranes, become cancerogenic and cause malformations in both animals and humans, reduce reproductive activity as well as alter immune system responses (Auta et al., 2017). Toxicological concerns are also raised because of the plastic litter's potential to enhance transportation and accumulation of Persistent, Bioaccumulative and Toxic (PBT) substances (Romeo et al., 2015).

Microplastic trophic transfer may act as a major pathway leading up to marine top predators (Nelms et al., 2018). The particles can be *directly* ingested by organisms by accidental intake through non-selective feeding mode, such as filter-feeding, or by misidentifying plastic particles for food. In addition to direct consumption, *indirect* ingestion routes include feeding on microplastic-contaminated prey, so-called secondary consumption, or feeding on fecal pellets containing microplastic particles ingested and egested by other organisms (Auta et al., 2017). Species at lower trophic levels tend to ingest microplastic particles indiscriminately as long as they are within the range of their prey size. Baltic fish at intermediate trophic levels, such as herring and sprat, may ingest microplastic either passively through filtering at low light levels (Batty et al., 1990), or actively, when mistaking these particles for other prey (Wright et al., 2013). Moreover, when predating on larger invertebrates, such as mysids and amphipods, these fish can ingest specimens that contain microplastic in their guts (Deliverable 3.2; MICROPOLL project).

Evidence of microplastic occurrence in large pelagic fish in the Mediterranean Sea was first presented by Romeo et al. (2015). The Baltic Sea, along with other closed waters, are known for relatively high levels of microplastic pollution compared to the open oceans (Setälä et al., 2018). Several laboratory studies have been carried out to look at the impacts of microplastic ingestion by fish, especially focusing on the transfer of toxic chemicals (Auta et al., 2017). The largest spatial overlap between microplastic and biota occurs in coastal waters (Clark et al., 2016); thus, these are the areas where the highest encounter rate and trophic transfer of microplastic in the food web can be expected. It is, however, very challenging to design experimental studies mimicking these conditions, including physical and ecological heterogeneity of this environment. As a result, we know little about the trophic transfer of microplastic in the real-world systems.

2.1.3 Complicating factors for microplastic exposure assessment

Risk assessment is largely dependent on the observational data providing exposure levels. However, several issues complicate microplastic research. Firstly, microplastic research is still a relatively young field of interest, with large knowledge gaps regarding plastic particle abundance and distribution in the environment as well as possible effects on biota. Secondly, collecting data on microplastic distribution in the Baltic Sea, as in many other systems, is problematic due to the lack of standardized sampling and identification techniques and inaccurate estimates of plastic microlitter abundance (Gewert et al., 2017). Identifying accumulation sites is as important as it is difficult (Magnusson et al., 2016), partly due to seasonal and spatial variations. Coastal waters and estuaries seem to be especially prone to microplastic pollution, but the high levels of organic materials in these locations make sampling difficult (Cole et al., 2014). Insufficient data for quantifying microplastic pathways and sources into the Swedish environment has also been reported by the Swedish Environmental Protection Agency (2016).

2.2 A modelling approach: Predicting plastic abundance in consumers

2.2.1 Consumers as indicators of microplastic occurrence

Mapping microplastic distribution and abundance in marine food webs is needed for a large-scale environmental assessment of microplastic exposure. Focusing research efforts on key- and indicator species is a good way to create a sufficiently accurate overview of microplastics in the food webs. Even though microplastic does not accumulate in fish guts, stomach content can be used to provide a general overview of the fish's feeding habits and surrounding habitat, including the levels of exposure to microplastic (Ogonowski et al., 2019). Moreover, such species are often important for human consumption, monitoring, and relevant for research concerning food-web and human health effects. Well-known examples of such animals are bivalves and herring (Ogonowski et al., 2019; Van Cauwenberghe & Janssen (2014). However, the analysis of microplastic in biological matricies is also challenging largely due to the same technical and analytical problems as for microplastic abundance analysis in water and sediments.

2.2.2 Mass-balance approach for microplastic modeling in consumer guts

Relatively low numbers of microplastics in herring (0-1 MP ind^{-1}) have been found in recent observational studies by both Ogonowski et al. (2019) and Budimir et al. (2018). However, due to spatial variabilities and differences in methods, such studies are difficult to compare (Setälä et al., 2018). Ogonowski et al. (2019) reported a Baltic Sea herring population average of 0.9 MP ind^{-1}. However, when only considering the fish containing microplastic particles, i.e. when zero values were excluded, MP burden was as high as 3.9 MP ind^{-1}. The authors presented a simple mass-balance model with output for MP burden being in acceptable agreement with the observed values. The model used literature-derived data on herring feeding- and egestion rates and ambient microplastic concentrations in the water. In this model, the direct ingestion of zooplankton and – by accident – MP is the only source of microplastic uptake by herring, which is a simplified version of the herring feeding habits (*Fig. 1*).

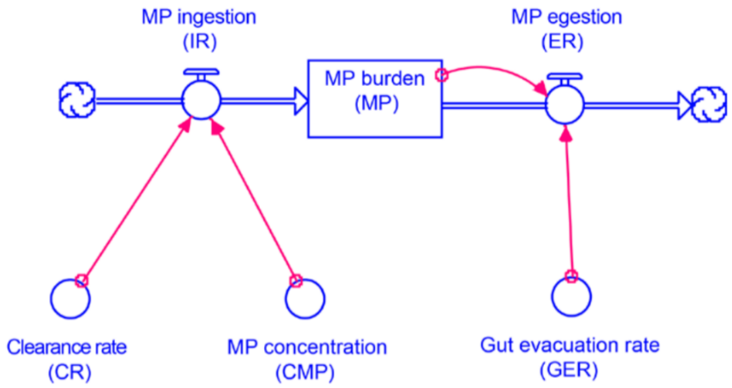

Figure 1. Schematic representation of the model by Ogonowski et al. (2019) developed to predict microplastic body burden (MP burden) in the Baltic herring using food intake by fish estimated from clearance rate (CR), ambient microplastic concentration in the water column (CMP) and gut evacuation rate of the fish (GER).

2.2.3 Feeding ecology of Baltic herring and mysids

Herring is one of the most studied fish in the Baltic Sea. It has been analyzed with regard to microplastic burden in the gut because of the species key role in the food web and a potential indicator species for monitoring microplastic abundance. These fish have a potential to ingest microplastic that are in the same size range as zooplankton. Baltic herring feeds primarily on zooplankton until it reaches a size of ~15-20 cm (Casini et al., 2003). This means that the younger herring (<~20 cm, and particularly those that are <15 cm) can ingest microplastic only by mistaking particles that are around 1 mm for zooplankters. At >20 cm, the adult herring is feeding by predation on pelagic (e.g., mysids) and benthic (e.g., amphipods) invertebrates in addition to feeding of zooplankton (ibid.). At this size, the fish can ingest microplastic particles both directly, but also via trophic transfer from the invertebrate prey containing plastic particles in the guts (or in the other body parts), i.e., via secondary consumption.

As mysids can make up a substantial part of the larger herrings' diet (Möllman et al., 2004), it makes sense to incorporate the transfer of microplastic particles from mysids to herring when modelling microplastic uptake by herring. These small crustaceans are globally common in estuarine systems. They feed primarily on zooplankton (Rudstam, 1989), which makes microplastic ingestion possible when mysids confuse plastic particles for prey. However, mysids are also filter-feeders consuming phytoplankton (Grossnickle, 1982) which means that they can ingest microplastic particles that are much smaller than 1 mm.

3 Materials and Methods

3.1 Model design

To predict microplastic body burden in herring, I created a dynamic model using the Vensim PLE® software. The model was based on the model presented by Ogonowski et al. (2019), where ingestion related to feeding on zooplankton was the only inflow of microplastic to the gut of individual herring. I included an additional feeding pathway representing predation on mysids, which are zooplanktivorous crustaceans and a common prey for herring (Casini et al., 2003). Hence, adding trophic transfer as a route of microplastic ingestion to herring should result in a more realistic prediction model. The mass-balance approach was used to predict microplastic burden – ultimately for herring, but also for mysids (*Fig. 2*). Thus, my model simulates direct and indirect uptake of microplastic in herring by feeding on zooplankton and mysids, respectively. With the mass-balance approach, microplastic abundance in the gut of individual consumers (MP_{gut}) at any given time can be described as:

$$MP_{gut} = MP_{intake} - MP_{egestion} \qquad \text{(Equation 1)}$$

where MP_{intake} is the rate at which microplastic particles are ingested by consumers. Here, the two inflows for microplastics are via direct intake and intake by predation. $MP_{egestion}$ is the rate at which microplastics are egested from the consumer's gut. The stock and flow diagram of this dynamics and the associated variables are presented in Fig. 1.

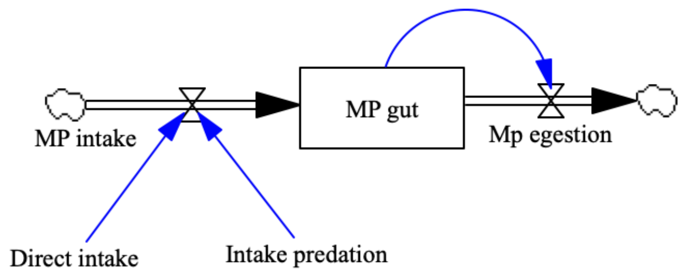

Figure 2. Stock and flow diagram of MP body burden in individual consumers ingesting microplastic through direct intake and intake of microplastic particles from predation.

3.2 Assumptions

According to Ogonowski et al. (2019), the predicted abundance of microplastic (1-5 mm in the longest dimension) in the gut should reflect average microplastic exposure levels in the same size range, if: (1) ambient microplastic distribution in the herring's feeding grounds are relatively homogenous; (2) microplastic concentrations in the water column where herring feeds, are similar to those in surface water where the data was sampled; (3) microplastic uptake is non-selective in both herring and mysids, making it proportional to the microplastic abundance in the water; and (4) microplastic is egested at the same rate as prey (i.e., zooplankton) remains in both herring and mysids. Additionally, I assumed that mysids and herring do not indirectly ingest microplastic > 1mm by feeding on zooplankton since particles of this size are too large to be ingested by Baltic copepods.

3.3 Model parameterization

To parameterize the model, I used literature-derived data on herring- and mysid feeding as well as ambient microplastic concentrations in the feeding grounds of herring. An overview of model parameters is presented in *Table 1*.

MP ingestion by predation on mysids

To calculate *intake of MP by predation (IR_P)* by herring, I modeled IR_P as a function of the number of mysids that a fish ingests per time unit ($Mysids_{fish\ stomach}$) and microplastic abundance in mysids *(MP Mysid)* as follows:

$$IR_p = Mysids_{fish\ stomach} * MP_{mysid} \quad \text{(Equation 2)}$$

where $Mysids_{fish\ stomach}$ (0.187 mysids h^{-1}) was calculated from literature data on feeding rates and diet composition of Baltic herring. Based on the herring size categories described by Möllmann et al. (2004), I assumed that mysids make up 30 percent of the herrings' diet. The derivation of $Mysids_{fish\ stomach}$ is presented in *Appendix A*.

MP ingestion by filtration associated with feeding on zooplankton

Since predation on mysids make up 30 percent of the fish diet in my model, the intake rates by filtration (IR_F) for will make up the remaining 70 percent, which was calculated as:

$$IR_F = 0.7 * CR_{consumer} * (CMP) \quad \text{(Equation 3)}$$

where *CMP* is the ambient microplastic concentration in the water column and *CR* is clearance rate, i.e., the volume of water swept clear of particles per individual and unit of time. The CR value for herring (1040 L $ind.^{-1}$ h^{-1}) was derived by Ogonowski et al. (2019) based on the estimated rates for Baltic herring feeding on the copepod *Calanus finmarchicus* (Varpe & Fiksen 2010). For mysids, I used mean CR values of 0.195 L $ind.^{-1}$ h^{-1} reported from feeding experiments on *Mysis relicta* (Cooper & Goldman 1982).

Concentration of suspended microplastic in the Baltic Sea

I used the same ambient microplastic concentration values (0.58 MP m^{-3}) for my model as Ogonowski et al. (2019). The data originally reported by Gewert et al. (2017) were obtained for surface waters of the outer Stockholm Archipelago, the feeding grounds of the Baltic herring. The microplastic size (1-5 mm) in the study of Gewert et al. (2017) corresponds to the size of the microplastic observed in the guts of the herring sampled from this area (Ogonowski et al. 2019).

Gut evacuation

Gut evacuation rates (GER) were used to model egestion rates of MP in the consumers. I used the 0.155 h^{-1}, which is the average value calculated using an upper limit (0.26 h^{-1}) reported for European pilchard *(*Costalago & Palomera, 2014) and a lower limit (0.05 h^{-1}) reported for South American pilchard (van der Lingen, 1998), which are the two fish species with similar feeding ecology and body size as the Baltic herring. For mysids, I used GER values estimated by Rudstam (1989). Rudstam assumed two different rates, 0.4 h^{-1} if feeding is constant over a 24-hour period, or 0.9 h^{-1} if they only feed at night. Due to the uncertainty in feeding frequency, I used the average value (0.65 h^{-1}). The number of microplastic egested by one individual at any given time (*Eg*) was modeled as a function of GER and MP abundance in the consumers as follows:

$$Eg = GER_{consumer} \times MP_{consumer} \quad \text{(Equation 4)}$$

Table 1. Values and equations used to calculate predation on mysids by herring with body mass 35 g (wet mass)

Parameter	***Species***	***Unit***	***Description***	***Equations and values***	***Reference***
MP		MP	Number of MP in stomach at time t	IR-Eg	
$CR_{herring}$	*Clupea harengus*	L $ind.^{-1}$ h^{-1}	Clearance rate herring	1040	Varpe & Fiksen 2010; Ogonowski et al. 2019
CR_{mysid}	*Mysis relicta*	L $ind.^{-1}$ h^{-1}	Clearance rate mysid	0.195	Cooper & Goldman 1982
$IR_{F(herring)}$		MP h^{-1}	Number of MP ingested by herring through filtration at time *t*	0.7 * $CR_{herring}$ * CMP	
$IR_{P(herring)}$		MP h^{-1}	Number of MP ingested by herring through predation at time *t*	$Mysids_{fish\ stomach}$ * MP_{mysid}	
$IR_{F(mysid)}$		MP h^{-1}	Number of MP ingested by mysid at time *t*	CR_{mysid} * CMP	
CMP		MP L^{-1}	MP concentration in the water column	0.00058	Gewert et al. 2017
$GER_{herring}$	*Sardina pilchardus, Sardinops sagax*	h^{-1}	Gut evacuation rate herring	0.155	Costalago & Palomera 2014; van der Lingen, 1998
GER_{mysid}	*Mysis mixta*	h^{-1}	Gut evacuation rate mysid	0.65	Rudstam 1989
$Eg_{herring}$		MP h^{-1}	Number of MP egested by herring at time *t*	$GER_{herring}$ * $MP_{herring}$	
Eg_{mysid}		MP h^{-1}	Number of MP egested by mysid at time *t*	GER_{mysid} * MP_{mysid}	
$Mysids_{fish\ stomach}$	*Clupea harengus*	1 h^{-1}	Rate of mysids consumed by herring	0.187	*Appendix A.*

3.4 Model validation

To evaluate the accuracy of the model predictions, I compared the results of my model to the field data on MP burden in the herring (Ogonowski et al. 2019); the output values for *MP herring* were compared to the range of the observed MP body burden. Since my model and the model created by Ogonowski and co-workers used the same values and processes for simulating herring MP intake by filtration, the comparison of *MP herring* values generated by the original model and the revised model allowed to (1) evaluate how the mixed diet (zooplankton and mysids) affected the total MP body burden in the fish, and (2) calculate the relative contribution of MP originated from predation on mysids to total MP burden in herring.

4 Results

4.1 The model

The revised model (*Figure* 3) represents trophic transfer of microplastic to the Baltic herring and could be used to predict MP burden in herring and mysids, respectively, as well as estimate relative contribution of MP transferred to herring via different pathways.

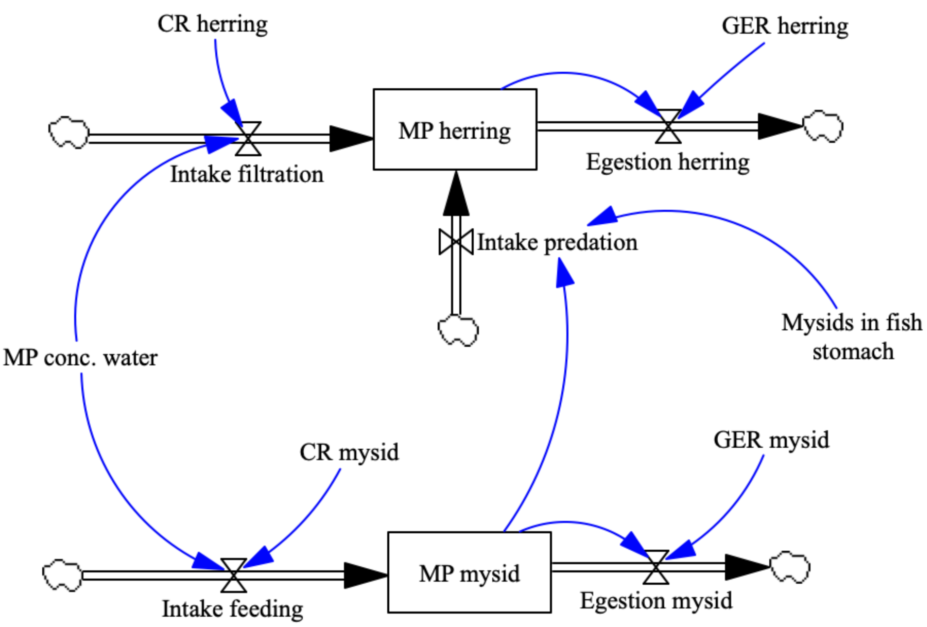

Figure 3. The revised model used to predict microplastic burden in Baltic herring through direct ingestion and secondary consumption via predation on mysids.

4.2 Predicted MP burden in herring through trophic transfer

My model predicted microplastic body burden in the Baltic herring when feeding on both zooplankton and mysids to be 2.7 MP ind^{-1} (*Fig. 4*). With the model run from time point 0, when both *MP herring* and *MP mysid* were zeroes, the MP body burden values (both stocks) reached steady state after 40 hours of simulation. Thus, the predicted microplastic body burden in fish (*MP herring*) was in the range of the values observed in the field-sampled herring (0-20 MP ind^{-1}) and three times as high as the observed population average (0.9 MP ind^{-1}). The modeled MP body burden in individual mysid after reaching steady state is 1.7×10^{-4} MP ind^{-1}. MP was ingested by herring through predation on mysids at a rate of 3.2×10^{-5} MP h^{-1}; which makes the relative contribution of MP in herring gut from this pathway negligibly low.

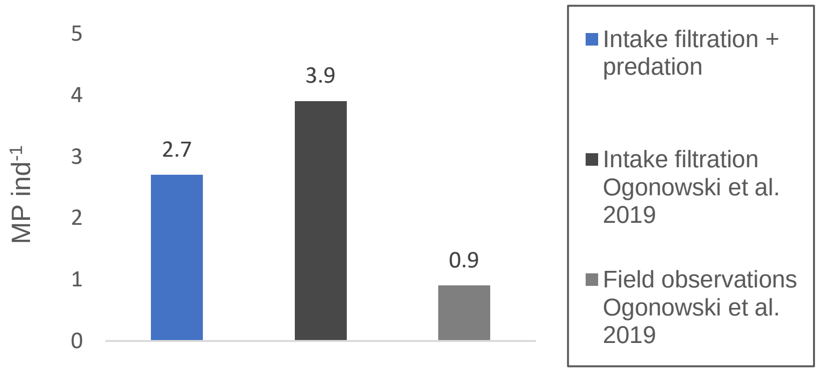

Figure 4. Predicted MP body burden in herring (MP ind^{-1}) through intake by filtration when feeding on zooplankton and predation on mysids. The model output (blue bar) is compared to the model results when filtration is the only route for MP intake (black bar) and to the field observations expressed as population average for MP body burden (grey bar); the last two values are based on the model and field data reported in Ogonowski et al. (2019).

4.3 Comparing the pathways

Running the model with direct ingestion as the only inflow of MP to herring resulted in *MP herring* to be 3.9 MP ind^{-1}; the same value as predicted by Ogonowski et al. (2019) for the same feeding process. When compared to the published model results by Ogonowski and co-workers, my model showed that the additional pathway of MP uptake via predation on mysids resulted in 30% lower *MP herring* compared to the scenario when only feeding by filtration was considered *(Fig. 4)*. Thus, the revised model produced a value which is closer to the reported mean MP burden in the field. Direct intake was the largest (close to 100%) contributor to microplastic uptake by herring in this model.

5 Discussion

The revised model and the model created by Ogonowski and co-workers (2019) produced the same result when treating filtration as the only source of MP intake by herring, which means that I successfully recreated the model in Vensim PLE and that the revised model share the same mathematical formulation. The modeled MP abundance in mysids was very low but seems reasonable considering that ingestion of 1-mm microplastic particles by mysids ought to be very low when exposed to such low concentrations of MP in the surrounding water. The low uptake of MP by mysids and the fact that this trophic transfer pathway does not contribute to MP in herring, implies that when feeding on a mixed diet of zooplankton and mysids, direct ingestion is by far the main contribution of MP to herring, and the secondary consumption of MP is virtually non-existent. As a result, the mysids are contributing MP-free food and "dilute" the MP body burden originated from the direct uptake.

When modeling the transfer of microplastic particles of this size (1-5 mm), the invertebrate zooplanktivores that are a part of the trophic guilds, would, most probably have a lower filtration efficiency and thus have a diluting effect on the body burden. However, mysids have been found to ingest MP particles <50 μm (Deliverable 3.2; MICROPOLL project). This means that to further develop the modeling approach for analysis of the MP transfer in the food webs, we need to focus on a smaller size category of MP. We would also have to take into consideration that incorporating smaller particles would lead to additional transportation routes of MP between the consumers. In fact, very small particles could also be ingested by zooplankton (Grossnickle, 1982; Deliverable 3.2; MICROPOLL project), which, in turn, would make ingestion of zooplankton a new pathway involving secondary consumption for MP to travel to the fish. Other possible prey organisms that contribute to herring diet and have been reported to ingest small (<50 μm; Deliverable 3.2) are amphipods and polychaetes. There are many other aspects that are relevant to consider for developing this model further. For example, parameterization to include size-dependent uptake and egestion rates in herring as well as onthogenetic variations in diet composition.

Based on the result that filtration seem to be the main contributor to microplastic uptake in consumers, I would suggest focusing research efforts on modeling other important filter-feeding consumers in the Baltic Sea. Shellfish, and especially bivalves are prone to ingest microplastic particles (Van Cauwenberghe & Janssen, 2014). In contrast to herring, their feeding mode is exclusively filter-feeding. Another important aspect is their commercial importance and availability for human consumption.

6 Conclusions

Consumption of MP my mysids is approaching zero, when MP in the size range 1-5 mm at the field concentration of 0.6 MP m^{-3} are considered. As a result, the added pathway of MP uptake by Baltic herring provided a 30% lower MP body burden in herring due to a diluting effect of mysids as a MP-containing prey for the fish. Thus, predation on mysids did not contribute to ingestion of MP by herring for particles 1-5 mm, which suggests that direct ingestion is the main source of MP intake for consumers. However, if microplastic particles of a smaller size are incorporated into the model, the predictions in this study might come to overestimate the MP accumulation of MP >1 mm in the Baltic food web.

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Appendix A – Derivation of predation rate on mysids by herring

To derive the predation rate on mysids, I first assumed the feeding rate for an adult herring individual on mysis to be 0.96 % of its body weight (ww day^{-1}) which equates to 30 % of the general feeding rate estimate for herring reported by Rudstam (1988) (variable $FR_{herring}$ in *Table 2)* as follows:

$$FR_{mysid/herring} = 0.3 * FR_{herring} \quad \text{(Equation 5)}$$

$$FR_{herring} = 0.032 * BW_{herring} \quad \text{(Equation 6)}$$

The average body weight of an adult mysid was estimated to be 10 mg dw (Horpilla et al., 2003). I converted mysis dry weight to wet weight assuming a water content of 86.7% (Rumohr et al. (1987) as follows:

$$BW_{mysid} = \frac{BW_{mysid(DW)}}{0.133} \quad \text{(Equation 7)}$$

Then, the predation rate on individual mysids could be calculated as:

$$Mysids_{fish\ stomach} = \frac{FR_{mysid/herring}}{BW_{mysid}} \quad \text{(Equation 8)}$$

where $FR_{mysid/herring}$ is the rate of mysid consumption by Baltic herring (h^{-1}) on a wet weight basis and BW_{mysid} is the individual body weight of a mysid (ww). $Mysids_{fish\ stomach}$ was estimated to be 0.187 mysids h^{-1}. A complete list of values and equations for calculating the number of mysids in one individual herring gut at any time is presented in *Table 1*.

Table 2. Complete list of values and equations used to calculate predation rate on mysids by herring

Parameter	*Species*	*Unit*	*Description*	*Equations and values*	*Reference*
$Mysids_{fish\ stomach}$	*Mysis* spp.	*1* h^{-1}	*Number of mysids ingested by herring*	*0.187;* $FR_{herring}$ / BW_{mysid} */24 h*	
$Mysids_{herring\ diet}$	*Mysis* spp.	*%*	*Percentage of mysid by weight (ww) in herring diet*	*30*	*Möllmann et al. 2004*
$FR_{herring}$	*Clupea harengus*	*g* Ind^{-1} d^{-1}	*Feeding rate herring*	*0.032 ** $BW_{herring}$	*Rudstam 1988*
$FR_{mysid/herring}$		*g* Ind^{-1} d^{-1}	*Mysis mass consumed by herring*	*0.3 ** $FR_{herring}$	
$BW_{herring}$	*Clupea harengus*	*g*	*Herring body mass (ww)*	*35*	
$BW_{mysid(DW)}$	*Mysis relicta*	*g*	*Adult mysid body mass (dw)*	*0.01*	*Horpilla et al. 2003*
BW_{mysid}	*Mysis mixta*	*g*	*Adult mysid body mass (ww)*	$BW_{mysid(DW)}$ */ 0.13*	*Rumohr et al. 1987*