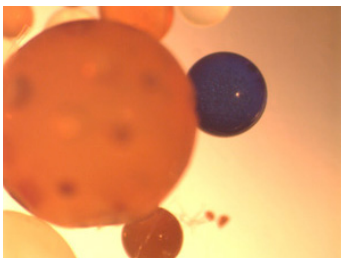
Socio-economic impact of microplastics in the 2 Seas, Channel and France Manche Region

An initial risk assessment

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Funded by:

Co-funded by:

Please refer to this document as:

Van der Meulen, M.D., De Vriese, L., Lee, J., Maes, T., Van Dalfsen, J.A., Huvet, A., Soudant, P., Robbens, J., Vethaak, A.D. (2014). Socio-economic impact of microplastics in the 2 Seas, Channel and France Manche Region: an initial risk assessment. MICRO Interreg project IVa

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Acknowledgements

This report has been produced under the Interreg IVa project MICRO. We would like to thank the Joint Technical Secretariat of Interreg, the Dutch Ministry of Infrastructure and the Environment for co-financing the work conducted in this project. Also, the Institute for Environmental Studies of the VU University in Amsterdam and Stichting de Zeeschelp in Kamperland, many thanks for your analyses and experimental support and advice.

Many thanks to all of the researchers who worked on this project, especially Christophe Lambert, David Mazurais, Rosanna Sussarellu, Ika Paul-Pont, Laura Frere, Anne-Laure Cassone, Dana Stuparu, Frank Kleissen, Ghada El Serafy, Sara Maes, Mattias Bossaer, Bavo De Witte, Johanna Gauquie, Caroline De Tender, Kevin Vanhalst.

1 Scope

‘MICRO: Is it a threat for the 2 Seas Area?’ is a project in which five scientific institutes study the occurrence and impact of microplastics in the Interreg 2 Seas area and the Franche Manche Channel region(Figure 1.1). It is a cooperation between the Belgian Institute for Agricultural and Fisheries research (EV-ILVO), the Centre for Environment, Fisheries and Aquaculture science (Cefas) in England, the Dutch Stichting Deltares and two French partners: l’Institut Français de Recherche pour l’ Exploitation de la Mer (IFREMER) and the Centre National de la Recherche Scientifique (CNRS).

The project started the first of July 2012 and the cross-border partnership is made until the end of September 2014. The project is funded by the European Interreg 2 Seas programme and is led by ILVO.

The main aims of the project are to:

– Evaluate the risk and impact of microplastics in the 2 Seas area
– Provide education on this topic and exchange expertise within the region
– Raise public and scientific awareness for the microplastics issue

To this end, several activities have been set up:

- In activity 1 we will map the **potential distribution of microplastics** in the Interreg Region and France Manche Channel Region based on a review of existing information, and use of existing models to simulate preferred transport pathways and potential accumulation zones.
- Activity 2 deals with the **impact evaluation of the risk assessment** of microplastics. At first, clean preproduction polymers are used to gather basic information of the impact. Further risk assessment will be performed comprising the effects of the chemical load or the bacterial load.
- The subject of Activity 3 is to determine **the socioeconomic impact of microplastics** in the 2 Seas and France Manche Channel Region. Different relevant cases will be evaluated, economical and more societal, including mitigating action to counter the problem.

This report deals with Activity 3, in which the socio-economic effects in the 2 Seas and Franche Manche Channel Region (hereafter called ‘the Interreg region’) are assessed and possible options for mitigating measures are discussed building on results from the previous activities.

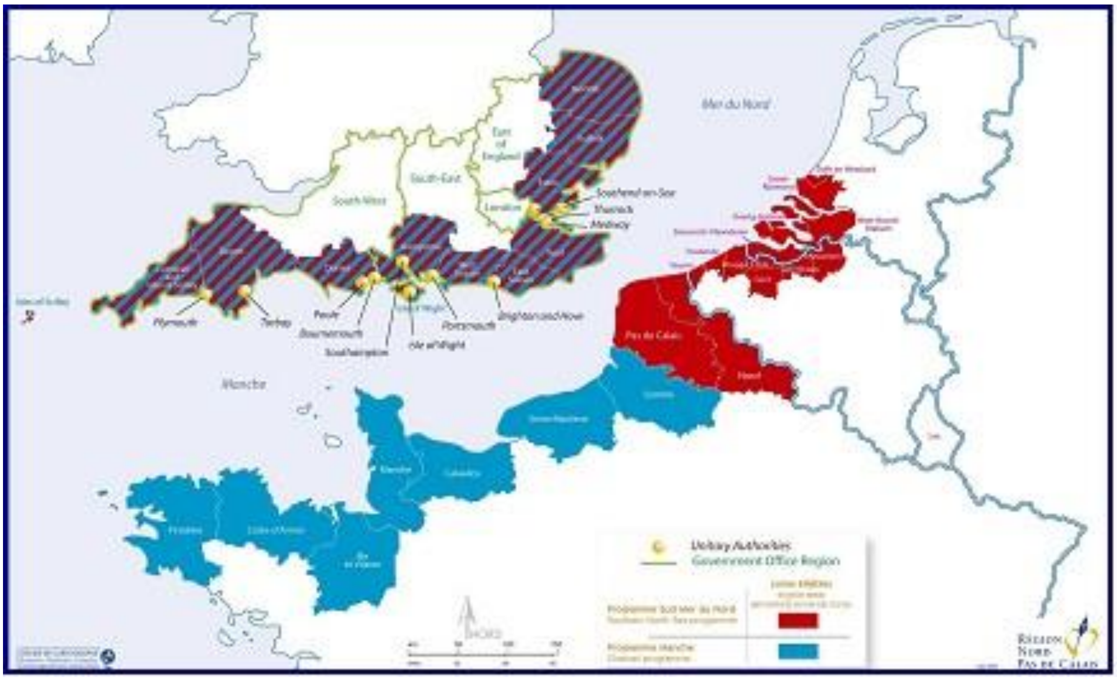

Figure 1.1 The Interreg region under study; the whole of South-England, the South of the Netherlands, the whole of Belgium and the Northern part of France (including the Bay of Brest).

The socio-economic risks, or rather the hazards, are analysed. This was mostly done in a qualitative manner, by describing the potential hazards and the chances that these may occur based upon evidence from literature and the results from Activity 1 and 2 of the MICRO project. Quantifications are provided where possible. The potential risks of MPs are evaluated for two cases:

1. Impact on the aquaculture sector, with oysters and mussel cultures as example.
2. Impact on coastal water quality, using bathing water quality as example.

For both of these cases, the UK was used as a case study for the calculations of the socio-economic risks.

A possible option for the mitigation of risks associated with microplastics is also discussed:

3. Bacterial biodegradation of plastic debris.

In Chapter 2, the methodology on which the risk assessment is based is discussed. Chapter 3 deals with the aquaculture sector. The case of bathing water quality is assessed is Chapter 4. Chapter 5 discusses the possibilities of degradation of microplastics by bacteria. In Chapter 6, overall points of discussion and conclusions are presented, as well as recommendations on how the input of microplastics in the 2 Seas area could be diminished.

We would like to note that this document and the presented data and discussions are preliminary. Many of the points addressed here require future work to be able to come to a more reliable risk assessment of microplastics in the marine environment.

2 Introduction

The accumulation of microplastics (MPs), plastic particles with a diameter smaller than 5 mm, in marine environments has raised health and safety concerns. Because of their small size, MPs are potentially bioavailable to a wide range of marine organisms. Microplastics can be ingested by low trophic suspension, filter and deposit feeders, detritivores and planktivores (Browne, 2008; Graham and Thompson, 2009; Murray and Cowie, 2011; Setälä et al., 2014; Thompson et al., 2004). Because of this, MPs can be transferred through the food web via planktonic organisms from one trophic level to the next (Setälä et al., 2014). Lusher et al. (2013), for example, found microplastics in 36.5% of fish belonging to 10 species sampled from the English Channel, irrespective of habitat (pelagic vs. demersal).

Microplastics can affect the feeding, movement, growth and breeding success of marine organisms. Recently, Wright et al. (2013) reviewed the consequences for the health and susceptibility of marine invertebrates to the physical impacts of microplastic uptake, including the concentrations found in the environment. These small particles do not only have an impact because of their physical effects and if translocated into tissues, particle toxicity, but also contain chemical substances that could be taken up by marine organisms affecting their health and functioning.

There is increasing evidence that MPs may be transferred through the food chain from prey to predator and may eventually lead to bioaccumulation of MPs or associated toxic substances. However, there is currently only limited evidence of transfer of chemicals from ingested plastics into tissues (Tanaka et al., 2013). Effects on the marine food-chain can by extension pose potential risks to human health through the consumption of seafood, and may lead to socio-economic costs.

3 Initial risk assessment: methodology used

In this report, an initial risk assessment of microplastics (MPs) in the 2 Seas/France Manche region is conducted. This is done in a qualitative manner by overlaying the predicted and measured availability of MPs (concentrations and distribution) from model results and field measurements.

The latter were conducted in the MICRO project with harmful concentrations taken from literature and *in vivo* experiments (also conducted within the project under Activity 2) and with information of the presence of aquaculture and touristic activities. The initial risk assessment consists of several steps**:**

- **Modelling MP particles distribution (activity 1):** The microplastics transport processes in the North Sea are modelled using the Delft3D suite software. The model can provide information on accumulation areas in the Interreg region based on hydrodynamics and particle tracking modelling. Here, plastic particles can move horizontally and vertically through the water column, providing information on transport and fate of the MPs. The model can be used for microplastics of different types and sizes, and was validated using data from literature and the field campaigns during the MICRO project. For more detail, please see Appendix A.
- **Sediment analysis (activity 1):** The Institute for Environmental Studies at the VU University (IVM) in the Netherlands has conducted an analysis of the concentrations of MPs in sediments collected by MICRO partners during the 2013-2014 field campaigns. These data were combined with data from literature to assess environmental concentrations of MPs in the Interreg region. Furthermore, ILVO analysed sediment parameters such as grain size and Total Organic Carbon (TOC).
- **Mapping aquaculture (activity 3):** Based on literature survey and contacts via the partners' networks, locations of existing aquaculture and shellfish were inventoried and mapped where possible.
- **Studying effects of microplastics on marine organisms (activity 2):** Based on experimental work conducted under the MICRO project, the effects of microplastics on marine organisms, focusing on oysters and mussels, was conducted. Information from experiments was augmented with additional information from literature. Key species such as the blue mussel (*Mytilus edulis*) and brown shrimp (*Crangon crangon*) were also used to determine microplastics ingestion organisms from the field.
- **Studying presence of chemicals and bacteria on microplastics (activity 3):** Based on experimental work conducted under this activity in the MICRO project, the type of chemical and bacteria associated with microplastic particles and marine litter in the Interreg region was studied. Potential effects on the water quality are also discussed.
- **Potential economic impacts (activity 3):** the possible economic effects of microplastics presence, especially the negative associations consumers of shellfish would have with eating seafood contaminated with plastic particles, were assessed and calculated for the UK case study. A socio-economic cost model (SECRMPs) was made based on data and a number of assumptions (see Appendix B for the complete analysis).

For each case study, the potential hazard is first described. Then, environmental concentrations of MPs are presented, followed by results from literature and our own experiments on the potential effect of MPs on the area of socio-economic interest (i.e. aquaculture, bathing water quality). Potential economic costs were calculated where possible.

4 Case 1: Aquaculture

In the MICRO project, aquaculture is used as a case study to assess the potential risks of microplastics associated with the economic value of the shellfish industry, especially oysters and mussels.

4.1 Description of hazard

Potential effects of MPs on the health and cultivation of oysters and mussels

Due to the similarity between the specific gravity and size of small plastic particles and algae, MPs have the potential to be ingested by filter feeders like mussels and oysters (Brillant and MacDonald, 2000). The ingestion of MPs can cause physical harm to the individual organism and leaching of toxic substances may interfere with its health. For the aquaculture case study, filter-feeders are the most relevant test and field organisms. Additional exposure studies on snails and phytoplankton were conducted within the MICRO project by the various partners and are published separately.

So far, only a limited number of studies have reported negative effects of nano- and microplastic particles on marine aquatic organisms (e.g., mussels, clams and abalones), including the combined effects of toxic pollutants and nanoparticles (Hull et al., 2011). In laboratory experiments, plastic particles were observed to retain in the guts of blue mussels (*Mytilus edulis.* Translocation, i.e. particles passing through cell membranes and becoming incorporated into body tissues with resulting foreign body or particle toxicity, was first looked at in mammals (Hussain et al., 2001). A diverse range of inert particles (including polymeric particles) in the low micro and nano-size ranges have been shown to be absorbed in various mammalian species including humans for the smallest microparticles (see Hussain et al. (2001). There is evidence for transition of MPS from gut to the circulary system and hemocytes in laboratory exposed mussels (Browne, 2008). More recent experimental studies by (von Moos et al., 2012) have shown that high density polyethylene (HDPE) powder (size range> 0-80 µm) are taken up into the cells of digestive tubules and transition into cell organelles of the lysosomal system of mussels. Wegner et al. (2012) found that blue mussels were filtering 30-nm polystyrene from the water and these could result in reduced filtering/feeding activity. The potential human health effects of microplastics are discussed later in this chapter.

In the MICRO project, experiments were conducted with Pacific oysters *Crassostrea gigas*, a species most common in aquaculture in France, to investigate the biological effects of MP on this species. Adult oysters were exposed to a high-concentration mixture of polystyrene MP (2 and 6 µm; 2000 particles mL-1) during two-months under controlled dietary conditions designed to induce the production of gametes (reproductive cells). Details of the study are described in Sussarellu et al. (2014). Overall, digestive modifications and repro-toxic effects of MP in oysters were observed. This means that the digestive tract and reproductive system of oysters was affected by microplastics, at least under laboratory conditions. Average consumption (retention) of microplastics was 20% of 2 µm particles and 85% of 6 µm particles. Effects were also seen in the MICRO project on the ingestion of microalgae, which was significantly higher in MP exposed oysters (Sussarellu et al., 2014). This increased feeding rate is thought to be the result of compensation for a lower energy intake due the high number of particles ingested. Significant negative effects were observed for reproductive features; decreases of oocyte total number (-38%) and relative oocyte size (-8%), as well as a lower sperm velocity (-23%) were observed in MP exposed oysters. Furthermore, the D-larval yield, estimated 48 h post fertilization, was decreased (-41%) in larvae produced from gametes collected in MP exposed female oysters (crossed with spermatozoa collected in control oysters). Finally, larval development was delayed in larvae produced from MP exposed female oysters (-20% larval growth, 6 days-lag of settlement), indicating trans-generational effects supposedly due to MP exposure during prior gametogenesis.

- ➔ This means that oysters exposed to microplastics under laboratory conditions were reproducing less, and smaller reproductive cells, fewer larvae were eventually produced and larval development was decreased. Also, oyster feeding rate increased, possibly to compensate for the lower energy intake when exposed to MPs. It has to be noted that the concentrations at which these effects occurred were much higher than those found in the field (an order of a magnitude of 500 to 1000x compared to known microplastic pollution).

Chronic exposure experiments with juvenile oysters conducted with field relevant concentrations have also been carried out under MICRO. However, the analysis of the results of this experiment is still underway and will be reported separately. A short overview of the preliminary results is provided in Annex C.

- ➔ Long-term experiments with young oysters chronically exposed to field relevant MP concentrations have been conducted under MICRO, but the results are not yet fully available.

Experiments assessing single and combined effects of microplastics and fluoranthene (FLU) in mussels *(Mytilus spp.)* conducted in the MICRO project showed no translocation of 2 and 6 µm polystyrene microplastics from the digestive tract into the circulary system, tissues or cells (Paul-Pont et al., 2014). This means that the plastic particles ingested by the mussels, stay in the gut and digestive tract and do not cross the cell-walls into the mussel tissues. MPs were excreted within 2 days during depuration. However, different effects of fluoranthene, a polycyclic aromatic hydrocarbon (PAH), were observed in mussels as expressed in haemocyte mortality and phagocytosis (cell-death) when exposed alone or in combination with microplastics.

- ➔ This means that microplastics can have a negative impact on the defence system of mussels; contaminated mussels were found to be possibly more susceptible to marine pathogenic agents (virus, bacteria) when exposed to microplastics and a pollutant such as fluorenthene (PAH) combined.

Field samples were taken from blue mussels and brown shrimp, to test the presence of microplastics in organisms fit for human consumption in the Interreg region. This provides an indication of the field concentrations in marine organisms. Here, it was demonstrated that mussels from the supermarket as well as from the 2 Seas coastal waters contain plastic fibres, 2.6-5.1 fibres per 10 g of mussel body (De Witte et al., 2014). Shrimp also contained fibres, approximately 9 fibres per 10 g of shrimp. These plastic particles were all present in the digestive system of these organisms, no fibres were found in the flesh of the organisms (De Vriese et al., 2014, in prep.).

- ➔ Commercially important seafood species, such as blue mussel and brown shrimp, contain microscopic synthetic fibres.

4.1.1 Distribution and concentration of MPs in the environment (field measurements)

Water

International research revealed that all sizes of plastic are commonly found in marine surface waters (Barnes et al., 2009; Ng and Obbard, 2006). Carpenter and Smith (1972) were amongst the first to identify the presence of microplastic in the Sargasso Sea where they sampled the sea surface with a plankton net (333 µm mesh size). Microplastics were present at average concentrations between 0.04 and 2,58 microplastic particles/m^3 with a maximum concentration of 14 microplastic particles/m^3. Forty years later Goldstein et al. (2012) described maximum concentrations and mass of 32.76 particles m^3 and 250 mg/m^3 respectively being recorded in the North Pacific Subtropical Gyre, whereas along a coastal area near a Swedish harbour area adjacent to a polyethylene (PE) production plant, microplastic concentrations of approximately 100 000 plastic particles/m^3 of seawater were found (Norén and Naustvoll, 2010). Such differences in values demonstrate that microplastics concentrations can vary markedly, depending on the area sampled, the methodology and detection level used during sampling (Table 4.1).

Archived plastic samples from the water surface of the west North Atlantic Ocean over the past 24 years have revealed a decrease in mean particle size from 10.66 mm in the 1990s to 5.05 mm in the 2000s using a 335 µm neuston net (Morét-Ferguson et al., 2010). Results from this study highlight an increased prevalence of small plastic particles from the 1990s to the 2000s. Given the continual fragmentation of plastic items, particle concentrations are likely to increase with decreasing size.

Table 4.1 Microplastics concentrations observed in seawater surface samples from the North Sea Area, (CPR: continuous plankton recorder (Leslie et al., 2011).

Sampling mesh size	Occurrence	Location	Reference
North Sea area			
127 mm^2 aperture in the CPR on to a scrolling 280 µm-mesh silkscreen	Microplastics in CPR records increased since 1960, peak: 0.04 - 0.05 fibres/m^3 (1980s).	Samples collected at 10 m over 40-year period on standard shipping routes	Thompson et al. 2004
80 µm	150-2400 particles/m^3	Harbour and ferry locations in Sweden, depth 0-0.3 m	Norén 2008
450 µm	0.01 to 0.04 particles/m^3	Harbour and ferry locations in Sweden, depth of 0-0.3 m	Norén 2008
0.5-2 mm	102,000 polyethylene particles/m^3	Harbour near polyethylene plant	Norén 2008
10-500 µm although method optimal for 10-300 µm	Microplastic fibres in samples same concentration as control (0.2 to 1 particle/L)	Skagerrak, Norwegian South coast	Norén & Naustoll 2011
Continuous Plankton Recorder studies	Microplastics widely detected over the North Atlantic Ocean.	UK coastal areas and North Atlantic Ocean	Edwards et al. 2011

Data on the presence of MPs in the water column of the UK, have been generated in 2014 as part of a Cefas project for Defra (Maes et al., 2012). Surveys carried out between January and March 2011 with three different sampling methods (manta trawl, fishing net and water filter with a fine mesh). The Manta trawl (mesh size 333 µm) proved to be the most effective method, with which a total of approximately 3500 plastic items were collected. Calculations based on the survey indicate that in a worst case outcome, there would be 0.6 x 10^{-3}

particles/litre of sea water. Higher concentrations of MPs were found inshore close to estuaries and the majority of the particles found were fragments (63%) and pieces of thin films (14%).

Detailed information on the composition and distribution of microplastics in the marine environment of the Interreg region is very limited. A field campaign in Belgian waters revealed that from the 28 samples taken, all samples contained microplastics, the majority of which was smaller than 500 µm. Furthermore, water samples taken with a Manta trawl from the Bay of Brest, a complex ecosystem with 3 rivers, with strong urbanization on the north side and characterized by different uses (tourism, aquaculture, fisheries), also revealed that microplastic particles are present in the water column, with mean concentrations ranging from 0,23 particles/m^3 to 0,78 particles/m^3.

- ➔ Results from the MICRO project, supported by findings from literature, indicate that microplastics occur in the waters of the Interreg region. Concentrations vary per location and demonstrate that the smaller particles (<500 µm) are most prevalent. In French waters concentrations range between 0,23 and 0,78 microplastic particles/ m^3

Sediments
Sediment analysis from other studies demonstrate that sediments can indeed act as a sink for microplastics (Andrady, 2011; Ivar do Sul, 2014). Since microplastic particles are thought to eventually end up in the sediment due to ageing, fouling and degradation, this matrix was sampled within the MICRO project. The IVM in Amsterdam conducted an analysis of the amounts and type (fibres, sphere and filaments) found in the sediments of the 2Seas/France Manche region Table 4.2.

Table 4.2 Average amounts of microplastics found per country in terms of number of samples, average fibres/kg dry weight sediment, average spheres/kg dry weight sediment, average fragments/kg dry weight sediment, average total particles, dry weight (% of wet weight), average median grain size of the sediment.

Country	# of samples	Average fibres/kg dry weight	Average spheres/kg dry weight	Average fragments/kg dry weight	Average total particles	Dw (% of ww)	Average median grain size (µm)
Netherlands	11	99	123	0	222	77	290
United Kingdom	5	117	453	0	570	71	260
Belgium	7	302	283	0	585	67	245
France	7	280	412	0	691	64	60

Microplastics particles were detected in the sediments of the MICRO partner countries. The main particles found are fibres and spheres, while fragments were not observed in any of the locations.

Concentrations of fibres range from 97-1934 particles/kg dry weight sediment, with spheres occurring at concentrations of 123-2578 particles/kg dry weight sediment. The spatial variation per location is very high. Analysis of the grain size of sediment particles in these sediments showed that the average median grain size for the French samples was much smaller (approximately 60 µm) compared to that of the other countries (245-290 µm). For more details see (Van der Meulen et al., 2014, in prep.).

Other studies have also demonstrated that the majority of the plastics found in sediment is fibrous microplastics, although most reported studies evaluate beach sediment, rather than seafloor sediment samples (Claessens et al., 2011; Reddy et al., 2006; Thompson et al., 2004).

The results above indicate that the sediments of the southern North Sea in four different countries, are relatively highly contaminated with microplastics and higher concentrations were observed when compared to previous existing microplastic observations for the North Sea water column and sea surface (Claessens et al., 2011; Van Cauwenberghe et al., 2013). This could be explained by the close proximity to highly populated areas, but can also be due to the transport mechanisms and ultimately sinking processes that determine concentrations in the sediment. On average, the highest concentrations of microplastics were found in Belgium and France, which can be explained by the fact that in some locations, for example harbour areas, very high concentrations were found, markedly increasing the average value for that country.

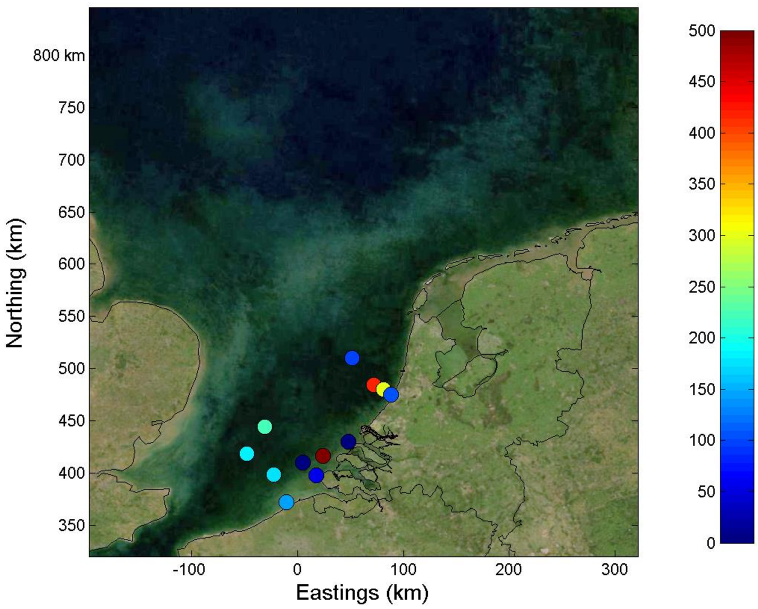

Figure 4.1 Selection of sampling points from the field campaigns carried out within the MICRO project demonstrating the total amount of particles per kd dry weight of sediment.

In the figure above (Figure 4.1), microplastic concentrations are shown on a geographical map. It is clear from the analysis that the concentrations found in the sediments are quite heterogeneous, varying markedly from sampling point to sampling point.

➔ Sediment analyses demonstrate that microplastics are found in all samples in the Interreg region. The particles were fibres and spheres, but no plastic fragments were detected. The average total particles found per country ranged from approximately 200 to approximately 700 particles/dry weight sediment. In some locations a total of 3000 particles/dry weight sediment were detected.

4.1.2 Distribution and concentration of MPs in the 2 Seas environment (model results)

Results from the sediment analysis and values from literature were added to the model to assess the extrapolated occurrence of microplastics in the Interreg region. Particles of different plastic type (PE, PS, PET and PVC with increasing densities) and sizes (10 µm, 330 µm and 5 mm diameter) have been modelled. The main characteristics of the model are described in this paragraph, for details, see Appendix A.

Deltares modelling

For simplification, the shape of all particles has been assumed to be spherical. This assumption has been made in order to develop a robust model, with as little as possible sources of variability. For this type of particles, Stokes law states that the settling velocity is defined in a way which takes into account the density of the fluid, the density of the particles and also the size of the particles. In the model setup, the results demonstrated that density is the main determining factor for the accumulation of plastics, even though size (especially between the 10 µm and that of 330 µm and 5 mm) can also have an effect on the accumulation areas.

Figure 4.2 shows the model result for a simulation at the water surface with polyethylene particles that are lighter than the water density (Dp = 900 kg/m^3). In total there were 5 million particles introduced into the model during a period of 365 days. This number has been chosen as a trade-off between numerical constraints and a pragmatic representation of the real number of plastic particles in the North Sea.

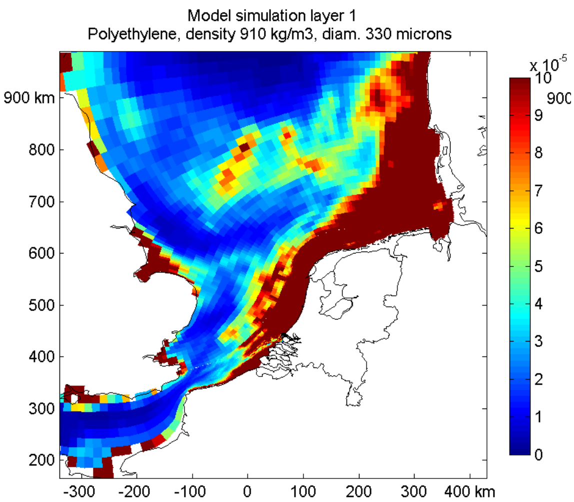

Figure 4.2 Mean plastic concentration of polyethylene (PE), seawater surface; particle density Dp=900 kg/m^3.

Results show that the polyethylene (PE) particles stay at the surface layer and accumulate according to the hydrodynamic transport processes, following the water flow to the North-East (German Bight and Scandinavia). Higher concentrations of particles are found in a broad band along the coasts and lower concentrations are seen scattered all over the North Sea.

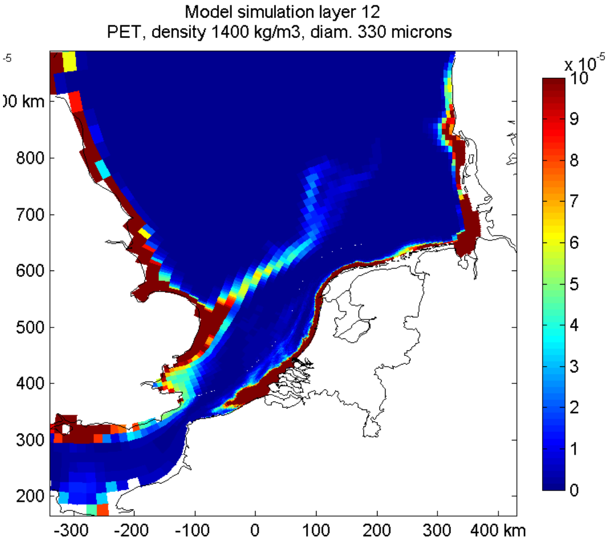

Figure 4.3 Mean plastic concentration for polyethylene therapthalate (PET), layer 12 (sea floor); particle density Dp=1400kg/m³.

Figure 4.3 illustrates the mean particle concentration of polyethylene therapthalate (PET) particles with a density considerable higher than the density of sea water (Dp=1400kg/m³) in the 12th layer of the water column, which is the closest to the sea bed. As PET particles have a high density, these particles settle quite fast towards the bottom and relatively little transport occurs, which means almost all particles settle very close to the land. The concentration of micro plastics is significantly higher close to the coastline and a band, probably following the discharge of the Thames, can be observed.

➔ Settling characteristics of the particles, driven by the density difference between the particle and the ambient water, appear to be a major factor determining where hotspots may occur and/or develop.

Model runs were also conducted with plastics from different sizes. An example can be found in Figure 4.4. Here, it can be observed that there is a slight difference between particles of 10 µm compared to those of 330 µm and 5 mm.

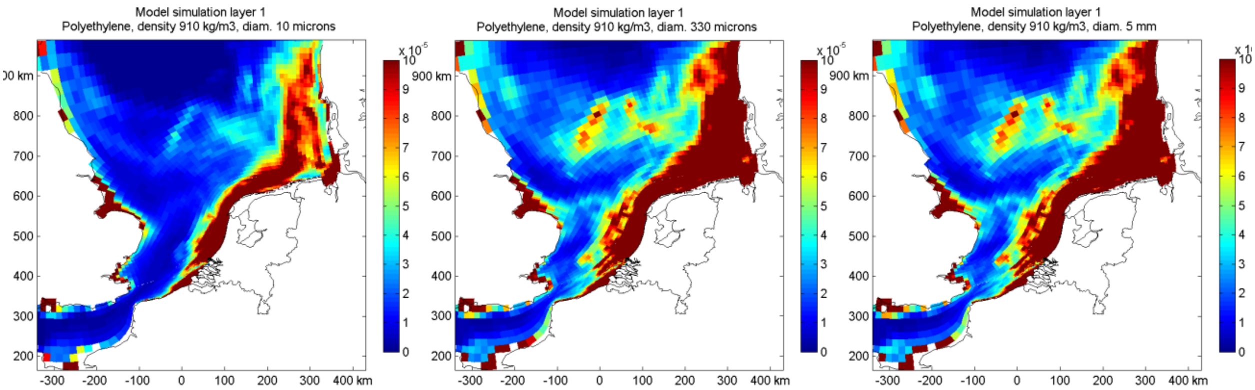

Figure 4.4 Size comparisons with polyethylene (PE) for the layer of the seawater surface. Left = 10 µm, middle = 330 µm and right = 5 mm.

In the analysis of sediment samples from the Interreg region, no assessment was made of which polymer type of microplastics were observed. This means that it is difficult to combine model data with data observed in the field, especially considering the heterogeneous nature of the distribution of MPs observed in sediments in the field. These model runs were a first attempt to demonstrate the processes occurring in the transport of microplastics in the marine environment of the Interreg region. Density in particular seems to be an important factor in the accumulation processes of the microplastics.

- ➔ Model runs show that accumulation areas of microplastics in the North Sea are around the coastal areas and floating microplastics follow the hydrodynamics to the north-east. The heavier particles tend to sink quite quickly and stay in the coastal areas. More runs are needed with a combination of particles with different densities to be able to make a better comparison with the measurements in the field.

Modelling work Cefas

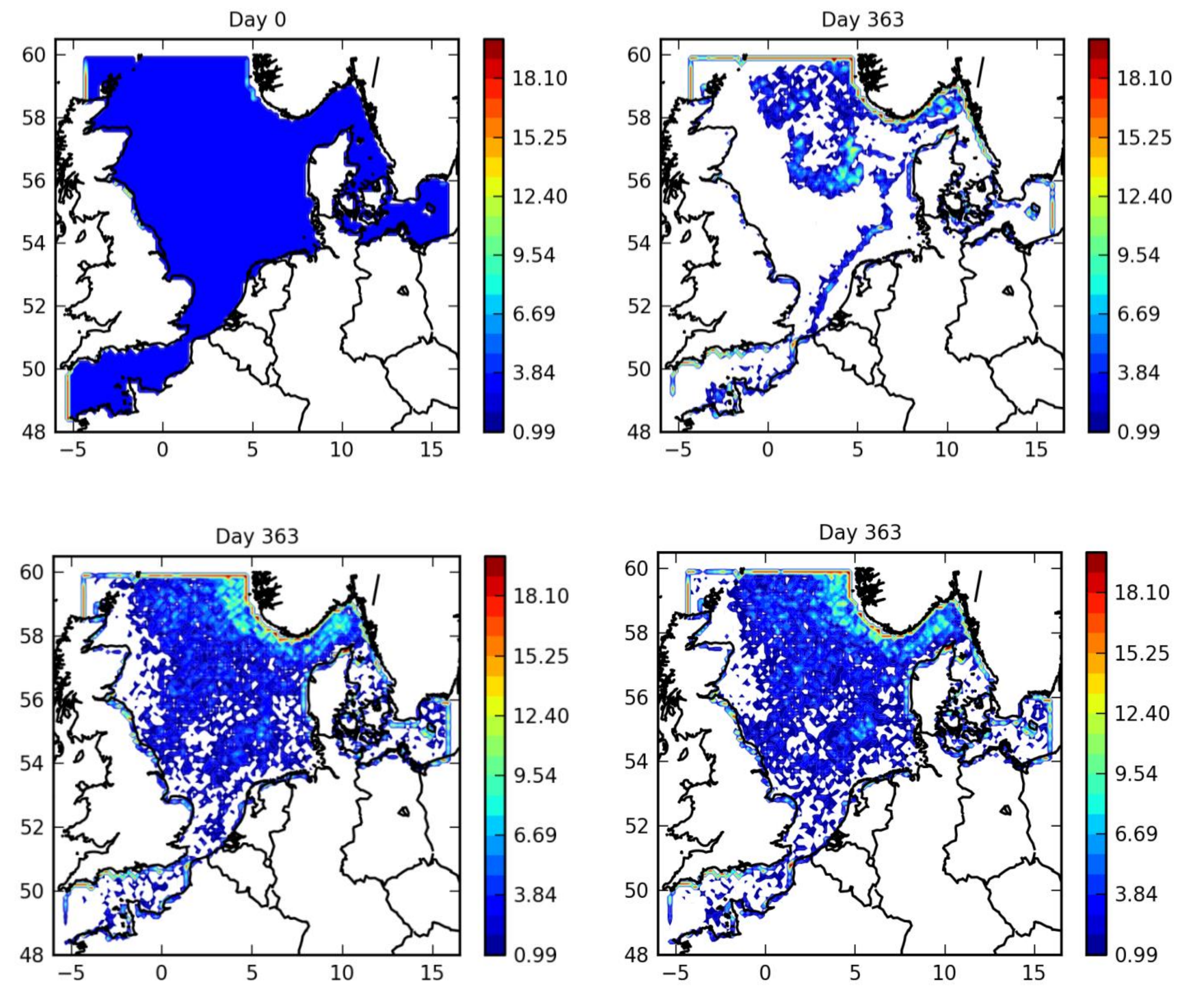

Figure 4.5 Results of instantaneous release scenario: contour plots of number of particles per model grid cell on 30 December 2008. Initial positions, floating particles (1 mm/s), sinking particles (-5 and -20 mm/s).

Some modelling work was also conducted by Cefas, using a different model in which particles were also continuously released from river, but an instantaneous release scenario was also modelled (see Figure 4.5 and Appendix B). The model shows roughly the same results as the Deltares models; the particles stay along the coastline (in this case mainly the UK and Swedish coast) and eventually end up in the North-East part of the North Sea and eventually in the Baltic.

- ➔ Cefas models show roughly the same pattern, with particles staying along the coast (in the UK) and eventually moving to the north-east into Scandinavian waters.

4.2 Presence of oyster and mussel aquaculture in the Interreg region

Netherlands

Figure 4.6 Location of mussel and oyster culture in the Netherlands (source: marchantmosselen.be).

The production of mussels (*Mytilus edulis*) in the Netherlands is a combination of managed fishing and farming activity. Wild mussel seed is fished and spread on natural culture plots to grow after which the stocks are transferred to other locations to ensure a better productivity from the banks by reducing the biomass, or to reach zones more protected from storms. Both the areas or rearing and fishing are in direct connection to the coastal waters and fresh water input, enabling the uptake of MPs (Figure 4.6). The mussel sector produced on average about 350 000 mussel tonnes (35 M kg) in 2012, with an average total auction price of around 175 Euro/100 kg (ProductschapVis, 2014). This means that the sector had a total worth of about 61,25 MEuros in 2012.

Oyster production in the Netherlands is limited but occurs in the same areas as that of mussels; the Oosterschelde and the Wadden Sea. The endemic species of oyster in the Netherlands is *Ostrea edulis*, however, a severe winter in 1962-1963 depleted stocks, after which the exotic Pacific cupped oyster (*Crassostrea gigas*) was introduced for farming purposes. In 2005 total production of Pacific cupped oyster was 3 347 tonnes at a farm gate value of €3.3 million (FAONetherlands, 2014). Most oyster growing companies raise both flat oysters and Pacific cupped oysters.

United Kingdom

The UK, together with France, Spain, Italy and Greece (EUFisheries, 2014) is one of the main aquaculture producers in Europe.

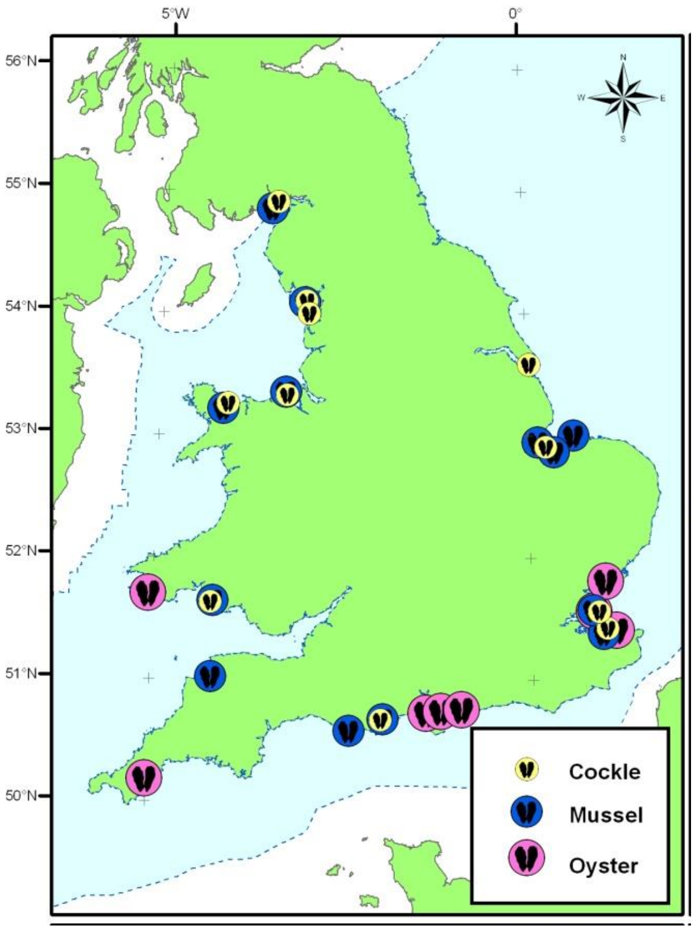

Figure 4.7 Major mollusc centres in England and Wales (source: D. Palmer, Cefas).

Table 4.3 Oyster and mussel landings in tonne excluding Scotland.

Oyster & mussel UK landings to UK excluding Scotland (tonne)									
	2005	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*
Total					288.60	305.89	310.11	241.39	122.27
Native Oyster	56	64	55	44	54	89	302.97	140.76	106.65
Pacific Oyster	428	680	587	598	815	649	80.53	70.86	34.61
Portuguese Oyster					2.35	0.05	1.55	0.005	0.11
Mussels	19544	13,340	13,270	15,025	17,612	12,193	11,497		

The UK shellfish industry is characterised by both wild-caught and cultured shellfish. Important areas for oysters, mussels and cockle are present in the Interreg region, with oysters and mussels as the most important species. The landings for these species have had a total production of over 122 tonnes, mostly consisting of native oysters (Table 4.3).

An analysis of the potential economic impact on the shellfish sector was conducted for the UK (See section 4.3 and Appendix C).

Belgium

In Belgium, oysters are cultured only at the De Oesterput-spuikom in Oostende. The oyster species, *Ostrea edulis* and *Crassostrea gigas* cultured here are called 'Ostendaise' and are reared in the North Sea. The aquaculture in Belgium is quite small in economic terms, and is decreasing; in 2004 more than 700 tons was produced, whereas in 2011 this was reduced to 49 tonnes (Table 4.4).

Table 4.4 Belgian aquaculture production (not only shellfish, but also fish) between 2004 and 2011 (in tons). Source: Rekenhof (2013).

Jaar	2004	2005	2006	2007	2008	2009	2010	2011
Geproduceerde hoeveelheid (ton)	739	414	128	128	126	576	538	49

France

France, together with the UK, Spain, Italy and Greece (EUFisheries, 2014) is one of the main aquaculture producers in Europe.

The production of mussels and oysters in France is mainly based on farming techniques while fishing provides only a minor contribution to the national production of mussels. The aquaculture areas are mainly located in the Atlantic Ocean, with the largest area of spat production at Poitou Charente (see figure 4.8). Brittany, including the Bay of Brest, is also an important area for the oyster production.

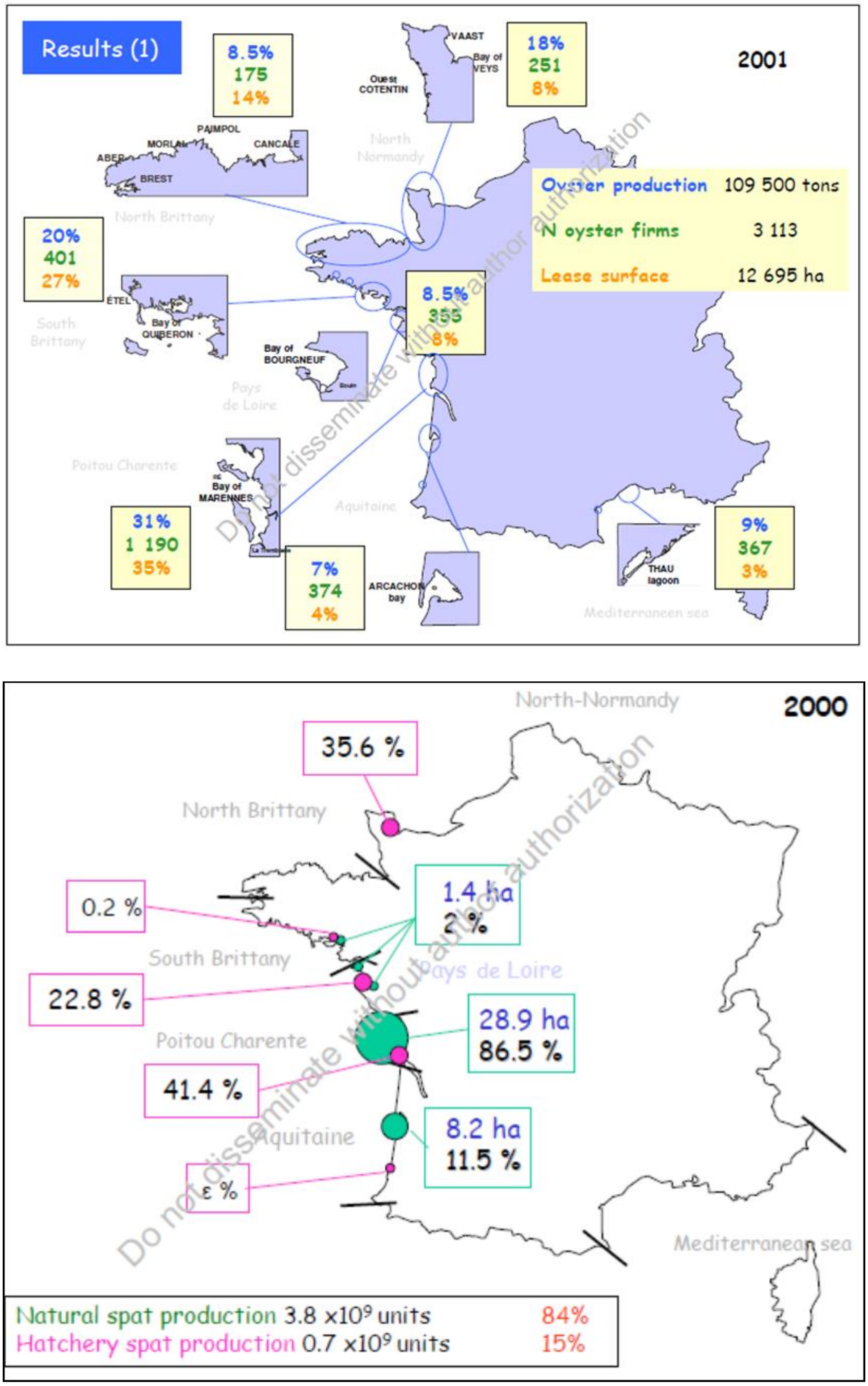

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Figure 4.8 Overview of the different aquaculture regions in France. Figures from Miossec et al. (2005) with permission.

The economic value of the mussel and oyster sector in France is high; in 2006 the oyster sector had a value of 296 million Euro's, producing 130 000 tonnes. Mussels in that same year resulted in a total value of 85 million euros, producing 58 000 tonnes (Table 4.5).

Table 4.5 Volumes of oysters (Huitres) and mussels (Moules) produced (tonnes) and market value (M Euro) in France (Kalaydjian et al., 2008).

	2001	2002	2003	2004	2005	2006
Huîtres	128 500	131 100	129 300	128 500	130 000	130 000
Moules	59 500	64 500	56 000	64 180	58 000	58 000
Autres coquillages	5 100	4 000	3 500	5 000	3 650	3 650
Poissons marins et amphihalins	5 605	6 943	6 748	7 229	7 998	7 998
Poissons marins tropicaux	163	269	342	309	318	318
Crevettes tropicales	1 854	1 860	1 748	2 256	2 439	2 278

Volumes de production dans l'aquaculture marine française. Unité : tonne.

Sources : Ofimer, Ifremer, SFAM, CNC

	2001	2002	2003	2004	2005	2006
Huîtres	238	287	286	289	296	296
Moules	85	91	82	97	85	85
Autres coquillages	17	17	16	23	17	17
Poissons marins et amphihalins	34	40	41	48	51	51
Poissons marins tropicaux	0,9	1,5	2,0	1,7	1,9	1,9
Perles d'élevage	125	124	86	95	108	101
Crevettes tropicales	14	16	13	17	16	13
Écloseries de poissons marins	14	15	17	16	15	14
Écloseries de coquillages	6	8	9	10	12	12

Chiffres d'affaires dans l'aquaculture marine française. Unité : million d'euros.

Sources : Ofimer, Ifremer, SFAM, CNC.

➔ There are aquaculture areas present in the Interreg region, especially in the coastal zones. These areas produce economic revenues, which, depending on the country and area can be in de order of tens of millions of euros per year.

4.3 Potential economic impact on the aquaculture sector in the UK, socio-economic model and cost benefit analysis

Based on data from the MICRO project as well as data available from literature, a Socio-Economic Costs Model for MPs (SECMMPs), was made (see Appendix C and D for more information). The model was based on a bio-economic theory according to the potential economic effects and sectors involved in Figure 4.9.

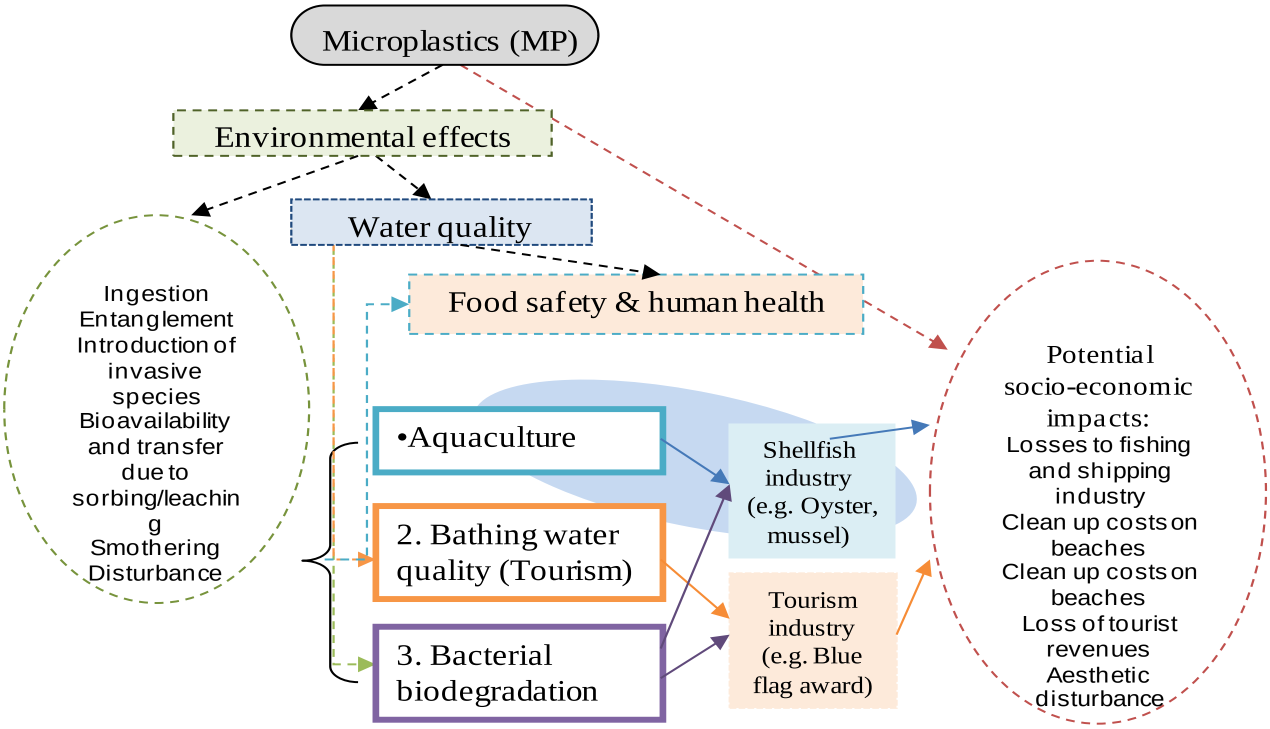

Figure 4.9 Schematic overview of the economic model used to assess the potential economic effects of microplastics UK case study.

The potential economic costs were determined based on the cost in the UK of beach clean-ups, degraded areas negatively affect tourism, damage to motors/fishing gear, shellfish industry including export, decreased housing price, residents of coastal communities, tourists, recreationists, well-being, consumer trust and health and safety (see Appendix B for a more detailed description of the model). Data on the biological effects on shellfish as well as the values of oyster and mussel landings, population size were also included.

Possible health costs as a result of pathogens or chemical substances associated with microplastics were not included. There are currently no studies assessing the economic costs of marine pathogens and diseases for the UK, due to a severe lack of data, e.g., the data availability on the cost of health treatments for each pathogen or the recorded severity from different diseases. The annual human health costs require an estimate of the incidence of disease and a cost per illness - a cost-of-illness model which is widely used by the United States Department of Agriculture's (USDA) Economic Research Service (ERS). For the US case, the combined cost of marine pathogens, *Vibrio alginolyticus* (bacteria causing wound infection) and aerosolised *Karenia brevis* (dinoflaggelate) are $30 million. *V. vulnificu* and *V. parahaemolyticus* (sea-food contamination) cost $350 million, the 5 million cases of gastro related diseases cost $300 million (about 60.80 million of which is made up for 80% of 76 million cases by food-borne diseases and 3.1 million cases are seafood related cases). The Norovirus alone costs approximately $306 million from 300 cases annually. These are an indirect impact on the tourism industry and its employment in coastal regions. All data from (EPA, 2006; Mead et al., 1999; Ralston et al., 2011).

Simulations for the years 2010-2100

The model simulates the potential cost of microplastics between the years 2010 and 2100. It includes the uncertainty in MP concentration in the area and distribution around the regions using simulation techniques on the responses of biological effects on short- or long-term exposure to MPs. This means that the cost estimates would be different with every simulation of the model. Furthermore, because threshold values for the biological effects of MPs have not yet been determined, data on these aspects of the model were based on a best and worst case, including almost no response in shellfish as well as a response similar to that in the experiments.

Table 4.6 Outcomes of model run for the potential economic impact of microplastics shellfish in the UK and the UK part of the Interreg region (£). These values are based on projections for 2010-2100 and must be treated with caution, as they are not predictions.

Scenarios	Low MPs/m^3 surface or L/kg sediment, predicted MPs concentration: Low 3-10 particles (Browne et al 2008, Maes 2014)		High MPs/m^3 surface or L/kg sediment, predicted MPs concentration: High 24-90 particles (Cedervall et al. 2012, Van Cauwenberghe, 2012)	
	~10% decrease	~25% decrease	~10% decrease	~25% decrease
Averaged annual costs from the total of 2010-2100 cummulated costs (£, at 2010 base year discounted at 3.5%)	Low biological response: 10% loss of effects_growth, stability,filtering	High biological response: 25% loss of effects_growth, stability,filtering	Low biological response: 10% loss of effects_growth, stability,filtering	High biological response: 25% loss of effects_growth, stability,filtering
1. Total Shellfish value landed in UK	**59,713**	**9,738,407**	**130,891**	**2,191,583**
2. Total UK Oyster Export	**371**	**78,973**	**3,632**	**7,299**
3. Total Oyster Value landed in the regional samples	**174**	**36,985**	**1,701**	**3,418**
4. Total Mussel Value landed in the regional samples	**2,913**	**618,139**	**28,425**	**5,713**
5. Total UK Mussel Export	**3,221**	**685,936**	**31,543**	**63,396**

Table 4.7 Regional potential total economic costs due to the consequence of MPs. These values are based on projections for 2010-2100 and must be treated with caution, as they are not predictions.

Annual regional costs	**min projection (in £)**	**max projection (in £)**
Oyster	174	36 985
Mussel	2 913	618 139
Beach cleaning	114 685	1 503 661
Sub	117 772	2 158 785
Tourism revenue	1 379 000	496 975 000
Total	**£1 496 772**	**£499 133 785**

These results are just an indication of the range of socio-economic costs that could occur in the UK, and should not be seen as predictions, rather as projections. There is a large difference between the minimum and maximum projection due to the large differences in biological response and thus economic costs associated with microplastics under best and worst case data and assumptions. Depending on the sectors included or excluded, these numbers change.

- ➔ Looking only at the estimated costs to the aquaculture sector in the UK (a proxy value of £300m) would be a broad range between 0.02% and 0.7% per year as a consequence of microplastics due to the uncertainty of the exposure of concentration and duration and the biological/chemical reactions.

The main economic cost (see Table 4.6) does not stem from costs to the aquaculture sector itself, but from the costs of beach cleaning and tourism revenues lost. The assumption here is that due to the negative associations tourists would have with the consumption of shellfish contaminated with microplastics, they would be less likely to visit the area, since one of the attractions for tourists is the consumption of shellfish. This means that measures to decrease the amount of microplastics in shellfish and the marine environment will result in an avoided cost of between £1.5 million and £499 million per year, mainly due to tourism costs (see Appendix C).

- ➔ The implication of the SECMPs model for the UK is that the avoided costs for clean-ups and costs to tourism for the whole region would range between £1.5 million and £499 million per year in 2010-2100.
- ➔ A cost benefit analysis including aquaculture, tourism and clean-ups showed that approximately 250 million pounds can be saved if microplastics were not present in the sea and ocean.
- ➔ There is a marked difference in the socio-economic costs if looking only at aquaculture or looking at aquaculture and other sectors.

Cost benefit analysis for one year

A cost benefit analysis has also been done for one year (see Table 4.8), with and without the different sectors, coming to the following analysis (also see Appendix C).

Table 4.8 Cost benefit analysis of microplastics in the UK case study for one year.

	Minimum cost	Maximum cost
1. Total costs incl. tourism	0.323 m£	507.6 m£
2. Total costs excl. tourism (i.e. oyster + mussel industry)	0.025 m£	4.4 m£
3. Beach cleaning costs	0.7 k£	5.5 m£
4. Total avoidable costs	0.324 m£	514 m£
5. Total costs (1+2)-total beach cleaning costs (3)	0.32 m£	503 m£

Vulnerable areas in the UK

The model also shows which areas are the most vulnerable to microplastics in terms of socio-economic costs. In the UK, Hampshire & Isle of Wight region are important oyster regions, Dorset is an important region for mussel aquaculture and Devon and Norfolk (on the Northern border of the Interreg region) receive many tourists every year coming especially for the beaches which makes them vulnerable, also in terms of corresponding employment. The economic costs in these areas can therefore be higher than the average costs in the whole of the UK.

➔ Some areas in the UK are more vulnerable to socio-economic costs due to their dependency on aquaculture or revenues from tourism.

4.4 Risk assessment of microplastics to aquaculture

It should be noted that the risk assessment of microplastics in the marine environment, including their impact on commercially important species, is still in the hazard characterisation phase due to limited information on exposure levels and established effect levels. Rationale policy measures are difficult to develop give the current incomplete and uncertain risk analysis, indicating that more work is needed in the future to come to a scientifically sound program of measures for microplastic litter.

Aquaculture

Within the MICRO project, data were obtained on the presence of MP in the near shore water and in sediments (Van der Meulen et al., 2014, in prep.). Sampling of the water column demonstrated that, at least in Belgium and France, microplastics are present at the sea surface. All over the Interreg region, microplastic particles were found in the upper layers of the seafloor sediment, providing an indication of the environmental concentration to which shellfish are exposed. Sediment from hotspot locations, like estuaries, contained up to 3000 particles/kg dry weight sediment.

Based on the model runs, in the Dutch part of the Interreg region, heavier particles such as PET show high concentrations in the Dutch Delta area and to a lesser extent in the Eastern Wadden Sea. Especially the Delta area is the region in which the Dutch mussel and oyster culture is concentrated. Mussels harvested in the Wadden Sea are transferred to the Delta area and remain there until harvested for consumption. For the UK, the model shows high concentrations in the Wash and the mouth of the river Humber. Both areas belong to East Anglia which is an important region for British aquaculture. In Belgian coastal waters, the model does show relatively low concentrations of microplastic particles present, however the field measurements show that microplastics are prevalent in sediments close to the coast. For France, the model shows concentrations of heavier particles at the mouth of the rivers Seine and the Somme.

Experiments within the MICRO project demonstrate that all test organisms are able to ingest microplastics. Under high concentrations of microplastics in the laboratory, effects can occur in oysters, mussels and fish larvae in terms of increased filtering capacity, negative effects on cells playing an important role in the immune system of oysters, negative effects on the reproduction of oysters (also trans-generational), negative effects on settling time of oyster larvae, negative effects on survival of sea bass larvae (Mazurais et al., 2013; Paul-Pont et al., 2014; Sussarellu et al., 2014). Furthermore, there is an overlap in production sites for aquaculture and the occurrence of MPs, meaning that microplastics could become available for ingestion in target species as mussels and oysters. Although effects of the ingestion of MPs on these bivalves have been described, the threshold values that lead to significant effects have not yet been described in detail, since to date little range finding has been done. Furthermore, the observed densities of MPs that induce effects in the experiments have not been observed in the field; the experimental concentrations used are many orders of magnitude higher than the field concentrations. In organisms sampled in the field, mostly fibres are found (De Vriese et al., 2014, in prep.; De Witte et al., 2014), suggesting that the shape of the plastics can affect the intake by marine organisms and their fate inside of the organism.

Mouat et al. (2010) studied the economic costs of marine litter to harbours in the UK, and found that a total of 2.4 MEuros each year was spent on cleaning up the harbour area, with an average of around €8000 per harbour. The overall conclusion of the research was that UK municipalities spend approximately 18 MEuros each year removing litter from beaches. In the Netherlands and Belgium this number is slightly lower, approximately 10 MEuros per year, see Mouat et al. (2010) for more details. Findings of the economic costs in the MICRO project for the aquaculture sector in the UK show a large range of uncertainty, depending on whether low or high concentrations and impacts were used. These range between 0.02% and 0.7% of the total value of the aquaculture sector per year. When the costs of clean-ups and the potential loss of revenues from tourism are included, the socio-economic costs are markedly higher. This can mainly be explained by the wide range of uncertainty included in the economic model, as well as by the fact that our calculations are for future developments between the years 2010 and 2100.

There is a hazard to the aquaculture sector in the Interreg region, however, whether there is a real risk is at the moment hard to assess. It is to be expected that the amount of MP in the environment in the coming years and decades will further increase 1) because of the increasing global production and consumption of plastic materials and 2) because of the fact that the existing macrosized plastic litter will eventually break down to increasingly smaller particles 3) because of the development and application of new products using primary micro and nanoplastics and nanoplastic technology. So far, the production of plastics has not significantly dropped, nor has the amount of plastic litter decreased. Because of weathering the already existing small particles will be further degraded to smaller particles leading to the already observed decrease in average particle size. Following the precautionary principle, one could argue that efforts should be made to reduce the amount of microplastics present in the Interreg region, to reduce potential impacts on ecosystem and human health.

Possible effects on human health

Fibrous microplastics are found in shrimp and mussels in the field, and for the latter also in individuals purchased at a supermarket. Van Cauwenberghe and Janssen (2014) extrapolated that Europeans consuming shellfish would be exposed to approximately 11000 microplastics particles/year. Our findings within the MICRO project suggest that intake could be a factor 2 higher for shrimp, since we find twice as many fibres per 10g of shrimp. In the case of shrimps, the intestines are removed prior to consumption, therefore the exposure of humans to microplastics through shrimp consumption is probably less than through the consumption of shellfish. Although it is evident that humans are exposed to microplastics through their diet and the presence of microplastics in seafood could pose a threat to food safety, our understanding of the fate and toxicity of microplastics in humans constitutes a major knowledge gap. Humans can be exposed to microplastics not only through commercial marine food products but also those of terrestrial origin, such as honey and sugar (Liebezeit and Liebezeit, 2013) and beer (Liebezeit and Liebezeit, 2014). Drug delivery and occupational exposure research have demonstrated that polyethylene microparticles (e.g. 150 µm) can also be absorbed by the gastro-intestinal lymph and circulatory systems of exposed humans (Leslie et al., 2011). Preliminary research indicates that nano-sized polystyrene particles (up to 240 nm) can enter the human blood stream and can cross the human placenta, possibly exposing the developing foetus to these particles (Wick et al., 2010). Plastic particles from the nm to the low µm range are likely to be absorbed by human tissue should exposure to nano- and microplastics arise and may cause particle toxicity (cell damage, inflammation and fibrous granuloma formation) in certain tissues. Therefore, an analysis and assessment of the potential health risk of ingested microplastics for humans should comprise dietary exposure from a range of foods across the total diet in order to assess the contributing risk of contaminated marine food items.

Risks to human health through consumption of contaminated shellfish appears to be limited, mainly due to the fact that shellfish are purified in ‘clean’ seawater prior to being sold. Questions can be raised as to how ‘clean’ this purified water is, however, since microplastics were found in mussels purchased in a supermarket. Even though it could be argued that microplastics may still be present in this purification water (except when filtered on a very small mesh), concentrations can be expected to be lower than in the field. However the uptake and fate of ingested microplastics in humans is still unknown and deserves special attention. Following the precautionary principle one could argue that efforts should be made to reduce the amount of microplastics in the Interreg region from a human health perspective.

Perception of risks

There is increased attention in the media for plastics, and to some extent also MPs, as an important global pollution issue. Even though there is still little to no evidence of direct impacts of MPs to seafood production in terms of economic value, nor for human health, the idea of ingesting MPs is not an attractive one. The presence of MPs in shellfish may influence the (public and/or regulatory) acceptance of shellfish products and certainly this will be an issue if harmful bacteria are found to reside on MPs. Therefore, the knowledge of the ingestion and of MPs by shellfish, apart from the physical and or toxicological impacts to the organisms themselves, could affect the perception of consumers of shellfish as a delicacy. This could lead to avoidance behaviour of consumers even before adverse effect have been scientifically proven. Little is known about the perception of ‘polluted’ shellfish in terms of microplastics.

Based on a limited number of interviews conducted as part of this study, it seems that in the Netherlands microplastic contamination is currently not seen as a threat by the shellfish producers. The food safety of the product is standard under stringent control aspects and regular monitoring of the water quality in undertaken as part of the standard quality assessment procedures. The industry itself is involved in studies on how to minimise their contribution of plastic into the marine environment from equipment and structures used for larval catchment.

Main conclusion of the effects of MPs on aquaculture

There is hazard of microplastics to the aquaculture sector in the Interreg region due to overlap in the areas in which microplastics occur and where aquaculture is conducted. Under high concentrations of microplastics, effects can be observed in mussels and oysters that could affect economic revenues. The extent of these economic consequences increases if beach cleaning is included and if tourism revenues decrease as a result of a perceived risk by consumers.

5 Case 2: Coastal water quality, bathing water

In recent years, the certification of environmental quality through eco-labels has become increasingly common. Among these, the Blue Flag Award (BFA), used as a label of good bathing water quality, has emerged as one of the most successful eco-labels since its first implementation in 1987. In order to obtain the BFA, several criteria must be met. In 2010, the Blue Flag Program revised its criteria for bathing water quality (following the 2006/7/EC Directive revoking 76/160/EEC Directive). The award is given for the following bathing season with the condition that the site will be monitored for compliance with BFA criteria (FEE, 2014). The total number of BFAs varies each year as new sites are awarded, or as old sites are removed. The latter case is often perceived as an indicator of declining water quality that might lead to a reduction in the number of visitors. The Blue Flag Award is strongly dependent on faecal bacterial thresholds.

5.1 Description of hazard

Microplastic contamination in coastal areas

Recent studies showed relatively high concentrations of microplastic particles in coastal sediments (Browne et al., 2011; Claessens et al., 2011). A recent inventory of the presence of microplastic particles in beach sediments across six continents revealed that MPs were present on all beaches with a tendency towards fibrous shapes (Brown, 2011). Bacteria potentially concentrate on MPs and therefore harmful bacteria might survive longer in marine coastal ecosystems as heavier MPs tend to accumulate close to input sources from e.g. rivers (see model results Case 1) and stay close to the coast. This could impact the water quality of coastal waters and increase the risk to human health. The focus of this case study is on bathing water quality, in particular the potential socio-economic consequences of microplastics on this quality and by extent on tourism.

It is thought that sewage-effluents are an important source for contamination of the marine environment with microplastics. A study by Browne et al. (2011) looked at microplastics on shorelines worldwide. Beaches located close to densely populated areas were contaminated with more microplastic than those further away from human populations. Beaches near sewage disposal sites had 250% more microplastic fibres - mostly polyester (78%) and acrylic (22%) - than beaches further from disposal sites, even though sewage had not been discharged at the disposal sites for over a decade. These results illustrate that MPs are accumulating on beaches and shorelines, and therefore must be present in coastal waters.

With an expected high residence time at sea, coastal waters and sediments, degradation of the MPs will be enhanced, which will result in an increased surface exposure and potentially concentration of bacteria. Especially in shoreline environments a prolonged exposure to UV light and physical abrasion will lead to photo-degradation and abrasion due to wave action and sediment movement (Barnes et al., 2009; Gregory, 1977; Thompson et al., 2004). Different types of microplastics (PS, PE, PP, etc.) occur in the environment and can degrade and age during their high residence time in the seas and oceans. This degradation makes them more susceptible to leaching and adsorption of chemicals.

Chemicals associated with microplastics in the field

Within the MICRO project, chemicals and micro-organisms on plastic litter in the marine environment were assessed through a screening on different types of plastic (synthetic monofilaments, hard plastic and plastic sheets) and beach pellets. Plastic items were collected from a beach in Oostende, Belgium and marine litter from Oostende, Zeebrugge and Nieuwpoort (Belgium)

More than 450 different chemicals were observed in the plastic material collected. Most of the observed chemicals are derived from the production of plastic itself, and other chemicals may be adsorbed from the surrounding environment. A first group of compounds identified by the screening consists of the chemicals used in the production process of plastics and additives, and the degradation products of plastics and additives. Most additives such as UV-stabilizers (e.g. benzophenone and octabenzone) and antioxidants may cause irritation to skin, eyes or the respiratory tract. Some additives such as bisphenol A, alkylphenols and phthalates are xenoestrogens and may act as weak endocrine disruptors. Some antioxidants such as BHT (butylated hydroxytoluene), stabilizers such as hydroquinone and dyes (toluidine) may even cause chronic mutagenic or carcinogenic health effects. Most compounds related to plastic or plastic production (branched alkane/alkene, alky, chloro-alkane/alkene) are mainly causing irritation to skin, eyes or the respiratory tract. Several additives such as optical brighteners (stilbene), dyes (toluidine), hydroquinone and BHT are harmful to aquatic organisms. Besides, a lot of identified plastic related compounds are relatively unknown and as a consequence, no information on the risks or toxicity is available (Gauquie et al. in prep.).

It has been suggested in literature that marine litter or microplastics may act as a vector for additives through the marine environment (Cole et al., 2011). Another large group of chemicals encloses petrogenic and pyrogenic compounds, mainly represented by the polycyclic aromatic hydrocarbons (PAHs) and the alkylated monocyclic and polycyclic aromatic hydrocarbons. Marine litter may also be a vector for chemicals present in the marine environment, adsorbing on the surface and in the cracks of the plastic pieces. So far, exposure experiments with persistent organic pollutants (POPs) adsorbed on microplastics within the MICRO project revealed only a small uptake of these chemicals by Norwegian lobster fed with PCB loaded microplastics (Devriese et al., in prep.). This could indicate that strongly adsorbed chemicals are not easily released by the plastic while it is passing the digestive tract of organisms and as a consequence the effect may be minimal. Pathogenic organisms living on plastic may even cause larger risk to ecosystem or human health if the immune barriers of the infected organisms aren’t able to prevent pathogens from entering into blood or lymph.

- ➔ Over 450 different chemicals were observed on marine litter and beach pellets collected in the Interreg region. These substances can be harmful to marine organisms as well as humans. Exposure experiments within MICRO demonstrated that only a small part of the PCBs loaded to microplastics were taken up by Norwegian lobsters. It is unclear however which role digestive enzymes play in the leaching process to the tissues.

5.2 Bacteria associated with microplastics in the field

Plastic items are not only 'mini sponges' for all kinds of toxic products, but also provide a habitat for a variety of marine bacteria. This phenomenon is thought to be more important than the associated chemicals (Koelmans et al., 2013). Information on the marine bacteria able to colonize the surface and cracks of plastic litter is limited (Zettler et al., 2013). The bacterial communities on plastic litter, microplastics and sediment were identified using Next Generation Sequencing (NGS). A high bacterial biodiversity was observed on beach pellets and especially on marine litter (Figure 5.1) indicating that micro- and nanoplastics function as a vector for bacteria through the marine environment.

At the moment, more than 150 different bacteria species are identified on microplastics by the MICRO consortium, of which no well-known pathogens are diagnosed. Nevertheless, potential pathogens identified on marine litter (see Figure 5.1) are *Bacteroides thetaiotaomicron* (infections), *Escherichia coli* (fecal contamination, infections), *Shewanella putrefaciens* (open lesions, sepsis), *Bacillus cereus* (diarrhea)**,** *Bacillus thuringiensis* (Bt-toxin)**,** *Aliivibrio wodani* (open lesions), *Stenotrophomonas maltophilia* (infections), *Pseudomonas anguilliseptica* (septicemia) and *Escherichia fergusoni* (open wound).

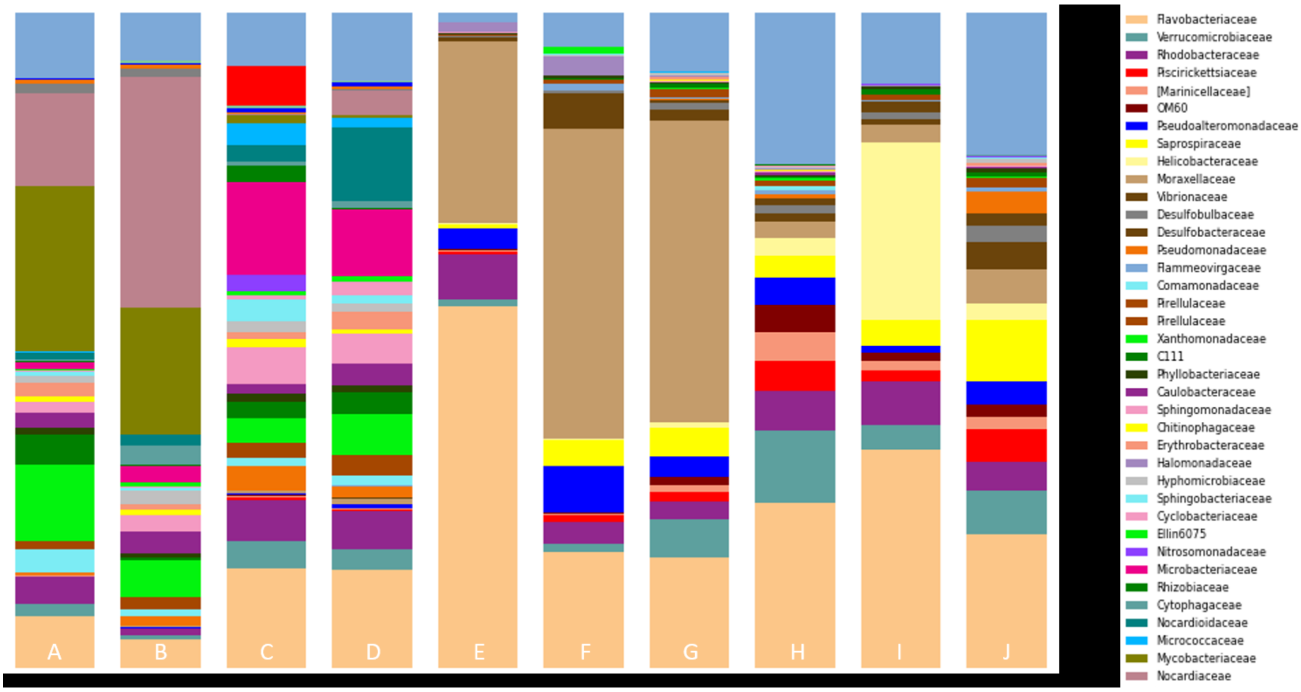

Figure 5.1 Bacterial families found after amplicon sequencing (NGS) demonstrate the high microbial biodiversity on beach pellets (A, B, C, D) and marine litter (E, F, G, H, I, J). (Caroline De Tender et al. unpublished work).

Considering the marine ecosystem, extra attention must be paid to collateral effects caused by plastic related chemicals or bacteria colonizing the plastic debris or microplastics. This is not only relevant for human health, but also for example for shellfish health. *Vibrio*, a well-known pathogen for adult oysters has also been found on the plastics assessed in the field. A short exposure experiment with oysters in which *Vibrio aestuarianus*, a pathogenic bacteria for adult oysters, was loaded to microplastics, showed that *Vibrio* has been found in the haemolymph of oyster that was infected (bathing) with a mixture of 6 µm polystyrene MP colonized by the *Vibrio* bacteria and other free bacteria. Therefore, MP may act as a potential vector of pathogenic bacteria that remains to be studied in the field.

- ➔ Plastic is a substrate for bacteria floating or drifting through the marine environment. Potential pathogens for humans and shellfish were found on the plastic pellets and marine litter sampled from the field in the Interreg region. Field analyses have been conducted up to genus level if possible.

5.3 Risk Mapping

A short analysis of the Blue Flag Program website (BlueFlagProgram, 2014) demonstrated that Blue Flag beaches occur in the Interreg region for all of the partner countries. The Blue Flag label is closely linked to water quality, including presence of *E. coli*.

5.4 Risk assessment of microplastics on bathing water quality

Results from our experiments demonstrate that chemicals and microorganisms occur in and on microplastics, however, well-known pathogenic bacteria were not observed within the MICRO project. Bacteria associated with diseases, such as *E.coli* were found on the microplastics studied. However, the amount of specific bacteria on microplastics has not yet been quantified, nor have bacteria been determined down to species level. This makes it hard to compare concentrations on the plastic material with background concentrations in the beach environment. This means that it is not possible to state whether or not microplastics contain more microorganisms than are present in the environment itself, and therefore a risk assessment as to the added risk of microplastics in the beach environment cannot be made. There is an overlap between areas in which microplastics and their associated chemicals and microorganisms occur and areas that are attractive to tourism.

Apart from the associated direct health risk, the presence of such bacteria might also interfere with the certification of environmental quality under the Blue Flag Program. Losing this international certification for a following bathing season is often perceived as an indicator of declining water quality and might result in a reduction of the number of visitors. This is projected to have socio- economic consequences to the local community who largely depend on these visitors for their income. A study on the socio-economic aspects of the Blue Flag Program was conducted in 2012 in Portugal. This study demonstrated that the number of visitors to the beach was strongly correlated with the cumulative effect of the Blue Flag Award and the available surface area and beach type, leading to an expected increase of visitors, employment and population after 5 years (Guimarães et al., 2012).

The potential impact of microplastics on the bathing water quality and the consequence of reputational risk to Blue Flag beaches was calculated with the SECMMPs model and may cost between 0.09% and 3.4% of the UK tourism revenue of selected coastal regions with a business-as-usual tourism revenue of £14.75 billion per year (see Annex B). The beach cleaning costs in the selected coastal regions in the UK due to the concentration of MPs are projected to be a range between £115k and £1.5m per year which reflects £0.45 and £0.94 per person (Stickel et al., 2012).

Main conclusion of the effects of MPs bathing water quality

There is hazard of microplastics to bathing water quality in the Interreg region due to the chemical substances and potentially pathogenic microorganisms found on (micro-)plastic items on the beach and on marine litter. The extent of the economic consequences to tourism in the UK ranges between 0.09 and 3.4% of the revenues of the tourism sector per year.

6 Case 3: Degradation of MP by bacteria

Larger plastic items in the marine environment can fragment into smaller micro- and nano-scale plastic particles, especially in areas with high UV irradiation and physical abrasion by waves. Biological degradation could also play an important role (e.g. by bacteria or fungi) in terms of cleaning up existing plastics in the environment, since this process would lead to complete degradation. This might provide a solution to mitigate the MP problem in the Interreg region. In the MICRO project, marine litter and beach pellets were screened (using advanced NGS-techiques-Next Generation Sequencing) for bacterial communities able to colonize plastic litter.

Despite the fact that most of the currently known polyethylene (PE) degrading micro-organisms were observed in a soil environment, a few bacterial and fungal strains of marine environments show potential to degrade PE beads. Lobelle and Cunliffe (2011) showed that after three weeks exposure of PE bags to a marine environment, a microbial biofilm is formed, indicating the presence of micro-organisms that could live on, and possibly degrade, the PE. According to this information two marine bacteria, *Arthrobacter* sp. and *Pseudomonas* sp., were isolated that were able to break down high-density PE in *in vitro* conditions (Balasubramanian et al., 2010). Also fungi isolated from sea water were capable to grow on a medium where low-density PE was the sole carbon source. These fungi were identified as *Aspergillus* spp. and the remark was made that these could be used in bioremediation (Pramila, 2011).

Using Raman spectroscopy and FT-IR, the beach pellets investigated during the MICRO project and used in this study could be identified as PE beads. In general PE is known for being a remarkably resistant polymer to degradation, whereby in general the process of PE degradation by micro-organisms is very slow, making degradation of this plastic in natural environments very hard (Restrepo-Flórez et al., 2014). Most of the organisms that show degradation of PE, are isolated from soil environments. Restrepo-Flórez et al. (2014) gave an overview of the bacterial and fungal strains that are associated, until now, with PE biodegradation. These strains are listed in Table 6.1.

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Table 6.1 Bacterial and fungal strains associated with polyethylene biodegradation.

Bacterial strains involved in PE degradation		**Fungal strains involved in PE degradation**	
Genus	**species**	**Genus**	**Species**
Acinetobacter	*Baumannii*	*Acremonium*	*Kiliense*
Arthrobacter	*Spp.*	*Aspergillus*	*Niger*
	Paraffineus		*Versicolor*
	Viscosus		*Flavus*
Bacillus	*Amyloliquefaciens*	*Chaetomium*	*Spp.*
	Brevies	*Cladosporium*	*Cladosporioides*
	Cereus	*Fusarium*	*Redolens*
	Circulans	*Gliocladium*	*VIrens*
	Halodenitrificans	*Mortierella*	*Alpina*
	Mycoides	*Mucor*	*Circinelloides*
	Pumilus	*Penicillium*	*Simplicissimum*
	Sphericus		*Pinophilum*
	Thuringiensis		*Frequentans*
Brevibacillus	*Borstelensis*	*Phanerochaete*	*Chrysosporium*
Delftia	*Acidovorans*	*Verticillium*	*Lecanii*
Flavobacterium	*Spp.*		
Micrococcus	*Luteus*		
	Lylae		
Microbacterium	*Paraoxydans*		
Nocardia	*Asteroides*		
Paenibacillus	*Macerans*		
Pseudomonas	*Spp.*		
	Aeruginosa		
	Fluorescens		
Rahnella	*Aquatilis*		
Ralstonia	*Spp.*		
Rhodococcus	*Ruber*		
	Rhodochrous		
	Erythropolis		
Staphylococcus	*Epidermidis*		
	Cohnii		
	Xylosus		
Stenotrophomonas	*Spp.*		
Streptomyces	*Badius*		
	Setonii		
	Viridosporus		

To identify possible biodegrading microorganisms on the beach pellets within the MICRO project, amplicon sequencing was used. In general a few bacterial families and genera were found to be abundant on the pellets and could play a role in biodegradation. Two strains of the suborder *Corynebacterineae* could be potential degraders of the PE pellets or of the pigments where the pellets were coated with. Generally these strains were found in higher abundance on colored microplastics than on white or black pellets. Further research needs to be done on these strains to confirm their degrading ability (De Tender, 2014, in prep.).

Main conclusion of bacterial degradation of MPs
Potentially biodegradable bacteria have been found on microplastics in the Interreg region. These strains need to be further studied to confirm their ability to degrade plastic materials.

7 Final considerations and recommendations

Considerations per case

Case 1: There is overlap between the areas where relatively high concentrations of microplastics are present (i.e. coastal areas) and areas in which aquaculture is conducted, indicating a potential hazard of microplastics for this sector. MPs are also found in seafood in the field. Under high concentrations of microplastics, mussels and oysters show a response in terms of decreased reproduction and immune system responses. Results of chronic exposures of young oysters to environmentally more realistic microplastic concentrations will become available later this year. An economic analysis demonstrated that there are potential costs associated with microplastics to the aquaculture sector in the UK. If tourism and beach cleaning are included, these costs are markedly higher, with a very broad range of uncertainty.

Case 2: For the bathing water quality, the presence of chemical substances and microorganisms on microplastics was confirmed in our research. This includes potential pathogens to marine life (i.e. *Vibrio*) as well as humans (i.e. *E. coli*), indicating that there is a hazard of microplastics in this area. It is too early to say whether microorganisms and chemicals are present in higher concentrations on the microplastics than in the environment itself.

Case 3: For the degradation of microplastics, some promising species were observed in our field study. It is too soon to tell however, whether these bacterial strains are actually suitable for cleaning the environment from (micro-)plastics.

General considerations

Based on the MICRO project there is a socio-economic hazard of MPs in the Interreg region. This hazard, based on results from the aquaculture and bathing water quality studies indicate that there is also a potential hazard for human health. Models and field studies have indicated the coincidence of microplastics and aquaculture areas, and seafood sampled from the field and supermarkets contain microplastics. Furthermore, bathing quality can be affected by the presence of potential pathogens, including pathogens for aquaculture species. The preliminary socio-economic model indicates potential economic costs associated with microplastics and an avoided cost if microplastics were not present in the Interreg region.

In general, the risk analysis of microplastics in the Intereg region is currently incomplete and uncertain due to limited information on exposure levels and established effect levels. Rationale policy measures are therefore difficult to develop. It seems however, that cleaning up of the microplastics that are already present in the marine environment is an impossible feat due to the wide spread of these particles in riverine, estuarine and marine systems as well as the technical limitations to filtering out only plastics, without also removing important organisms in the food chain. Degradation by bacteria could be a potential solution.

The conclusions from the MICRO project should be used as a foundation for further research to better assess the risks of microplastics in the marine environment.

In the MICRO project, we have found that:

- ➔ Models provide valuable large scale information on transport trends and can help focus monitoring questions within the framework of the MSFD, even though many unknowns remain and more data from the field and experiments are needed to provide a full validation;
- ➔ Beach cleaning can aid in reducing fragmentation of macroplastics, thereby diminishing the input of microplastics into the marine environment and reducing the risk of microplastics acting as a vector for chemicals and/or potential pathogens;
- ➔ The socio-economic model developed within MICRO is a useful tool in quantifying the hazard of microplastics to certain sectors and should be further developed and applied;

We propose that future Interreg projects include the following topics:

- ➔ Primary (engineered) nanoplastics are an emerging issue in the marine environment, and are more and more perceived as a separate, even more hazardous, group of plastic particles due to their specific effects associated with their physical properties. Little is known about the occurrence and effects of these nanoplastics however, since the detection levels in the environment are at a µm range. The first studies imply that these could have more extensive effects than microplastics, mainly because of their ability to cross cell-membranes and thus enter tissues and the stronger sorption of environmental contaminants such as POPs.
- ➔ The freshwater environment is perceived as a transport route for plastic particles from land-based sources. Little quantitative information is available on the extent to which, for example rivers, add to the plastics problem at sea. Such studies should be conducted on a catchment area basis, and could also include the role of lakes and groundwater.
- ➔ Further study on the effects of the exposure of marine organisms to microplastics should be conducted looking at chronic exposure of marine organisms using field relevant concentrations. Also, experiments should be conducted with fibrous plastics, since these are, next to spheres, mostly observed in the field as well as in marine organisms.
- ➔ Further study on the potentially biodegradable bacteria identified should be conducted, since this would provide opportunities for clean-ups. Of course any potential risks of such measures should be well studied prior to their execution.
- ➔ Further raising awareness on microplastics in the environment and seafood is of importance as well as the further studying of potential risks of microplastics to humans.
- ➔ Threshold values for ‘acceptable’ microplastic levels in the environment could be set up (as part of the implementation of the Marine Strategy Framework Directive), however, more research is necessary into what these values could be. Also, there are possible downsides to threshold values, for example that concentrations are allowed to rise up to the level of the threshold value, even if they were initially far below this level. Therefore, relative change in microplastic level in relation to a baseline would be more advisable, to ensure that microplastic levels do not increase over time.

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A Appendix A: modelling method described (Deltares)

The Delft3D modelling software has been developed by Deltares and consists of a unique, fully integrated computer suite for multi-disciplinary modelling of coastal, river and estuarine areas. It can carry out simulations of flows, sediment transports, waves, water quality, morphological developments and ecology. Delft3D is composed of several modules, grouped around a mutual interface, while being capable to interact with one another. In this study the hydrodynamic Delft3D-FLOW module is linked with a particle tracking module, denoted Delft3D-PART (Deltares, 2014a, b) .
Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary fitted grid. The hydrodynamic conditions (velocities, water elevations, density, salinity, vertical eddy viscosity and vertical eddy diffusivity) calculated in the Delft3D-FLOW modules are used as input for the PART module. The PART module simulates transport and simple water quality processes by means of a particle tracking method using the (2 or 3-dimensional) flow data from the FLOW module. The particle tracking is conducted using the PART Tracer module that simulates conservative or first order decaying substances. The present work extends the Tracer module to enhance improved modelling of the microplastic particles in the North Sea.

The position of every individual particle can be influenced by:

- advection (transport by water flow)
- diffusion/dispersion (random component)
- settling (including sedimentation/erosion characteristics)

The advection of the particles is driven by the results of an existing validated hydrodynamic model of the North Sea (Deltares, 2013).

Since no data is available on the settling characteristics of the plastics, it is assumed that the settling follows Stoke's settling velocity, which means that the plastic particle is a sphere and that the settling depends on the density difference between the particle and the ambient water, the particle's diameter and the viscosity of the water. It is also assumed that there is no interaction with the seabed and that the particles remain in suspension and do not get immobilised in the bed.

For this type of particles, Stokes law states that the settling velocity is defined in a way which takes in to account the density of the fluid, the density of the particles and also the size of the particles:

$$V_s = \frac{2}{9}\frac{\left(\rho_{particle} - \rho_{fluid}\right)}{\mu} g R^2$$

Equation 1 Settling velocity of particles according to Stokes, where:

V_s – Settling velocity
$\rho_{particle}$ – Density of the particles
ρ_{fluid} – Density of the sea water
μ – Dynamic viscosity
g – Gravitational acceleration.
R – Radius of particle

As the purpose of the model is to predict particle transport via particle tracking, it is necessary to define the quantity of particles introduced in the model. With this scope, continuous release points corresponding to the main river estuaries have been defined (Figure A.1).

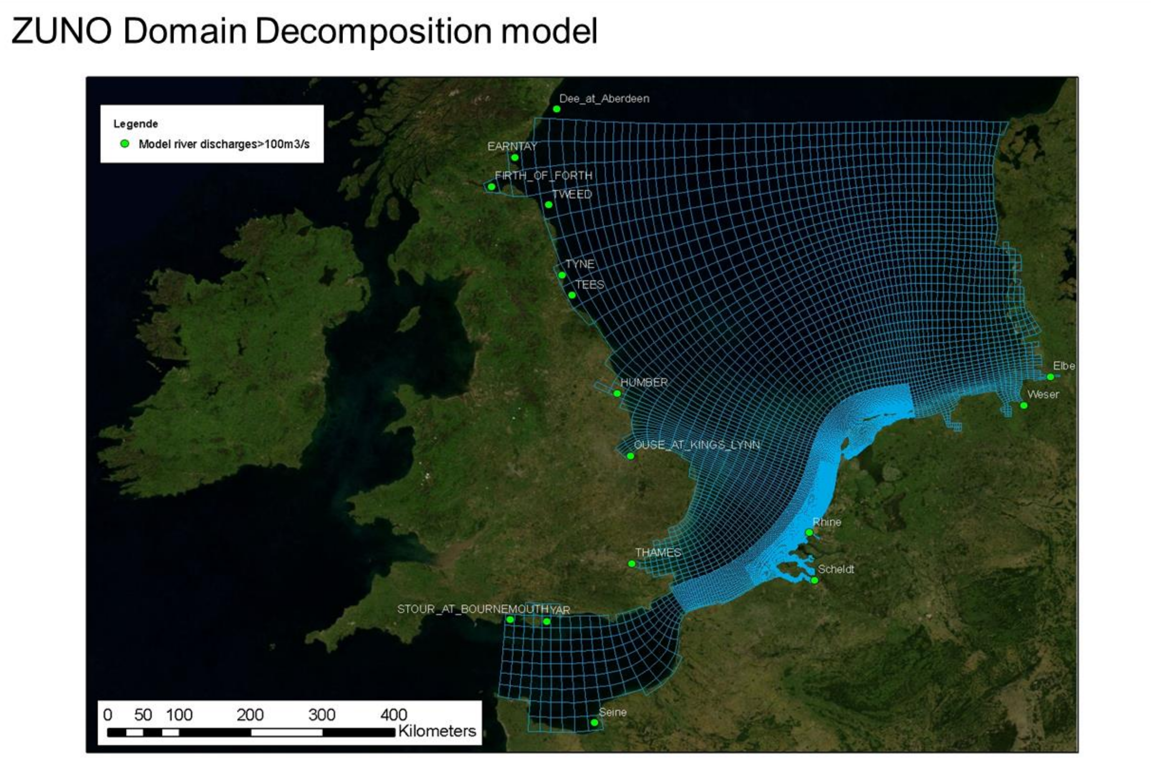

Figure A.1 Release points.

Also, the plastic incoming from rivers has been divided between each of the rivers by percentages according to the following table:

Table A.1 Plastic allocation per river.

	River name	Percentage
1	Dee_et_Aberdeen	1.1
2	EARN	0.7
3	Elbe	14.7
4	Firth_of_Forth	1.9
5	Humber	8.3
6	Ouse_at_kings_lynn	2.1
7	Rhine	33.9
8	Seine	10.4
9	Scheldt	3.2
10	Stour_at_bournemouth	0.4
11	Tay	4.2
12	Tees	1.2
13	Thames	3.1
14	Tweed	1.9
15	Tyne	1.7
16	Weser	9.3
17	Yar	1.8
18	*TOTAL*	*100*

In this first study the model does not account for aging of the plastic, which leads to fragmentation (leading to reduction of the particle sizes), degradation and changes in bulk density of the particle (due to for example algal or bacterial growth or interaction with sediments). The transport routes of four plastic types are predicted, their densities are given in the table below:

Nr.	Name	Chemical formula	Density Dp [kg/m3]
1	Polystyrene	$(C_8H_8)_n$	1050
2	Polyethylene	$(C_2H_4)_nH_2$	880-940
3	Polyvinyl chloride (PVC)	$(C_2H_3Cl)_n$	1100-1450
4	Polyethylene terephthalate (PET)	$(C_{10}H_8O_4)_n$	1380-1450

On average, the density of sea water is 1024 kg/m^3. Therefore, the particles having a density lighter than water will float to the surface and accumulate according to the hydrodynamic transport processes. On the other side, the particles having a density higher than the density of sea water should settle down towards the bottom layer of the model.

An important aspect in the modelling is the uncertainty and the variability in the characteristics of different types of plastic materials. This was accounted for by assuming a normal distribution on the size of the plastic particles which will in turn result in different settling velocities. Details are described in El Serafy et al. (2014).

Microplastics can be introduced in the model either by instantaneous releases (such as an accidental ship discharge) or continuous releases (together with river input, taking into account temporal variation). In this project, 17 continuous discharges are considered, representing the main rivers entering the North Sea. The number of particles flowing from the rivers to the sea is proportional to the river inflow. Also the particles are released at the surface layer. The rivers Rhine, Seine and Elbe are modelled as having the highest three discharge rates.

The above method allows predicting plastic hotspots that can be associated with a certain probability (for example high concentration of particles, high number of particles, and residence time in the water column). This information can be further used to for example design risk maps, based on separate or combined criteria.

B Cefas modelling work (Cefas)

B.1 Introduction

Computer models can be used to investigate scenarios of litter dispersal in the marine environment to complement and inform field work, and to investigate the potential effects of management decisions. Here, a particle tracking model, coupled to a hydrodynamics model, was used to obtain initial model estimates of litter dispersal patterns in the North Sea for litter with a number of assumed, schematic buoyancy properties, and two assumed, schematic release scenario's. The results provide useful first insights into potential litter dispersal patterns, and are used to formulate more detailed model experiments to be carried out in subsequent stages of the project and to inform field work.

B.2 Material and Methods

B.2.1 Model description

The model consists of the 3D hydrodynamic model GETM (www.getm.eu, Burchard & Bolding, 2002) and an Individual Behaviour Model (IBM) for particle tracking (General Individuals Tracking Model, GITM). Three-dimensional flow fields were stored every hour by the hydrodynamic model, and used off-line by the IBM to calculate particle advection and diffusion.

GETM solves the shallow-water, heat balance and density equations, and was run on a spherical grid covering the North Sea with approximately 6 nautical mile horizontal resolution and with 25 layers in the vertical. The model was forced with realistic winds, temperature and humidity data derived from the ECMWF operational reanalysis obtained through the British Atmospheric Data Centre (badc.nerc.ac.uk). The open boundaries were forced with tidal elevations and depth-averaged velocities derived from a barotropic shelf-wide model setup using Flather boundary conditions (Flather, 1976; Carter & Merrifield, 2007). The shelf-wide model was forced with tidal elevations derived from gridded harmonic constituents based on Topex Poseidon satellite altimetry. Moreover, the open boundaries were forced with depth-resolved climatological boundary conditions for temperature and salinity based on the World Ocean Database (www.nodc.noaa.gov). Fresh water was introduced into the model at 132 river mouth locations based on observations from the National River Flow Archive (www.ceh.ac.uk/data/nrfa/index.html) for UK rivers, the Agence de l'eau Loire-Bretagne, Agence de l'eau Seine-Normandie and IFREMER for French rivers, the DONAR database for Netherlands rivers, ARGE Elbe, the Niedersächsisches Landesamt für Ökologie and the Bundesanstalt für Gewässerkunde for German rivers, and the Institute for Marine Research, Bergen, for Norwegian rivers (see also Lenhart et al., 2010).

The IBM GITM includes particle advection and diffusion, and biological development and behaviour. The advection-diffusion elements of GITM were based on a re-coded version (Nagai et al., 2003) of the lagrangean advection-diffusion method developed by Wolk (2003). The method uses a semi-analytical advection method, which ensures that particles follow stream lines exactly, and a random walk method with advective correction (Visser, 1997) to simulate diffusion (Hunter et al., 1993), which uses a constant diffusion coefficient in the horizontal and a variable diffusion coefficient in the vertical that is based on the vertical diffusivity obtained from the turbulence closure model in GETM.

The biological development and behaviour module of GITM allows particles to progress through a user-defined number of egg and larval development stages. For the litter particles used here, this was reduced to simple floating or sinking behaviour.

B.3 Model setup and experiments

Two types of litter particle tracking runs were carried out:

1. releasing a steady stream of particles from the open boundaries and river mouths (1 particle released from each location every 2 days, 45756 particles in total)
2. instantaneous release of particles uniformly distributed over the model domain (3 particles released in every grid cell on 1 January 2008, 20835 particles in total)

Type 1 was intended to obtain first estimates of dispersal patterns for particles from potential sources. Type 2 was intended to identify potential accumulation areas.

For each type of model setup, a number of runs were carried out with different vertical particle velocities, selected from: 0 mm/s (neutral particles, representing water particles), 1 mm/s (positively buoyant, located near surface), -1, -5 or -20 mm/s (negatively buoyant, located near the bottom).

B.4 Validation

Particle tracks of the first batch of particles released in the type 1 experiment (steady release from sources) were compared visually with tracks of ARGOS floats (courtesy Liam Fernand, projects **). Results show good qualitative agreement (Figure B.1 and Figure B.2). A more detailed inter-comparison involving model runs with particles released to specifically simulate ARGOS drifters with long tracks are planned for FY12/13.

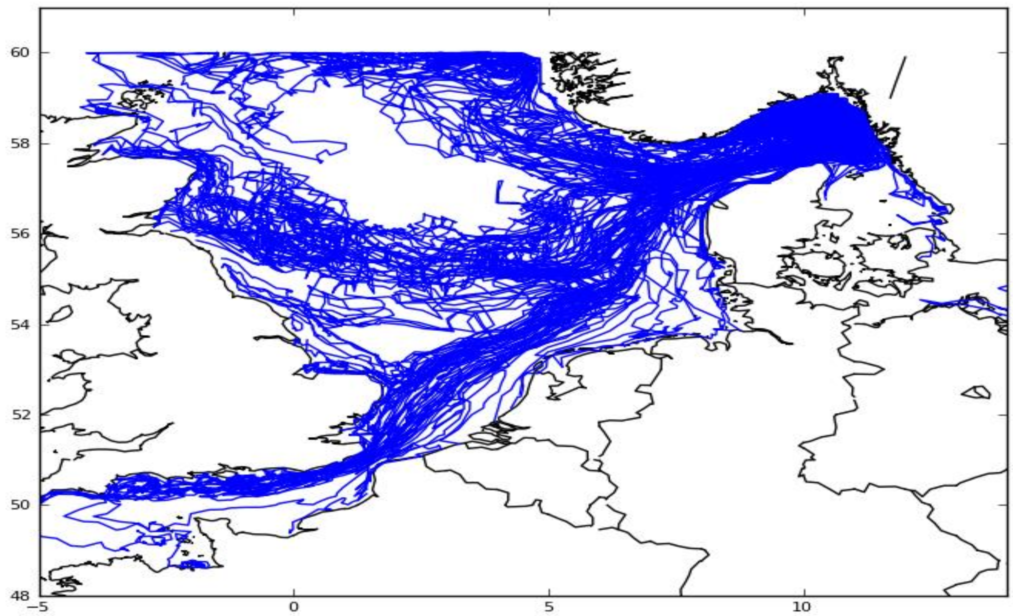

Figure B.1 Tracks of particles released at river mouths and open boundaries 1 January 2008 to 30 December 2008.

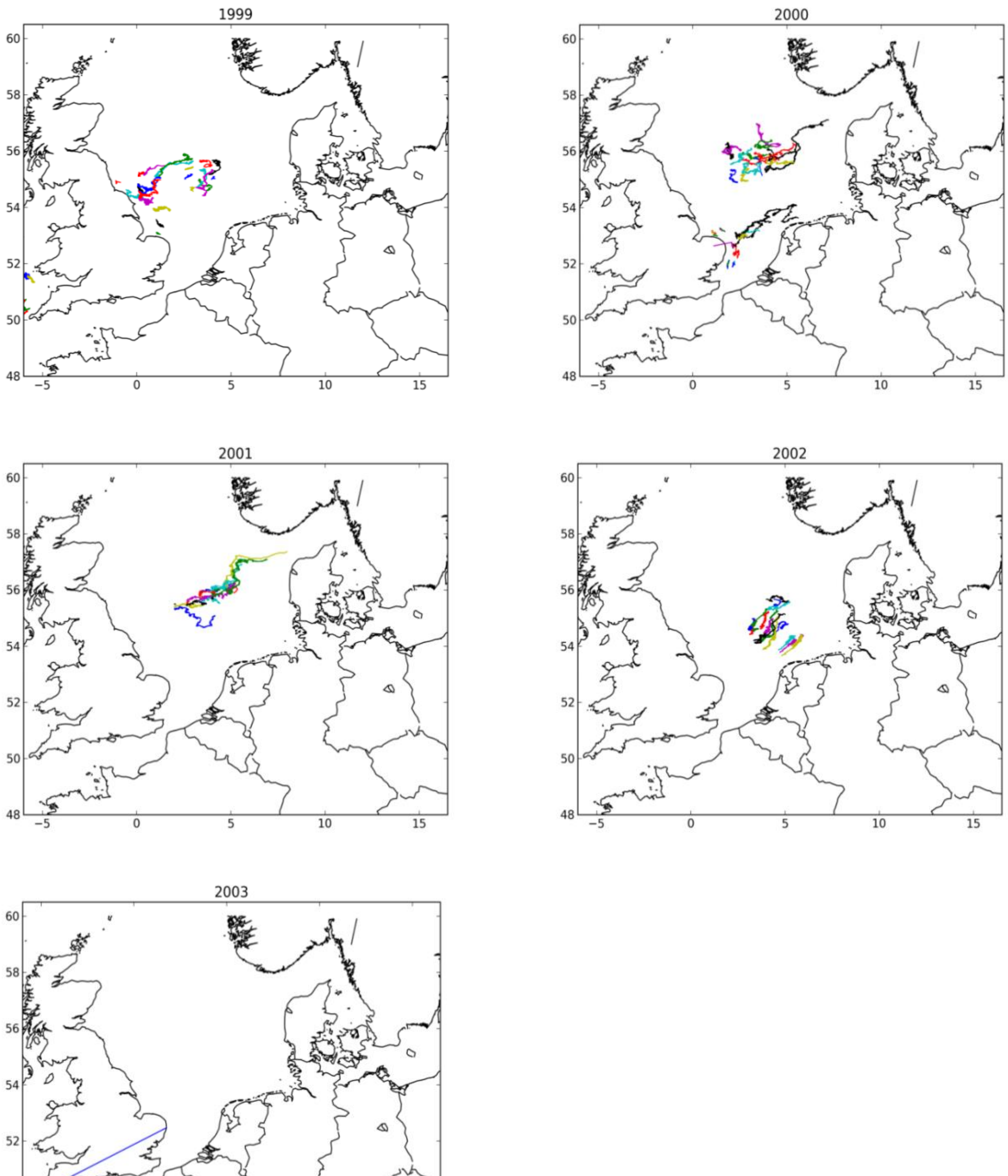

Figure B.2 ARGOS drifter tracks. (Data provided courtesy of Liam Fernand, Cefas).

B.5 Results

In the following, the results of the particle tracking runs are presented as contour plots of the number of particles per grid cell of the hydrodynamic model at the end of the model runs (30 December 2008). This method of representation was chosen over particle tracks (as in Figure B.3) or particle positions; as such types of plots would get cluttered for the high number of particles used here.

B.6 Steady release

Results for the steady release case showed strong similarity in the particle distribution on 30 December 2008 for neutral and sinking particles, with particles present in a broad band along the coast and absent in the central North Sea. In these results, the magnitude of the concentrations should not be interpreted as a realistic reflection of reality, as all the sources of particles in the model had equal intensity. This assumption is not realistic, as the oceanic boundaries are probably a very weak source, whereas the intensity of riverine sources of litter is likely to be a function of runoff and population density. Model runs with scaled intensity of riverine source will be carried out in FY12/13. The magnitude of the sinking velocity did not appear to have much influence on the results. The results for floating particles, however, were distinctly different, with more pronounced, smaller scale features. It is inferred that these are associated with stratification, in particular salinity and temperature fronts. Floating litter has been observed to concentrate in frontal areas (Barnes et al., 2009). The current results suggest that the model captures this behaviour. This will be analysed further in FY12/13.

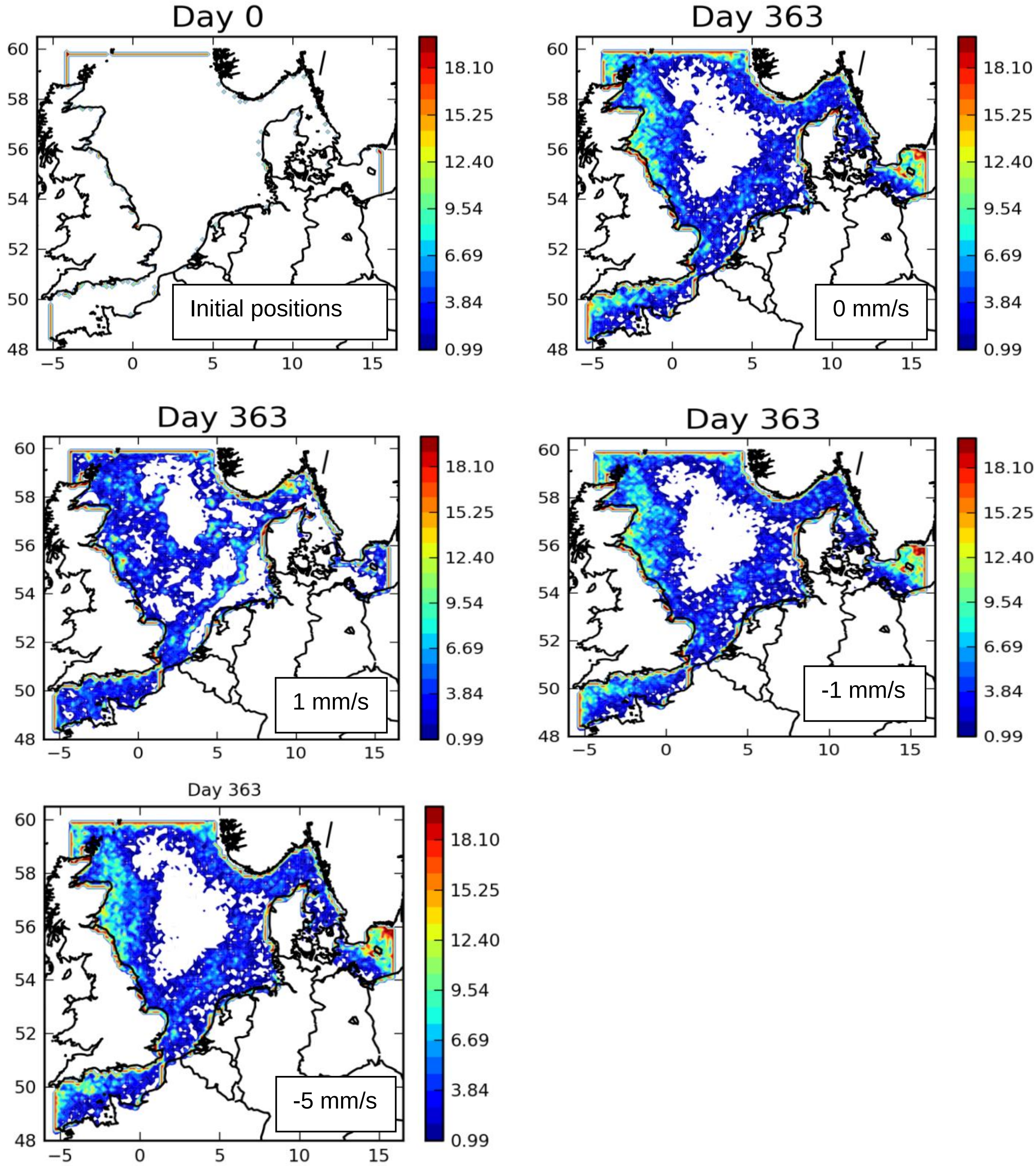

Figure B.3 Results of steady release scenario: contour plots of number of particles per model grid cell on 30 December 2008. Initial positions, neutral particles (0 mm/s), floating particles (1 mm/s), sinking particles (-1 and -5 mm/s).

These results can be decomposed into contributions from individual rivers, or groups of rivers in the same geographical area. As an example, this was done for some of the OSPAR eutrophication model assessment areas .3(Humber, UKC2, and Thames, UKC1, Figure B.4 and B.5, see also Lenhart et al., 2010). The results showed that a substantial proportion of particles beached within approximately 200 km from the source.

The remaining particles dispersed as well-defined river plumes, the location of which could be different for floating and sinking particles, in particular in areas where summer stratification occurs (central North Sea). Also, floating particles were transported further away from the source than sinking particles.

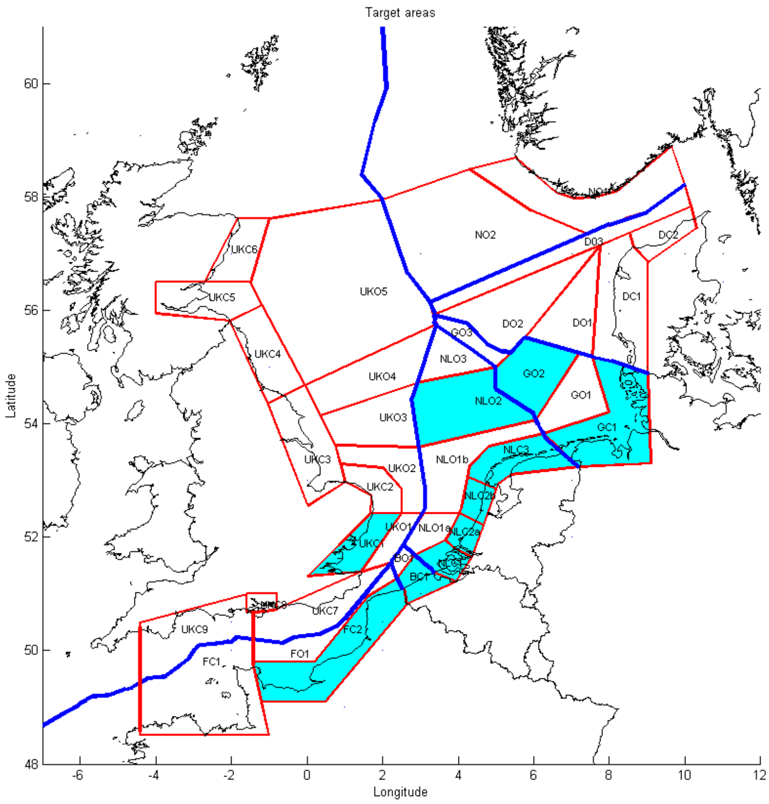

Figure B.4 Areas used within OSPAR to assess eutrophication using models, used here to group rivers.

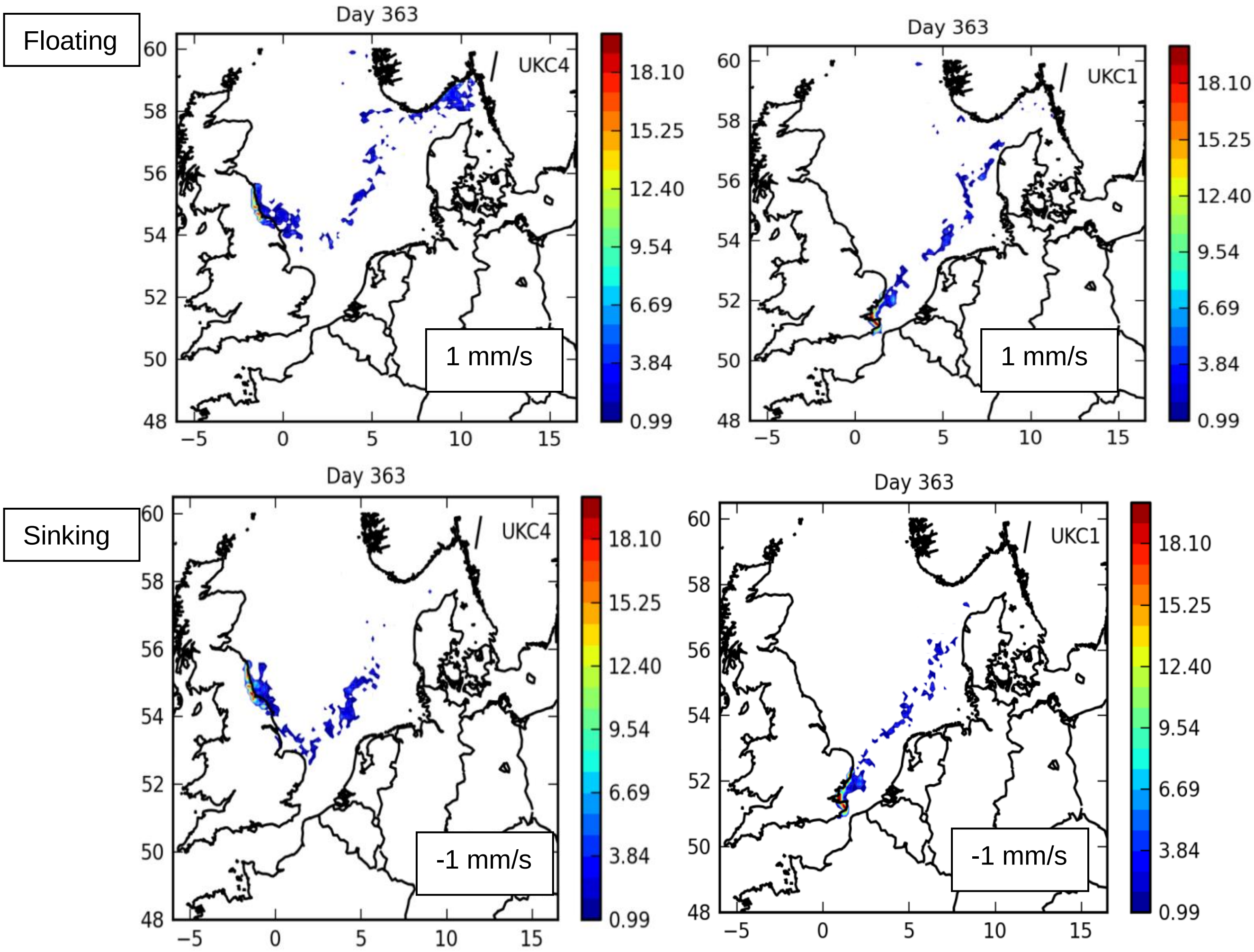

Figure B.5 Pattern of contributions by groups of rivers from Humber (UKC4, left) and Thames (UKC1, right), for floating (top) and sinking (bottom) particles.

B.7 Instantaneous release

Results of the uniform, instantaneous release experiment showed (Figure B.6), for floating particles, beaching on the Channel, Norfolk, Danish and Scandinavian North Sea coasts, accumulation in the frontal zone separating the continental Region of Freshwater Influence (ROFI) from more saline waters, as well as accumulation in the central North Sea and Skagerrak. For sinking particles, the final distribution was more diffuse, with accumulations in the Oyster Grounds, the central North Sea and in particular the Norwegian Trench. Again, the results were not sensitive to the magnitude of the sinking velocity.

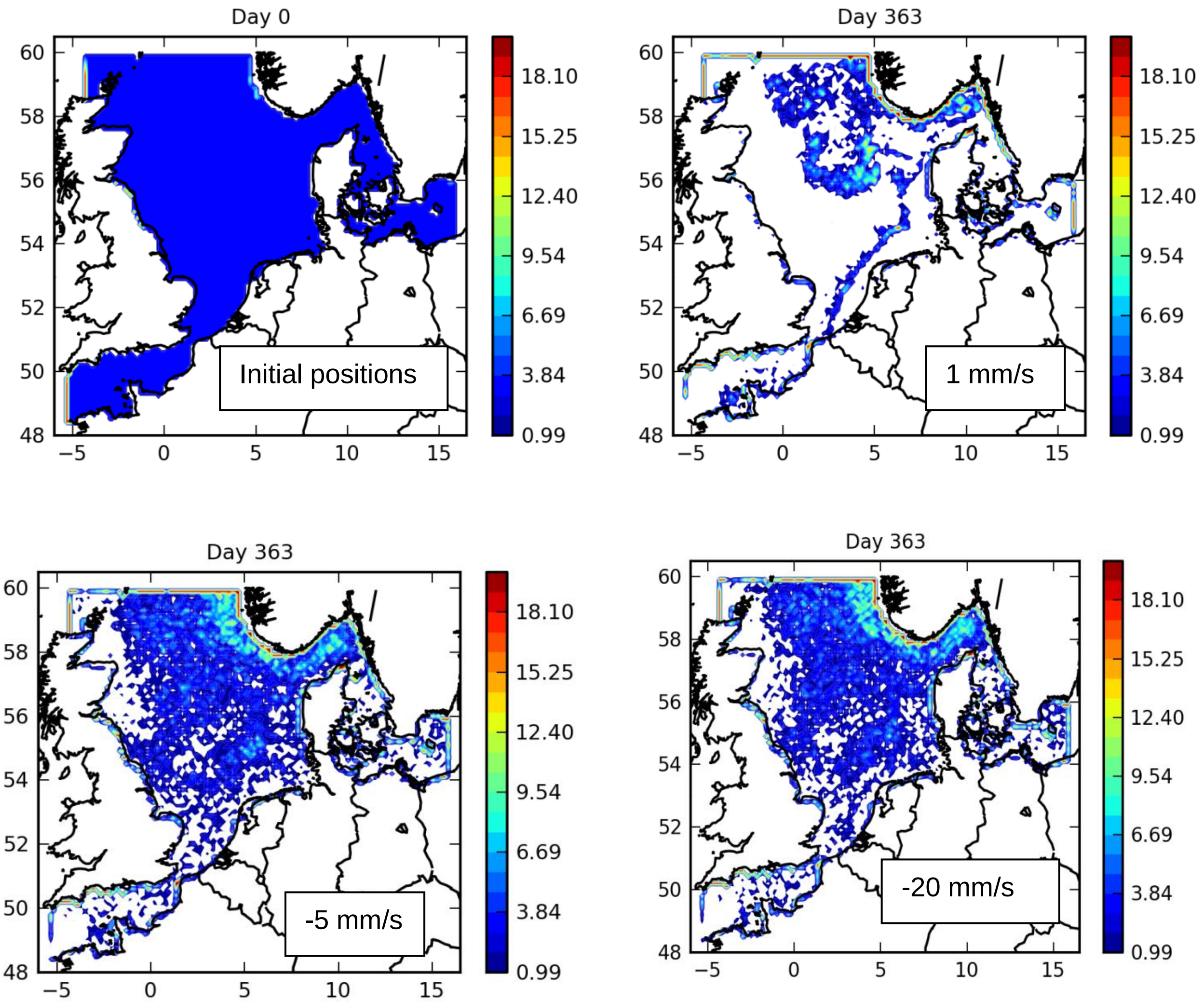

Figure B.6 Results of instantaneous release scenario: contour plots of number of particles per model grid cell on 30 December 2008. Initial positions, floating particles (1 mm/s), and sinking particles (-5 and -20 mm/s).

B.8 Discussion and conclusions

Visual comparison of modelled particle tracks with ARGOS drifter observations from several years indicated good agreement, which gives some confidence in the litter simulations. This validation should be carried further by simulating the ARGOS drifters specifically, and comparing the modelled dispersal quantitatively. This work is envisaged for FY12/13.

A substantial proportion of the particles beached within approximately 200 km from the source. This result suggests that large sources can be identified by beach monitoring. Such information could then feed into combined modelling and monitoring work to identify the marine dispersal of the part of the litter that does not beach and enters the marine environment.

Sinking particles were diffused over wider areas than floating particles, but travelled more slowly along the paths of the plumes. Also, plume paths of sinking particles were different from those of floating particles, in particular in regions that experience summer stratification. The actual sinking speeds were not very important in determining this behaviour.

Floating particles tended to concentrate in areas that are known for the presence of density (temperature or salinity) fronts, in agreement with observations (Barnes et al., 2009). This behaviour gives confidence in the model results, and could be analysed in more detail by comparing 3D particle tracks with 3D density information. Such work could be carried out in FY12/13. The difference in transport paths of floating and sinking particles indicates that litter of mixed behaviour (floating first, sinking later e.g. because of biofouling) are likely to have different dispersal and accumulation characteristics, which will depend on the timing of the change in buoyancy. This change will depend on the initial buoyancy of the litter, and on the rate and nature of the biofouling. The latter is likely to depend on the time of year. In combination with the seasonality of stratification, this is an interesting topic that could be investigated further in FY12/13.

The current results suggest the following accumulation areas:

For floating particles:

- beaches (for UK in particular South Coast and North Norfolk)
- salinity front off continental coast
- Skagerrak gyre
- central North Sea

For sinking particles:

- beaches
- deeper areas (in particular Oyster Grounds, Norwegian Trench)

The Central North Sea accumulation area for floating particles may be hypothetical, as it was identified in the uniform release experiment, but not in the experiment with riverine and boundary sources. This result suggests that litter that ends up in this area will probably remain there for a considerable period of time, but also that, because of the location of the sources in relation to the residual currents, litter originating from terrestrial or oceanic sources does not have a high likelihood of being transported to this area.

The density patterns of particles from the simulations with steady riverine and boundary sources are not realistic, because potential differences in intensity between the sources, and potential temporal variability in the intensity of the sources was not taken into account. Further simulations will be carried out in FY12/13 with litter release intensity of riverine sources proportional to the river runoff to achieve more realistic estimates of potential litter density patterns. Such simulations may allow for a comparison with litter retrieval observations from the field programme.

The current results were obtained by simulating one particular year (2008), coinciding with the availability of field observations. Additional simulations could be considered for other years to assess potential interannual variability in litter dispersal, for instance by identifying and using contrasting years in terms of average wind patterns (i.e. residual circulation), temperature (i.e. stratification) and/or river runoff (i.e. source distribution).

The results above will be used in the following year to guide and adapt the field programme i.e. where to look and vice versa the monitoring data will be used to validate the model.

C Socio-economic cost model (Cefas)

C.1 Cost-benefit analysis for microplastics on aquaculture in the UK

C.1.1 Socio-economic cost model of the potential Impacts microplastics

C.1.1.1 Background information

Motivation:
The number of scientific investigations has increased, along with public interest and pressure on decision makers to response. A number of international initiatives are under way to determine the physical and chemical effects of microplastic (plastic particles up to 5 mm in diameter) in the ocean, and to identify ways to address this emerging issue (UNEP WG40, 2012, 2014 in press Microplastics).
A broad categories of Socio-economic impacts of MPs are: (1) Economic costs and risks; (2) Costs of beach cleanups; (3) Degraded areas negatively affect tourism; (4) Damage to motors/fishing gear. There are also social impact of plastic include (5) Residents of coastal communities, tourists, recreationists; (6) Well-being; and (7) consumer trust (food safety).
Currently there are research gaps in data collection of biological and ecological degrading reaction to the potential impacts of MPs. Without scientific evidence and generalised scientific results, quantification of the potential losses or adverse impacts of socio-economic measurement are limited. Further study on socio-economic assessment based on data collection and scientific experiments for longer term effects should be done to support policy implementation and decision making on legislations against MPs accumulation and concentration.
As far as we know there is no publication of quantifying the economic assessment of MPs effects and risks.

C.1.1.2 Aims:

i) Estimating minimum potential direct impacts of socio-economic costs (losses) for a UK case study (sample regions and selected species (e.g. oysters & mussels).

ii) Modelling a generalised SECMPs (Socio-Economic Cost Model of MPs) in order to apply for other regions in the Europe in the future.

Note that we only produce a minimum proxy of the economic potential costs.

C.1.1.3 Justification of Shellfish selection of species (Oysters (excremental study in Cefas Weymouth Lab), and Mussels)

(1) Van Cauwenberghe, L., M. Claessens and C.R. Janssen (2014)
(Lisbeth.VanCauwenberghe@UGent.be: LETAC, Ghent University) –
They tested with Mussel natural and cultured (0.2+-0.3 particles, 0.36+-0.07 particles) and Oysters (0.35+-0.05 particles), and established that mussels and oysters contain microplastics, this is the first report so far on microplastics in foodstuffs. Due to a lack of dedicated studies, the complexity of estimating particle toxicity hinders a comprehensive assessment of the hazards associated with microplastics. Estimations of the potential risks for human health posed by microplastics in food stuffs is not yet possible but they

extrapolated that Europeans consuming shellfish would be exposed to app. 11000 microplastics particles/year. (Van Cauwenberghe et al. 2014).
Other studies of microplastic uptake by marine filter feeding organisms (lab): Mussel (Browne et al., 2008; Ward & Kach, 2009, Claessens et al., 2012, Moos et al. 2012); Oyster (Ward & Kach, 2009).

C.1.1.4 Potential effects of MPs on oysters and mussels (based on MICRO findings)

Due to the similarity between the specific gravity and size of small plastic particles and algae, MPs have the potential to be ingested by filter feeders like mussels and oysters (Brillant and MacDonald, 2000). The ingestion of MPs can cause physical harm to the individual organism and leaching of toxic substances may interfere with its health.

The potential for toxicity becomes larger if the particles reach the nanoparticle range, due to the surface-to-volume ration. So far, only a limited number of studies have reported negative effects of nanoparticles on marine aquatic organisms (e.g., mussels, clams and abalones), including the combined effects of toxic pollutants and nanoparticles (Koehler et al., 2008; Hull et al., 2011; Zhu et al., 2011; Wegner et al., 2012). In laboratory experiments, plastic particles were observed to retain in the guts of mussels (*Mytilus edulis*) from which these were translocated to the circulatory system for over 48 days (Browne et al. 2008). As smaller particles were found more abundantly than larger particles, the potential for accumulation in the tissues of an organism seems to increases with the decrease of MP size. Wegner et al. (2012) found that blue mussels were filtering 30-nm polysterene from the water and these could be found around the foot tissue.

Oyster: In the MICRO project Sussarellu et al. (2014) exposed adult oysters to a high-concentration mixture of MP (2 and 6 µm; 2000 particles ml^{-1}) during two-months under controlled dietary conditions designed to induce the production of gametes (reproductive cells). Average consumption (retention) of microplastics was 20% of 2 µm particles and 85% of 6 µm particles. Effects were also seen on the ingestion of microalgae which was significantly higher in MP exposed animals. This increased feeding rate is thought to be the result of compensation for a lower energy intake due the high number of particles ingested. Significant negative effects were observed for reproductive features; decreases of oocyte total number (-38%) and relative oocyte size (-8%), as well as a lower sperm velocity (-23%) were observed in MP exposed animals. Furthermore, the D-larval yield, estimated 48 h post fertilization, was decreased (-41%) in larvae produced from gametes collected in MP exposed oysters. Finally, larval development was delayed in larvae produced from MP exposed oysters (-20% larval growth, 6 days-lag of settlement), indicating trans-generational effects supposedly due to MP. This means that oysters exposed to microplastics were reproducing less, and smaller reproductive cells, less larvae were eventually produced and larval development was decreased. Also in the MICRO project Thomas Maes et al. (2014) carried out a 3 months laboratory experiment of juvenile oysters exposed to low dose of 6m PS red fluorescent microbeads. End points measured included: growth, condition index, lysosomal stability, histology. So far, no clear effects could be observed. The final results are expected by the end of 2014.

Mussels: Experiments assessing single and combined effects of microplastics (MP) and fluoranthene (FLU) in mussels *(Mytilus spp.)* conducted in the MICRO project showed no translocation of 2 and 6 µm microplastics from the digestive tract to other tissues (Paul-Pont et al., 2014). This means that the plastic particles ingested by the mussels, stay in the organs and do not cross the cell-walls into the mussel tissues.

➔ This means that microplastics can have a negative impact on the defence system of mussels; contaminated mussels were found to be possibly more susceptible to pathogen agents (viruses, bacteria) present in marine environment when exposed to microplastics and fluorenthene (PAH) combined.

C.1.2 Overview of socio-economic impacts of Microplastics

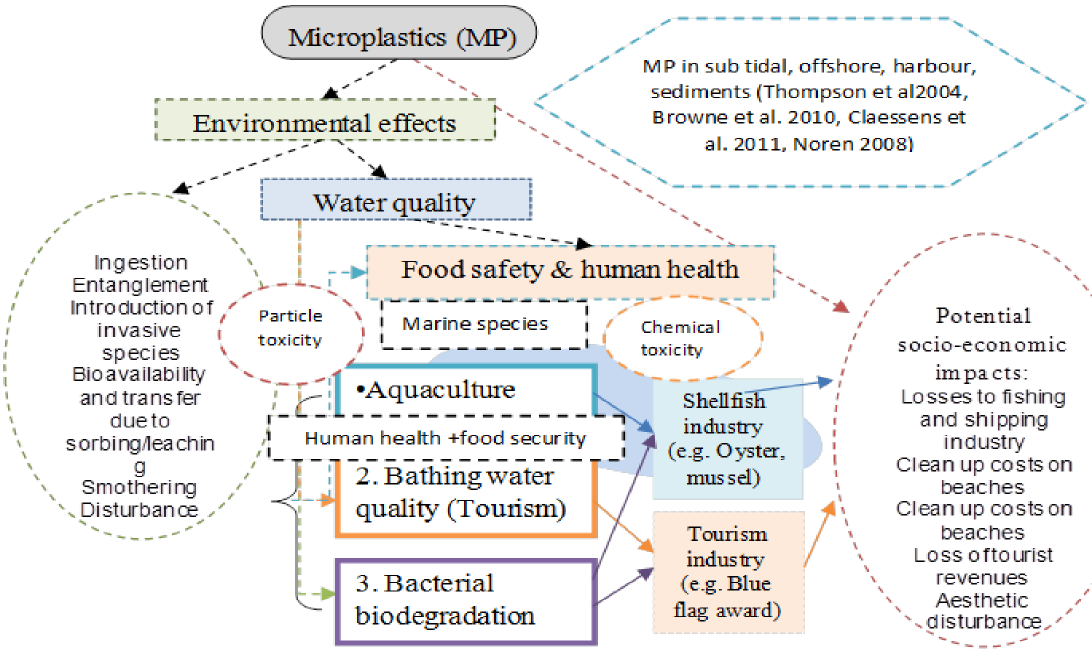

Figure C.1 schematic representation of socio-economic model.

C.1.2.1 Model

$$(1) TC1 = a_0 + a_1 \sum(\beta + \tau + \epsilon + S + P + \mathrm{OE} + \varepsilon_1)$$

$$+ a_2 \sum (C + W + H + F + R + \mathrm{OS} + 2) + a_3 \sum(\mathrm{IDE} + \mathrm{OIDE} + \varepsilon_3)$$

$$+ a_4 \sum(\mathrm{IDS} + \mathrm{OIDS} + \varepsilon_4)$$

$$(2) TC2 = f(I, P, MPs, SD, S, V, PO).$$

The Equation (1) represents the potential consequence i.e. socio economic impact of plastics effects. Equation (2) represent the causal factors to which attribute to the total costs.
Equation 1 consist with mainly direct costs which are clearly traceable potential costs from MPs. For example, beach cleanup includes costs to clean up litter from waterways and beaches within the coastal community. We assume that not all communities conduct water and beach cleanups, and coastal communities incur larger expenses for beach cleanups than do inland communities.

Table C.1 Abbreviation of equations.

(The coverage of the SECMPs in this paper is highlighted in red below)

Equation (1) TC1 (the combination of total costs of direct (eg. oysters industry, beach cleanups), indirect (e.g. trust of consumer of shellfish or fish, tourism losses of degraded areas due to ocean surface water quality for swimming for example) and induced socio-economic costs (e.g. losses of coastal jobs due to tourism collapse and the income loss to the local economy)	
TC	Total Costs
(β)	Costs of beach cleanups
(τ);	degraded areas negatively affect tourism
(ϵ);	damage to motors/fishing gear
(S);	shellfish industry including export
(C)	social (welfare) costs of residents of coastal communities (non-market, non-priced commodity of quality of life)
(W);	well-being or quality of life
(P)	decreased housing price in coastal areas
(R)	Tourists or recreationists (beach swimmers)
(H).	health & safety due to particle and chemical toxicity
(F)	Consumer trust of food safety
IDE; OIDE	Indirect economic; omitted indirect economic costs
IDS, OIDS	Indirect social costs, omitted indirect social costs
Equation (2) TC2 is the all factors involved with the causations of total costs rather than the results.	
I	**input factors (+)** (input via ships, wave height/speed, wind height/speed, rivers
P	**process factors** (+)(physical processes +chemicals + biota); and chemical pollutants and additives in the environment; particle toxicity +chemical toxicity
S	**sensitivity (+S)** of reaction to MPs. Microplastic exposure and effect of Blue mussel (Granulocytoma formation (inflammation)increases in SB haemocytes, decrease in lysosome stability (Koehler & von moos, 2010) Exposure to 10,30,90 mm mps indications for selective update of 10mm mps reduced clearance rate (Van cauwenberghe, 2012) Exposure to /absorption of 30 nm ps causes reduced valve opening and filtering activity (Wegner et al. 2012); Carp (absorption of 24 nm nps Food chain transport of nps affects behaviour and fat metabolism (Cedervall et al. 2012)).
MPs	**MPs factors** (+)(concentration, distribution and transport of MPs Microplastics in seawater 0.04-1.6 (102-2400) microplastics/m^3, shipping routes, 10m depth (UK), sea surface (Swedish coast, harbour), Norwegian S coast, sea surface, Doggerbank (Thompson et al. 2004, Noren 2008, Noren & Naustoll 2011, Leslie, 2011). Microplastics in subtidal, offshore, harbour sediments (20-3320 particles (estuarine, subtidle, wet sediment, harbours, offshore, sediment), in UK coast estuarine areas, tamar estuary, Belgian coast, Swedish cost (Thompson et al, 2004) Browne et al, 2010, Claessens et al., 2011, and Noren 2008). Biota chemical pollutants (chemical additives) in the environment and plastic particle (uptake, additives, sorption, leaching, adhered pollutants: Cole, Lindeque, Halsband, Galloway, 2011).
SD	**socio-demographic factors** (+SD) population density and population growth,
V	**Locational vulnerability** (MPs in sub tidal, offshore, harbour, sediments). Input via ships, wave action, degradation to smaller particle sizes, weathering biofouling and sinking, sink of plastic and chemicals in sediments. Floating plastics encounter pops at contaminant risk surface microlayer, chemicals dissolved in seawater sorb to and concentrate in plastic. Chemical additives leach from plastic; equilibrate in water phase; re-suspension of chemicals via plastic in sediment. Input via wind and rivers, interaction at water surface with algae, invasive species, food chain transfer, ingestion of plastic, leaching of additives to

	organisms. Bioaccumulation of pops taken up with plastic.
PO	**policy and intervention factors (-PO)**
$\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4$	errors or not explained variables that not included due to data availability

C.1.2.2 Assumptions & Data used for Parameters setup for the Cost model

Table C.2 Assumptions and parameters entered into the SECMPs

#	Description	Unit
1	Low 3-10 particles (Browne et al 2008, Maes 2014): Average value between 3 and 10	3-10
2	High 24-90 particles (Cedervall et al. 2012, Van Cauwenberghe, 2012): Averaged value	24-90
3	Low MPs/m^3 surface or L/kg sediment with -10% negative effect coefficient	10%
4	Low MPs/m^3 surface or L/kg sediment with -25% negative effect coefficient	25%
5	High MPs/m^3 surface or L/kg sediment with -10% negative effect coefficient	10%
6	High MPs/m^3 surface or L/kg sediment with -25% negative effect coefficient	25%
7	Social discount rate: UK HM recommended discount rate	3.50%
8	Simulation years: 2010*-2100 time scope to cover long term effect under uncertainty	90 years
9	Total shellfish value landed in the UK by UK vessels: An averaged value 2009-2013	£280 m
1 0	Total Oyster export in 2011: Value (£million) with no MPs impact at discount rate:£ 2300x 998tonnes=£ 2,295,400	£2.295 mil
1	Total oyster value landed in the county by UK vessels: £29.40859 million	£29.409
1	Oyster value landed in Cornwall & the Isles of Scilly by UK vessels: Averaged value	£7,285
1	Oyster value landed in Dorset by UK vessels: Averaged value between 2009-2013	£181,037
1	Oyster value landed in Devon by UK vessels : Averaged value between 2009-2013	£1,295
1	Oyster value landed in Hampshire and Isle of Wight by UK vessels : Averaged value	£1,412,81
1	Oyster value landed in West Sussex by UK vessels : Averaged value between 2009-2013	£101,204
1	Oyster value landed in East Sussex by UK vessels: Averaged value between 2009-2013	£5,824.27
1	Oyster value landed in Essex by UK vessels : Averaged value between 2009-2013	£317,137
1	Oyster value landed in Suffolk by UK vessels : Averaged value between 2009-2013	£169,356
2	Oyster value landed in Norfolk by UK vessels : Averaged value between 2009-2013	N/A
2	Oyster value landed in Kent by UK vessels : Averaged value between 2009-2014	N/A
2	Mussel value landed in Cornwall & the Isles of Scilly by UK vessels: Averaged value	£1,457
2	Mussel value landed in Dorset by UK vessels: Averaged value between 2009-2013	£36,207.4
2	Mussel value landed in Devon by UK vessels : Averaged value between 2009-2013	£259
2	Mussel value landed in Hampshire and Isle of Wight by UK vessels : Averaged value	£282,563.
2	Mussel value landed in West Sussex by UK vessels : Averaged value between 2009-2013	£20,240.8
2	Mussel value landed in East Sussex by UK vessels: Averaged value between 2009-2013	£1,164.85
2	Mussel value landed in Essex by UK vessels : Averaged value between 2009-2013	£63,427.4
2	Mussel value landed in Suffolk by UK vessels : Averaged value between 2009-2013	N/A
3	Mussel value landed in Norfolk by UK vessels : Averaged value between 2009-2013	N/A
3	Mussel value landed in Kent by UK vessels : Averaged value between 2009-2014	£33,871.2
3	Mussel value regional total averaged value between 2009-2014	£17.96659
3	Total Mussel export in 2011: Value (£million) with no MPs impact £1615x12345tonnes	£19.937
3	Population in Dorset in 2012 (persons)	745,400
3	Population Devon in 2012 (persons)	1902000
3	Population in Hampshire and Isle of Wight in 2012(persons)	1135700
3	Population in West Sussex in 2012 (persons)	808900
3	Population in East Sussex in 2012 (persons)	800200
3	Population in Essex (persons)	1729200
4	Population in Suffolk (persons)	730100

4	Population in Norfolk (persons)	859400
4	Population Cornwall & Isle of Scilly (persons)	538200
4	Population in Kent (persons)	1731400
4	Population growth based on 2012 the UK average rates (persons)	0.06%
4 5	Economic costs of beach cleaning include waterway and beach cleanup, installation of storm water capture devices, storm drain cleaning, manual cleanup of litter, public	£0.45, £0.94,£3.7
4	Regional tourism revenue total averaged between 2010 and 2012:	£14.749
4 7-	Tourism: Dorset (£2150m); Devon (£1440m); Hampshire & Isle of Wight (£2500m); W. Susses(£1671m); E. Sussex(£9000m); Essex (£276m); Suffolk (£1475m); Norfolk (£2781m); Cornwall &	

Sources: Various sources including Cefas Seafish News Series 2010-2013 Spring/Summer & Auttom/Winter issues 32-38, Cefas database of regional ports and species.

C.1.3 Data on aquaculture in the UK

C.1.3.1 Presence of Aquaculture industry in UK Channel region

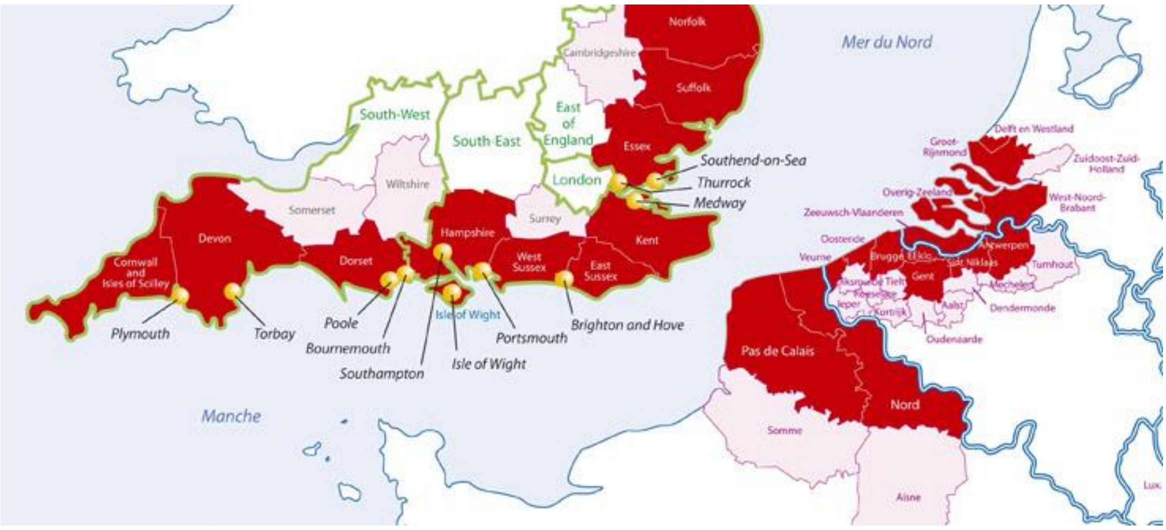

Figure C.2 Sample UK regions and distribution map (Source: http://www.2seastrade.eu/about/the-eu-interreg-programme).

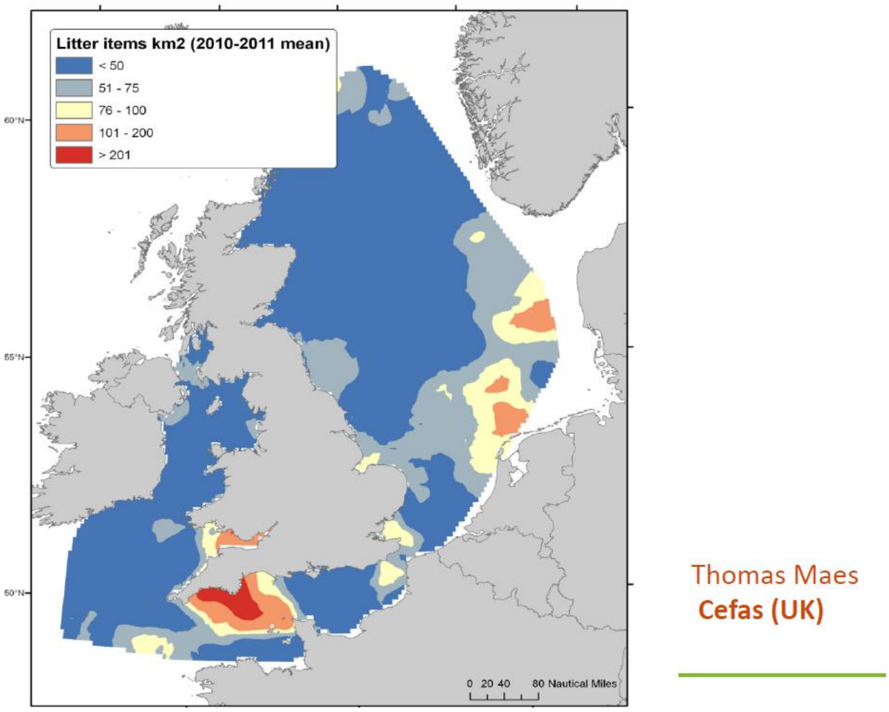

Figure C.3 Floating litter items in the North Sea (Cefas).

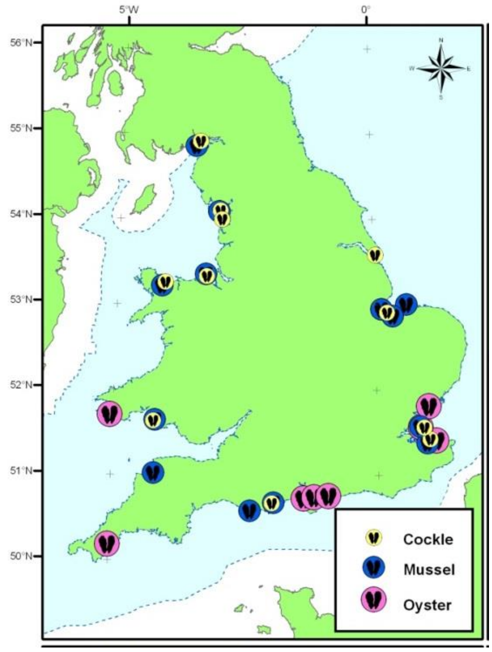

Figure C.4 Major mollusc centres in England and Wales (source: D. Palmer, Cefas).

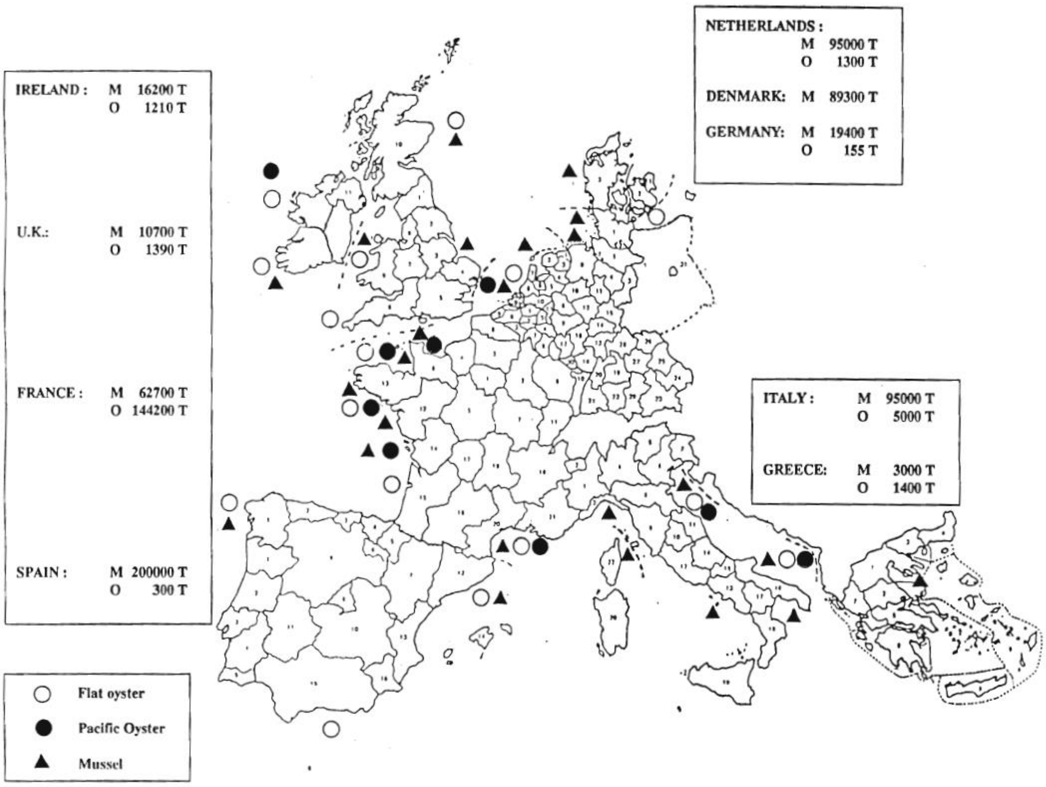

Figure C.5 Aquaculture in the whole of Europe (from Antona et al. 1993).

C.1.3.2 UK Sea Fisheries Statistics 2009-2012

Table C.3 Oyster & Mussel landings in tonne excluding Scotland.

	2005	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*
Total					288.60	305.89	310.11	241.39	122.27
Native Oyster	56	64	55	44	54	89	302.97	140.76	106.65
Pacific Oyster	428	680	587	598	815	649	80.53	70.86	34.61
Portuguese Oyster					2.35	0.05	1.55	0.005	0.11
	2005	2006	2007	2008	2009	2010	2011	2012	2013
Mussels	19544	13,340	13,270	15,025	17,612	12,193	11,497		

Table C.4 Regional landings averaged value between 2009 and 2012.

Oysters(£)	**2009-**	**Averaged value (£)**	**Population**
Norfolk	Not		859400
Suffolk	Not		730100
Essex	317137	63427.4	1729200
Kent	169356	33871.2	1731400
East Sussex	5824.27	1164.854	800200
West Sussex	101204	20240.8	808900
Hampshire & Isle of Wight	1412818	282563.6	1763600+138400
Dorset	181037	36207.4	745400
Devon	1295	259	1135700
Cornwall & Isle of Scilly	7285	1457	536000+2200
Total (2009-2013)	2633594.		
Averaged annual Oysters (2009-2013) 439191 (£)			
2009 total in the regions	437638	2011 total in the regions	668691
2010 total in the regions	376740	2012 total in the regions	469519
2013 total in the regions	233208		
Mussels (£)	**2009-**	**Averaged value**	**Tourism (£)**
Norfolk	1063854	212770.8	
Suffolk	172289	34457.8	
Essex	15637	3127.4	
Kent	15	3	
East Sussex	Not		
West Sussex	Not		
Hampshire & Isle of Wight	23913	4782.6	
Dorset	146800	29360	
Devon	18	3.6	
Cornwall & Isle of Scilly	Not		
Total (2009-2013) Mussel	7266900.	**Tourism regional revenue averaged between 2010-2012:**	
Averaged annual Mussels (2009-2013) 284505.2(£)			
2009	1215047	2011	2746459.8
2010	1149471	2012	2583606
2013	491791.4		

Sources: Cefas database of port landings and species 2009-2013, the data shows minimum values based on reported landings and excluding not reported values.

Table C.5 UK trade in selected shellfish in 2011 (tonnes).

2011	**To EU countries (£388m)**		**To other countries**	
Species	**Export**	**Import**	**Export**	**Import**
Molluscs total	39,569	58,66	827	6,841
Mussels	12,345	2,022	015	1,285
Oysters	998	665	575	122
2009				
Mussels	1,5358	3,599		
Oysters	929	347		

Table C.6 Shellfish landings in the UK & selected EU member states (Belgium, France and Netherlands).

Year	Species	Tonnes	Value (£m)	Unit Value (£ tonne)
2012	**Total shellfish (UK)**	**16.2754**	**301**	
	France	**94.086**		
	Netherlands	**1.921-**		
	Belgium	**2.032**		
	Musels (UK)	.600	0.338	563.34
	Oysters(UK)	.211	0.468	2218
2011	**Total shellfish (UK)**	**152.379 (89.154)**	**283**	
	Total native oyster(England)	*.114(.086)*	*0.1254*	*1100*
	Total pacific oyster(England, Wales)	*.754(*447, 06)	*0.9494*	*2300*
	Total mussel (England, Wales)	*26.158(*3127,8.370)	*18*	*995*
	France	**93.421 (75.413)**		
	Netherlands	**20.956(3.731)**		
	Belgium	**2.776(1.592)**	( ) indicates oyster	
2010	**Total shellfish UK**		**255**	
	Oyster UK (England, Wales)	1266.85(153.1,3.05)		
	Mussel UK (England, Wales)	30212(3.4, 6.1)		
	Europe (Mussel: 477000); Europe (P. Oyster:105000)			
2009	Mussels UK (England, Wales)	31929(3800, 13812)		
	Oysters (England, Wales)	1576(865, 4)		
2008	World Molluscs cultivation (USD 13.2 billion)		Europe Molluscs cultivation (USD 1.55 billion)	
	World Crustaceans cultivation (USD 22.7 billion)		Europe Crustaceans cultivation (USD 4.6 million)	

Shellfish industry UK summary (source: various issues of Cefas Shellfish News 2010-2012):

(i) In 2012 shellfish landings represent nearly 40% of the value of total landings from UK vessels, hence shellfish sector is significant to the UK economy.

(ii) Over the last 10 years (2002-2012), weight and value f shellfish landings in the UK has been increased over the time.

(iii) Among France, Netherlands, and Belgium, the UK is the largest recorded contributor for both molluscs and crustaceans in both 2011 & 2012.

(iv) In 2011, due to OSHV, pacific oyster production down to 754 tonnes.

(v) In 2011, the UK is a net exporter of shellfish of which exports are worth a total of £410 million to the UK with imports costing about £372 million. The UK exports shellfish to the EU with the most important being France 921083 tonnes in 27 product categories followed by the Netherlands 16621 tonnes in 22 products of which live mussels make up 46%.

C.1.4 Methods

This section estimates the direct socio-economic impacts of the MPS risk effects using a combination of bio-economic model (i.e. Socio-Economic Cost Model of MPs: SECMPs) that uses the causal factors to determine the total costs. The assumptions of reactions functions under low and high concentration and under low and high reaction of filter feeding organisms (Oysters and Mussels) that forms the bio-economic modelling approach. The bio-economic model integrates biophysical data (e.g. an organism's growth, conditional index, ingestion, or MPs concentration or) and biophysical model that predicts the organism's growth, and conditional index associated MPS caused water degradation. Economic model reflects the aggregate welfare of a coastal community measured as the discounted value of future monetary income and the opportunity cost of beach clean-up. The Monte Carlo Method allows all the possible outcomes of consequences of MPs and assess the impact of risk for better decision making under uncertainty to account for risk in quantitative analysis, hence it shows the extreme possibilities by substituting a range of values that produces distributions of possible outcome values based on real values of the oysters and mussels values per each regions.

The uniqueness of this study is to oversee a long term time frame that we set a reference year as 2010 and up to 2100 for 90 years of projections as the concentration and distribution of MPs and the reaction of ecology or biology might be both short and longer term. We aim to capture a long term consequence of various degree of MPs impacts as ecological and particles evolve over decades. A long term costs can be measured using the Net Present Value (NPV) which can be used discounted future damage or cost to present value using a Government recommended interest rate (3.5% for the UK HM blue book). The Low (3-10 mm) and High (20-90 mm) are certain in reality due to MPs floating over all oceans with a certain direction over decades hence we set the low and high will be randomly transform within the low and high ranges up to year 2100. A randomly chosen reaction coefficients for low and high responses of oysters and mussels are set however they are placeholders that can be replaced with any updated parameters from future experiments.

We assume that there will be no benefit from MPs but only adverse or losses effects to marine environmental degradation. Therefore we compared the potential losses will be the gap between with no MPs (i.e., business-as-usual situation in shellfish industry) and with MPs (i.e. potential and randomly cumulated losses). The potential economic costs are reported in Tables above. The range between minimum and maximum is overall wide due to the uncertainty of no-response and potential reaction subject to vulnerability (spatially) and sensitivity (biology, chemistry, toxicity).

C.1.5 Results & Discussion

UK Case based on Socio-Economic Costs Model of MPs (SECMPs), the minimum annual costs (as only two direct costs (shellfish + beach cleaning costs) + one indirect cost (impacts on tourism) are included in the estimation) based on Assumptions (Table C.2) and Data (Table 6), the followings are overall results. Averaged annual economic costs:

- The potential economic costs per year in **the UK shellfish** industry are projected a range between £60k and £2.2 million depends on the biological reaction of MPs pollutants. [Table C.7]

- The potential economic costs per year in the **UK export of Oyster** industry are projected a range between £371 and £7.9k. [Table C.7]

- The potential economic costs per year of the regional oyster production in the sample areas are projected a range between £174 and £37k depends on the biological reaction of MPs pollutants. [Table C.7]

- The potential economic costs per year of the regional Mussel production in the sample areas are projected a range between £2913 and £618k depends on the biological reaction of MPs pollutants. [Table C.7]

- The potential economic costs per year of the UK mussel export are projected a range between £3221 and £686k depends on the biological reaction of MPs pollutants. [Table C.7]

- The most vulnerable region in the sample areas in the UK case would be Hampshire & Isle of Wight region (potential annual losses of £994k in oyster sector while Dorset region in Mussel production with a potential annual losses of £9104. [Tables C.8 & C.9]

- The total regional beach cleaning costs due to the concentration of MPs are projected to be a range between £114.7k and £1.504 million per year. [Table C.10 below]

- The most vulnerable region in terms of beach cleaning costs is projected in Devon with an annual cost of a range 20k and 260.5k. [Table C.10]

- The potential impacts to regional tourism per annum are estimated at a range between £1.38 million and £500 million where a parameter of regional tourism revenue of £14.75 billion is used. Devon and Norfolk are relatively vulnerable regions. [Table C.11]

- In summary table:

Regional potential total economic costs due to the consequence of MPs

Annual regional costs	min projection	max projection
Oyster	174	36985
Mussel	2913	618139
Beach cleaning	114685	1503661
Sub	117772	2158785
Tourism revenue	1379000	496975000
Total	**£1,496,772**	**£499,133,785**

(!)Implication from the outputs of the SECMPs model is that the government policy and control (e.g. monitoring, regulatory restrictions on MPs) costs on MPs will be benefited for avoidable costs a range between £1.5 million and £499 million per year.

C.1.6 In the tables below some more detailed information is provided in term of socio-economic effects on the shellfish industry in the UK case study.

Table C.7 Potential economic impacts of MPs to Shellfish industry in the UK and Regional total (£).

Scenarios	Low MPs/m^3 surface or L/kg sediment, predicted MPs concentration: Low 3-10 particles (Browne et al 2008, Maes 2014)		High MPs/m^3 surface or L/kg sediment, predicted MPs concentration: High 24-90 particles (Cedervall et al. 2012, Van Cauwenberghe, 2012)	
	~10% decrease	~25% decrease	~10% decrease	~25% decrease
Averaged annual costs from the total of 2010-2100 cummulated costs (£, at 2010 base year discounted at 3.5%)	Low biological response: 10% loss of effects_growth, stability,filtering	High biological response: 25% loss of effects_growth, stability,filtering	Low biological response: 10% loss of effects_growth, stability,filtering	High biological response: 25% loss of effects_growth, stability,filtering
1. Total Shellfish value landed in UK	**59,713**	**9,738,407**	**130,891**	**2,191,583**
2. Total UK Oyster Export	**371**	**78,973**	**3,632**	**7,299**
3. Total Oyster Value landed in the regional samples	**174**	**36,985**	**1,701**	**3,418**
4. Total Mussel Value landed in the regional samples	**2,913**	**618,139**	**28,425**	**5,713**
5. Total UK Mussel Export	**3,221**	**685,936**	**31,543**	**63,396**

Table C.8 Potential economic impacts of MPs to the UK regional Oyster industry in the sample areas Oyster & Mussel value landed in each region by UK vessels in the sample areas (averaged annual economic costs £: 2010-2100)

Oyster value landed in each region by UK vessels in the sample areas	~10% decrease (Low-Low)	~25% decrease (High-High)
Cornwall & the Isle of Scilly by UK vessels		
	9	51
Devon		
	1	9
Dorset		
	10	1274
Hampshire & Isle of Wight		
	8104	994086
West Sussex		
	6	712
East Sussex		

	2	41
	Essex	
	18	2231
	Kent	
	10	1192
	Suffolk	
	Not reported landings	
	Norfolk	
	Not reported landings	
Potential impacts of MPs to Oyster production in the regions: Range £8160 - £999596 per year.		

Table C.9 Potential economic impacts of MPs to the UK regional Mussel industry in the sample areas (based on mussel value landed in each region).

	~10% decrease (Low-Low)	~25% decrease (High-High)
Mussel value landed in each region by UK vessels in the sample areas	Cornwall & the Isle of Scilly by UK vessels	
	1	166
	Devon	
	Insignificant	Insignificant
	Dorset	
	7902	9104
	Hampshire & Isle of Wight	
	1	166
	West Sussex	
	Not reported landings	
	East Sussex	
	Not reported landings	
	Essex	
	1	109
	Kent	
	Insignificant	Insignificant
	Suffolk	
	8	1199
	Norfolk	
	47	7402
Potential impacts of MPs to Mussel in the regions: Range £7960 - £18146 per year.		

Table C.10 Potential economic costs of MPs to the UK Regional Beach Cleaning in the sample areas.

	Low MPs/m^3 surface or L/kg sediment, predicted MPs concentration: Low 3-10 particles (Browne et al 2008, Maes 2014)_low beach cleaning cost £0.45 per capita	**High MPs/m^3 surface or L/kg sediment, predicted MPs concentration: High 24-90 particles (Cedervall et al. 2012, Van Cauwenberghe, 2012)_low beach cleaning cost £7.42 per capita**
Regional population total 10,980,500; Persons, 0.6% UK population growth	**Regional total (£ per annual averaged costs 2010-2100)**	
	114685	**1503661**
	Cornwall & the Isle of Scilly by UK vessels	
	5621	73701
	Devon	
	19865	260458
	Dorset	
	7785	102074

	Hampshire & Isle of Wight	
	11862	155522
	West Sussex	
	8448	109579
	East Sussex	
	8358	109579
	Essex	
	18060	236795
	Kent	
	18083	237097
	Suffolk	
	7625	99979

Table C.11 The potential impacts of MPs to regional tourism (annual costs averaged 2010-2100 £).

Low MPs/m^3 surface or L/kg sediment, predicted MPs concentration: Low 3-10 particles (Browne et al 2008, Maes 2014)_Low-Low	**High MPs/m^3 surface or L/kg sediment, predicted MPs concentration: High 24-90 particles (Cedervall et al. 2012, Van Cauwenberghe, 2012)_High-High**
Regional total tourism revenue (averaged between 2010-2012: £14.749 billion): (£ per annual averaged costs 2010-2100)	
1.379 million (£)	**496.975 million (£)**
Cornwall & the Isle of Scilly (£1156 million, 8% of regional total)	
£0.108 m	£38.951 m
Devon (£2150 million), 15% of regional total	
0.201	72.000
Dorset (£1440 million, 10% of regional total)	
0.135	48.521
Hampshire & Isle of Wight (£2500 million, 17% of regional total)	
0.234	84.238
West Sussex (~£1671.15 million, 11% of regional total)	
0.156	56.310
East Sussex (~£900 million, 6% of regional total)	
0.084	30.321
Essex (£276 million, 2% of regional total)	
0.026	9.300
Kent (£400 million, 3% of regional total)	
0.037	13.478
Suffolk (£1475 million, 10% of regional total)	
0.138	49.700
Norfolk (£2781 million, 19% of regional total)	
0.260	0.260

C.1.7 Discussion & conclusion

Note that the cost estimates reported above would be minimum costs as they are some of direct costs. For example, other direct costs of fishing engine or gear damages are not included. Furthermore, indirect costs such as consumer's perception and reputation of the food hygienic and safety (water borne pathogens or virus in seafood) or the regional job losses or unemployment benefit costs due to coastal deprivation of decreasing tourism industry are not included in this estimation.

For example, MPs could be transferred through the food chain (Teuten et al. 2009) and potentially could be consumed by people (Van Cauwenberghe et al., 2014 on oysters and mussels) that Europeans consuming shellfish would be exposed to approximately 11000 microplastics particles per year.

The estimates reported in Tables C.7-C.11 are simplified proxy projections with more than 50 assumptions were made in the reactions together with a rough tourism revenue data due to the availability. And therefore the projections provided should be viewed with a great deal of caution and should not be considered a prediction.

The costs estimates would be different each time of simulation as we reflect the uncertainty of the MPs concentration and distribution around the regions using simulation techniques on the responses of biological effects on short- or long-term exposure to MPs.

C.1.7.1 Further study

In Europe, tourism industry is significant for coastal community revenue generation and job creation and the indirect effect of decreasing tourism revenue would be significant for regional and local coastal areas that are left for future research. Induced costs will be the income losses that could be spent by household consumers for boosting the economy. We have also excluded the indirect and non-marketable or non-price impacts such as the well-being or the quality of life to enjoy clean-seas and waters and healthy ecology or marine animals that are also left for further research. The quantification can assist decision makers in MPs factors that threaten the sustainability and stability of an environmental health risk-prone coastal areas and marine environment in order to help policy makers understand how to reduce social and economic vulnerability to MPs in the seas.

Further work using a wider range of organisms, polymers, and periods of exposure will be required to establish the biological consequences of this debris as plastics are exceedingly durable (Brown, 2008).

C.1.7.2 Policy consideration and recommendations

For prevention:

- MPs sources need to be controlled by legislation or industry standard that will reduce the beach cleaning costs and depredating environmental health and bio-degradation.
- Continuous and regular monitoring of MPs' concentration and distribution can be justified from the potential damages/losses/costs of socio-economic aspects of the consequence of MPs risk effects.
- Continuous and regular monitoring of shellfish inspection should be implemented for human health.
- Further research on data collection of ecological damage and water quality.

C.2 Cost-Benefit Analysis & Optimal Policies

Assumption based on Tables above million (£)

Gross revenue per region without MPs impacts	[oyster & mussel production]	£47.38
	[oyster & mussel exports]	£22.23
	[tourism]	£14,769
Cost of cleaning per year	[range:0.688; 1.503;2.755;5.509]	£2.61
Total number of regions in the UK		10

Summary (£million)		
No MPs impact		0
Total gross Revenue (oysters & mussels + tourism)		£14,838.608
Scenario 1 (best case)		
MPs, do nothing		0
sample regional minimum costs: oyster industry		0.024
sample regional minimum costs: mussel industry		**0.001**
sample regional minimum costs: tourism industry		0.298
Total potential impacts		*0.323*
Gross revenue -Total minimum direct costs of oyster and mussle industry		*£14,838.5832*
Gross revenue -Total minimum indirect costs of tourism		***£14,838.309***
Net revenue with MPs minimum impacts		**14838.285**
Scenario 2 (worst case)		
MPs, do nothing		
sample regional max costs: oyster industry		0.116
sample regional max costs: mussel industry		1.305
sample regional max costs: tourism industry		507.682
Total potential impacts		*509.103*
Gross revenue -Total max direct costs of oyster and mussel industry		*£14,837.1625*
Gross revenue -Total max indirect costs of tourism		***£14,330.901***
Net revenue with MPs max impacts		
MPs control (beach cleaning)		
	min	**0.688**
	max	**5.535**
Other costs (e.g. monitoring)		
Total gross revenue-beach min cleaning costs		**£14,838**
Total gross revenue-beach max cleaning costs		£14,833.0477
Avoided cost (averaged)		£254.713
Cost of control (averaged)		£3.11
Δ Cost (cost - benefit)		£252

In summary, there are benefit of £252 m on average annual benefit of policy options (here is beach cleaning mitigation).

D The findings of the CEFAS ecotox study in Weymouth, general conclusions as not all data is ready yet

Cefas Ecotox Study Experimental Setup of Impact of MP 01/Nov/2013 – 20/01/2014
Oyster Exposure Study: Thomas Mae & Cefas Ecotox team

Activity 2. Effect/impact of MP. oyster exposure study
Timeframe: Weymouth – Start Nov 2013 – 20 January 2014
Long term low dose experiment with juvenile oysters at environmental concentrations
6 micron PS red fluorescent
1-10000-100000-1000000 particles/ while feeding
Endpoint. Growth, condition index, lysosomal stability, histology (clearance rate).
Mm red fluorescent PS
Algae mixture of tetraselmis, pavlova and shellfish 1800
Complete water change and refill with MPs live algae concentrations 1 top up with Shellfish 1800 diet
Concentrations declined in tanks over time
Agglomeration and accumulation areas in tanks and tubes
Pumps>airlifts
Costs of algae and microplastics
Oyster plasticity
Glue
Experimental setup
Daily routine
Morning 1 complete water change and refill with MPs and live algae concentrations
Evening: 1 top up with shellfish 1800 diet
Influence of biofilms
Flow cytometric analysis
Biomarkers
10 oysters Lysosomal Stability
15 oysters Growth Condition Index
5 oysters Histology

Preliminary results 35% analysed
a) Growth no effect
b) Condition index no effect
c) lysosomal stability limited effect
d) Histology – oyster has mechanism for removal of low quantities