Microplastics in the Oresund Region of the Baltic Sea

- Sources and Effects

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Abstract

Plastic production is only increasing, and it’s not showing any signs of slowing down. Microplastics are particles smaller than 5 mm, either produced intentionally, or created from items being withered into small particles. Microplastic contamination in marine environments is higher closer to cities, and most of the plastic litter eventually ends up in the oceans. Microplastics have been found in habitats all over the planet however, and are a huge environmental concern. This literary review study aims to assess the current knowledge concerning terrestrial sources of microplastics, and possible effects of microplastics in a marine environment. Specifically this study will focus on the Oresund, a shallow strait, in-between Denmark and Sweden, two densely populated areas. The literature reviewed in this study indicates that over 1100 tonnes of microplastics could come from the Swedish coastline and into the Oresund. Several major sources and pathways were identified: littering, artificial turfs, roads, runoff, wastewater treatment plants (WWTPs) and wastewater sludge. Most microplastics entering into WWTPs get caught in the wastewater sludge. A percentage. however escapes into water courses leading to the Oresund. The filtered out microplastics get retained in the waste sludge, which is spread on agricultural soils. Soils adjacent to Oresund receive approximately 139 tonnes microplastic via waste sludge every year. Trafficated roads in the Oresund region yearly release 798 tonnes of microplastic from tyres and markings, and artificial turfs release 145 – 248 tonnes of microplastic. In Oresund microplastics can be consumed by plankton, molluscs, echinoderms, crustaceans and vertebrates. Microplastics impact the entire ecosystem, proving toxic and lethal to many filter-feeders and disruptive and damaging to fish. Via Oresund, which also functions as a nursery to nearby fish populations, microplastics can negatively affect adjacent regions, but more research is needed to fully understand the potential effects of microplastics throughout Oresund.

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Introduction

The production of plastics have increased steadily over the past decades and in 2016 a total of 335 million tonnes of plastic was produced globally (PlasticsEurope, 2017). The production and consumer trends all point towards even more plastics being produced in the future. These plastic products can be created as large items of plastic that then fragment and wither down thru abrasion and UV-radiation to create smaller pieces of microplastics, known as secondary microplastics. Primary microplastics are created as small plastic beads from the outset to be used in for example personal care products (Auta, Emenike and Fauziah, 2017). Microplastics are generally defined as small plastic fibers, particles or fragments with a size smaller than 5 millimetres (Cole *et al.*, 2011). The occurrence of plastics and microplastics in the marine environment has gotten a lot of media exposure in the last few years because of how widespread they are. Generally the occurrence of microplastics have been found to be higher in environments close to cities or areas with plenty of human activity (Browne, Galloway and Thompson, 2010; Cole *et al.*, 2011; Dris *et al.*, 2016). However there have also been several incidents where microplastic contamination has been detected in very remote locations (Derraik, 2002) from sediments in the deep-sea (Cauwenberghe *et al.*, 2013) to remote mountain lakes in Mongolia (Free *et al.*, 2014). The fact that microplastics are so widespread in nature, yet we have a limited understanding of their sources and effects in our marine environments is cause for concern.

A few studies have been done to try and give an overview of the available research on pathways and sources of microplastics in both Denmark, Germany and Sweden (Essel *et al.*, 2015; Lassen *et al.*, 2015; Magnusson *et al.*, 2016), identifying water from wastewater treatment plants (WWTPs), landfill leachates, sewage sludge on agricultural lands and stormwater runoff as a few possible sources. Horton et al. (2017) identified agricultural land, landfill leachates, as well as rivers and WWTPs as possible sources and aggregation areas for microplastics in the environment. These areas where microplastics accumulate could later effectively function as individual sources for microplastics. The degradation of plastics in these areas can also change the toxicity of the resulting microplastics and in some cases make them more harmful to aquatic organisms (Bejgarn *et al.*, 2015). Recent research have shown the detrimental effects that microplastics can have on organisms in both the marine (Bejgarn *et al.*, 2015; e Silva *et al.*, 2016) and in freshwater environments (Lithner, Larsson and Dave, 2011) which is why it is so important to map the sources and pathways of microplastics. Microplastics have also been shown to cause problems in marine food webs where they are present in both fish (Rummel *et al.*, 2016) and the invertebrate community (Setälä, Norkko and Lehtiniemi, 2016). Being a relatively new field of research however, there are still plenty of gaps in our knowledge about the sources, pathways of and effects that these microplastics will have in our environment (Horton, Walton, *et al.*, 2017).

The Oresund region of the Baltic Sea is a shallow strait in between two densely populated coastal areas of Sweden and Denmark. The strait, being largely surrounded by urban areas could conceivably be at high risk of contamination by microplastics. The Oresund strait has been closed to trawling since 1932 because of the large amount of ship traffic in the area. This stop in trawling has led to a large and healthy population of commercially important fish such as Whiting *Merlangius merlangus* and Atlantic Cod *Gadus morhua* in Oresund when compared to e.g. Kattegat to the north where trawling has taken place since the early 1900s (Andersson, 2014; Svedäng and Hornborg, 2017). The Oresund region has plenty of stretches with sand and gravel bottom substrate with large areas covered with eelgrass *Zostera marina* which functions as important breeding grounds for many of the species of fish and invertebrates in the sound (Lilley and Unsworth, 2014). Future climate change and ocean acidification could greatly reduce the fish recruitment in Oresund (Stiasny *et al.*, 2016). With the Oresund functioning as a nursery and a refuge from heavy fishing for the fish population in the surrounding areas, a negative effect of microplastics in this region could have a severe impact on not only Oresund but the surrounding areas as well.

The aim of this study is to compile the available knowledge and estimate the size of potential terrestrial sources of microplastics and potential effects on marine environment, as well as the possible particular effects of microplastics on the biota in the Oresund strait.

Methods

This literary review was conducted using a search of scientific articles and recent publications on the subjects in question. The search was mainly done using Web of Science, searching all available databases however some additional searches were done using Google Scholar. The initial search was focused on microplastics in general, as well as their sources and fate in an aquatic environment using a combination of relevant keywords (i.e. microplastic(s), microbead(s), aquatic, marine, “treatment plant”, wastewater, agriculture, effect(s), runoff, turf(s), “Baltic sea”, Oresund, fish, ecosystem(s)). Articles were selected based on the relevance of their information to the subject of this study. Once the initial articles had been selected a method of snowballing was used to find new relevant articles and information that may have been missed in the initial search, for a comprehensive explanation of snowballing see e.g. Wohlin (2014).

Publications on sampling of microplastics in the proximity of the Oresund were of primary interest to this study. Secondly, publications which were conducted in a similar climate to Oresund, or studies done on biota prevalent in the Oresund region was also of interest and as such were included in this review. To try and establish the current level of understanding of the pathways and effects of microplastics in the marine environment this study included articles available up to, and including May 2018.

Results and Analysis

Major sources of microplastics to the Oresund region

This study identified several potential major sources and pathways of microplastics from the Swedish west coast to the Oresund strait: littering and waste management, artificial turfs, wear and tear from roads and traffic, surface runoff, effluent from municipal wastewater treatment plants and wastewater sludge on agricultural soil. In the following section each pathway will be explained and analysed in greater detail.

It should be stated that the sources listed below are not the only sources of microplastic, however for the sake of the restricted scope of this study the focus was placed on these major sources of microplastics.

Littering and waste management

It is roughly estimated that between 4.8 and 12.7 million tonnes of plastic waste and trash from terrestrial sources and up in the ocean globally every year (Jambeck *et al.*, 2015). A recent study that was conducted in cities in 13 municipalities throughout Sweden, established that 34.2 % of all trash that was found consisted of plastic when excluding tobacco products (i.e. cigarette butts and suns) (Håll Sverige Rent, 2018). Mismanaged plastic waste and littering of plastic products such as wrappers, containers and plastic bags are often considered a local issue however these plastics can eventually reach the ocean by transportation via wastewater, waterways, urban runoff and wind (Jambeck *et al.*, 2015).

These plastics can be broken down into secondary microplastics through several different chemical, physical and biological processes. UV-radiation causing photo-degradation of plastics is a common cause of fragmentation, on beaches especially where the temperature often is higher, and physical abrasion from wind and waves can speed up the degradation process even further (Andrady, 2011; Cole *et al.*, 2011; Auta, Emenike and Fauziah, 2017). Andrady

(2011) estimates that on a worldwide scale, the microplastic content from plastic items withering on beaches and in coastal environments is a major source of microplastics in the ocean. A recent study examining the littering on Swedish beaches found an average of 117 pieces of trash per 100m of beach, of which the largest component, 70 % was plastic (Håll Sverige Rent, 2018). Once the microplastics enter the ocean the temperature is cooler and the reduced UV-radiation slows down the degradation, meaning that the plastic particles will stay around for much longer and possibly accumulate once in the ocean (Auta, Emenike and Fauziah, 2017). While there are some data available on the amount of plastic items and fragments found on beaches and in cities there are at this time no studies or data to sufficiently support a meaningful or reliable estimation of microplastics from littering to Oresund.

The waste management systems in Northern Europe in general are functioning well and as a result it is estimated that more than 90% of the collected plastic waste is recovered (Sundt, Schulze and Syversen, 2014), and total of 81 tonnes of plastic waste was recycled in Sweden in 2014 (SCB, 2014). While a ban on landfilling waste with a waste fraction higher than 10 % volume combustible waste or waste with a weight percentage of total organic carbon (TOC) higher than 10% (NFS 2204:4) has led to decreasing amounts of plastic waste being landfilled today, it was estimated that a total of approximately 30 million tonnes of waste is present in municipal landfills in Sweden and 8% of that is made up of plastic (Frändegård *et al.*, 2013; Magnusson *et al.*, 2016). While studies have been done on hazardous compounds and polymers leaching from plastics at landfills and ending up in the leachate, such as bisphenol-a (BPA) (Morin, Arp and Hale, 2015; Li *et al.*, 2018) there are at present no studies examining the microplastic content of the leachate directly, making an estimation of the microplastic load from landfills to Oresund difficult.

It is clear through the available research that littering and a use, and misuse of waste management techniques are contributing to the total load of microplastic in Oresund even though it’s difficult to assess just how big the amount of microplastic entering the sound is at this time.

Artificial turfs

Artificial turfs are used for football fields and recreational areas instead of actual grass. The artificial turf is constructed from a carpet with plastic straws and to help the straws stand up the carpet is dressed with sand and small microplastic granulates. The granules usually consist of SBR (styrene-butadiene rubber), EPDM (Ethylene Propylene Diene M-class rubber) or TPE (thermoplastic elastomers) with SBR being the most commonly used, on 60-70% of all artificial turfs in Sweden (Swedish Environmental Agency, 2018). When the turfs first are constructed a total of 120 – 150 Tonnes of microplastic granules are dressed on the field, then as the field is used there's a loss of particles, and on average 3 – 5 tonnes of new microplastics are used to recover the lost particles each year on a full sized football field (DHI, 2013).

A study done in Sweden estimated a total loss of microplastic from artificial fields to be 2300 - 3900 tonnes every year (Magnusson *et al.*, 2016), however they were not able to make an estimation on the amount of this plastic that made it into the Ocean. Lassen *et al.* (2015) investigated the loss of microplastic granules, as well as the loss of artificial grass fibers fragments each year from artificial football fields in Denmark. They estimated a total loss of granules to be 380 - 640 tonnes per year and the loss of microplastic grass fragments to be 70 – 150 tonnes. Lassen *et al.* (2015) continue to evaluate the possible pathways for the microplastic, and surmises that the majority of the particles will be contained in the surrounding soil and 5-20% of the total mass of particles to reach the sewage system via grates in surrounding paved areas and from laundry of football uniforms and shoes, from where it likely continues to the nearest WWTPs.

The eight coastal municipalities adjacent to Oresund (Burlov, Helsingborg, Hoganas, Kavlinge, Landskrona, Lomma, Malmo and Vellinge) contain 42 full sized outdoor football fields, as well as 21 recreational/sport outdoor fields with artificial turf (Svenska Fotbollsförbundet, 2016). The full size football fields, based on the average size of a regulation-size field (Svenska Fotbollförlaget AB, 2013), have an area of 7 087,5 m^2 and the recreational/sport fields have an average area of 800 m^2 (Svenska Fotbollsförbundet, 2015). This would mean that the municipalities have a combined total area of 314 475 m^2 of artificial turf. A loss of 3-5 tonnes per year of microplastic per full size football field (DHI, 2013) would equal a microplastic loss of 0.42 – 0.71 kg /m^2. This would mean a loss of 132 – 223 tonnes of microplastic per year.

Based on a 2005 report from the Norwegian Institute for Water Research the mass of the artificial grass fibers are 0.8 kg/m^2 (Källqvist, 2005), when combined with the estimation by Lassen *et al.* (2015) of a loss of 5-10 % of grass fiber fragments per year it's is possible to estimate a total loss of microplastic from the fibers to 12.6 – 25.2 tonnes per year.

This would result in a total loss of microplastics from grass fragments and granules from the artificial turfs of approximately 145 – 248 tonnes each year.

More research would be needed to be able to evaluate how much of this that would actually end up reaching the ocean through waterways and WWTPs, however it is obvious that artificial turfs are a considerable source of microplastic to our environment.

Roads, markings and tyres

Plastics are commonly used in asphalt in order to improve its quality and properties, making it more flexible and resistant. Most of the microplastics released from roads to the aquatic environment however are estimated to come from abrasion of the thermoplastic from road markings and paints as well as the degradation of the car tyres (Sundt, Schulze and Syversen, 2014; Magnusson, Eliasson, *et al.*, 2016; Horton, Svendsen, *et al.*, 2017; Kole *et al.*, 2017).

A study examining the microplastic sources to the river Thames, UK found an abundance of microplastics in the rivers water and sediment. Based on the colouration and composition of the plastic fragments they determined that road markings was the most likely source (Horton, Svendsen, *et al.*, 2017). Earlier studies have shown the possibility of microplastics from tyres to be transported from the road and into river systems and from there out into the oceans (Browne, Galloway and Thompson, 2010).

Based on Norwegian data by Sundt, Schulze and Syversen (2014), Magnusson *et al.* (2016) was able to make an estimation on the total amount of microplastics that are emitted from road wear and abrasion from public roads each year in Sweden to be 519 tonnes or 2,32 kg/km public road. It is undoubtedly very difficult to estimate how much of this plastic that makes it into the ocean each year, however it is possible to make an assessment of the microplastic load from the road network based on data from the municipals adjacent to Oresund.

The road network in the eight municipalities along the western coast of Skane that are adjacent to Oresund is comprised of 3 661 km of public municipal and state roads (SCB, 2010). For the ease of this estimation the road network is assumed to consist entirely of asphalt roads. Based on the estimation of (Magnusson *et al.*, 2016) this would mean that approximately 8.5 tonnes of microplastic could potentially reach the Oresund from the road network of the costal municipalities each year.

As cars and other vehicles travel across the roads their tyres are worn down and tiny microplastic particles are lost. Several studies have looked at the microplastics generated from tyres being worn down in traffic. The loss of microplastic particles from tyres in traffic have been estimated to be between 1 and 1.4 kg per capita, depending on the study (Norén and Naustvoll, 2011; Sundt, Schulze and Syversen, 2014; Magnusson *et al.*, 2016). Using an average of 1.2 kg/capita loss of microplastic from tyres each year the same eight coastal municipalities with a population of roughly 946 800 persons would release 789 tonnes of microplastic. Combined with the estimation of microplastics lost from the roads this would result in a total of approximately 798 tonnes of microplastics being released that could potentially reach Oresund each year.

It is of course very difficult to know how much of the microplastics that are released each year that eventually ends up in the ocean, and at this time more research is needed to fully understand how the microplastics are transported from surfaces such as roads and walkways to the ocean, and how much is deposited in sediments and soils.

Microplastics in Surface Runoff

Surface runoff relevant to this study occurs mostly in urban areas, from paved surfaces such as roads and walkways. When precipitation falls on the impenetrable surfaces of a city the water can't be infiltrated into the ground but is instead funnelled into storm drains to prevent flooding. Litter, pollutants and particles, such as microplastics, from the roads and paved surfaces can get swept up with the stormwater flow and brought down into the drains and waterways. The stormwater can either enter a combined sewage system, which would result in the stormwater entering a WWTP, or the stormwater can enter a separate waterway to the recipient water, with or without receiving any form of treatment. Lassen *et al.* (2015) studied the situation of stormwater runoff in Denmark, and concluded that approximately a half of the water was drained into combined sewage systems and WWTPs, and of the remaining stormwater one third entered sedimentation ponds for treatment, where some larger and heavier microplastic particles could settle. The remaining two thirds entered the recipient waters without any treatment. The available data and research didn't allow Lassen *et al.* (2015) to calculate any quantitative measurements of the amount of microplastics that are spread via the Danish stormwater, they did however estimate that about 80 – 90 % of the microplastics that doesn't enter the combined sewage system would eventually reach the recipient waters.

A similar estimation of microplastic loads from stormwater drains was conducted in Sweden, with similar findings to the previously mentioned Danish study (Magnusson *et al.*, 2016). Magnusson *et al.* (2016) estimated that only 12 % of the stormdrains in Sweden are entering into combined sewage systems where the potential stormwater would receive treatment in a WWTP. Only about 4 % of the Swedish stormwater that doesn't reach a WWTP is treated in sedimentation ponds. The study manages to give an estimate on the total amount of microplastics in stormwater in Sweden of a total of roughly 8 tonnes per year, however they state that the estimations are made with limited information and should be interpreted with caution.

Even though in situ sampling on the subject of microplastics in runoff in particular is scarce, there are interesting studies and research being made. Nizzetto *et al.* (2016) constructed a mathematical model to calculate the retention of microplastics in soils and river sediments and their transport in river catchments. The model, based on physical controls on soil erosion and transport of natural sediment, estimated that microplastic particles greater than 0.2 mm would not be retained in sediments regardless of density, whereas large particles with a density slightly higher than that of water would be retained in river sediments. They do state that strong water flow e.g. stormwater, could still dislodge and remobilize these particles to some extent.

In order to calculate a relatively reliable amount of microplastics that enter the Oresund each year more research on the concentration of plastic particles in runoff from different areas of different land use would be very valuable, as well as more data on actual retention of microplastics in ponds and waterways.

Wastewater treatment plants

The municipal wastewater treatment plants (WWTPs) along the western coast of Skane, Sweden that discharge their effluent waters directly or indirectly into Oresund receive wastewater from a variety of different sources. Domestic sources such as homes, offices and commercial buildings, but the WWTPs also receive wastewater from industries and stormwater run-off. Depending on the origin of the wastewater the amount and composition of microplastics would be expected to vary. In situ studies however have found microplastic particles consistent with those found in personal care products, such as toothpaste and facial creams, as well as synthetic fibers consistent with clothing, to be among the most common (Habib, Locke and Cannone, 1998; Carr, Liu and Tesoro, 2016; Mason *et al.*, 2016; Vollertsen and Hansen, 2017).

A number of studies that have documented the transportation of microplastic particles thru individual wastewater treatment plants have found the retention of particles to be very effective, removing roughly 95-99 % of the microplastic content from the influent (Magnusson and Norén, 2014; Carr, Liu and Tesoro, 2016; Magnusson, Jorundsdottir, *et al.*, 2016; Mason *et al.*, 2016; Murphy *et al.*, 2016).

Murphy et al. (2016) studied a large, modern WWTP in Glasgow with mechanical, chemical and biological processing of the wastewater. The WWTP received influent from a population equivalent (PE) of 650 000 and produced an average of 260 954 m^3 effluent/day. The influent contained an average of 15.7 microplastic particles per litre which was reduced to 0.25 microplastic particles per litre in the effluent stream, a reduction of 98.41 %. Despite strongly reducing the amount of microplastic particles in the effluent this WWTP is still releasing roughly 65 million particles into the recipient waters every day (Murphy *et al.*, 2016).

In Sweden and Finland Magnusson *et al.* (2016) found that four WWTPs with mechanical, chemical and biological wastewater treatment achieved a retention of microplastic particles of between 99.71 – 99.97 %. On average however the WWTPs in Finland and Sweden still released an average of 9 microplastic particles per population equivalent and day (Magnusson, Jorundsdottir, *et al.*, 2016).

Magnusson and Wahlberg (2014) sampled microplastic particles in the influent and effluent of three different Swedish WWTPs, serving between 750 00 and 12 000 PE, all with mechanical, chemical and biological treatments. They examined the retention of two different size fractions of particles, between 5mm > 300 µm and 5 mm > 20 µm. They found that the treatment plants retained on average 99,4 % of all microplastic particles larger than 300 µm but only 82.4 % of particles larger than 20 µm. This study highlights the importance of mesh and sieve sizes when studying microplastic particles.

A recent study conducted on ten separate Danish WWTPs examined the retention of microplastics and found that the treatment plants filter out 99.7 % of the mass of the microplastic particles that enter the plant, however only 92.6 % of the total number of actual particles (Vollertsen and Hansen, 2017). They explain the big difference in efficiency in retention between mass and particles by making the point that larger particles would settle faster in the settling tanks, as well as the possibility that larger particles are broken down in to smaller ones as the microplastic travels thru the plant.

Treated wastewater from six municipal WWTPs is discharged to the Oresund from the Swedish coast and an estimated total of 552 million m^3 treated wastewater reached the Oresund during 2016 (Sundin, Dimberg and Hytterbom, 2018). These six WWTPs are serving from 9 600 PE at the smallest site, to 477 400 PE at the largest, in total they are connected to approximately 930 000 PE (European Environment Agency, 2017). Based on data from Magnusson and Wahlberg (2014), which studied three Swedish WWTPs, that covered a wide range of different PE from 750 000 to 12 000, it’s possible to make an estimation of the microplastic load that the six WWTPs along the coast could propagate to the Oresund. The data from Magnusson and Wahlberg (2014) showed an average of 5 492 microplastic particles/m^3 being released from the three WWTPs, combining this with the outflow of the six municipal WWTPs along the coast of Oresund, 552 million m^3/year allows us to calculate a possible microplastic load of 3x10^{12} particles released at the plants every year.

These estimations may seem very high but are based on similar data to previous estimations done when calculating microplastic loads in Sweden (Magnusson *et al.*, 2016).

Because the influent to the WWTPs contains such extensive amounts of microplastic particles to begin with, even if only a small percentage of the total amount escapes the filtration, the microplastic load on the recipient waters can be substantial.

Spreading of sewage sludge on agricultural soil

As stated previously it’s been found that most of the microplastics that enter into the WWTPs along the western coast of Skane gets filtered out of the wastewater and retained in the wastewater sludge. A few studies have been done specifically on the subject of microplastics in waste sludge and they confirm the presence of microplastic particles throughout the sludge (Habib, Locke and Cannone, 1998; Zubris and Richards, 2005; Vollertsen and Hansen, 2017).

The wastewater sludge is processed in the plant until it reaches the desired water content. The sludge is then often spread onto agricultural soils as a way to replenish important nutrients such as phosphorus and nitrate back into the soil. There are restrictions on the amount of hazardous substances, such as heavy metals that can be present in the sludge if it is to be used on agricultural soils (Svenskt Vatten, 2017). However there are at this time no such restrictions when it comes to the microplastic content of the sludge.

In the previously mentioned Danish study Vollertsen and Hansen (2017) also investigated the microplastic concentrations in the waste sludge at five different WWTPs. They concluded that approximately 2% of the total dry-matter, and approximately 0.7 % of the weight of digested wastewater sludge in the facilities they studied to be comprised of microplastic particles. They do stress that there are some uncertainties in the measurements because of limited data, however this is one of the few studies to date that tries to quantify the microplastic content in wastewater sludge.

Zubris and Richards (2005) studied plastic fibers in wastewater sludge that had been spread on fields. They found that while a lot of the plastic fibers had separated from the sludge because of precipitation and erosion plastic fibers could still be found at the sites 15 years after application of the sludge. This may mean that sludge spread on agricultural soils containing relatively high concentrations of microplastics could act as a source for many years to come.

In a separate study however Vollertsen and Hansen (2017) compared farmland sites which had been covered with wastewater sludge as fertilizer to control sites which had not been covered with sludge. Interestingly they found the opposite to what they were expecting, with slightly higher microplastic content in the control sites. They ascribe this result to uncertainties in the sampling method and small sample size of only five sites each of control and sludge covered sites. Still the fact that microplastics were found in both sites raises the concern of how widespread the issue with microplastic in nature really is.

In 2016 a total of approximately 58 000 tonnes of wastewater sludge (dry weight) was used to revitalize the agricultural soils in Sweden (Svenskt Vatten, 2017). In the eight municipalities adjacent to Oresund the total amount of wastewater sludge spread on agricultural soils in 2017 was 19 841 tonnes, see table 1

(DataväxtAB, 2017). Taking into account the previously mentioned estimation by Vollertsen and Hansen (2017) of microplastic particles making up 0.7 % of the total weight of the sludge these figures would result in a possible microplastic load of approximately 139 tonnes from wastewater sludge on agricultural soils in these municipalities every year.

Table 1

Displays the amount of wastewater sludge spread on agricultural soils during 2017 in the eight coastal municipalities adjacent to Oresund (DataväxtAB, 2017).

Municipality	Wastewater Sludge on Agricultural Soil in 2017 (1000kg)
Burlov	1 107
Helsingborg	7 956
Hoganas	1 802
Kavlinge	3 211
Landskrona	3 216
Lomma	847
Malmo	949
Vellinge	753
Total	19 841

While the amount of research on the retention of microplastics in the wastewater sludge after it has been spread on farmland is very sparse, there has been one study looking at the theoretical retention of microplastics in soils by Nizzetto *et al.* (2016). Nizzetto used a mathematical model based on transport and retention of sediment by flowing water to assess the retention of microplastics. The model applied a total of 10 000kg of waste sludge containing 1% microplastic particles by weight to farmlands spread evenly over 6 times per simulated year. After the soil containing microplastics (i.e. wastewater sludge) was exposed to the modelled natural precipitation and erosion the study found that 16 – 38 % of the total amount of microplastic was still retained in the agricultural soils, while the rest had been washed away. This gives a first estimation of the retention of microplastics in agricultural soils and highlights the risk of microplastics accumulating in soils, as well as the case that 62 - 84 % of the particles are washed away from the soils and potentially makes their way into the aquatic and marine environment.

Considering the study by Nizzetto *et al.* (2016) it would be possible to estimate that 62 - 84 % of the microplastic particles in the agricultural soils get dislodged and could make their way to the Oresund. Based on the previously estimated 139 tonnes microplastics present in the sludge that would result in 86.2 – 117.8 tonnes of microplastic potentially making its way to Oresund every year. It should be considered that these estimations are based on a theoretical model and that the available data on actual microplastic content and retention in wastewater sludge and agricultural soils are very sparse which should be taken into account when viewing these estimations. Nonetheless the likely load of microplastic from agricultural soils to Oresund every year could be rather substantial.

Considering most of the microplastic that enter the WWTPs end up in the wastewater sludge there have been surprisingly few studies done on the fate of the microplastic particles once they've left the effluent. More studies will be needed to fully understand how the plastic particles behave once the sludge has been spread on for example agricultural soils.

This literary review study highlights the fact that the sources of microplastic that can get into the marine environment are plenty, and that the potential load of microplastics on the Oresund every year can be substantial, see table 2. The amounts of microplastics listed for the source in the table is an estimate, and it's, as previously stated, very difficult to assess how much of this that actually reach the Oresund every year.

Even so there are other potential sources of microplastics that fall outside the scope of this study, such as airborne microplastic downfall and microplastic emitting from marine sources such as hull paints and fishing gear. These are sources that also should be taken into account when trying to assess the microplastic situation in Oresund.

Table 2

An overview of the estimations of the loss of microplastic every year at different sources in the eight municipalities adjacent to Oresund.

Source/Pathway	MP at source	References
Litter & Waste Management	N/A	-
Artificial Turfs	145 - 248 tonnes	(Källqvist, 2005; DHI, 2013; Lassen *et al.*, 2015; Svenska Fotbollsförbundet, 2016)
Roads, Markings and Tyres	Approx. 798 tonnes	(SCB, 2010; Norén and Naustvoll, 2011; Sundt, Schulze and Syversen, 2014; Magnusson *et al.*, 2016)
Surface Runoff	N/A	-
Wastewater Treatment Plants	$3x10^{12}$ particles/year	(Magnusson and Wahlberg, 2014; Sundin, Dimberg and Hytterbom, 2018)
Sewage Sludge on Agricultural soils	Approx. 139 tonnes	(DataväxtAB, 2017; Vollertsen and Hansen, 2017)
Estimated yearly total	1 082 - 1 185 tonnes + $3x10^{12}$ particles	

Microplastics in the Oresund

Microplastics entering the food chain

For the microplastics to be able to have an effect on the marine biota in Oresund the particles need to be taken up by organisms and integrated into the food web in one way or another. Depending on the shape, density and composition of the plastic particles they can either be floating, sinking or neutral and thus they spread thru the entire water column and the sediments. Because of the slow degradation and breakdown of microplastics they have the ability and time to accumulate and transfer between organisms at different trophic levels in the food chain.

It is possible for marine microplastic to enter the food chain via planktivores that confuse the plastic particles with food since they are of a similar size (Brillant and MacDonald, 2000; Wright, Thompson and Galloway, 2013). Steer et al. (2017) even showed that planktonic fish larvae, sampled in the English Channel could ingest microplastic. Direct ingestion of microplastic particles have also been demonstrated in several different organisms such as the benthic feeding Holothurians (Graham and Thompson, 2009) as well as several other echinoderms (Christaki et a. 1998) and in marine polychaete worms (Wright et al., 2013). The species examined in these studies are all representative of potential prey for commercially important fish species such as the Atlantic Cod (*Gadus morhua*) present in the Oresund region. Kach and Ward (2008) showed the ability of several benthic and filter feeders such as bivalves: a scallop (*Argopecten irradiances*), a mussel (*Mytilus edulis*), a clam (*Mercenaria mercenaria*), an oyster (*Crassostrea virginica*), and a gastropod snail (*Crepidula fornicate*), to ingest microplastic particles that were suspended in water. A separate study on *Mytilus edulis* ingesting microplastic particles found that the particles translocated from the gut of the bivalve to the haemolymph where it persisted for over 48 days after the initial ingestion (Browne et al., 2008).

Farrell and Nelson (2013) studied the transfer of microplastics between Blue mussels, *Mytilus edulis* and the common littoral crab *Carcinus maenas*, both species that can be found in the Baltic Sea and Oresund. Microplastic particles were fed to the mussels and the mussels in turn were fed to the crabs. Microplastic particles were found in the haemolymph of the crabs, as well as in the gills, ovaries, stomach and the hepatopancreas, proving the transfer of microplastics between different trophic levels. The haemolymph of the crabs contained on average 15 000 microplastic particles per ml, which gradually disappeared over the 21 day study. In a real ecosystem, the authors speculate, biomagnification and accumulation could increase the microplastics concentration in the mussels as well as in their predators.

When studying pelagic and demersal fish species in the English channel they found microplastic particles in 36.5 % of all the 504 fish that were sampled, and all ten species, five pelagic and five demersal was found to have ingested microplastics (Lusher, McHugh and Thompson, 2013). The study showed that fish irrespective of feeding habitat where affected by the microplastics, and among the species in this study are several of the Gadidae and Soleidae families, both of which many fish are commercially important and present in the Oresund.

In a recent study conducted in the North Sea, as well as in the Baltic Sea Rummel *et al.* (2016) found that 3.4 % of all demersal and 10.7 % of all pelagic fish examined had ingested microplastic. Murphy *et al.*, (2017) studied the uptake of micro- and macroplastics by demersal, as well as pelagic fish in the Northeast Atlantic Ocean. They found that 47.7 % of all coastal fish examined had ingested some form of plastic particles. Further offshore they found that only 2.4 % of the fish had ingested plastic. This suggests that coastal species could be at greater risk of ingesting microplastics. Foekema *et al.* (2013) studied the occurrence of microplastics in the guts of 1203 separate individuals from seven common fish species in the North Sea. The results showed that 2.6 % of fish from five species, including herring, whiting, haddock and cod had microplastic contents in their gut.

A few studies have recently found very low numbers of microplastic ingestion in pelagic and demersal fish, as low as in only 0.25 % of the fish sampled and they suggest that the previously recorded higher numbers could be because of airborne contamination of the samples (Torre *et al.*, 2016; Hermsen *et al.*, 2017). More research would be needed to be able to estimate with certainty the actual spread of microplastics throughout the fish populations. The needed prerequisites for the microplastics to spread throughout the marine fish populations are most definitely present.

Effects of microplastics

The direct effects of microplastics on marine fish could be expected to be either because of toxicological or physical effects, while indirect effects would be caused by shifts in prey communities (Anderson, Park and Palace, 2016). Microplastics entering the food chain by ingestion at lower trophic levels, i.e. planktivores, can spread upwards thru the trophic levels. Mattsson *et al.* (2015) studied the effects and possibility of trophic transfer of microplastics in a freshwater environment. Microplastic particles was mixed with algae and subsequently fed to *Daphia magna* which in turn was fed to carp *Carassius carassius*. This feeding cycle continued over 61 days after which several changes to behaviour, physiology and metabolism could be observed in the carp. The fish displayed reduced feeding activity, damages to the liver, changes in muscle metabolism as well as changes in brain histology. Similar changes in fish and trophic accumulation of microplastics could be expected to happen in a marine environment.

A recent study conducted on two commonly used model organisms, the freshwater pelagic Zebrafish, *Danio rerio* as well as the benthic nematode *Caenorhabditis elegans* was able to show that microplastic particles caused adverse effects in both organisms (Lei *et al.*, 2018). The study exposed the organisms to microplastic concentrations that have been reported in the natural aquatic environment for ten days. The plastic particles was showed to cause a low rate of mortality in *D. rerio*, there was however substantial damage done to the intestinal tract of approximately 80% of the exposed fish. In *C. elegans* there was sever effects on the survival of the organisms, as well as negative effects on their development and reproduction. Particle size was shown to have a large effect on the toxicity of the plastic particles with a size of 1 µm being the most damaging. This study highlights the fact that the microplastic can cause harm throughout the aquatic food chain.

Apart from the physiological effects of ingesting microplastics particles themselves, there can be other negative effects caused by the properties of the plastic polymers. Substances that are a part of the plastic or are added to the polymers intentionally during production can leach out of the plastic and into the marine environment. Phthalates and antioxidants such as bisphenol A (BPA) are some of the compounds that can leach from the microplastics and effect the marine organisms (Lassen *et al.*, 2015; Anderson, Park and Palace, 2016; Li *et al.*, 2018).

Gambardella *et al.* (2017) studied the effect of microplastic exposure on two different planktonic larval crustaceans, a barnacle *Amphibalanus amphitrite* and a shrimp *Artemia fransciscana.* The results showed an accumulation of microplastics in the crustaceans and significantly affecting the enzyme activity, indicating oxidative stress and neurotoxic effects at all the sub lethal concentrations tested. This shows that even small microplastic concentrations, from 0.001 mg L^{-1} can cause measurable effects after only 24h of exposure. Another study observed the microplastic exposure of larval stages of planktonic sea urchins as well as juvenile ascidians, where the presence of microplastic concentrations as low as 0.125 µg L^{-1} was shown to alter and slow down development and metamorphosis of the organisms (Messinetti *et al.*, 2018). While these two studies don’t show acute effects on survival when exposed to microplastics at these concentrations, effects on larval development could still cause effects on long time survival and reproduction rates in the populations.

In addition microplastic particles can acts as vectors to transport other hazardous chemical compounds into organisms. The small particles have a relatively large surface area and the often hydrophobic surface can adsorb and accumulate a wide variety of persistent organic pollutants (POPs) such as DDT, PCBs, PAHs, polybrominated diphenyls (PBDEs) and phenanthrene (Bakir, Rowland and Thompson, 2014; Napper et al., 2015; Anderson, Park and Palace, 2016). Once these chemical compounds have adhered to the microplastics they can be transferred into and taken up by organisms more easily.

The transfer and accumulation of PCBs via microplastics were studied in the Lugworm Arenicola marina where they found that the microplastic particles alone affected the survival, body mass and activity in the lugworms, and the PCBs bioaccumulated in the lugworms during the 28 day study (Besseling et al., 2013).

Rochman et al. (2013) studied the transfer of hazardous chemicals, namely PAHs, PCBs and PBDEs, via sorption to microplastic particles when exposed in a small dose to a fish model organism, the Japanese Medaka (Oryzias latipes). The study showed that the fish ingesting virgin microplastic particles, without the extra chemicals (the control) still showed a stress response, and liver damage though less severe than the group receiving the particles laced with the chemicals. The fish exposed to the particles with chemical pollutants showed stress responses, lived damage and pathological effects more severe than those in the control. The chemical compounds also showed signs on bioaccumulating in the exposed fish over the duration of the two month study.

The scientific literature shows that the microplastics can affect a wide range of the organisms present in Oresund and that the particles can harm the fauna via several different mechanisms. The effects that these microplastic particles will have on a larger population or ecosystem scale in the Oresund remains to be seen. Changes such as shifts in fish and invertebrate community structures based on the previously mentioned microplastic effects could be possible, but more research is needed to comprehend these relationships.

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Conclusion

The scientific literature reviewed in this study points to the possibility of a large amount, roughly 1 100 tonnes of microplastics that could come from a relatively small stretch of the Swedish coastline and into the Oresund region each year. Even though most of the large amount of microplastics entering into wastewater treatment plants from households and industries gets filtered out, a few percent still flows straight thru the system and ends up in waterways leading, in most cases to Oresund. The microplastic that do get filtered out from the wastewater instead end up in the waste sludge which is then spread across many of the agricultural soils and farmlands in southern Sweden where the sludge can act as a source of microplastics, possibly for decades. Massive amounts of microplastic from wear and tear of the heavily trafficated roads along the coastline where particles from tyres and road markings flow with run-off into streams and waterways each year. Considering the amount of microplastics that get retained in the wastewater sludge and the fact that we spread it on our crops the knowledge of the fate of microplastics in sludge is limited. Further research will be crucial to understand the retention of microplastics in sewage sludge and to be able to better understand where the large amounts of microplastics that we spread on our important agricultural soils in southern Sweden ends up.

When the microplastics reach Oresund they can be taken up by several organisms of the local fauna. Planktivores, benthic feeders, filter feeders and fish can all incorporate or directly ingest the small plastic particles allowing the particles to spread throughout the marine food chain. Microplastic can have an impact on the entire ecosystem, proving lethal to small invertebrate fauna, induce toxicity responses and reduced feeding behaviours in fish, and negative effects on larval development in crustaceans and echinoderms. These changes in a relatively small ecosystem such as the Oresund, which also functions as a nursery for important fish populations in adjacent regions, can have severe effects on the entire ecosystem not only in the Oresund but also in the neighbouring seas, possibly causing trophic cascades. The cod population in Oresund is also one of the few stocks left in the entire Baltic Sea region that does not show signs of changes in length distribution and size reductions, believed to be happening due to selective fishing pressure on larger fish. With the probable effect of ocean acidification as a result of climate change in the near future, which could greatly affect the larval stages and force the recruitment of cod to extremely low levels, it is important to minimize the possible total amount of stressors on the fish populations in the Oresund. The results from previous studies on fish model organisms show that the microplastics can reduce the feeding behaviour and cause liver damage in adult fish, as well as in larvae. While the long term effects on entire populations because of these pathological responses to microplastics needs further research before we can fully appreciate the risk, it seems safe to assume that there would be a long term energy cost to the fish and other organisms which ingest microplastics.

With the amount of plastics being produced and consumed in Sweden, and globally each year the prevalence of microplastics in nature and the issues with them could be expected to increase in the coming years which is why it’s important further our understanding of how these particles spread in nature and the effects they have on our ecosystems.

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