A Plastic Ocean

The Science behind the Film

PLASTIC OCEANS

Brunel University London

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PREFACE

In this document we present scientific information and key facts underpinning the production of the film, *A Plastic Ocean*. This is part of an on-going collaboration between Brunel University London and the Plastic Oceans Foundation to communicate concerns about the potential threats posed by plastic waste to planetary health: the health of human civilization and the state of the natural system on which it depends (Whitmee *et al.*, 2015).

We live in a world in which plastics are an essential part of everyday life. However, increasing global consumption, combined with inadequate waste management, are leading to an unsustainable quantity of plastic waste in the global ocean. Worldwide annual production of plastics is close to 300 million metric tons, equivalent to the entire biomass of the adult human population. Estimates suggest that up to 10% of discarded plastic, around 8 million metric tons per annum, ends up in the ocean, comprising the greatest component of marine litter. Evidence is mounting of the environmental and health burden placed by plastic waste, and chemicals leaching from plastics, although the significance and reach of the global impacts of plastic litter on freshwater and marine ecologies, human health and wellbeing remain largely unclear.

Whilst *A Plastic Ocean* was being produced, the United Nations Environment Program (UNEP) pursued the issue of plastic marine litter in their Regional Sea Program and published a review of their global initiative on marine litter in 2009 and a comprehensive report on plastic pollution in 2016 (UNEP, 2016). In 2012, the Rio +20 United Nations Conference on Sustainable Development called for management action on marine litter and ocean plastics by 2025. GESAMP (the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) produced a two part assessment of the issue in 2015 and 2016 (GESAMP, 2016; GESAMP, 2015) and the plastics industries have also acknowledged that marine litter has become a global challenge (Plastics Europe, 2016). In March 2011, the Global Declaration for Solutions on Marine Litter was launched by 47 plastics associations from regions across the globe, supporting projects aimed at education, research, public policy, sharing best practices, plastics recycling/recovery, and plastic pellet containment.

It is likely that large uncertainties in the extent of ecological, social and economic impacts will remain for some time. However, all stakeholders agree that there is a strong moral reason that humanity should not allow the ocean to become more polluted by plastic debris and that there is a clear need to move towards a more circular economic model for the plastic production cycle. Some attention also needs to be directed at safer plastic chemical additives because inadequate separation of waste streams during plastic recycling may result in contamination of consumer goods with additives that have hazardous properties. Exposures of humans to such chemicals already occurs through our use of plastic and from foods that have been in contact with plastic, so it is important to minimize these exposures wherever possible. Some of these chemicals may affect the reproductive, endocrine, immune or nervous systems and there are international objectives to achieve sound management of such chemicals throughout their life cycle by 2020.

Education is essential to solving the problem of plastic oceans. The lack of public awareness about the consequences of mass consumption of plastic and how their choices affect the environment needs to be addressed and this is what the film and it's intended legacy aims to achieve.

In this document, we have included scientific information underpinning the film and key concerns for members of the public. The authors of this document served as individual scientists and not as representatives of any organisation, government or industry. Dr Christopher Green was supported by funds provided to Brunel University London by The Plastic Oceans Foundation (UK). Pofessor Susan Jobling is an employee of Brunel University London. The contents are solely the responsibility of the contributors.

KEY MESSAGES

The importance of a healthy ocean

- The ocean provides a life support system for our civilization through climate regulation, provision of food and other materials, and cultural, spiritual and recreational services.
- As such a healthy ocean is vital for human health, wellbeing and economy.
- Despite this, the services that the oceans provide are under human threat from overexploitation, climate change and pollution. These are impairing the ability of the ocean to provide these services.
- The vast quantity of plastic accumulating in our ocean presents a significant emerging global threat to the health of the oceans.

Plastics as materials

- Plastics are a group of synthetic polymers, mainly derived from fossil fuels.
- Plastic is a resource efficient, low cost, durable and lightweight material with a range of applications that benefit society.
- Plastics are essential components of innovative products and technologies in healthcare, energy generation, aerospace, automotive, maritime, construction, electronics, packaging or textile. Innovation in many industrial sectors would be much reduced without plastic materials.
- Plastic production and the use of plastic for single use applications are creating an increasingly vast waste stream that is outstripping our capacity for waste management. This is unsustainable in the long term.
- Half of all plastics are used in "single-use" applications, used just once and then disposed of. Many of the marine litter plastics are single use products.
- Plastics may take hundreds if not thousands of years to degrade, allowing them to accumulate in the environment in landfill, on land or in the aquatic environment.
- Plastics contain a complex mixture of chemicals including additives, unreacted monomers and manufacturing by-products within the polymer structure that can leach out during their use to contaminate the environment and lead to human exposure prior to their disposal.
- The chemical ingredients used in over 50% of plastics are described as hazardous chemicals. This means they have the potential to cause harm to humans, animals or the environment, although the risk of this occurring is dependent on the degree of exposure.

Plastics in the environment

- Plastics make up around 75% of marine litter, although this can be up to 100% at some sites.
- Plastics enter the ocean from a variety of sources on land and at sea, although a majority (~80%) are land based.
- An estimated 8 million metric tons of plastics enters the oceans from land based sources every year and this is expected to increase by an order of magnitude by 2025.
- Rivers can act as delivery systems to transport plastics from further in land to the sea.
- Plastics can be transported long distances on ocean currents to reach even remote areas, far from major human settlements.
- Plastics can be considered ubiquitous in the ocean, having been identified in globally from the Arctic to Antarctic and from sea surface to sea bed.
- Plastics accumulate in highly populated coastal areas, enclosed

seas and the ocean gyres. The gyres are five large systems of circular ocean currents. In the North Pacific Gyre, the Great Pacific Garbage Patch is not an island of plastic, but a plastic soup of microplastic.

- The sea floor may be the ultimate destination for a majority of plastic debris, since denser plastic sinks and floating plastic may eventually sink as it degrades or is weighed down by biota that attach to it.
- The size range of plastic varies widely from meters or even kilometres in size in the case of abandoned, lost or discarded fishing gear, all the way down to microplastics and nanoplastics.
- Plastic debris degrades over time, progressively fragmenting into smaller pieces through exposure to UV light and wave action. Fragments <5mm in size are called secondary *"microplastics"*. These are likely to break up further into nanometre sized *"nanoplastics"*.
- Some microplastics are manufactured (primary microplastics) at this small size. Examples include pre-production plastic pellets and microbeads in cosmetics.
- Some microplastics are also generated as a plastic product is used, such as polyester *"microfibres"* from synthetic clothing.
- Microplastics (predominantly secondary microplastics) are estimated to make up over 90% of the estimated 5 trillion pieces of plastic floating in the global ocean. They are also considered to be ubiquitous in the global ocean.
- Plastic debris in the ocean is both a source of contaminants, from the chemicals it contains from manufacture, and a sink, since it can adsorb pollutants such as pesticides and polychlorinated biphenyls from the surrounding environment. Concentrations of adsorbed plastics can reach over one million times that of surrounding seawater.

Plastic and its effects on wildlife health

- Plastic debris can affect wildlife through physical impacts such as entanglement, ingestion, transportation, and alteration of habitat, as well as potential chemical impacts.
- Plastic debris in the ocean has been shown to impact over 600 species of wildlife from across the marine food chain from plankton to whales.
- Plastic debris can alter habitat by smothering or physical damage and it may transport invasive species or harmful bacteria and algae to new areas. It may also provide benefits for some species by providing dwelling and protection.
- Entanglement in plastic debris can cause mortality through drowning and asphyxiation or when not immediately fatal can affect an animal's ability to grow and feed, affecting its long term survival. This is mostly associated with abandoned, lost or discarded fishing gear.
- Entanglement in has been observed in all species of sea turtles, half of all species of sea mammals, and 25% of seabird species.
- Ingestion can provide a point of entry for plastic debris into the food chain, reaching a wide range of species from whales to zooplankton at the base of the food chain that can ingest microplastics. Laboratory studies show that plastic can be transferred from prey to predator.
- Birds as a group are highly susceptible to plastic ingestion and it is estimated that over 90% of all seabirds have ingested plastic.
- Once ingested, plastic debris can be a direct cause of mortality through physical damage to the gut, obstruction of the gut resulting in starvation. Sub-lethal effects that impact long term survival and ability to reproduce are likely to be more common, such as reduced nutrient uptake.

- In laboratory studies, ingestion of microplastics by fish, crustaceans and invertebrates caused immune responses, reduced feeding and body mass, liver toxicity and adverse reproductive effects.
- By reducing the ability of individuals to survive and reproduce, there is concern that plastic debris could impact some wildlife populations. However, more data are required to fully risk assess the effects of plastics on populations and marine ecosystems.
- Laboratory studies show that chemicals derived from or adsorbed to plastics debris from the surrounding environment can be taken up by animals that ingest plastics. These chemicals have a range of adverse health outcomes for animals in laboratory studies.
- Because there are multiple pathways of exposure to these chemicals (food, water, air, dermal contact), it is unclear to what extent ingesting plastic debris contributes to the overall body burden of these chemicals in wildlife.
- It is also worth noting that chemicals derived from plastic, such as bisphenol A, phthalates and polybrominated diphenyl ethers (PBDEs), have also become global environmental contaminants from their manufacture, plastic use and disposal.
- Wildlife health could be impacted by exposure to bisphenol A and phthalates in some freshwater localities near point sources of contamination where their environmental concentrations coincide with those that cause adverse health effects in laboratory studies.

<u>Plastics and their human impacts</u>

- Plastics can impact humans through chemical exposure and physical interactions, as well as effects on wellbeing and economy.
- Microplastics have been identified in a variety of commercial fish and shellfish species consumed by humans. The implications of this exposure to plastics and their associated chemicals for human health present a major knowledge gap.
- There is widespread human exposure to plastic related chemicals, such as bisphenol A, phthalates and flame retardants through societal exposure to plastic products and consumption of food in contact with plastic *prior* to their disposal.
- These chemicals are known to be endocrine disruptors, in that they can alter the function of the endocrine system to cause adverse health effects. This has been demonstrated in animals in laboratory studies.
- Foetal development is a very sensitive window of development where exposure to endocrine disrupting chemicals can lead to irreversible developmental effects. More subtle disruption may also lead to increased risk of dysfunction and disease later in life.
- Epidemiological studies have reported associations between exposures to endocrine disrupting chemicals derived from plastics and a range of adverse health outcomes. These include impacts on reproductive development, neurodevelopment and immune function, adverse birth outcomes, delayed growth and puberty, altered behaviour, obesity, increased risk of allergic diseases, type II diabetes and cardiovascular disease.
- Public health concerns have led to bans on some chemicals in the manufacture of some plastic products, such as bisphenol A in baby bottles and phthalates in children's toys. Some commercial PBDE mixtures have been removed from the market under the Stockholm Convention.
- A range of health issues are also associated with inadequate waste management as municipal solid waste, including plastics, builds up in local environments, particularly in low and

middle income countries. This can lead to unsanitary conditions and spread of disease vectors.

- Waste dumps provide income for scavenging communities in extremely poor working and living conditions. They are a source of plastic pollution for the ocean, as well as chemical contamination of drinking water and soil for growing crops. Open burning of municipal solid waste can contribute to air pollution by particulate matter with local and regional implications for respiratory health.
- The presence of plastic waste visually degrades the environment and causes a loss of its aesthetic value, with implications for human wellbeing, recreation and tourism.
- Plastic debris in the ocean presents a navigational hazard that poses risks of injury, potential threats to life and loss of income. This reduces recreational value of the marine environment and impacts businesses and individuals whose livelihoods depend on the sea.
- Economic consequences are also significant, with marine debris costing the APEC region US$1.265 billion in 2008. Costs included clean-up of marine debris, loss of fisheries and wildlife, reductions in tourism, damage to vessels and the rescue costs as well as human health risks associated with damaged vessels.

Solutions

- The plastic pollution problem is a common concern for mankind that requires urgent, global action. Solving it will require international cooperation and the combined actions of the public, industry and policymakers, informed by sound science.
- There is no single solution and a strategic mix of approaches specific to a given locality will be required. This will be aided by an understanding of local cultural attitudes and behaviours of consumers.
- Improved public awareness through education is critical to engaging people with the problem and empowering them to be part of the solution, as consumers, designers, manufacturers or politicians.
- It is generally considered that the greatest impact can be had through preventative strategies to significantly reduce the volume of plastic entering the environment in the first place.
- In the immediate short term there is a need to rapidly improve waste collection and management, particularly in countries where this infrastructure is underdeveloped that are significant sources of ocean plastic.
- In the long term there is a need to value end of life plastic as a resource that is maintained within a circular economy to improve resource efficiency, reduce waste generation and reduce the escape of plastic into the environment.
- This can be achieved through 6 R's: Reduce, Remove, Re-design, Re-use, Recycle and Recovery of energy.
- Reduction in plastics consumption, particularly those of single use, presents the most resource efficient intervention. Members of the public can make simple changes such as buying loose fruit and vegetables and using reusable products.
- In some cases, legislation or local public action can be used to drive change by removing products from the market (e.g. single use plastic bags). Policies should be enacted globally to removal products using plastics that are designed to be littered (e.g. microbeads in cosmetics) from the market.
- Re-design of products can improve their longevity and make them easier to recycle at end of life. In addition, there is an opportunity to create safer plastics with safer chemical components instead of known endocrine disruptors through green chemistry. There are also applications for bioplastics produced from a renewable feedstock.

- Re-use of products is a more resource efficient option than use of single use products. Recycling can also help maintain plastics within a circular loop as they are remanufactured into new products. However, there are material separation and economic challenges to recycling.
- For plastics that are not easily recyclable, energy recovery is a final option to produce energy and usable by-products with commercial value from plastic waste, such as oils for fuel. However, there are concerns about emissions of toxic by-products and the economic viability of more advanced, cleaner treatments.
- In localities where plastic debris is accessible, typically closer to their sources, clean-ups can bring benefits. However, investment in prevention at source is required to avoid debris continually returning on the next tide and to provide a long term solution to plastic pollution. The removal of microplastics from the oceans is impractical.

Moving forward

- Without intervention the volume of waste that we produce and the volume of plastics entering the environment will increase in the coming decades and thus global action is required now to turn the tide on plastic pollution.

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1. Introduction

It has been said that we live in a plastic age. Since the large scale production of plastic began in the 1950s, plastics have become a part of our everyday life with very many benefits for society. Despite many technological advances, however, it is clear that increasing plastic production and the use of plastic for single use applications is creating an increasingly vast waste stream that is outstripping our capacity for waste management. As a result, plastics make up around 75% of marine litter, which can adversely impact wildlife through entanglement, ingestion and by altering habitats. At the same time, chemicals used in plastic manufacture, such as bisphenol A, phthalates and PBDE flame retardants have become global contaminants of air, water, soil, wildlife and humans. Environmental health burdens are possible, though not directly proven. Social impacts likely include reduced benefits from access to coastal environments and significant effects on wellbeing from living in a polluted, degraded environment which can affect sense of identity and community, and reduced opportunities for recreational activities. Whilst this can have a significant economic impact on tourism, economic losses are also experienced by fisheries and other coastal and marine sectors.

The film *A Plastic Ocean* is a feature length exploration of the enormous mess we are making in the world's oceans as a result of the sheer volume of plastic waste that deliberately or accidentally makes its way into our seas. This document presents a lay summary of scientific information underpinning the film. It is designed to support the desired legacy of the film in inspiring a wave of change in public attitudes to plastic within a generation. It starts by explaining the fate and behavior of plastic waste in the marine environment and then reviews our current knowledge of effects of plastic consumption and disposal on marine animals and humans.

Intensive scientific work is gradually improving our understanding of the impacts of plastic waste on human and wildlife health although there are still many knowledge gaps. Emerging evidence over the last decade has shown that plastic waste entering the ocean is broken into small fragments by UV light and the action of the wind and the waves. These microplastics, less than 5 mm in diameter, are estimated to make up over 90% of all ocean plastics. They may potentially be adding to the body burden of toxic chemical pollutants in aquatic wildlife by transferring chemicals from their structure into animal tissues and/or other persistent organic toxic pollutants attached to their surfaces. Concentrations of these chemicals on plastics can build to a million times greater than that of surrounding seawater. Microplastics enter the food chain through ingestion and are available for human consumption, having being identified in a variety of commercial fish and shellfish. The toxicological relevance of these exposures for human health is currently unclear. Evidence is mounting to support an environmental and health burden placed by plastic consumption, although the significance and reach of the global impacts of unmanaged plastic waste on freshwater and marine ecologies, human health and wellbeing remain unclear.

The greatest proportion of human exposure to chemicals within plastic occurs through consumption of food that has been in contact with plastic *before* it enters the waste stream. Some of these chemicals are known to disrupt the hormonal system of humans and wildlife, a phenomenon called endocrine disruption. Pioneering research on this topic at Brunel University London and elsewhere has highlighted the potential dangers posed by exposures of the developing foetus, newborns and children to certain plastic additives. This has led to a reduction in the use or banning of these chemicals in some countries.

The general conclusion from the film and the underlying science is that planetary health; the safeguarding of human health *and* the natural systems that underpin it, is likely at risk if manufacturers and users of plastics do not work together to create a "plastic safe" society. This is entirely possible through interventions that invest in the design of safer plastics through green chemistry and by stopping the flow of plastic to the environment in the first place. This can be achieved through improvements in waste collection and management and by increasing public value of end of life plastic as a resource that is maintained within a circular economy.

2. The importance of a healthy ocean

> *"No matter how you look at it, this planet is governed by the blue part. The world truly is mostly a blue place"*
> **Dr Sylvia Earle, Marine Biologist and Explorer**

The global ocean covers 71% of the Earth's surface, providing 99% of its available living space, and is home to some of the world's most productive and biodiverse ecosystems. The world is indeed governed by its "blue part" and the ocean is essential to a global climate that is suitable for human life (Costanza, 1999). The ocean stores heat, acts as a sink for carbon dioxide (CO_2) and forms a major part of the hydrological cycle as water evaporates from the sea surface to be deposited on land as rain. As well as providing fresh water, the ocean is also estimated to provide around 70% of the oxygen in the atmosphere, produced by photosynthesising phytoplankton (Sekerci and Petrovskii, 2015).

The ocean provides us with food. More than 2.6 billion people depend on the seas for their primary source of protein, making this the world's largest protein source. Fisheries and aquaculture employ tens of millions of people globally and support the livelihoods of hundreds of millions, particularly in low and middle income countries (FAO, 2014). New medicines are also being produced from compounds discovered in marine animals. For example, the venom of the cone snail has been developed as an analgesic for relieving pain and a compound isolated from the invertebrate sea squirts is now being used as an anti-cancer drug (Molinski *et al.*, 2009).

The ocean also holds a non-material value to us from a cultural and spiritual perspective that enriches us and benefits our wellbeing. We value the ocean for recreation, aesthetic enjoyment, and cultural and spiritual identity (UNEP, 2006). Studies from the UK suggest that visiting the coast leaves us feeling restored and less stressed, as well as encouraging physical activity and social and family interaction (White *et al.*, 2016; Depledge and Bird, 2009). Such benefits promote coastal tourism, which along with fisheries, provides another major source of coastal employment (UNEP, 2006).

Taken together the economic value of these "ecosystem services" that the ocean provides has been estimated at around US$20.9 trillion per year. A contribution of 63% of the total value of the entire world's ecosystem services (US$33 trillion per year) (Costanza *et al.*, 1997). Coastal environments, such as estuaries, mangroves, wetlands and coral reefs, have a disproportionately high value, covering 6.3% of the Earth's surface but contributing 43% of the value of the world's ecosystem services (Costanza, 1999).

Despite its role as a life support system for our civilisation, the ocean and the services that it provides are under human threat from overexploitation, climate change, habitat destruction and pollution. The loss of wildlife biodiversity that has resulted from these pressures is impairing the ability of the ocean to provide these services (Worm *et al.*, 2006). As Sir David Attenborough puts it:

> *"The ecosystems of the world are based on a healthy ocean and if that part of the planet becomes dysfunctional, if it goes wrong, then the whole of life on this planet will suffer."*

Within the context of these human pressures, the vast quantity of plastic accumulating in our ocean presents a significant emerging environmental threat that could be reducing the resilience of the marine environment to adapt successfully to other human pressures. It has now been described alongside climate change, ocean acidification and ozone depletion as a human induced disruption to the environment so major that it is potentially capable of destabilising the Earth's normal function on a global scale (Galloway and Lewis, 2016).

3. Plastic as a material

Plastics are a group of synthetic polymers derived from fossil fuels, although some plants, such as maize, and biomass sources can also be used as a feedstock to produce bioplastics (UNEP, 2016). There are six main classes of plastic: polyethylene (PE, high and low density), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS, including expanded EPS), polyurethane (PUR) and polyethylene terephthalate (PET) (GESAMP, 2015).

We live in a plastic age. Since the large scale production of plastic began in the 1950's production has rapidly increased to over 300 million tons worldwide in 2014, with China, Europe and the US dominating the market. In this century it is highly likely that we have already produced more plastic than in the entire 20th Century. As such, plastic has been referred to as "the Material of the 21st Century" (Plastics Europe, 2015).

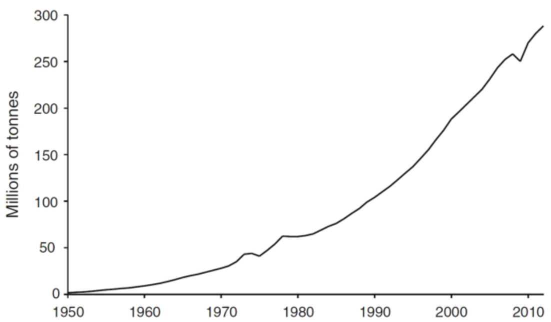

Figure 1: Plastic production from 1950 to 2012 (from Ryan, 2015; based on data from Plastics Europe, 2013)

The rise in plastic production has been driven by its global consumption. This is at its highest in the US and Europe, which used 139 and 136 kg of plastic per person in 2015 in comparison to only 16 kg in the Middle East and Africa (Plastics Insight, 2016). Its global consumption is driven in turn by its material properties and its low cost. Plastics are incredibly durable and ductile; they are strong materials and yet they are still lightweight. Used in the manufacture of a huge range of products, plastics are corrosion resistant, both electrically and thermally insulating and can take on any shape and colour (Andrady and Neal, 2009).

Plastic polymers are rarely used in products alone and are normally mixed with additive chemicals during the manufacturing process to further enhance its performance. There are several thousand such additives in use, with different plastics requiring different formulations dependent on their use (Lithner *et al.*, 2011). Organic fillers (such as silica) can impart strength, flame retardants such as polybrominated diphenyl ethers (PBDEs) can improve fire resistance, and plasticisers like phthalates can be used to impart flexibility. Colourants and other additives can also be used to enhance the appearance of the material (Andrady and Neal, 2009). In addition, alkylphenol ethoxylates are used as anti-oxidants and organotins as stabilising agents (Teuten *et al.*, 2009). These additives can make up a large proportion of plastic material, with the phthalates reported to contribute 10 to 60% to PVC by weight (Rudel and Perovich, 2009), whilst PBDEs can contribute 5 to 30% of a product by weight (Meeker *et al.*, 2009). Plastics also contain unreacted monomers and other impurities from incomplete polymerisation reactions that may be retained within the polymer structure as an artefact of the manufacturing process, such as bisphenol A (BPA) (Lithner *et al.*, 2011; Koch and Calafat, 2009). However, all of these additional chemicals are not chemically bound to the plastic polymer (Andrady and Neal, 2009; Teuten *et al.*, 2009) and are able to leach from the material. As a result, there has been concern raised about contamination of the environment by these chemicals and their potential impacts on wildlife and human health.

The properties of plastics allow them to be used in a wide variety of beneficial applications. They can be used as building materials, including in water distribution networks and insulation for houses. They are also used in transport to reduce the weight of cars, trains and planes, reducing their energy consumption and thus their cost and CO_2 emissions. Similarly the use of plastic in packaging makes products lighter and more resource efficient to transport. This also reduces food wastage by prolonging the life of foods and delivering clean water to areas in need. Plastics are also used in medical devices, to make clothing, electronics and renewable energy technology (reviewed in Andrady and Neal, 2009). Up to half of all plastics are used in single use applications – they are used just once and then disposed of (Hopewell *et al.*, 2009), creating a vast waste stream where an insufficient amount is re-used, recycled or is used to generate energy. A single use plastic shopping bag for example may be used for only 12 minutes on average before it is discarded (State of New South Wales and the Environment Protection Authority, 2016). In Europe, 8 million metric tons of plastic waste is landfilled each year, resulting in the loss of this economically valuable resource (Plastics Europe, 2015) and storing the problem of unprocessed plastic waste for future generations to cope with, since plastics could take hundreds if not thousands of years to degrade (Barnes *et al.*, 2009).

As the material of the 21st Century, global production of plastic is expected to rise to meet the demands of an increasing population and consequently, the waste stream will continue to grow whilst landfill space is in decline (UNEP, 2016; Barnes *et al.*, 2009). This will also increase the drain on limited fossil fuels, with plastic production potentially accounting for 20% of annual oil consumption by 2050 compared with 6-8% today (World Economic Forum *et al.*, 2016). Combine these issues with the volume of plastic used in single use and short lifespan products and it is clear that the way that we produce, use and dispose of this valuable material is simply unsustainable (Thompson *et al.*, 2009; Hopewell *et al.*, 2009).

4. Plastic in the environment

Plastics can enter the environment at all stages of their production-use-disposal cycle, although this is especially prevalent at disposal due to inadequate waste management and inappropriate disposal (UNEP, 2016). Whilst we may consider plastics to be disposable, the reality is that once they have entered the environment their durability, which gives them such an advantage as materials, makes them persistent, pervasive and accumulating global pollutants that resist biodegradation (Andrady, 2015). As a result, apart from the proportion of plastic that has been incinerated, it can be argued that all of the plastic waste that has ever been produced is still somewhere in the environment today, either in landfill or on our land, in our rivers, or in our oceans (Andrady, 2000). Even though they only account for around 10% of all municipal solid waste (Hoornweg and Bhada-Tata, 2012), plastics make up a vast majority of all marine litter in the ocean. On average this is around 75% (Hartley *et al.*, 2015; OSPAR, 2007), although in some locations plastics can account for 95-100% of all marine litter (Galgani *et al.*, 2015).

> *“Plastic is wonderful because it is durable, and plastic is terrible because it is durable”.*
> **Craig Lesson, Director, *A Plastic Ocean***

Although plastics are durable, constant exposure to environmental conditions causes plastic materials to degrade slowly over time. Degradation primarily occurs as a result of exposure to UV radiation from the sun, through a process of photo-oxidation that weakens the structure of plastic, making it increasingly brittle. Eventually, degrading plastic breaks up into smaller and smaller fragments or *“microplastics”*, particularly when it is exposed to additional weathering processes such as wave action. Consequently, it has become clear that as well as large items of plastic debris, fragments and fibres of microplastic are also abundant and widespread throughout the ocean (Law and Thompson, 2014; Thompson *et al.*, 2004). Microplastics in the environment may fragment further into even smaller *“nanoplastics”*, which has been observed in laboratory studies (Andrady, 2011). However, because of their small size, nanoplastics have yet to be identified in the aquatic environment due to challenges in sampling and analysis. Whilst their presence in the environment is highly plausible, they represent one of the least known aspects of marine litter (reviewed by Koelmans *et al.*, 2015).

This progressive process of degradation is fastest where exposure to UV light and temperature is higher. As a result, the degradation of plastics is fastest in photic environments, such as on beaches and at the sea surface. However, below the photic zone in the benthic deep sea environment, where there is no natural light and low temperature, the process is much slower and plastic waste is much more persistent (Andrady, 2015). As a result of the input of a diverse range of plastic products into the ocean and its progressive degradation, the size range of plastic debris in the ocean is very wide. It ranges from the *"macroplastics"* that can be meters or even kilometres in size, in the case of abandoned, lost or otherwise discarded fishing gear, all the way down to the nanometre sized nanoplastics that have fragmented from microplastic (GESAMP, 2015; Koelmans *et al.*, 2015).

4.1 Microplastics

Microplastics are commonly defined as plastics less than 5 mm in size with no lower size limit, a definition used because particles of this size are considered to be available for ingestion by a wide range of marine organisms (GESAMP, 2015). Microplastics are generally divided into two types: primary and secondary.
Primary microplastics are specifically manufactured at this small size and include microbeads found in facial scrubs, toothpastes and other cosmetics where they are used as an exfoliating agent (**Figure 2C**) (Napper *et al.*, 2015). Indeed, it is estimated that a single facial scrub product could contain between 137,000 and 2.8 million microbeads (Napper *et al.*, 2015). These can enter the environment through wastewater treatment works after they are used by consumers. For example, 8 trillion microbeads are estimated to be emitted into freshwater and marine habitats of the US every day (Rochman *et al.*, 2015a). As a result, many of the microplastic particles collected from the surface waters of the Great Lakes in the US were thought to be microbeads originating from cosmetics (Eriksen *et al.*, 2013a). There are also pre-production plastic pellets or *"nurdles"* (**Figure 2B**) used as a feedstock for manufacturing plastic, which can enter the environment through industrial discharges and through loss from cargo ships during transport. Other examples include small plastics used to blast clean surfaces, plastic powders used in moulding and plastic nanoparticles from other industrial processes (GESAMP, 2015).

Secondary microplastics result from the progressive degradation and fragmentation of larger plastic products during their use or through weathering processes in the environment after their disposal (GESAMP, 2015). This can include fragments from plastic products (**Figure 2A**) and their packaging, as well as plastics used in construction and agriculture, and pieces of fishing gear. However, other examples include plastic dust from the wear of car tyres, which are thought to be entering the environment through road runoff and could be a significant source of microplastics from land. Indeed, one report estimated annual emissions of plastic tyre dust from Germany to be in the order of 110,000 metric tons (NEA, 2014). Similarly, fragments of road marking paints, which have been found in the River Thames basin in the UK having been washed from the roads into storm drains (Horton *et al.*, 2017). Plastic *"microfibres"* are also a commonly identified type of microplastic in the environment, having been found in sediments, the water column and biota across the globe (**Figure 2D**) (Napper and Thompson, 2016; Thompson *et al.*, 2004). These originate from synthetic textiles used for clothing, carpets and upholstery, which release thousands of microfibres when they are washed and enter the environment through the sewage system (Browne *et al.*, 2011). It has been estimated that a 6 kg wash of acrylic fabric can release around 700,000 microfibres (Napper and Thompson, 2016).

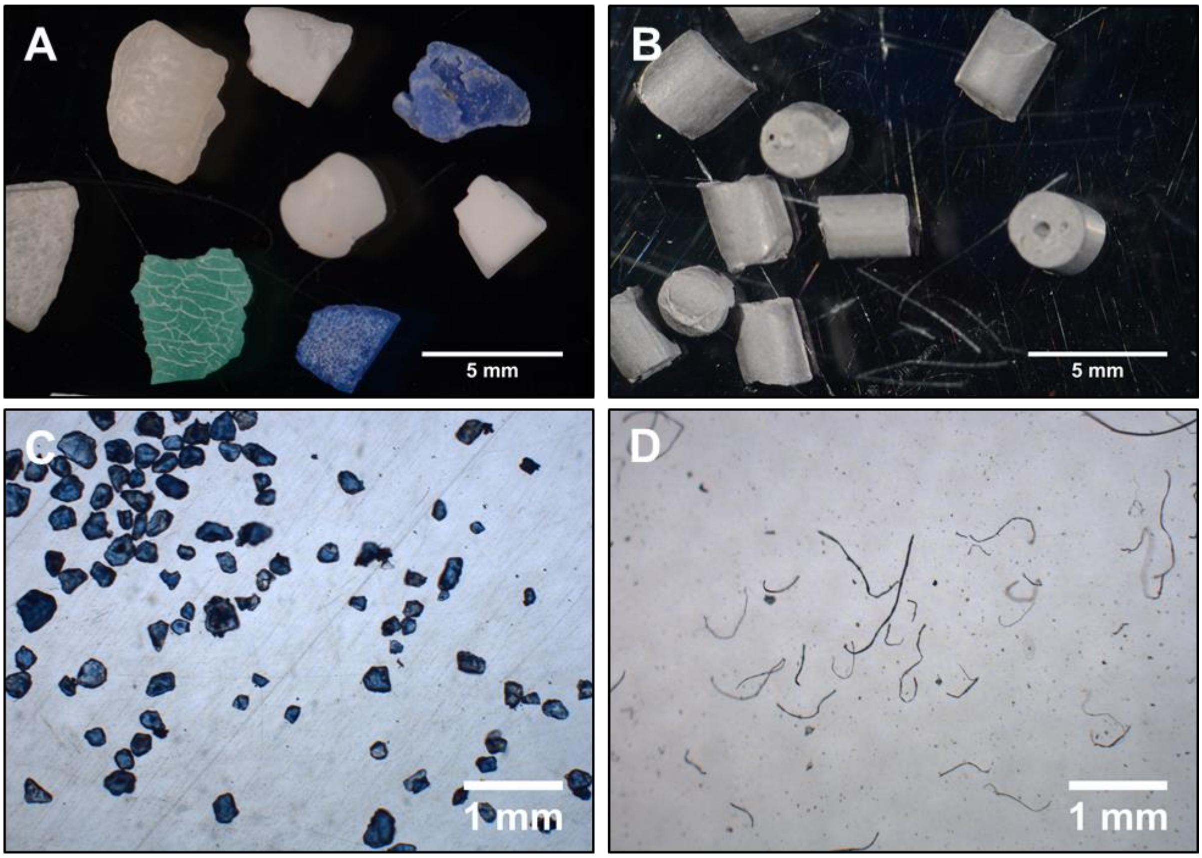

Figure 2: A selection of microplastics: Microplastics fragments collected from beach sediment in Tulum, Mexico (A); Polycarbonate nurdles (B); Microbeads recovered from toothpaste (C); Polyester microfibres from a synthetic clothing material – in this example a fleece jacket (D)

4.2 Sources of marine plastic

It has been widely reported that around 80% of the plastic in the ocean originates from the land, with the remaining 20% coming from marine sources (Eunomia, 2016; Andrady, 2011). Although this specific figure is not well substantiated, land is still likely to be the predominant source and it has been estimated that between 4.8 to 12.7 million metric tons, with an average of around 8 million metric tons, of plastic entered the ocean from coastal countries in 2010 (Jambeck *et al.*, 2015). Regional differences in plastic emissions entering the ocean occur due to variations in population size and the standard of waste management practices between countries. The top 4 major contributors were low and middle income countries in South East Asia including China, Indonesia, the Philippines and Vietnam, which have limited waste management infrastructure. Despite their lower percentage of mismanaged waste, the US and the combined EU nations also make the top 20 most prolific polluters because of their high use of plastics per capita (Jambeck *et al.*, 2015). It is also worth noting that high income countries, including those in Europe and the US, have been exporting their own plastic waste to the top plastic emitting countries, such as Indonesia and China, for recycling. Here any material that is not recycled and is of little use to companies can also be lost from the waste management system to contribute to marine litter (GESAMP, 2016). In 2012, China implemented "Operation Green Fence" to reduce the import of low quality materials and material ineffectively sorted from food waste and other contaminants, which were inappropriate for recycling and had been adding to their waste burden and resulting in environmental contamination (Flower, 2016).

With over half of the world's population living within 60 km of the ocean and 75% of large cities located near the coast, these areas exhibit high use and disposal of plastic (UNEP, 2016). Here, plastic can be washed off the land by rain or blown directly into the ocean by wind. At the same time, storm drains can transport plastic from the city streets to rivers and eventually the seas. Consequently, littering from the general public and coastal tourism, particularly on beaches, contributes to ocean plastic. Illegal dumping of municipal solid waste into storm drains and the ocean itself, particularly in areas with poor waste management infrastructure, is also a significant issue (Guerrero *et al.*, 2013). Many of the littered plastics are single use products linked to our disposable lifestyles, as demonstrated by the top litter items recovered during coastal clean ups across the globe **(Table 1**). As well as consumer products, there may also be contributions from the construction and agricultural sectors who both use plastics, although this is not well quantified (UNEP, 2016).

Poor waste management in towns and cities and open waste dumps near the coast can also be significant sources of plastics, particularly in low and middle income countries. This was evident when the *Plastic Oceans* team visited the Smokey Mountain II waste dump at Pier 18 in the Philippines, which was overflowing into the ocean (**Figure 3**). Jim Mallari of the Pasig River Rehabilitation Commission estimated that this was contributing 1,500 metric tons of plastic to the ocean every day. The influx of plastic waste from land can also be exacerbated by extreme weather events, such as the 2011 Tohoku tsunami in Japan which washed a vast amount of debris into the Pacific Ocean, where some was transported across the Pacific to wash up on the east coast of the US (Lebreton and Borrero, 2013).

Top 10 litter items		
1	Cigarette Butts	2,127,565
2	Plastic Beverage Bottles	1,024,470
3	Food Wrappers	888,589
4	Plastic Bottle Caps	861,340
5	Straws, Stirrers	439,571
6	Other Plastic Bags	424,934
7	Glass Beverage Bottles	402,375
8	Plastic Grocery Bags	402,122
9	Metal Bottle Caps	381,669
10	Plastic Lids	351,585

Table 1: The top 10 litter items recovered from 91 countries during the Ocean Conservancy's International Coastal Clean-up in 2015 (Ocean Conservancy, 2016).

Figure 3: An open landfill site on the edge of Manilla Bay at Pier 18, Philippines

Interconnected waterways of lakes, canals, rivers and estuaries can stretch many miles inland and can act as a transport mechanism to deliver plastics to the ocean. Indeed, microplastic and macroplastic debris have been identified in the freshwater environment globally, with some studies showing that contamination is as severe as in the ocean (reviewed by Dris *et al.*, 2015; Eerkes-Medrano *et al.*, 2015; Wagner *et al.*, 2014). A good example of this is the Great Lakes in the US which flow into the North Atlantic Ocean via the St Lawrence River. Here on the lakes, 80% of the litter recovered from the shoreline is plastic, whilst microplastics are found throughout their tributaries as well as in the waters of the lakes themselves (Baldwin *et al.*, 2016; Driedger *et al.*, 2015; Eriksen *et al.*, 2013a). In some areas within the lakes the surface water densities of microplastics are as high as in accumulation zones in oceanic gyres (Driedger *et al.*, 2015).

"Even if you don't live near the ocean, the chances are your plastic garbage has found its way to the sea"
Dr Sylvia Earle, Marine Biologist and Explorer

In comparison, in low and middle income countries, the use of rivers as a disposal pathway by local residents illegally dumping municipal solid waste, undoubtedly contributes to the issue of plastics in the environment downstream (Guerrero *et al.*, 2013; Henry *et al.*, 2006; Pokhrel and Viraraghavan, 2005). This is driven by lack of effective waste management infrastructure to cope with the plastic products being sold. Globally it has been estimated that between 1.15 and 2.41 million metric tons of plastic waste enters the ocean from rivers annually, of which 67% comes from rivers in low and middle income countries, mainly in Asia (Lebreton and Borrero, 2013).

Whilst litter entering rivers and lakes from land through runoff is clearly a problem, there are also other point sources that flow directly into the freshwater environment and the ocean. For example, waste water treatment works effluent is a source of microplastics, such as microbeads in cosmetics and microfibres from clothing. These originate from our households and are not effectively removed at wastewater treatment works before the effluent is discharged (Eriksen *et al.*, 2013a; Browne *et al.*, 2011; Fendall and Sewell, 2009). Flakes, films and plastic foams of unknown origin have also been recovered (Murphy *et al.*, 2016). Wastewater can also be a source of larger plastics when untreated effluent is discharged, for example during storm conditions or a blockage within the treatment works. In the River Thames in the UK, one study showed that the most contaminated sites were in the vicinity of sewage treatment works. Of the plastic recovered, 20% were components of sanitary products, such as condoms and the plastic backing strips from sanitary towels that had been inappropriately disposed of via lavatories (Morritt *et al.*, 2014). These can also be found on beaches, along with cotton bud sticks, wet wipes and tampon applicators following discharge of sewage off the coast (Marine Conservation Society, 2015).

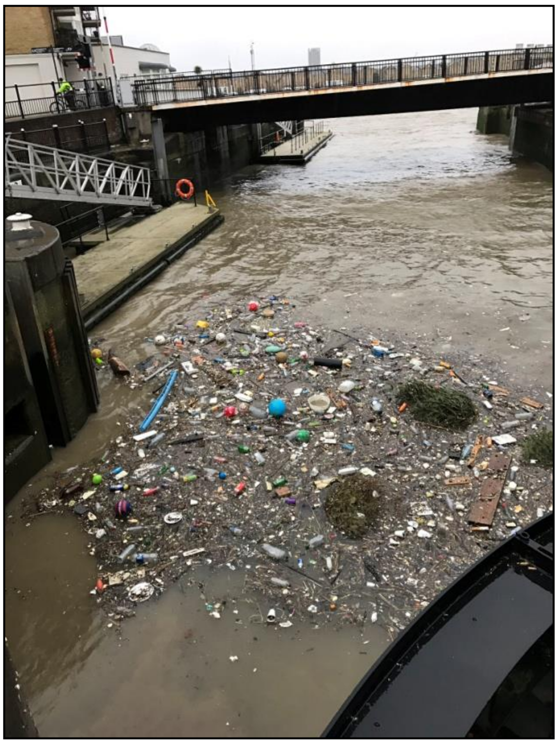

Figure 4: Plastic debris floating in the River Thames in London, UK (from Paul Hyman, Active360)

Industrial wastewater can also be a source of microplastics, particularly nurdles. For example, in Europe's second largest river, the Danube, the amount of plastic recovered in surface water in Austria was greater than the amount of drifting larval fish and was estimated to input 4.2 tons of plastic into the Black Sea every day (Lechner *et al.*, 2014). Around 79% of this was made up of pre-production pellets, spherules and flakes from industrial plastic production sites.

Of the estimated 20% of marine plastics that originate from the sea, the fishing industry is likely to be the most significant contributor through their use and abandonment, loss or discard of plastic fishing gear, including nets, lines and traps (Andrady, 2011). Indeed, it has been suggested that 70% by weight of global large, macroplastic litter is fishing related (Eriksen *et al.*, 2014). The nets can form the largest examples of marine litter, potentially spanning kilometres in length when they are initially lost. As they are rolled in the waves they can form large masses that float on the ocean surface due to the attached buoys and be transported long distances. Some of the masses of nets recovered from the Hawaiian Islands have exceeded 25 m^2 in size and one net weighed 11.5 tons alone (NOAA News, 2014; Donohue *et al.*, 2001). Aquaculture can also be a source of marine plastic, as demonstrated by the expanded polystyrene spherules washed onto the South Korean shoreline having fragmented from the buoys used in hanging culture farms for mussels and oysters. These made up 95% of all plastics debris recovered from one site (Heo *et al.*, 2013). Disposal of plastic waste by ships is regulated under the 1978 Protocol to the International Convention for the Prevention of Pollution from Ships (MARPOL). However, lack of compliance still results in plastic being illegally dumped at sea (Derraik, 2002). Accidental loss of cargo during transport of plastics can also occur, particularly during extreme weather events. Indeed, in 2013 six containers and an estimated 150 metric tons of polypropylene nurdles produced by the plastics manufacturer Sinopek Ltd were lost from a cargo ship off Hong Kong during Typhoon Vicente (UNEP, 2016). Here the *Plastic Oceans* team witnessed the aftermath as local beaches became littered with nurdles.

4.3 Distribution and Fate

Once plastic has entered the ocean it can be distributed throughout each of five compartments based on its material properties and environmental processes, although the degree of transfer of plastics between these compartments is still subject to research (UNEP, 2016). These five compartments include: the coastline, the ocean surface (**Figure 5**), the main water column, the seabed and biota – the animals and plants that live there. Plastic has been identified in all of these compartments and is found accumulating in marine environments globally from the Arctic to the Antarctic, and can now be considered to be ubiquitous in the global ocean (Cózar *et al.*, 2017; Lusher *et al.*, 2015b; Obbard *et al.*, 2014; Law and Thompson, 2014; Barnes *et al.*, 2010; Barnes *et al.*, 2009).

> *“Where can you go in the world anymore and not find plastic?”*
> **Mike deGruy, Marine Biologist and Filmmaker**

Figure 5: A Plastic Ocean cameraman Doug Allen films plastic debris at the sea surface off the coast of Sri Lanka after filming a pygmy blue whale calf

4.3.1 Plastics on the sea surface and the ocean "Garbage Patches"

Whist plastics have been found throughout the water column, we know the most about their distribution at the sea surface (Van Sebille *et al.*, 2015). Here, they are the most visible and accessible to us and even the floating microplastics are able to be captured by trawling with plankton nets. These include plastics with low density, such as polyethylene and polypropylene that naturally float, as well as normally non-buoyant plastics that are filled with air, such as empty bottles and fishing gear with its air filled buoys still attached. Large, buoyant macroplastics float at the surface and the highest densities of buoyant microplastics can be found within the first 5 meters depth (Kooi *et al.*, 2016). Because of their slow degradation and the interconnected nature of the ocean (see **Figure 6**), floating plastics can be transported vast distances, potentially thousands of kilometres, across the globe on ocean currents. As a result, they will even reach remote environments far from human habitation and their original source (Heskett *et al.*, 2012; Barnes *et al.*, 2009). On Midway Island in middle of the Pacific Ocean, which is part of a World Heritage site, the Papahānaumokuākea Marine National Monument; one of the world's largest marine protected areas. The *Plastic Oceans* team found plastic debris deposited all along the shoreline when they visited the island with Dr Jenifer Lavers (Institute for Marine and Antarctic Studies, University of Tasmania) to record the impacts of ocean plastic on the native Laysan albatross (*Phoebastria immutabilis*) population. Since 1996, the US National Oceanic and Atmospheric Administration (NOAA) have removed 904 tons of marine debris from the islands within the monument. In 2014, as well as derelict fishing gear they also removed 7,436 hard plastic fragments, 3,758 bottle caps, 1,469 plastic beverage bottles and 477 cigarette lighters from Midway Island alone (NOAA News, 2014).

Similarly, the remote and uninhabited Henderson Island in the Pitcairn group in the South Pacific has been found to host the highest density of marine debris recorded in the world, with up to 671.6 items/m^2 recovered from the surface of its beaches (Lavers and Bond, 2017). In total it is estimated that there are 37.7 million plastic debris items weighing a total of 17.6 tons currently present on the island and that this is increasing daily. As such, plastic litter does not respect borders and, in reality, there is only one ocean with no boundaries which provides a global distribution for plastic litter.

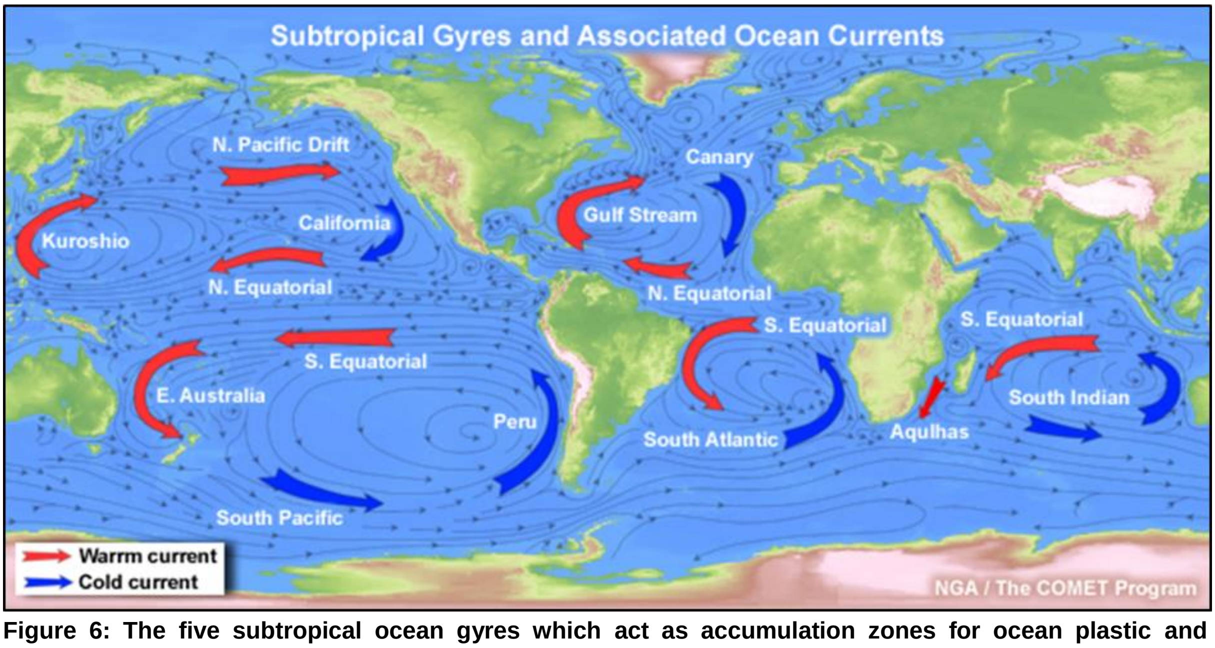

Figure 6: The five subtropical ocean gyres which act as accumulation zones for ocean plastic and associated ocean currents (from Laing and Evans, 2011 © The COMET Program)

The amount of plastic found on the ocean surface varies geographically, with microplastics reported at low concentrations of 3 particles/m^3 recovered in the coastal waters of California to the highest concentrations recovered of 102,000 particles/m^3 in the coastal waters of Sweden (Fischer *et al.*, 2015; Doyle *et al.*, 2011; Noren and Naustvoll, 2010). There are areas where plastics accumulate, such as semi-enclosed seas (like the Caribbean and the Mediterranean), areas near densely populated coastlines, and the subtropical ocean gyres (Law and Thompson, 2014; Barnes *et al.*, 2009). The subtropical gyres are large systems of circulating ocean currents north and south of the equator which are formed by global wind patterns and the forces of Earth's rotation (National Geographic Society, 2014) as shown in **Figure 6**. These circular currents can act to aggregate, concentrate and retain floating debris.

In 1997, Captain Charles Moore sailed through the North Pacific Gyre on his return from Hawaii to Los Angeles after the Transpac sailing race. This was an area not normally frequented by sailors due to the lack of wind and he was alarmed to find abundant plastic debris in this remote area. He wrote about his experience and his continuing investigations into this phenomenon in an article for the Natural History Magazine in 2003, in which oceanographer Curtis Ebbesmeyer described the area as the "Eastern Garbage Patch" (Moore, 2003). The story developed and gained media notoriety and public interest, with the garbage patch renamed the "Great Pacific Garbage Patch". Eventually this idea evolved in media reports to fuel the perception that there is a floating island of plastic in the North Pacific Ocean. These claims drove the *Plastic Oceans* team to investigate the Great Pacific Garbage patch for themselves. Producer Jo Ruxton travelled with Dr Andrea Neal (University of California at Santa Barbara) to the sub-tropical convergence zone, part of the North Pacific Gyre to the north of the Hawaiian Islands. At first glance they found the sea appeared to be clear of plastic. However, when they sampled the sea surface with a manta trawl net the problem became visible as they recovered small fragments of microplastic in abundance (**Figure 7**).

> *"There is no island of plastic, what exists is more insidious. What exists is a kind of plastic smog"*
> **Craig Leeson, Director, *A Plastic Ocean***

The idea of the Great Pacific Garbage Patch as an "island of trash" is undoubtedly a misconception. Although there is large macroplastic debris here, studies have shown that the gyre contains a high concentration of microplastics (Law and Thompson, 2014). Indeed, Captain Moore's 2001 survey estimated that the gyre contained a mean abundance of 334,271 small pieces of plastic per km^2. The mass of the plastic they recovered was also approximately six times that of plankton (Moore *et al.*, 2001). As such, what actually exists in the gyre is more like "plastic soup" than a plastic island.

Figure 7: A manta trawl for microplastic in the North Pacific Gyre (top); Microplastics recovered from the trawl net (bottom)

To see if this was also happening elsewhere, The *Plastic Oceans* team also visited the South Pacific subtropical gyre north of Fiji where Director Craig Leeson joined Dr Bonnie

Monteleone (University of North Carolina) and Assistant Professor Michael Gonsior (University of Maryland) to trawl for plastic debris. Again, sampling in this gyre has revealed high concentrations of microplastic accumulating towards the centre of the gyre (Eriksen *et al.*, 2013b).

The North and South Pacific Gyres are two of five major ocean gyres in the Pacific, Atlantic and Indian Oceans (**Figure 6**), all of which have been shown to act as accumulation zones for plastics (Cózar *et al.*, 2014; Eriksen *et al.*, 2014; Ryan, 2014; Eriksen *et al.*, 2013b; Law *et al.*, 2010). It is in these gyres that the highest concentrations of microplastic in the ocean surface are likely to be achieved, with the North Pacific Gyre containing the most microplastic due to its vast size and plastic inputs from the US and Asia (Van Sebille *et al.*, 2015).

In total, it has been estimated that there are over 5 trillion pieces of plastic floating in the global ocean (Eriksen *et al.*, 2014), although a study using a larger dataset of microplastic measurements in the ocean suggested that it could be even higher, ranging from 15 to 51 trillion particles (Van Sebille *et al.*, 2015). Microplastics make up the vast majority (estimated to be over 90%) of all plastic at the sea surface (Eriksen *et al.*, 2014). However, because of the small size of microplastics, around 75% of the total mass of plastic in the ocean is made up of larger plastics (Eriksen *et al.*, 2014). Interestingly, the amount of plastic floating in the ocean is far less than we may expect, with a global weight of hundreds of thousands of tons in comparison to the estimated 8 million tons input in 2010 alone (Van Sebille *et al.*, 2015; Jambeck *et al.*, 2015; Eriksen *et al.*, 2014). When specific sources of plastic waste are reduced, such as industrial pellet discharge, this can cause an observable reduction in concentrations of ocean plastics within a limited number of years, indicating that plastics disappear from the sea surface in relatively short time scales (Van Franeker and Law, 2015). As a result, there must be other sinks for plastic in the environment, such as deposition on the shoreline, consumption by biota and sinking to the seafloor, the last of which may be a significant environmental sink for plastic debris. Research is continuing to answer the question posed in 2004: *"Where is all the Plastic?"* (Thompson *et al.*, 2004)

4.3.2 Plastic on the sea floor

The sea floor may be the ultimate destination for plastic litter following a range of environmental interactions along the way (Eriksen *et al.*, 2014). Indeed, it is estimated that more than 50% of plastic litter will immediately sink to the sea floor because of its high density (Galgani *et al.*, 2015). Buoyant plastic can eventually be transported to the sea bed as it degrades and its material density changes. Interactions with biota can also weigh buoyant plastic down as plants and animals colonise plastic debris (Galgani *et al.*, 2015; Barnes *et al.*, 2009). As a result it has been estimated that over 90% of ocean plastic litter will eventually end up on the sea floor (Eunomia, 2016), which has a high potential to impact these benthic habitats and their biota (Galgani *et al.*, 2015). With low light and low temperature in this environment there is little to enhance the degradation of plastic debris and so its fate is to be covered and buried in deep sea sediment slowly over time.

Figure 8: Plastic bags and bottles filmed from an ROV 20km off the French Mediterranean coast at 1000 m depth (from Galgani *et al.*, 2015)

To investigate the presence of plastic on the seafloor, the *Plastic Oceans* team joined marine biologist and filmmaker Mike deGruy in the Mediterranean. This is a semi-enclosed sea with little water circulation or tidal flow that can trap debris. With its densely populated coastlines, shipping in coastal waters and its status as one of the world's leading tourist areas; the Mediterranean contains some of the highest densities of plastic litter in the world (Barnes *et al.*, 2009). Indeed, concentrations of microplastics at the Mediterranean sea surface are comparable to those found in the subtropical gyres (Ruiz-Orejón *et al.*, 2016; Cózar *et al.*, 2015; Collignon *et al.*, 2012), although interestingly there is a higher proportion of large plastic objects here due to the closer proximity to its sources (Cózar *et al.*, 2015).

Using a submersible, the *Plastic Oceans* team dived to a depth of 367 meters (~1200 feet) off the coast of Marseille, France, finding plastic bottles, tyres, fishing line and even an old parachute on the sea floor (**Figure 8**). A remote operated vehicle (ROV) was sent even deeper to 1600 meters (~5249 feet) and still found bottles, yoghurt pots and plastic bags. Surveys of the sea floor of the Mediterranean have found high densities of litter, up to 101,000 pieces per km^2, of which over 70% was plastic (Galgani *et al.*, 2000). This is not the only seafloor where litter accumulates, in fact plastic has been found on the seabed of all seas and oceans where its presence has been investigated, although it is currently uncommon in remote areas such as Antarctica (reviewed in Galgani *et al.*, 2015). Plastic litter has even been discovered at the wreck site of the *Titanic* at 3,800 meters (~12,000 feet) (Arnshav, 2014). Microplastic fragments and fibres, which have a global distribution in marine sediments (reviewed by Van Cauwenberghe *et al.*, 2015b) are also found in the deep and abyssal ocean, one of the largest and least researched marine habitats on the planet, even at sites beyond 5000 meters (over 16,000 feet) in depth (Taylor *et al.*, 2016; Fischer *et al.*, 2015; Woodall *et al.*, 2014; Van Cauwenberghe *et al.*, 2013). In these studies, concentrations of microplastics in deep sea sediment were found to be similar to those found in inter-tidal and shallow sub-tidal sediment (Taylor *et al.*, 2016) and microfibres have been found with abundance up to four orders of magnitude greater than at the sea surface (Woodall *et al.*, 2014). These microplastics descend to the ocean floor with marine snow, the organic debris that falls from the euphotic zone to provide a vital food source for deep sea organisms. Since microplastics are similar in size to the particles of marine snow, they can be ingested by deep sea organisms (Taylor *et al.*, 2016).

5. Plastic and its effects on wildlife health

Whilst plastic litter in the environment may appear to be an aesthetic problem blighting our surrounding environment, it is becoming increasingly clear that it can also physically harm wildlife with potentially fatal consequences (Barnes *et al.*, 2009). The size of debris, the type and its quantity all determine the consequences for wildlife, which can include physical impacts such as entanglement, ingestion, transportation, and alteration of habitat, as well as potential chemical impacts (Rochman *et al.*, 2016).

Because of its widespread presence in the global ocean, plastic debris impacts a wide range of species across the food chain, from plankton to whales. A recent review of the scientific literature found that at least 690 species had encountered marine debris. In total, 243 species were reported to have ingested marine debris and 208 species were reported to have been entangled in it. Of these species impacted through ingestion or entanglement, 17% were on the International Union for the Conservation of Nature (IUCN)'s red list as threatened or near threatened. Given the high proportion of plastics within marine litter, it is perhaps unsurprising that of all the recorded species encounters with debris, 92% involving plastic (Gall and Thompson, 2015).

Whilst there are many reports of plastics causing harm to individual animals, the impact that this has on wildlife populations is still largely unknown (Wilcox *et al.*, 2016). However, some ecological changes to species assemblages caused by plastic debris have been demonstrated (reviewed by Rochman *et al.*, 2016). For example, coral and sponge cover was lost as a result of physical damage caused by lost lobster pots during winter storms in the Florida Keys (Lewis *et al.*, 2009). Conversely, increased organism abundance and species diversity was observed in a soft sediment benthic habitat after the addition of plastic bottles and glass jars, which provided them with more refuge and reproduction sites (Katsanevakis *et al.*, 2007). It has been argued that more data are required to fully risk assess the effects of plastics at the population and ecological level of biological organisation (Rochman *et al.*, 2016; Browne *et al.*, 2015). This is particularly important given that adverse effects, such as those caused by ingestion of microplastics, on the ability of individual organisms to survive and reproduce may have population and ecological level impacts in the long term (Rochman *et al.*, 2016; Galloway and Lewis, 2016; Browne *et al.*, 2015).

5.1 Entanglement

The effects and health implications of entanglement in plastics are well documented in comparison to plastic ingestion, largely because of its visibility and ease of observation (Wilcox *et al.*, 2016). Entanglement, particularly in fishing netting but also in other plastic debris, can cause death of marine organisms through drowning and asphyxiation. Indeed, entanglement is one of the major causes of sea turtle mortality in areas such as the Northern Territories in Australia and the Mediterranean Sea (Nelms *et al.*, 2016). However, it is not always fatal and can cause chronic effects that get worse over time, particularly as the animal grows, causing the entangling material to cut into the body, causing wounds susceptible to infection or even leading to limb amputation or restriction of blood supply. Alternatively, entanglement in plastic can lead to increased drag, making swimming more energy intensive and eventually exhausting the animal. All of these chronic effects eventually lead to mortality by affecting the ability of the entangled animal to feed and survive (reviewed in Kühn *et al.*, 2015; Butterworth *et al.*, 2012).

Of the recorded entanglement encounters, a majority (71%) were between an individual and plastic rope or netting (Gall and Thompson, 2015). Fishing gear, designed specifically to capture through entrapment and entanglement, is a major issue if it is lost, discarded or abandoned, continuing to indiscriminately capture a wide range of marine animals in a process referred to as "*ghost fishing*". The same can occur with abandoned traps such as lobster pots, in which animals become trapped and starve with their bodies acting as bait for further victims (Kühn *et al.*, 2015). Such loss of wildlife also poses a loss of valuable resource to commercial fisheries (Gilardi *et al.*, 2010). Nonetheless, it is important to recognise that it is not just fishing gear that causes entanglement but also ropes, balloons, plastic bags, sheets and six-pack drink holders (Kühn *et al.*, 2015). In general entanglement is more commonly associated with larger plastic debris than microplastics (GESAMP, 2015).

Figure 9: A Hawaiian monk seal caught in ghost netting on Kure Atoll in the North West Hawaiian Islands

In some groups of animals, the percentage of species for which entanglement has been recorded is high. For example, entanglement has been observed in all seven sea turtle species, 45% of sea mammal species and around 25% of sea bird species, although other reptiles, fish and invertebrates are also affected (Kühn *et al.*, 2015; Gall and Thompson, 2015). Rates of entanglement can also be high in some specific populations, with between 52 and 78% of Humpback whales (*Megaptera novaeangliae*) in South-eastern Alaska found to have scarring related to entanglement, potentially from fishing gear (Neilson *et al.*, 2007). Seals and sea lions are also highly susceptible and Hawaiian monk seals (*Neomonachus schauinslandi*) have one of the highest documented rates of entanglement of these species (Antonelis *et al.*, 2006). Indeed, in *A Plastic Ocean* a Hawaiian monk seal was shown entangled in a mass of fishing netting (**Figure 9**). This presents a significant threat to this species, which is one of worlds the most endangered marine mammals with only around 1200 individuals left in the wild (Antonelis *et al.*, 2006).

5.2 Ingestion

Ingestion of plastics provides another pathway through which plastic can be transferred into different environmental compartments. Some plastic can be excreted by animals allowing it to re-enter the environment, or the animal can die and sink to transport plastics to the deep sea. Ingestion also provides a point of entry for plastic debris into the food chain that can be transferred to predators, including the human population through our consumption of seafood.

Ingestion can be associated with a wide size range of plastic debris dependent on the size and capacity of animal that ingests it. For example, a Bryde's (pronounced "broodus") whale (*Balaenoptera edeni*) that beached and died in Cairns Australia seen in *A Plastic Ocean* was found to have a stomach tightly packed with six square meters of plastic supermarket bags, food packaging and three large plastic sheets (Department of the Environment and Heritage, 2002). In comparison, microplastics are within the size range of food that is ingested filter-feeding whales, fish and other organisms as well as by plankton and other small, species at lower trophic levels. This ingestion by biota may be a significant reservoir for plastic debris, with mesopelagic fish that dominate the worlds fish biomass (Irigoien *et al.*, 2014), such as planktivorous lanternfish (*Myctophidae spp.*), estimated to consume 12-24 thousand metric tons of microplastic annually in the North Pacific (Van Sebille *et al.*, 2015; Davison and Asch, 2011). Ingestion of plastic by lanternfish caught in the South Pacific subtropical gyre was also demonstrated by Dr Bonnie Monteleone and Dr Michael Gonsior during the filming of *A Plastic Ocean*.

Plastics can be ingested by animals intentionally or accidentally (Kühn *et al.*, 2015). For example, sea turtles are visual feeders that can intentionally ingest floating plastic bags, having mistaken them for their natural prey, jellyfish (Nelms *et al.*, 2016; Campani *et al.*, 2013). Plastic can also be ingested accidentally along with food to which they are attached, as is the case for debris attached to the microalgae consumed by juvenile green turtles (*Chelonia mydas*) (Nelms *et al.*, 2016). Alternatively, accidental ingestion can occur during the non-selective process of filter feeding. Indeed, filter feeders from mussels to baleen whales have been found to have ingested microplastic (Lusher *et al.*, 2015a; Besseling *et al.*, 2015; Van Cauwenberghe and Janssen, 2014). Indeed, fin whales (*Balaenoptera physalus*) and basking sharks (*Cetorhinus maximus*) in the Pelagos Sanctuary in the Mediterranean are estimated to be ingesting 3,653 and 13,110 pieces of microplastic debris respectively on a daily basis (Fossi *et al.*, 2014).

There is also the potential for secondary ingestion – the ingestion of prey containing plastic by a predator. Indeed, in one study the presence of plastics in the faeces of fur seals has been attributed to the fish that they consumed (Kühn *et al.*, 2015; Eriksson and Burton, 2003). This trophic transfer of microplastics has been demonstrated in laboratory studies (Mattsson *et al.*, 2015; Setälä *et al.*, 2014; Farrell and Nelson, 2013), including one in which mussels that had ingested small microplastic spheres (<0.5 µm) were then fed to crabs. Once inside the crabs, the microplastic spheres were able to translocate out of the gut and into the circulatory system (haemolymph) and the tissue of the animal (Farrell and Nelson, 2013). Other studies also support the translocation of small microplastics in the µm size range from the gut into the organism (Watts *et al.*, 2016; Von Moos *et al.*, 2012). Theoretically this may facilitate biomagnification, the increase in concentrations of plastics at progressively higher trophic levels within the food chain, as suggested by some scientists in *A Plastic Ocean*. However, this has not yet been demonstrated.

5.2.1 Seabirds: *A Plastic Ocean* case study

Seabirds as a group appear to be at particularly high risk of ingestion. Indeed, it has been estimated that over 90% of all seabirds have ingested plastic and that 99% of all seabird species could be impacted by 2050 (Wilcox *et al.*, 2015). As part of filming *A Plastic Ocean* the team joined Dr Jennifer Lavers to investigate the impacts of ocean plastics on Flesh-footed shearwaters (*Puffinus carneipes*) at their breeding site on Lord Howe Island, Australia. Here, they nest in burrows and adults feed off shore before returning to feed their chicks through regurgitation, transferring plastics to them. Dr Laver's research found that 90% of the 38 fledglings she tested contained plastic, with one bird containing 276 pieces of plastic, which accounted for around 14% of its body weight (Lavers *et al.*, 2014). Dr Lavers also travelled to Midway Atoll in the Northwest Hawaiian Islands to work with the Laysan albatross, the most severely contaminated of all the albatross species, which has become an icon of plastic pollution as a result of the vivid imagery of their plastic filled carcasses (**Figure 10**). She found that 100% of the forty dead fledglings that she studied contained plastics, with over 100 pieces of plastic on average per bird (Lavers and Bond, 2016).

Figure 10: Dr Jennifer Lavers and Craig Leeson examine dead shearwater chicks on Lord Howe Island (top); the carcass of a Laysan albatross chick filled with plastic on Midway Island (© Chris Jordan) (middle); some of the plastic objects recovered from Laysan albatross chicks by the *Plastic Oceans* team (bottom)

The shearwaters and albatross, as well as Northern fulmars (*Fulmarus glacialis*) from the North Sea which also have been found to ingest plastic (Van Franeker *et al.*, 2011), are all tubenosed birds of the order *Procellariiformes*. They have a glandular first stomach (the proventriculus) connected by a constricted passage to a second muscular stomach (the gizzard). As such they can only regurgitate, or spit, material from their first stomach, whilst plastics are retained in the gizzard and can only be excreted once they have been ground up to a small enough size to pass through the gut (Van Franeker and Law, 2015; Kühn *et al.*, 2015).

Ingestion of plastic can be the direct cause of mortality through physical damage, such as perforation of the stomach lining or obstruction of the passage of food through the gut leading to starvation in birds (Lavers *et al.*, 2014; Pierce *et al.*, 2004). This has also been observed in turtles and whales, although reports of death caused by plastic ingestion in wildlife are rare and there are difficulties in attributing death directly to plastic (Kühn *et al.*, 2015). As such, it is the sub-lethal effects that could be resulting in mortality, such as a reduction in the stomach volume available for food or a reduction in the feeling of hunger (false-satiation) that in turn can reduce the drive to search for food (Kühn *et al.*, 2015). For the Flesh-footed shearwater chicks filmed in *A Plastic Ocean*, small numbers die as a result of stomach perforation by plastic. In addition, chicks that had ingested higher levels of plastic were found to have a reduced body condition (lower body weight and wing length), probably as a result of their reduced stomach capacity and nutrient intake (Lavers, 2014). This could impact juvenile survival, particularly during their first year at sea as they learn to forage and their food supply is initially limited.

> *"To try and wrap your mind around the condition of this animal and the quality of its life really is quite an overwhelming thing"*
> **Dr Jennifer Lavers, Seabird Biologist**

For Laysan albatross populations, the ingestion of plastic has been linked to a 5.7% reduction in chick survival to fledging, which is small in comparison to other causes of death such as dehydration, which can lead to increased susceptibility to disease (Lavers and Bond, 2016; Arata *et al.*, 2009). However, a wide range of other potential impacts of plastic ingestion in this species are still not fully understood (Lavers and Bond, 2016). It has been suggested, for example, that the impacts on plastic on this species are underestimated and that plastic ingestion could also be causing gastric blockage, dehydration and alterations in immune system function, which could in turn cause bird mortality and reduced reproductive output in survivors (Browne *et al.*, 2015).

The implications of ingesting plastics for seabirds at the population level are also largely unknown but this clearly presents an additional stressor for many species of seabirds, which already have to cope with changing environments and increasing human pressure. In the case of the Flesh-footed shearwaters there is some evidence to suggest that their population is declining and there are concerns that plastic pollution may be a causal factor (Lavers, 2014).

5.2.2 Impacts of microplastic ingestion

In comparison to larger plastics, determining the impact on animals from ingestion of microplastics is an emerging research area (reviewed by Lusher, 2015; Wright *et al.*, 2013b). Because of their small size they are bioavailable to a wide range of species from whales (Lusher *et al.*, 2015a; Besseling *et al.*, 2015) to the zooplankton at the base of the marine food chain (Desforges *et al.*, 2015; Frias *et al.*, 2014; Cole *et al.*, 2013) that provide vital ecosystem services or are important to fisheries (Galloway and Lewis, 2016). Microplastics can cause similar impacts on organisms to those of larger macroplastic debris, including abrasions or blockages of the gut and a range of sub lethal effects (Wright *et al.*, 2013b). These have been demonstrated in laboratory studies of animals exposed to microplastics and include liver toxicity and hepatic stress in the fish species, Japanese medaka (*Oryzias latipes*) (Rochman *et al.*, 2013c), and strong inflammatory responses with the formation of granulocytomas and immune responses in blue mussels (*Mytilus edulis*) (Von Moos *et al.*, 2012; Köhler, 2010). Oxidative stress, depletion of energy reserves and reduced feeding have been shown in marine lugworms (*Arenicola marina*), which is of particular concern given the importance of these worms (*Arenicolidae spp.*) in intertidal ecosystems, where they irrigate the sediment and provide a food source for fish and wading birds (Wright *et al.*, 2013a; Browne *et al.*, 2013; Besseling *et al.*, 2013). A reduction in feeding rate, body mass and metabolic rate, as well as reduced catabolism of stored lipids, was observed in Norway lobster (*Nephrops norvegicus*) fed microfibres from polypropylene rope, indicating reduced nutrient uptake (Welden and Cowie, 2016). Interestingly, microplastic fibres thought to originate from fishing nets and ropes that were ingested by langoustines in the Clyde Sea, UK were found to have become knotted together in the gut (Murray and Cowie, 2011), which may facilitate their retention and blockage of the gut. By reducing energy uptake, an animal's energy reserves can be reallocated away from ecologically important functions, such as reproduction, to growth and maintenance (Galloway and Lewis, 2016). Indeed, exposure to microplastics has been shown to have adverse reproductive impacts, reducing gamete quality of Pacific oysters (*Crassostrea gigas*) and the quality of their offspring (Sussarellu *et al.*, 2016), as well as reducing fecundity in marine copepods (*Tigriopus japonicus* and *Calanus helgolandicus*) (Cole *et al.*, 2015; Lee *et al.*, 2013). There are concerns that if these effects are occurring in the wild, reducing the ability of individuals to survive and reproduce, then there could be consequences for populations of these lower trophic species. This could have further knock on effects on marine ecosystems due to their importance to ecosystem function and fisheries (Galloway and Lewis, 2016).

5.3 Chemical effects

As well as presenting a physical hazard to wildlife, plastics may also present a chemical hazard. Indeed, plastics contribute to global contamination and wildlife exposure to some of the chemicals which are used in their manufacture, as a result of discharge during manufacturing and leaching from plastic during use or after disposal. In addition, microplastics may provide a direct route for chemicals to enter wildlife through ingestion as they leach chemicals that they are manufactured with, as well as those they have adsorbed and concentrated from the environment (reviewed by Rochman, 2015; Koelmans, 2015; Teuten *et al.*, 2009).

5.3.1 Chemicals derived from plastics in the environment

Plastics contain by-products from the manufacturing process such as polyaromatic hydrocarbons (PAHs), unreacted monomers such as bisphenol A (BPA), and additive chemicals such as phthalates, alkylphenol enthoxylates, organotins and flame retardant polybrominated diphenyl ethers (PBDEs), (Rochman, 2015; Teuten *et al.*, 2009). In the case of the additives, these chemicals can make up a large proportion of the plastic material, up to 60% of PVC product weight for phthalates (Rudel and Perovich, 2009). Because of their importance in plastic products, chemicals such as BPA, phthalates and PBDEs are high production volume chemicals and can enter the environment from manufacturing, transport and processing (Flint *et al.*, 2012). In addition, since they are not chemically bound to the plastic polymer they can migrate out of the material and into the environment over time during a products use or after its disposal (Andrady and Neal, 2009; Teuten *et al.*, 2009). Waste disposal through open burning can also be a source of air pollution by these chemicals (Fu and Kawamura, 2010; Simoneit *et al.*, 2005) and this is of particular concern for PBDEs, whose combustion can produce toxic dioxins and furans (polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans) (Rahman *et al.*, 2001).

Some of the most significant sources of these chemicals for the aquatic environment are wastewater discharges and landfill leachates, where they are frequently detected globally (Akortia *et al.*, 2016; Gao and Wen, 2016; Li *et al.*, 2012; Teuten *et al.*, 2009; Crain *et al.*, 2007). Removal rates of phthalates, BPA and PBDEs are general high during wastewater treatment, at around 60-95% for phthalates, over 90% for BPA and around 90% for PBDEs (Margot *et al.*, 2015). However, because of their high production and consumption they are still detected in wastewater effluents and receiving environments, despite of this high rate of removal (Akortia *et al.*, 2016; Zhang *et al.*, 2015; Flint *et al.*, 2012). In comparison, concentrations in landfill leachates that result from the chemicals leaching from landfilled plastic waste are significantly higher than those in wastewater effluents (Akortia *et al.*, 2016; Gao and Wen, 2016; Teuten *et al.*, 2009). These are of particular concern for low and middle income countries where leachates may not be treated and greater concentrations can enter the aquatic environment (Teuten *et al.*, 2009). Interestingly, in the case of BPA, its concentrations in landfill leachate from municipal waste sites in several Asian countries at different stages of economic development were positively correlated with the country's GDP (Teuten *et al.*, 2009). This likely reflects the larger quantities of plastics used by the most industrialized countries, resulting in the generation of more plastic waste.

Despite the rapid degradation of phthalates and BPA under environmental conditions, their constant release has led to their frequent detection in air, sediment and water (Flint *et al.*, 2012; Fu and Kawamura, 2010; Oehlmann *et al.*, 2009). In comparison, PBDEs are very persistent, ubiquitous contaminants (Rahman *et al.*, 2001), for which there is some evidence to suggest that their concentrations in the environment have been increasing over time (Akortia *et al.*, 2016; Hites, 2004). Less is known about the concentrations of these chemicals in the marine environment, but research suggests that they are lower than in freshwater environments where they are closer to their point sources (Akortia *et al.*, 2016; Zhang *et al.*, 2016; Zhang *et al.*, 2015; Xu *et al.*, 2014; Oehlmann *et al.*, 2008a; Crain *et al.*, 2007). Nonetheless, waste dumps, atmospheric deposition, direct effluent discharges and river outflow are still likely to be sources to the marine environment. One study showed greater concentrations of phthalates and BPA in the Mediterranean closer to coastal areas, as well as in ports where plastic use and disposal is likely to be more intensive (Sánchez-Avila *et al.*, 2012). Because leaching of chemicals can be more rapid in the marine environment, there is also concern that accumulations of plastics will produce greater levels of local contamination, particularly in low and middle income countries (Flint *et al.*, 2012). In addition, these chemicals can also be transported long distances through atmospheric transport to contaminate even remote areas, such as the Arctic (de Wit *et al.*, 2010; Xie *et al.*, 2007).

In the environment, wildlife are exposed to these chemicals through food, sediment, water and air. Whilst the bioconcentration factors for phthalates and BPA from water to the tissues of biota are relatively low, some populations may still be chronically exposed (Canesi and Fabbri, 2015; Corrales *et al.*, 2015; Oehlmann *et al.*, 2008b). In comparison, PBDEs can accumulate in biota and biomagnify in the marine food chain (Rahman *et al.*, 2001). In laboratory studies these chemicals can cause adverse impacts on a range of species (Oehlmann *et al.*, 2009; Talsness *et al.*, 2009; Oehlmann *et al.*, 2008a), which includes impacts on reproduction and development by interfering with the normal functioning of the hormone system, a mechanism termed *"endocrine disruption"* (WHO/UNEP, 2013).

The implications of these exposures for wildlife health are still under research. However, environmental concentrations of BPA detected at high exposure sites coincide with those that cause adverse health outcomes in animal models during laboratory exposures. This suggests that some wildlife populations in high exposure locations in close proximity to point sources, such as wastewater effluent discharges, may be adversely impacted by BPA (Corrales *et al.*, 2015; Flint *et al.*, 2012; Wright-Walters *et al.*, 2011; Oehlmann *et al.*, 2009; Crain *et al.*, 2007). This may be similar for phthalates where concentrations that cause adverse effects in the laboratory also occur in some high exposure environments (Oehlmann *et al.*, 2009). Indeed, one study in China indicated that there is also the potential for adverse effects in wildlife in some urban rivers and lakes based on the phthalate concentrations detected (Zhang *et al.*, 2015).

5.3.2 Adsorption of additional contaminants by plastic debris

Although plastic debris contains a variety of chemicals from the manufacturing process, once they enter the ocean, plastics also adsorb chemicals that originate from industry and agriculture from their surrounding environment. These include a range of persistent bioaccumulative and toxic substances (PBTs) such as the pesticide DDT, polychlorinated biphenyls (PCBs), PAHs, PBDEs, the alkylphenol surfactant nonylphenol, and heavy metals, which are also ubiquitous global contaminants (Rochman, 2015). In total, around 78% of the chemicals listed by the US EPA as priority pollutants are associated with marine plastics and some, such as DDT and PCBs, are subject to global regulation to eliminate or restrict their production under the Stockholm Convention on Persistent Organic Pollutants (Rochman *et al.*, 2013a). Many of these chemicals, including DDT, PCBs and nonylphenol, are also known to have endocrine disrupting effects on biota (WHO/UNEP, 2013).

Because many of these chemicals are hydrophobic, they preferentially adsorb to plastics from the water column, although the rate at which they are adsorbed and the concentrations they achieve on the outside of plastic particles depends on the type of plastic. For example, PAHs and PCBs have been found at higher concentrations on polypropylene and high density polyethylene than on polyethylene tetraphthalate and polyvinyl chloride (Rochman *et al.*, 2013b). Concentrations are also determined by the size and surface area of plastics and the degree to which they are weathered. There are also spatial differences which have been observed on local and global scales. Indeed, concentrations of hydrophobic contaminants adsorbed on plastics show distinct spatial variations that reflect global pollution patterns (Rochman, 2015). In some areas, this adsorption from the environment is very high with one study of polypropylene pellets in coastal waters in Japan finding that the concentrations of PCBs and DDE (a metabolite of DDT) on plastics reached up to a million times their concentrations in the surrounding seawater (Mato *et al.*, 2001).

As such, plastic is both a *source* of chemical contamination to the environment from its manufactured chemicals and a *sink* for chemicals already present in the environment. Through its global distribution on ocean currents, plastic is capable of transporting these chemicals long distances and to different environmental compartments. Because of the high concentrations of contaminants on plastic debris, concern has been raised that it could act as a vector, delivering these chemicals into biota through ingestion where they desorb from the plastic in the gut to become bioavailable to the organism (Rochman, 2015; Teuten *et al.*, 2009).

5.3.3 Ingestion of plastic as a route of chemical exposure

By providing an additional entry for chemicals into the food chain, it has been hypothesised that ingestion of plastics may also contribute to the bioaccumulation of chemicals in individuals and their biomagnification up the food chain. Consequently, they could cause additional sublethal, chemical effects on exposed organisms beyond the physical impacts of ingestion (Engler, 2012). However, because these chemicals are global contaminants, organisms are already exposed to them externally in their surrounding environment. It has been demonstrated that some of these are bioaccumulating in aquatic organisms and biomagnifying in the marine food chain, particularly in the case of DDT and PCBs, potentially causing adverse biological effects. For example, PCB concentrations in the blubber of some cetacean populations, including striped dolphins (*Stenella coeruleoalba*), bottlenose dolphins (*Tursiops truncatus*) and killer whales (*Orcinus orca*), were recently shown to be high enough to likely be causing population decline or suppressing population recovery (Jepson *et al.*, 2016). Consequently, it is difficult to determine the contribution of microplastic ingestion to the overall body burden when there are multiple pathways of exposure.

Under laboratory conditions some studies have demonstrated that chemicals can be transferred from ingested plastics into the tissues of an organism (Wardrop *et al.*, 2016; Rochman *et al.*, 2014; Chua *et al.*, 2014; Rochman *et al.*, 2013c; Browne *et al.*, 2013; Besseling *et al.*, 2013; Teuten *et al.*, 2009). This can lead to adverse effects including mortality, reduced feeding and immunity, hepatic stress and potentially alterations to the endocrine system (Rochman *et al.*, 2014; Rochman *et al.*, 2013c; Browne *et al.*, 2013). However, it is not clear whether chemicals from plastic ingestion cause these effects on wildlife in the natural environment. Because the animals used in these studies are expected to be relatively free of these contaminants, it has been argued that this favours the uptake of chemicals from plastic during laboratory exposure. In comparison, the concentration gradient between plastic debris and animals in the aquatic environment may be much smaller since they have a background body burden of these contaminants from multiple routes of exposure. Theoretically, this will facilitate less transfer of chemicals from ingested plastic into the tissues of exposed wildlife than in a controlled laboratory experiment in which the "ambient" tissue concentrations of the exposed animals are lower (Koelmans, 2015). In addition, depending on the concentration gradient, chemical transfer can also occur *from* the organism back to ingested plastic because of the lipophilic/hydrophobic nature of plastic particles (Herzke *et al.*, 2016; Koelmans, 2015).

Figure 11: Professor Maria Cristina Fossi takes aim at a dolphin with a biopsy dart in the Mediterranean

Some studies have demonstrated that the plastic load of some animals correlates with their chemical load. Dr Jennifer Lavers studies of wild Flesh-footed shearwater and Laysan albatross both found that the birds that had ingested greater amounts of plastics also had a greater body burden of heavy metals (Lavers and Bond, 2016; Lavers *et al.*, 2014). A study of Streaked shearwater (*Calonectris leucomelas*) chicks that were fed microplastics contaminated with PCBs also found that these birds body burden of PCBs increased compared with control birds (Teuten *et al.*, 2009). However, a study of wild Northern fulmars in the North Sea found no correlation between plastic ingestion and the body burden of PCBs, DDT and PBDEs (Herzke *et al.*, 2016).

Other studies have detected plastic related chemicals in organisms and suggested that these are linked to the ingestion of plastics. In *A Plastic Ocean*, the team joined Professor Maria Cristina Fossi who has been studying the impacts of microplastics on cetaceans. She took tissue samples from dolphins in the Mediterranean using a biopsy dart shot from a crossbow and found that these samples contained phthalates (**Figure 11**). Her team has also detected phthalates, as well as DDT and PCBs, in fin whales which feed in areas with high microplastic density (Fossi *et al.*, 2016; Fossi *et al.*, 2012). However, as previously noted it is not clear whether the presence of plastic additives and contaminants known to adsorb to plastic debris in animals in these studies occurred due to ingestion of microplastic in comparison to the other additional routes of chemical exposure from food, water, sediment and air. Nonetheless, wildlife exposure to some phthalates in the environment indicates a link to our manufacture, use and disposal of plastics since they are a significant source.

Because of the complexity of multiple exposures to chemicals, there has been an increasing use of mathematical bioavailability models to assess the chemical hazard posed by ingested plastics (reviewed by Koelmans, 2015). These predict the chemical transfer to the organism based on the partitioning of chemicals between plastic and the organism, bioaccumulation and how plastic particles degrade. Generally these suggest that the contribution of plastic to the overall chemical body burden is low in comparison to food and water intake of these chemicals (Herzke *et al.*, 2016; Koelmans *et al.*, 2016; Bakir *et al.*, 2016). Nonetheless, these models also have their limitations and do not take into account additional sublethal impacts of plastic ingestion in an organism. For example, ingestion of plastics could also cause changes to organisms that will affect gut uptake of chemicals, such as physical damage to the gut or false satiation leading to changes in lipid content (Koelmans, 2015). In addition, if plastics are small enough they could potentially cross the gut wall and translocate into organs to directly deliver their chemical load, although this has yet to be demonstrated (Galloway, 2015). Consequently, whilst it is clear that ingested plastic can act as a vector for a range of chemicals, we still have much to understand about the chemical risk that this poses to wildlife.

5.4 Other implications

As well as specific impacts on wildlife, plastics can alter their habitats. This can occur through smothering of biota, which can lead to losses in vegetation (Uhrin and Schellinger, 2011), and abrasive damage, such as when derelict fishing gear is moved through coral reefs by storms (Lewis *et al.*, 2009; Donohue *et al.*, 2001). However, there can also be more subtle changes to the physical environment, since there could be changes in the permeability and temperatures of beach sediments that contain plastics (Carson *et al.*, 2011). It has been argued that this could potentially increase desiccation stress on beach organisms that inhabit the sands. It has also been hypothesised that temperature changes could alter the sex ratio of sea turtle hatchlings, whose eggs are buried in the sand by their mother and whose sexual differentiation is temperature dependent (Carson *et al.*, 2011).

Plastics also have other impacts on the lives of wildlife, some of which are positive for some animals' survival. For example, during the filming of deep sea plastics in the Mediterranean the *Plastic Oceans* team found an octopus living in the debris. Similarly, hermit crabs have been known to use bottle tops for protection instead of shells (Katsanevakis *et al.*, 2007; Barnes, 2005). As well as a home or transport vector, plastic can be used by some species that need hard surfaces to deposit their eggs (Majer *et al.*, 2012; Goldstein *et al.*, 2012). The team also found other crustaceans and molluscs on the plastic debris that they recovered off the coast of Sri Lanka when filming the Pygmy Blue Whales (*Balaenoptera musculus brevicauda*).

Because plastic debris can be transported long distances in the oceans, there is concern that the increasing abundance of plastics could enhance the dispersal of some marine organisms, increasing their range or introducing them to areas from which they were previously absent (Gregory, 2009; Derraik, 2002; Barnes, 2002). Indeed, a range of species have been found *"rafting"* on plastic debris including bryozoans, barnacles, polychaete worms, hydroids and molluscs (Gregory, 2009; Barnes, 2002). In previous incidences where invasive species have established viable populations in new habitats, they can pose a significant threat to native biodiversity and cause significant ecological changes (Molnar *et al.*, 2008). However, so far the establishment of a viable population of an invasive species introduced to a new habitat by plastic debris is yet to be demonstrated and as such the ecological impacts of this rafting effect of ocean plastics are unclear (Browne *et al.*, 2015).

It has also been hypothesised that floating plastic debris could act as a vector for dispersing species of algae associated with harmful algal blooms (Masó *et al.*, 2003). Algae have also been found to be adversely effected by exposure to plastics around 20 nm in size in a laboratory study where a reduction in photosynthesis was demonstrated (Bhattacharya *et al.*, 2010).

6. Plastics and their human impacts

Whilst there are societal benefits to using plastics, our use (or misuse) and inappropriate disposal of this material has consequences for human health and society. They are a source of exposure to a variety of chemicals during their use and after disposal they are an accumulating part of municipal solid waste on land and in the ocean. This accumulation can potentially impact ecosystem services that we rely on, such as clean air, clean water, food and the aesthetic value of the surrounding environment itself. This environmental deterioration comes not just with implications for health and wellbeing, but also economic consequences.

6.1 The use of plastic, chemical exposures and health concerns

Plastics are integrated into our daily lives in our homes, workplaces, modes of transport and surrounding environments as building materials and in the products we use. As a result, the greatest exposure of humans to plastics and plastic derived chemicals (especially in high income countries) likely occurs during their use rather than through their disposal (Koch *et al.*, 2013; Geens *et al.*, 2012; Koch and Calafat, 2009; Vandenberg *et al.*, 2007). As has been discussed, plastics contain a complex chemical mixture of additives, unreacted monomers and manufacturing by-products within the polymer structure that can leach out during their use (Galloway, 2015). This can lead to exposure through dermal contact with plastic products and ingestion as the chemicals leach into food and drink from packaging. In addition, there are exposures from the indoor environment in homes and workplaces from the air and dust which are contaminated by chemicals from plastic goods and building materials such as carpets, PVC flooring, furniture and electronics (WHO/UNEP, 2013; Rudel and Perovich, 2009).

Whilst the polymers themselves are generally considered to be inert, some of the additives and unreacted monomers are known carcinogens and toxicants, which has resulted in calls for more thorough risk assessment and moves to using safer plastic types and formulations (Lithner *et al.*, 2011), particularly for those used in food contact materials.. Indeed, one study found that chemical ingredients in more than 50% of plastics were hazardous (Lithner *et al.*, 2011). This means they have the potential to cause harm to humans, animals or the environment, although the risk of this occurring is dependent on the degree of exposure. Some of these chemicals have been labelled as "endocrine disrupting chemicals" (EDCs), which are defined as *"exogenous substances or mixtures that alter function(s) of the endocrine system and consequently causes adverse health effects in an intact organism, or its progeny, or (sub) populations"* (WHO/UNEP, 2013; International Programme on Chemical Safety, 2002).

> *"Endocrine disruption is disruption of the normal functioning of the body's hormonal system. They fool the body into thinking that they are hormones and then they either block or mimic the action or production of hormones and in doing so they interfere with very many bodily processes, growth, metabolism, reproduction and critically early development"*
>
> **Professor Susan Jobling, Ecotoxicologist**

These plastic derived chemicals are part of the diverse chemical cocktail that the human population is exposed to daily through ingestion, inhalation and dermal contact and there is concern that these chemicals could be having adverse effects on human health (comprehensively reviewed in Gore *et al.*, 2015; WHO/UNEP, 2013; European Environment Agency, 2012; Kortenkamp *et al.*, 2011; Diamanti-Kandarakis *et al.*, 2009).

To investigate the issue of EDC exposures as a result of our increasing consumption of plastic products, in *A Plastic Ocean*, the freediver Tanya Streeter visited Plastipure and CertiChem in the US to meet with Dr George Bittner of the University of Texas and Mike Usey, the CEO. These companies evaluate materials, packaging, and products to determine if they leach chemicals with oestrogenic activity. They also certify products to be "PlastiPure-Safe® EA-Free" when they comply with this higher safety level. In 2011, Dr Bittner's team had finished a study in which they tested over 500 commercially available plastic products and concluded that most plastic products released chemicals that could mimic the action of natural oestrogens at the oestrogen receptor (Yang *et al.*, 2011). Indeed, the chemicals that leached from plastics could bind to the oestrogen receptor in the MCF-7 mammalian cell line (E-SCREEN) to induce an oestrogenic response (Yang *et al.*, 2011). As already mentioned, oestrogenic chemicals associated with plastic manufacture and highlighted in the film are bisphenol A and some phthalates (Talsness *et al.*, 2009; Meeker *et al.*, 2009; Welshons *et al.*, 2006). Although not highlighted in the film, the concern about the potential endocrine disrupting effects of chemicals derived from plastics is broader that just oestrogenic effects. Indeed, there are chemicals that can disrupt metabolism, neuro-development and the immune system and have anti-androgenic and thyroid disrupting effects.

6.1.1 Exposure to EDCs during foetal development and early childhood

During the filming of *A Plastic Ocean*, Tanya expressed great concern about the implications of exposure to these plastic derived chemicals on children's health. During pregnancy, whilst she could control her lifestyle choices, she felt that chemical exposure was outside of her control. Indeed, exposure of pregnant women to EDCs is widespread, with a study of pregnant women from the US finding detectable concentrations of bisphenol A, phthalates and PBDEs in over 95-100% of their participants (Woodruff *et al.*, 2011). Because these chemicals can cross the placental barrier, exposure of the pregnant mother can lead to exposure of the embryo or foetus at an incredibly sensitive life stage when tissues and organ systems are forming (Barr *et al.*, 2007). Indeed, disruption to these systems when they are forming can lead to irreversible developmental effects. Alternatively, more subtle effects at this life stage which do not result in clear physical abnormalities may lead to increased risk of dysfunction and disease later in life (Barouki *et al.*, 2012). This is referred to as the "*Developmental Origins of Adult Health and Disease*" hypothesis, which has been used to explain the potential role of chemical exposure, along with nutrition and maternal stress, on the increasing prevalence of many non-communicable diseases related to the functioning of the endocrine system in the human population (WHO/UNEP, 2013; Barouki *et al.*, 2012; Heindel, 2007).

Childhood development also presents a sensitive window of exposure and some studies have found body burdens of the plastic derived chemicals, bisphenol A, PBDEs and phthalates to be higher in neonates and young children than in adults (Katsikantami *et al.*, 2016; Linares *et al.*, 2015; Vandenberg *et al.*, 2010). This is because they are exposed through additional routes, such as maternal milk, crawling that leads to greater exposure to dust and mouthing of objects, and they also have a higher air consumption and food intake relative to their size (Linares *et al.*, 2015; Koch and Calafat, 2009; Meeker *et al.*, 2009). In addition, premature babies in intensive care units have above average body burdens of these chemicals due to exposure from plastic medical equipment (Calafat *et al.*, 2009; Green *et al.*, 2005). Some studies indicate that most children's daily intake of phthalates exceeds the maximum reference dose set by the US EPA that is considered unlikely to cause adverse effects (Katsikantami *et al.*, 2016).

6.1.2 EDCs in plastics: bisphenol A

One of the most researched chemicals derived from plastics production and use is bisphenol A, used as monomer in the production of plastics and epoxy resins for food packaging. Bisphenol A exists as an unreacted chemical in plastic polymers or as a remobilised breakdown product of the plastic polymer itself. It has been found in bottles, food contact materials, including the protective coatings in metal food containers, and composites and sealants used in dentistry (Koch and Calafat, 2009). Repeated use of bisphenol A containing products, such as water bottles and food storage containers can increase leaching of this chemical into water and food, as can heating or microwaving (Talsness *et al.*, 2009; Brede *et al.*, 2003). As a result, human exposure mainly results from the ingestion of bisphenol A contaminated food, although there are additional exposures from water, air and household dust, as well as dermal contact (Geens *et al.*, 2012; Koch and Calafat, 2009; Vandenberg *et al.*, 2007). Such exposure is widespread in the human population, with studies from the US, Europe and Asia frequently detecting these chemicals in the blood or urine of the majority (>90%) of their participants (reviewed in Vandenberg *et al.*, 2010). Indeed, in one study by the Centre for Disease Control in the US, 92.6% of the 2,517 participants who were over six years old and representative of the general US population had bisphenol A detected in their urine (Calafat *et al.*, 2007). The European Food Safety Authorization (EFSA) recently estimated the highest aggregate exposure is 1.449 µg per kg of body weight per day for European adolescents (EFSA Panel on Food Contact Materials, Enzymes, Flavourings and Processing Aids (CEF), 2015), although other estimates indicate exposure from dietary sources alone range from 0.01 to 14.7 µg/kg/day for infants and children (Geens *et al.*, 2012).

As well as being able to bind to nuclear oestrogen receptors, bisphenol A can also bind to oestrogen receptors on the cell membrane to induce rapid responses at low doses by activating cell signalling pathways, as well as interacting with the androgen and thyroid receptors (Vandenberg and Prins, 2016; Rubin, 2011; Welshons *et al.*, 2006). Very many scientific studies have been focused on the human risks related to the presence of BPA in food and a plethora of data has been published regarding exposure to BPA and its toxicology. Indeed, it has been shown to cause a range of effects in laboratory studies using animal models. These include disruption of the male and female reproductive systems, the prostate and mammary glands, tissues and organs involved in metabolism, and the brain, as well as altering neurobehaviour and sensitising tissues to hormones and carcinogens (Vandenberg and Prins, 2016; vom Saal, 2016; Vandenberg *et al.*, 2013; Vandenberg *et al.*, 2012; Richter *et al.*, 2007; vom Saal *et al.*, 2007; Vom Saal *et al.*, 1998). The effects in these laboratory animal exposures show a great similarity to adverse health outcomes observed in human populations that have been reported to be associated with bisphenol A exposure in 91 epidemiological studies (reviewed by Rochester, 2013). The range of adverse health outcomes that may result from adult exposure to bisphenol A are shown below in **Table 2**.

- Reduced ovarian response and IVF success
- Reduced fertilization success and embryo quality
- Implantation failure
- Miscarriage
- Premature delivery
- Reduced male sexual function
- Reduced sperm quality
- Altered sex hormone concentrations
- Polycystic ovary syndrome
- Altered thyroid hormone concentrations
- Blunted immune function
- Type-2 diabetes
- Cardiovascular disease (i.e. Heart disease, hypertension, and cholesterol levels)
- Altered liver function
- Obesity
- Albuminuria
- Oxidative stress and inflammation

Table 2: The adverse health outcomes associated with bisphenol A exposure in a review of 91 epidemiological studies (from Rochester, 2013)

In childhood, bisphenol A exposure was also found to be strongly associated with altered behaviour and disrupted neurodevelopment in children as well as an increased probability of childhood wheeze and asthma (Rochester, 2013). The potential for altered behaviour is further supported by a recent systematic review that found that childhood exposure was also associated with higher levels of anxiety, depression, hyperactivity and inattention. Similarly, this review reported that prenatal exposure to bisphenol A was also associated higher levels of anxiety, depression, aggression, and hyperactivity in children (Ejaredar *et al.*, 2016). Increased risk of spontaneous abortion, abnormal gestation time, reduced birth weight, increased risk of genital abnormalities and childhood obesity later in life has also been associated with bisphenol A exposure during foetal development (Rochester, 2013).

Currently, regulatory bodies in the US consider that the tolerable daily intake (TDI) of bisphenol A is 50 µg/kg/day, whilst the European Food Standards Authority has recently reduced their TDI to 4 µg/kg/day. Both consider there to be no current consumer health risk from exposure to bisphenol A (FDA, 2016; EFSA Panel on Food Contact Materials, Enzymes, Flavourings and Processing Aids (CEF), 2015). However, in its last re-evaluation of BPA, EFSA identified important scientific uncertainties mainly regarding the effects of BPA on the mammary gland and on the reproductive, metabolic, neurobehavioral and immune systems, as well as exposure by non-dietary sources (EFSA Panel on Food Contact Materials, Enzymes, Flavourings and Processing Aids (CEF), 2015). The new TDI is intended as a precautionary and temporary measure pending the results of further long-term laboratory studies in rats. There is also considerable uncertainty in the exposure estimates for non-dietary sources (e.g. dermal exposure to thermal paper, air inhalation, dust and ingestion). In the midst of this uncertainty and as a result of increasing public concern and public pressure, the US Food and Drug Administration banned the use of bisphenol A in baby bottles based on market abandonment (not safety) at the request of the American Chemistry Council in 2012 (FDA, 2016). The manufacture of baby bottles containing BPA was also banned in the EU in 2011 as a result of concerns about infant health (European Commission, 2016).

6.1.3 Other EDCs in plastics

Bisphenol A is not the only EDC that can leach from plastics. Indeed, oestrogenic chemicals have been shown to leach from plastic products that were advertised as “BPA-free” (Bittner *et al.*, 2014b; Bittner *et al.*, 2014a; Yang *et al.*, 2011). A recent review has also demonstrated that chemicals produced to replace bisphenol A, bisphenol S and bisphenol F, are actually just as hormonally active and can also have endocrine disruptive effects in laboratory animal studies (Rochester and Bolden, 2015). In addition to the bisphenols, additives including phthalates and PBDE’s have also been shown to have endocrine disruptive effects in animal models (Talsness *et al.*, 2009). Phthalates are a huge class of chemicals that include compounds such as di-2-ethylhexyl phthalate (DEHP), di-butyl phthalate (DBP) and benzyl butyl phthalate (BBP). Higher molecular weight phthalates, such as DEHP, are essential components for providing flexibility in plastics, primarily PVC resins, and can therefore be found in a range of consumer products such as flooring, clothing and toys, as well as food contact materials and medical devices. In comparison, low molecular weight phthalates, such as DBP, are used as solvents in some personal care products, such as perfumes and cosmetics, or to provide timed release in some pharmaceuticals (Meeker *et al.*, 2009; Koch and Calafat, 2009). In comparison, PBDEs are sold as commercial mixtures, the most common of which is deca-bromadiphenyl ether, and can be found in textiles, thermoplastics in electronics, plastic vehicle interiors and polyurethane foam used in furniture and mattresses (Meeker *et al.*, 2009; Rudel and Perovich, 2009). As flame retardants they aim to reduce the speed at which fires can spread to reduce property damage and risk to life.

As to their biological effects, in animal models some phthalates have been shown to cause a wide range of toxicities, the most studied of which is developmental reproductive toxicity through anti-androgenic mechanisms, blocking the androgen receptor or reducing testosterone synthesis (Hotchkiss *et al.*, 2008; Wilson *et al.*, 2008; Gray *et al.*, 2006). Specifically, studies conducted over the last 20 years show that exposing pregnant rats to certain phthalates causes a syndrome of male reproductive abnormalities, referred to as the “phthalate syndrome”, in their offspring by disrupting embryonic programing and development (Swan, 2008; Gray *et al.*, 2006; Swan *et al.*, 2005; Fisher, 2004; Fisher *et al.*, 2003). The phthalate syndrome in rats shares many features with *“testicular dysgenesis syndrome”* (TDS) in humans, which includes poor semen quality, testis cancer, cryptorchidism, and hypospadias, and which also has its origins during male fetal development (Swan, 2008; Swan *et al.*, 2005; Skakkebæk *et al.*, 2001). In epidemiological studies, human exposure to phthalates and their metabolites during foetal development has been associated with reduced ano-genital distance and penile width (Martino-Andrade *et al.*, 2016; Swan, 2008; Swan *et al.*, 2005), pre-term birth, low birth weight, altered reproductive hormone levels as well as neurobehavioral disorders and behavioural syndromes (Katsikantami *et al.*, 2016). In addition, childhood exposures have been associated with allergic diseases such as asthma and eczema, obesity, changes in blood pressure and delayed growth and puberty (Katsikantami *et al.*, 2016).

In comparison, PBDEs can disrupt thyroid hormones as well as oestrogens and androgens and have been shown to cause adverse effects on neurodevelopment and reproductive development in animal models (Shaw *et al.*, 2010; McDonald, 2005; Zhou *et al.*, 2002). Similarly, in epidemiological studies of some populations, PBDE exposure has been reported to be associated with changes in some hormone levels and neurodevelopmental, reproductive and adverse birth outcomes (reviewed in Shaw *et al.*, 2010). These include associations between PBDE exposures and lower IQ performance in children (Herbstman *et al.*, 2010), reduced fertility in women (Harley *et al.*, 2010) and reduced birth weights (Chao *et al.*, 2007) and cryptorchidism in newborns (Main *et al.*, 2007).

Like bisphenol-A, phthalates and PBDEs are ubiquitous environmental contaminants and human exposure has also been demonstrated in biomonitoring studies, with phthalates frequently found in the blood or urine of over 90% of study participants (Katsikantami *et al.*, 2016; WHO/UNEP, 2013; Frederiksen *et al.*, 2009). This results from exposures through the diet as well as other routes, such as air and household dust, dermal contact with plastic products and, in the case of phthalates, use of certain pharmaceuticals and personal care products. For phthalates the highest exposures are likely to come from the diet and some pharmaceuticals, whilst for PBDEs the major sources are more likely to be contaminated indoor air and household dust (Koch *et al.*, 2013; Shaw *et al.*, 2010; Rudel and Perovich, 2009).

Because people are exposed to multiple chemicals simultaneously there is concern that they may act together to cause adverse effects. Indeed, studies in animals have shown that mixtures of phthalates act together in an additive fashion in causing toxic effects (Kortenkamp and Faust, 2010; Howdeshell *et al.*, 2008). One study from the Centre for Disease Control in the USA reported that roughly 5% of women of reproductive age from the general population of the USA were contaminated with 75% or more of the level of just one of the phthalates, DBP, that were near to or above regulatory levels for the developing male reproductive toxicity endpoint (Digangi *et al.*, 2002). Because these women will also be regularly exposed to significant amounts of other phthalates, their aggregate exposures will pose even greater risks.

The weight of evidence on the toxicological and epidemiological effects of phthalates has caused regulatory bodies in various high income countries of the world to take action to permanently ban certain types of phthalates in any amount greater than 0.1 percent in children’s toys. Some have also placed interim or permanent bans on additional types of phthalates (Consumer Product Safety Commission, 2015). Environmental and public health concerns around PBDEs also led to government bans and voluntary phase outs by manufacturers of some commercial PBDE mixtures (penta and octa-bromadiphenylether) in some countries (Frederiksen *et al.*, 2009). However, more recently these mixtures have been listed under the Stockholm Convention as persistent organic pollutants and are now banned from production and use globally (Shaw *et al.*, 2010). However, exposure of the general population has continued because these chemical mixtures are environmentally persistent and they still leach from older plastic products, such as computers (Meeker *et al.*, 2009; Rudel and Perovich, 2009)

6.2 Plastic in the environment and its human impacts

6.2.1 Microplastics in food and potential risks to human health

The ingestion of plastic by marine organisms presents an introduction of this debris and its associated chemicals into the marine food chain, for which humans are an apex predator. A range of fish, crustaceans and shellfish species that are fished or farmed for the seafood market ingest plastic and potentially provide a direct route by which our plastic waste could be returned to us on our plates. Indeed, there are a number of studies that have found plastics in fish species exploited by the fishing industry (Bellas *et al.*, 2016; Rochman *et al.*, 2015b; Romeo *et al.*, 2015; Neves *et al.*, 2015). For example, one study of fish from the English Channel found plastic in the guts of 36.5% of the 504 fish from 10 species, all of which had ingested plastic. However, only one or two pieces were recovered on average from each fish suggesting that ingestion rates were low (Lusher *et al.*, 2013). Similarly, a study of fish from markets in Makassar, Indonesia and California, USA found plastic debris in 6 out of 11 species (28% of individuals) and 8 out of 12 species (25% of individuals), respectively (Rochman *et al.*, 2015b). Again the amount of debris per fish was low. Given that we do not tend to consume the gut of fish where microplastics have been found, this may not be considered an issue. However, evidence from laboratory studies does show that plastic particles can pass through the gut and into the tissue of an organism if the particles are small enough (Von Moos *et al.*, 2012), although this has not been demonstrated in the field. In addition, microplastics have also been found in filter feeding molluscs and crustaceans, which we tend to eat whole or with the gut (Li *et al.*, 2016b; Santana *et al.*, 2016; Rochman *et al.*, 2015b; Devriese *et al.*, 2015; Van Cauwenberghe and Janssen, 2014; Mathalon and Hill, 2014; Murray and Cowie, 2011). The prevalence of ingestion within some populations is high, with one study of Blue mussels from the French, Belgian and Dutch coastline finding that 100% of the animals collected contained plastics (Van Cauwenberghe *et al.*, 2015a). Another found plastic in 83% of sampled Norway lobster (langoustines) off the coast of Scotland (Murray and Cowie, 2011).

As a result of consuming contaminated oysters and mussels one study estimated that the average European seafood consumer will consume 11,000 pieces of microplastic per year (Van Cauwenberghe and Janssen, 2014). However, this is not the only source of microplastics in the human diet. Indeed, microplastics and microfibres have also been discovered in sea salts sold at Chinese supermarkets, again showing a link with contamination of the sea by plastics (Yang *et al.*, 2015). One study also detected synthetic microfibres in beer, although it has been suggested that this was an artefact of the laboratory contamination (Lachenmeier *et al.*, 2015; Liebezeit and Liebezeit, 2014). Whilst it is clear from this data that humans are exposed to microplastics through the diet, the implications for human health from microplastics and their associated chemicals present a major knowledge gap (GESAMP, 2015). In 2014, an expert discussion forum in the US agreed that the current state of the science does not allow for an assessment of human health risk through ingestion of microplastic contaminated with persistent, bioaccumulative, and toxic chemicals (EPA, 2015). Nonetheless, recently published expert reports from GESAMP and the United Nations Environment Program (UNEP) have stated that at this point there is not considered to be a human health risk from ingestion of microplastics from seafood. However, they appreciate that data is scarce, uncertainties remain and that this justifies further research attention (UNEP, 2016; GESAMP, 2016).

A major area of uncertainty surrounds the potential for microplastics and nanoplastics to enter the human body via the gut after ingestion (reviewed in Galloway, 2015). The plausibility of this has been demonstrated in medical research where the uptake of micro and nano-particles across the gut is used as a delivery system for drugs and vaccines (O'Hagan, 1990). Such translocation in the mammalian gut (including in humans) can occur with particles up to 150 μm, implying that internal organs and tissues could be exposed to particles of this size (Bouwmeester *et al.*, 2015). Given that nanoplastics also strongly adsorb chemicals, they may also act as carriers to deliver these chemicals directly to organs, enhancing overall chemical uptake (Velzeboer *et al.*, 2014). However, whether this occurs due to environmental exposure is unknown.

6.2.2 Poor waste management, links with poverty and human health

The annual global costs of solid waste management are estimated at US$205 billion and are anticipated to increase to US$375 billion by 2025 (Hoornweg and Bhada-Tata, 2012) as a by-product of increasing human population, urbanisation, consumerism and economic development. The costs are anticipated to increase most severely in low income countries where the generation of waste is already outstripping their government's capacity to safely collect and dispose of it. In the cities of some low and middle income countries which hold some of the world's poorest communities, 80-90% of waste is not collected or safely disposed of and instead is dumped in open spaces, water bodies and surface drains (Boadi and Kuitunen, 2005; UN-HABITAT, 1996). This creates a range of environmental and human health risks for people who are already living on low income or in poverty.

The *Plastic Oceans* team observed first-hand what happens when the use of plastic outstrips the ability to manage the waste stream when they visited the small island nation Tuvalu in the South Pacific (**Figure 12**). Here, the increased import of goods following their independence in 1978 led to a rapid increase in the waste generated, particularly from food packaging. Inadequate waste management infrastructure led to illegal dumping, burning of waste and when their landfill capacity was reached in one area, rubbish began to be piled up on the adjacent road (Asian Development Bank, 2014). One local resident told of how they used to swim and fish in pools in the borrow pits left over from the Second World War construction and that these had now become 'aquatic landfills' where the fish that they catch are instead fed to their pigs.

Figure 12: Municipal waste in Tuvalu piles up along the coastline

> *"This is a nice place but because of the import of packaging they destroyed our paradise. I want a good future for my children, because I love my children"*
> **Marao Apisai, Tuvaluan resident**

In urban areas, uncollected waste and indiscriminate disposal can create unsanitary conditions for residents, where it can block drains and cause local flooding and sewage overflow (Bernardo, 2008). As well as increasing the risk of sewage related disease, this also provides a good breeding environment for mosquitoes in tropical areas (Paul *et al.*, 2012), as does the plastic waste itself, which can hold water and potentially provide a reservoir for diseases such as dengue fever, malaria and zika virus (UNEP, 2016; Banerjee *et al.*, 2015; Boadi and Kuitunen, 2005; UNEP, 2005). It has also been suggested that plastics in freshwater may create favourable habitats for species of snails that act as an intermediate host for parasites that can cause human diseases such as schistosomiasis (Vethaak and Leslie, 2016). To dispose of waste, some communities employ open burning in both low and middle income and high income countries. This was observed by the *Plastic Oceans* team in a community in Tuvalu. Burning can contribute to air pollution by particulate matter with local and regional implications for respiratory health. Indeed, respiratory disorders have been linked to the burning of waste (Wiedinmyer *et al.*, 2014; Boadi and Kuitunen, 2005) and concerns for respiratory health and premature deaths in India due to air pollution has led to legal restrictions on open burning in cities such as Delhi, although the practice still continues (Ramaswami *et al.*, 2016). Other toxic chemicals are also produced by the open burning of plastic, including bisphenol A and phthalates, as well as carcinogens such as polyaromatic hydrocarbons (PAH's), polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans (Fu and Kawamura, 2010; Valavanidis *et al.*, 2008; Fiedler, 2007; Simoneit *et al.*, 2005; Sidhu *et al.*, 2005; Lemieux *et al.*, 2004; Steenland *et al.*, 2004). This generation of toxic chemicals is of particular concern for the health of those practicing the open burning of plastics, such as the families in Fiji who lit their cooking fires with plastic and children in Tuvalu who were melting down plastic waste to make jewellery.

Figure 13: Children scavenging for plastics and other materials at the Smokey Mountain II waste dump at Pier 18

The increasing generation of waste in low and middle income countries has led to the rise of formal and informal waste dumping sites inhabited by communities of scavengers (**Figure 13**). Plastics make up around 10% of municipal solid waste (Hoornweg and Bhada-Tata, 2012), but they are a sought after resource for scavengers due to their economic value as recyclable material, which supplies them with a source of income. Such scavenging communities within the informal waste sector build their homes at these waste sites and are economically dependent on the continuous stream of waste for sustainable employment. Microeconomies have emerged around them with junkshops acting as middlemen between the scavengers and the recycling industry, whilst others provide goods and services for scavengers. Waste material can also be fashioned into products and sold at local markets (Galarpe and Parilla, 2014; Sia Su, 2007). These communities were filmed in Manilla in the Philippines when director Craig Leeson and the *Plastic Oceans* team visited the waste dump site "Smokey Mountain II" at Pier 18 and its predecessor Smokey Mountain. Even though Smokey Mountain was shut down in 1995, it had functioned for over 40 years and scavengers still use the site to mine for recyclable plastic (**Figure 14**).

Figure 14: A local scavenger mining the Smokey Mountain site for recyclable material to sell

Whilst the waste dumps provide informal employment, there are significant health risks associated with scavenging for plastics and other recyclable materials in slum areas covered in waste and with little sanitation. In one study of the children living and working in these conditions at Smokey Mountain prior to its closure almost all (96%) had intestinal parasites, and respiratory infections (such as tuberculosis), diarrhoea and malnutrition were frequently reported as causes of ill health and death (Auer, 1990). Lack of sanitation at these sites can lead to contamination of garbage with faecal bacteria and emerging populations of disease vectors, such as rats and insects, further increasing the risk of disease (UN-HABITAT, 1996). Working conditions are also far from safe, as demonstrated at another waste dump in the Philippines, Payatas, where many Smokey Mountain workers migrated to after its closure. In 2000, part of the rubbish dump collapsed, burying residents of the slums at the bottom of the site under the garbage before it set on fire. 218 people were killed and another 300 people were reported missing (UN-HABITAT, 2001).

> *"At another level, the collapse of the Payatas garbage heap acutely illustrates what may happen when consumption patterns, made possible by globalization, produce waste that accumulates in unmanageable volumes to threaten environmental and human health. The scavenger families eked out a living from recycling the final discards of a global consumer culture. They dwelled daily amid fumes from synthetic decomposition whose toxicity prompted the cessation of emergency aid operations out of concern for the health of the rescue workers."*
> **Cities in a Globalizing World Report 2001, (UN-HABITAT, 2001).**

Such sites also pollute the land, air and water that surround them. Open burning pollutes the air, whilst leaching chemicals, heavy metals and faecal bacteria can make drinking water unsafe for human consumption, although it is still used by local communities (Galarpe and Parilla, 2014). Chemicals can also accumulate in the soil and heavy metals can be taken up by plants, including vegetables grown in the vicinity of waste sites (Ajah *et al.*, 2015; Nazareno *et al.*, 2011). This practice was observed by Craig Leeson at the Smokey Mountain site, where locals were growing corn, sweet potatoes and sugar cane. Inevitably for waste dumps near rivers and seas they also become sources of plastic waste entering the ocean.

A particularly hazardous plastic containing waste type is that of electronic waste, for which around 20-25 million metric tons is produced globally and this is rising. In despite of the Basel Convention on Transboundary Movements of Hazardous Waste, there is still a large export of e-waste from high income countries to low and middle income countries where it is processed in poor conditions by waste workers to extract their valuable metals. This can involve burning away plastic or use of strong acids, with little or no protective equipment. These processes release pollutants, such as dioxins and furans, heavy metals and PBDEs to cause significant local contamination and threats to environment and human health, particularly for the waste workers and local residents who experience high exposures (WHO/UNEP, 2013; Robinson, 2009).

6.2.3 Ocean plastics, public health and wellbeing

The presence of plastic in the ocean also has a number additional of impacts on people, particularly those for whom the sea is a source of employment or leisure. Indeed, plastics present a range of similar problems for fisheries, yachting and shipping by posing a navigational hazard. Propellers and become entangled, particularly with fishing line and netting, and intake pipes can be blocked by litter. Both of these are common problems in some areas, such as Scotland (Mouat *et al.*, 2010). Damage to a vessel can put the crew at risk and may require divers to recover debris to fix the problem in difficult and potentially dangerous conditions (Macfadyen *et al.*, 2009). For the *Plastic Oceans* team in the submersible diving into deep sea environments in the Mediterranean, this was a serious concern when they discovered lines and netting on the sea floor. Perhaps the worst documented case of vessel entanglement is the sinking of the Seo-Hut passenger ferry off South Korea in 1993 when the prop became entangled in rope, causing it to capsize and sink with the loss of 362 passengers and crew (Macfadyen *et al.*, 2009).

Beach litter, including fishing line, can also cause injury to beachgoers, and for SCUBA divers fishing nets can also pose a risk of entanglement and threaten life (Campbell *et al.*, 2016; Mouat *et al.*, 2010; Sheavly and Register, 2007). Plastic material in the sea also provides a surface for a range of microorganisms, including human pathogens such as *Escherichia coli*, to colonise (Vethaak and Leslie, 2016). This may be particularly relevant to plastic and microplastic that enters the environment via wastewater treatment works which will have experienced close contact with faecal pathogens. Consequently, there is concern that plastics on beaches and in bathing waters could act as vectors to transmit disease to exposed recreational water users (Keswani *et al.*, 2016).

In addition, the presence of plastics in the coastal environment visually degrades the environment and causes a loss of its aesthetic value, with implications for human wellbeing and tourism. Visits to natural environments can provide major health benefits, increasing physical activity and reducing stress (Depledge and Bird, 2009). Indeed, studies in the UK have shown that such visits leave people feeling mentally calmer, more relaxed, refreshed and revitalised, and that these effects was strongest in coastal environments (White *et al.*, 2016; White *et al.*, 2013). Interestingly, a recent study has suggested that the presence of litter on the coast may undermine and reduce these restorative effects (Wyles *et al.*, 2015). Such loss in aesthetic and amenity value may also result in losses in tourism, since cleanliness is highly valued by tourists when choosing a beach (Chen and Bau, 2016; McKenna *et al.*, 2011; Tudor and Williams, 2006; Ballance *et al.*, 2000).

It could also be argued that the visual degradation of the surrounding environment by plastics and its negative impacts could lead to 'solastalgia' in those living with pollution, threatening the personal, cultural and spiritual connections that individuals and communities have with the environment. Solastalgia is distress caused by environmental change and characterised by feelings of sadness, worry, fear or distress and declining sense of self, belonging and familiarity (McNamara and Westoby, 2011; Albrecht *et al.*, 2007). Whilst it is yet to be studied in the context of plastic pollution, solastalgia has been discussed in connection with the environmental impacts of climate change, such as sea level rise and drought. In one example, a study described how older women living in the Torres Strait islands discussed their feelings of sadness at their perceived declining familiarity and connection with their surrounding environment and the distress caused by threats to their homes by rising tides (McNamara and Westoby, 2011).

A further example of effects of plastic pollution on people's spiritual connection with wildlife and environment is the ingestion of plastic litter, particularly bags, by free roaming sacred cows in India. This can result in starvation as their digestive tracts become blocked, which was a key motivation for restrictions on plastic bags by policymakers in India (Clapp and Swanston, 2009).

6.2.4 Economic impacts of plastic pollution

Plastic debris typically makes up the majority of marine litter, which is responsible for a range of significant economic consequences for coastal and marine sectors, increasing costs to activities and reducing benefits (reviewed by Newman *et al.*, 2015). These costs are rarely borne by the producers of plastic or the polluters. In their review, Newman *et al.* identified agriculture, aquaculture, fisheries, commercial shipping and recreational boating, coastal municipalities, coastal tourism and the emergency rescue services as impacted sectors. The costs associated with fisheries and tourism are the best known, but gaps in our understanding of the impacts of plastics on human health, wildlife and ecosystem services make these costs less well defined and difficult to truly quantify. In the Asia-Pacific Economic Cooperation region alone, it was estimated that marine debris carried costs of approximately US$1.265 billion in 2008 (McIlgorm *et al.*, 2008). Costs include those associated with clean-ups, loss of fisheries and wildlife, reductions in tourism, damage to vessels and the rescue costs as well as human health risks associated with damaged vessels.

By posing a navigational hazard to vessels used for fisheries, yachting and shipping, plastics and other marine litter can cause loss of earnings whilst the damage is fixed, leading to a restricted catch in fisheries, and may threaten the lives of the crew with vessels needing to be rescued. In UK waters in 2008, between €830,000 and €2,189,000 was spent rescuing vessels with entangled propellers (Mouat *et al.*, 2010). There are also additional losses to earnings caused by damage to equipment, such as fishing nets which can become snagged on marine litter, and catches contaminated with marine litter for the fishing industry. In one small community of subsistence fishermen in Indonesia, these impacts of marine litter were serious enough for them to modify their fishing behaviour by travelling longer distances to avoid some fishing areas and by using different types of gear, despite potentially greater economic costs (Nash, 1992). In comparison, for the Scottish fishing fleet, the estimated annual loss attributed to marine litter as a result of these impacts is around €11-13 million (Mouat *et al.*, 2010). Clean up costs for removing marine litter from ports and harbours are also high, at an estimated €2.4 million in the UK alone. In addition to these direct costs, there are also indirect costs for fisheries from adverse impacts of marine litter on the sustainability and value of their catch (Newman *et al.*, 2015). Entrapment and mortality of Dungeness crabs in derelict traps in the Puget Sound, USA, was estimated to convey an annual loss of up to US$744,296, up to 4.5% of the value of the total catch (Antonelis *et al.*, 2011). Aquaculture can also be affected, with clean-up costs to remove litter from facilities. In *A Plastic Ocean*, a fish farmer from Hong Kong who found nurdles in his fish from the Sinopec cargo ship spill reported that supermarkets would not buy his fish (**Figure 15**).

Figure 15: Plastic nurdles recovered from the gut of a fish at a Hong Kong fish farm after the Sinopec spill

For tourism, the negative impact of marine litter on the aesthetics of coastal environments valued by tourists can also have financial consequences, with litter detracting tourists and leading to significant loss of earnings for local economies (Tudor and Williams, 2006; Ballance *et al.*, 2000). This was demonstrated in South Korea in 2011 when a large volume of marine debris was washed up on popular tourist beaches on Geoje Island following heavy rainfall. This resulted in a 63% reduction in visitors and a loss of US$29-37 million in tourist revenue in comparison to the previous year (Jang *et al.*, 2014). One study from the US also showed that local residents are impacted by littered beaches as they spend additional time and money travelling to other beaches or pursuing other activities. Indeed, avoiding littered beaches was estimated to cost local residents of Orange County, California, millions of dollars per year (Leggett *et al.*, 2014).

Cleaning up litter also presents significant economic costs for governments and local authorities, presenting a drain on public finances that could be spent on other services. In England for example, the cost to the taxpayer for cleaning up street litter and improving local environmental quality was estimated to be around £850 million in 2013/14 (House of Commons Communities and Local Government Committee, 2015). In the US, litter on the west coast costs taxpayers $520 million per annum (Rochman *et al.*, 2013a). Returning to the marine environment, it is estimated that the UK spends €2.4 million cleaning up marine litter from ports and harbours, whilst in Belgium and the Netherlands removing beach litter costs around €10.4 million per year (Mouat *et al.*, 2010). Similarly, plans to combat plastic debris in the Great Lakes could cost over US$400 million annually (Driedger *et al.*, 2015).

7. Solutions

The benefits of plastics to society are significant, but it is becoming increasingly clear that these need to be weighed against their adverse impacts on humans and environment. Marine plastics are now being discussed at a global political level. In 2012, at the Rio +20 United Nations Conference on Sustainable Development, the UN expressed its concern about the negative effects of marine litter (particularly plastic) on the health of the oceans and marine biodiversity. They also committed to take action to achieve significant reductions in marine debris by 2025 as part of Sustainable Development Goal 14 – to conserve and sustainably use the oceans, seas and marine resources for sustainable development (United Nations, 2012). The Global Partnership on Marine Litter was also launched at this time, led by UNEP to encourage governments, business, commerce and society to work together to reduce inputs of marine litter to the ocean (GESAMP, 2015). In response to these concerns, the UN Environment Assembly within UNEP adopted a resolution that specifically focused on marine plastic debris and microplastics in 2014, calling for urgent action (United Nations, 2014). This was echoed by an expert group writing for UNEP, who described the issue of plastic in the ocean and its widespread impacts as a *"common cause for mankind"* that requires urgent, pre-cautionary action to reduce plastic input to the environment to minimise the risks that it poses to humans and wildlife (UNEP, 2016).

Whilst the accumulation of plastic in the environment presents a significant problem, it is one that is avoidable and solvable (Thompson *et al.*, 2009). To achieve this a global intervention with international co-operation and the combined actions of the public, industry and policymakers, informed by sound science to drive decision making is required (Engler, 2012; Thompson *et al.*, 2009). It is generally considered that the greatest impact can be had through preventative strategies to significantly reduce the volume of plastic entering the environment in the first place (Engler, 2012; Thompson *et al.*, 2009). Since an estimated 80% of plastic originates from land based sources (Eunomia, 2016; Andrady, 2011) significant interventions can be made here in the way that we produce, use and dispose of plastics.

There is no single solution to the global plastic pollution problem and a strategic mix of approaches will be required in different localities dependent on the use of plastics per capita, the volume of waste generated, the local infrastructure and available investment. This will be aided by an understanding of local cultural attitudes and behaviours of publics to ensure that intervention strategies are appropriately and effectively targeted and are able to empower local people to positively contribute. In addition, there is a need for greater education of consumers, designers, manufacturers and politicians to raise awareness and to improve understanding of the issue to promote positive and effective changes. Indeed, public awareness is critical to reducing waste generation, to accomplishing effective environmental policy and for engagement in wider solutions to this marine conservation issue (Jefferson *et al.*, 2015; Hartley *et al.*, 2015; Steel *et al.*, 2005).

Although improvements in waste collection and management are required, in the longer term there needs to be a drive towards a more sustainable and safer future for plastic as a material. A clear message from *A Plastic Ocean*, and from the response to the film, is that increasingly, Governments, communities and individuals no longer accept the fallacy that this durable material is simply disposable. Instead it must be valued as a resource in a closed loop, circular economy. Within this concept there is a need for the public, industry and policymakers, to change behaviours to take responsibility for the waste that they produce and how it is disposed of. For this, education and engagement with stakeholders is crucial (Sheavly and Register, 2007).

> *"Every piece of debris and litter found in our waterways at one point involved a person who made an improper decision. In a way, it can be said that every piece of debris has human fingerprints on it. Knowledge is key for consumers to make appropriate choices when it comes to using and disposing of waste items"*
> **Marine Debris & Plastics: Environmental Concerns, Sources, Impacts and Solutions (Sheavly and Register, 2007)**

Some scientists have also called for countries to classify plastic waste as hazardous

(Rochman *et al.*, 2013a). By doing so they argue this would allow existing laws to be used to eliminate sources and restore habitats, as well as promoting research into safer polymers and shifting the burden of proof towards the manufacturer to demonstrate their safety (Rochman *et al.*, 2016; Rochman *et al.*, 2013a). Such demands are already made of the food and pharmaceutical industries. It has also been suggested that microplastics could be considered as persistent organic pollutants and listed under the international Stockholm Convention treaty, which would provide a regulatory framework to reduce their sources (Lohmann, 2017).

So what should the outcome be? In essence, the film A Plastic Ocean advocates that no more plastic should enter the aquatic environment, and for the plastic already produced to be collected, and reprocessed into products – that plastic is valued for what it is and the benefits it can bring, and against the costs of impacts it is already causing to human health and the environment.

7.1 Improved waste collection and management

In the short term, there is an urgent need for improvements in waste collection and management, particularly in low and middle income countries where such infrastructure is underdeveloped. This will start to clean up the land and to pave the way for more long term, sustainable approaches (UNEP, 2016; Ocean Conservancy, 2015). In China, Indonesia, the Philippines, Thailand, and Vietnam (who between them contribute over half of land based plastic to the ocean), 75% of the plastic that enters the ocean originates from uncollected waste (Ocean Conservancy, 2015). Consequently, improvements in waste collection could significantly reduce the volume of plastic escaping into the environment. This, in addition to the provision of more bins in public spaces, emptied by authorities in a timely fashion, can also decrease waste dumping and littering by empowering people to make the right decisions (UNEP, 2016). However additional measures including education of the public to drive behavioural change and enforcement of legislation are also important in this context. Since behaviour change takes time, faster regulatory interventions will be important to drive changes forward as part of this multi-pronged approach. This is particularly true for high income countries where littering is still an issue with significant economic costs associated with its clean up.

Improving waste collection, will also improve the financial viability of waste management technologies and facilities within a circular economy model, such as recycling and conversion of waste to energy or fuel, by providing a constant feedstock. Such improvements in technology and infrastructure should be rapidly progressed but will need public funding and additional funding from private sector investments is likely to be required, particularly in low and middle income countries (Ocean Conservancy, 2015). This could also be supported by policy to limit waste discharges to water from land (Engler, 2012), since discharge from land is not sufficiently covered by legislation at present (Van Sebille *et al.*, 2016). In comparison, legislation in the form of MARPOOL already exists to ban disposal of plastic waste at sea. However, there is evidence to suggest that waste disposal at sea still occurs and education and encouragement of behavioural change by seafarers may provide an effective solution, given the difficulty of enforcement (UNEP, 2016). To enable this and to promote safe disposal of waste the European Commission is also examining options to increase waste collection and treatment from ships at port reception facilities (European Commission, 2015). Nonetheless, regulatory options could involve enhanced environmental reporting and disclosure with transparency towards financial stakeholders (such as insurers and investors) in shipping, fisheries and other maritime activities. Such stakeholders can exert pressure on operators to account for their waste in reporting to avoid potential penalties or other liabilities. This kind of pressure and scrutiny could be more effective than some other policies and awareness raising campaigns

One area that needs to be examined is the waste-water from business and households, since this directly links to rivers and coastal waters through discharges. The effectiveness of wastewater treatment systems in dealing with 'down the drain' plastics remains poorly understood, and its efficacy may require the development of treatment solutions within the household before discharge to the collecting sewers, such as filters on washing machines to remove fibres. The implementation of this type of technology could be sped up by clear regulatory policy to speed up their integration into the design of washing machines. However, there is also room here for clothing manufacturers to look at how best to reduce outputs of microfibres from their own products.

As well as technological solutions, campaigns to promote behaviour change are already being employed by water companies in the UK to reduce inappropriate disposal of "disposable" and sanitary items such as cotton buds and wet wipes via the lavatory and sewerage system. Examples include Anglian Water's 'Keep It Clear' campaign and Thames Water's 'Bin It – Don't Block It'. Improvements in product labelling to indicate that they are non-flushable and not to be disposed of through the lavatory will also assist behaviour change.

7.2 Plastic as a valuable resource in a circular economy

There is a need to start to shift away from the current plastics model of production – use – disposal and towards a closed loop, circular economy that manages the end of life of plastics in a way that values plastic waste as a resource for producing new materials and energy (UNEP, 2016; GESAMP, 2016; GESAMP, 2015; Rochman *et al.*, 2013a). This will reduce the dependence on virgin plastic and its hydrocarbon feedstock, reducing CO_2 emissions and the volume of waste generated that requires disposal (Hopewell *et al.*, 2009). By repurposing used plastics in this way, it creates a secondary market for raw materials for other processes, such as recycled material for manufacturing or feedstock for energy recovery. This also aims to keep plastic material in the economy at its highest possible value for as long as possible. In doing so, this will incentivise avoiding the escape of plastics into the environment and disposal to landfill where its value is lost. Indeed, in the case of plastic packaging it is estimated that 95% of its material value is currently lost after its single use, which holds a value of US$80-120 billion annually and thus presents a significant financial opportunity to be exploited (World Economic Forum *et al.*, 2016).

The implementation of circular economy on the world stage is at an early phase of development. In China it is promoted as a top-down national political objective, whilst in Japan and some Asian countries, such as Vietnam and South Korea, its principles are used in waste management policies. Some of these principles of recycling and re-use as top of the waste hierarchy are also seen in some US states, but there is an absence of any federal policy initiative on the circular economy (Ghisellini *et al.*, 2016). In comparison, Australia and New Zealand are evaluating and accelerating an action agenda for implementing circular economy (Ghisellini *et al.*, 2016) and the European Union is implementing a transition away from a linear economy through a circular economy action plan, published in 2015 (see European Commission, 2015). This is relevant to waste generation in the EU as a whole, but considers plastics as a priority area. It is being seen as a way of generating new and sustainable competitive advantages for Europe and protecting businesses against resource scarcity and volatile prices, whilst creating more jobs and business opportunities, generating energy savings and reducing CO_2 emissions (European Commission, 2015; Ellen MacArthur Foundation *et al.*, 2015). Indeed, such a transition is projected to increase the EU's GDP by up to 7% (Ellen MacArthur Foundation *et al.*, 2015). It will also help meet their 2030 Sustainable Development Goals, which include the requirements to prevent and reduce marine pollution, including marine litter. There is also support from industry organisations, such as Plastics Europe, who consider plastics as a key resource in a circular economy and avoiding landfill as making environmental and economic sense (Plastics Europe, 2015). In the Ellen MacArthur Foundation's *"New Plastics Economy"* report it was suggested that the principles of circular economy should be expanded to cover Asia and the US as well as the EU, which between them generate 85% of global plastics production and a majority of marine plastics (World Economic Forum *et al.*, 2016).

The key aspects of a circular economy for plastics are 6 R's: Reduce, Remove, Re-design, Re-use, Recycle and Recover which are interlinked and required in combination to maximise the value of plastic waste and to avoid losses to the environment in a successful waste management hierarchical infrastructure (UNEP, 2016). Within this system a single polymer can be used in a product, disposed of, recycled, and reused in another product before eventually its energy is recovered. At the same time incentives and economic instruments can be used to ensure that product prices better reflect environmental costs (European Commission, 2015). *A Plastic Ocean* presents a range of solutions within the context of these 6 R's.

Whilst there are numerous examples across the world of plastic reprocessing and reuse, there are also a number of challenges to overcome to achieve a more resource efficient circular economy for plastics. Some of the specific challenges, such as recycling challenges, are detailed in the sections below. It is also worth noting that different locations will need to evaluate their own plastic economies. This will allow them to implement solutions that are fit for their local purpose within their own 'waste management strategy', which looks at all waste generated in a locality (national – to community scales) across all waste streams – plastic, glass, construction, commercial and industrial, and biodegradable.

7.2.1 Reduce

Reducing the use of raw materials is a key concept for reducing the waste stream in a circular economy and can be driven by increased uptake of plastic re-use and recycling for producing commercial products. Concurrently, a reduction in our individual and societal consumption of plastics, particularly in high income countries where our per capita use is high, has been described as fundamental (UNEP, 2016). Instead of restricting the supply of goods and services, this is about delivering them more efficiently, for example through more efficient production, more compact and lightweight goods and reduced single use packaging (UNEP, 2016; Ghisellini *et al.*, 2016). Reducing plastics use when appropriate presents the most resource efficient part of the solution to the plastics issue by reducing the drain on the limited, non-renewable hydrocarbons, mainly from crude oil, as a feedstock. This concept requires acceptance and co-operation from industry since reduced use of virgin polymers presents a reduction in income (Thompson *et al.*, 2009), although there will be gradually increasing opportunities for using recycled feedstocks. In addition, industry can lead in reducing the weight of plastic used in packaging and avoiding over packaging of goods (Thompson *et al.*, 2009), an aspect that regulatory policy could incentivise. There is opportunity here for consumers to drive changes through their own purchases to reduce the amount plastic waste that they generate as individuals. Here simple changes can be made, particularly by avoiding the use of single use plastics where possible, opting instead for products that are not packaged in plastic, such as loose fruit and vegetables, not using plastic drinking straws or stirrers and re-using products such as bags and water bottles.

> *"It starts with the individual, it starts with us"*
>
> **Craig Leeson, Director, *A Plastic Ocean***

Consumer choice and purchasing power, along with effective campaigning, can reduce use and engage with industry to remove some plastics on the market. This was demonstrated with the consumer dissatisfaction towards plastic microbeads in cosmetic products and the international *"Beat the Microbead"* campaign, which led to voluntary phase outs by cosmetics brands and retailers. Eventually public pressure has led to policymakers intervening to remove microbead containing products from the market, with the Microbead Free Waters Act in the US in 2015 and plans for bans in the UK, Canada and Taiwan announced in 2016. Well targeted awareness raising and educational programs such as these must be expanded and sustained to foster wider consumer actions around plastic use, waste generation and disposal. Whilst behaviour change in a population can take some time, it is positive to see receptive and proactive parts of the civil population and opinion leaders already taking action.

Policymakers can also provide incentive for the public and businesses to change behaviour and practices to reduce their use of some plastic products with tariffs and charges, such as the 5p plastic bag charge in the UK which reduced plastic bag use in England by over 6 billion in the first six months after its introduction (DEFRA, 2016). In South Korea, the Zero Waste Movement Network of NGO's led initiatives for reducing the use of non-disposable items from fast food restaurants in 1997. This led to government legislation in 1999 to restrict the use of single use cups, plates, plastic and paper bags in restaurants, department stores and other businesses (European Commission, 2009).

7.2.2 Remove

In some cases there is sufficient reason for policymakers to intervene with bans to remove products from the market, particularly those with singular use. This has started to occur with microbeads in cosmetics in some countries and should be expanded to a global ban, along with other policies to phase out other plastics in products that are designed to be littered (GESAMP, 2016). This has also been demonstrated by the bans on single use plastic bags, which are now occurring at various jurisdictional levels in some cities, states and countries internationally (Florida Department of Environmental Protection, 2010). This includes low and middle income countries, with Bangladesh in 2002 being the first country to ban the use and manufacture of plastic shopping bags after they were blamed for blocking drains and allowing flood waters to persist (Clapp and Swanston, 2009). In *A Plastic Ocean*, the ban on plastic bags less than 100 microns thick in Rwanda was shown, which began in 2005 before San Francisco became the first US city to ban plastic shopping bags in 2007 (Clapp and Swanston, 2009). More recently, as well as banning the distribution of plastic bags at checkouts from January 2016, France is in the process of implementing a ban on disposable plastic cooking utensils in 2020 as part of their Energy Transition for Green Growth Act to tackle waste and promote a circular economy (Ministry of Ecology, Sustainable Development and Energy, 2015). Similarly, the National Green Tribunal in Delhi, India, ban on disposable plastics in the city came into force in 2017 to reduce waste dumping and to combat air pollution from open burning. In the absence of action from policymakers action can still be taken by local communities. Indeed, in England by 2007 around 80 towns and villages implemented self-regulated bans on single use plastic bag (Clapp and Swanston, 2009).

7.2.3 Re-design

There is role for designers in creating more environmentally friendly product designs that make it easier for them to be reused, repaired or recycled to reduce the volume of waste produced and to maintain plastics and other material resources within the circular loop at the end of a product's life (European Commission, 2015; Hopewell *et al.*, 2009). Indeed, designing products that are easier to repair will increase their lifespan, allowing consumers to reduce their plastic consumption. In addition, designing products that are easier to dismantle increases the ability of recyclers to recover valuable materials for reprocessing, (European Commission, 2015). Even simple changes, such as changing the colour of plastics in products, can make a difference. Indeed, transparent plastic has a higher market value than dyed or pigmented plastic because it can be re-dyed to a wider range of colours, which had led to some dyed recyclable plastic simply being disposed of (Szaky, 2015). Nonetheless, companies can also make use of darker colours in products they manufacture from recycled plastic, such as Electrolux launching vacuum cleaners made only in black from recycled plastics (Carey, 2017). Policymakers can facilitate and promote environmentally friendly design. For example, in the EU there are plans to propose mandatory requirements for product design of electronic displays (such as computer and television screens) to make them easier and safer to dismantle, reuse and recycle under the framework of the Ecodesign Directive (European Commission, 2015).

Within product re-design there is also an opportunity for manufacturers to move towards using safer formulations of plastics or to phase out of some polymers to reduce human exposure to endocrine disrupting chemicals (Lithner *et al.*, 2011; Thompson *et al.*, 2009). For example, there are a number of strategies for re-designing medical devices to reduce exposure of patients to DEHP. These include manufacturing products from an alternative polymer to PVC with DEHP, using an alternative plasticiser with PVC, and modifying PVC chemically or physically to entrap DEHP within the PVC matrix to reduce leaching (Chiellini *et al.*, 2013).

Whilst manufacturers have a responsibility for the safety of plastic in its role as the "material of the 21st century", there is also a role here for the public and policymakers in demanding safer plastic of manufacturers. Indeed, there have already been bans on BPA in baby bottles due to market abandonment by consumers in the US (FDA, 2016) and concerns about infant health in the EU (European Commission, 2016). Legislation has also been put in place to ban some phthalates from children's toys in a range of countries including the US and in Europe and some commercial mixtures of PBDEs have had production halted globally. It is nonetheless important that alternatives used to replace potentially hazardous chemicals are properly tested to ensure that they are safe for use, in that they themselves do not also have hazardous properties. This is emphasised by the bisphenol A alternatives, bisphenol S and F, which are in use despite them demonstrating endocrine disruptive effects in animal models (Rochester and Bolden, 2015). Consequently, there is scope here for innovation through the principles of green chemistry. This aims to design safer and more sustainable chemicals for commerce to reduce negative impacts on human health and the environment, and can be achieved through interdisciplinary collaborations between chemists and biologists (EPA, 2016; Thompson *et al.*, 2009). This is in keeping with international objectives to achieve sound management of chemicals throughout their lifecycle and to minimise significant adverse impacts on the environment and human health by 2020 under UNEP's Strategic Approach to International Chemicals Management (SAICM) (SAICM, 2017).

The need for safer chemicals in plastics is further emphasised by the ability of plastic derived chemicals to be recirculated into new plastic products during recycling (Ionas *et al.*, 2014; Kajiwara *et al.*, 2011). Indeed, one Dutch study found penta and octa-BDEs, which were banned from manufacture globally through the Stockholm Convention in 2009, in recycled plastic nurdles and consumer products, including children toys, produced from recycled plastics (Leslie *et al.*, 2016). Indeed, since they are not removed from the waste stream during recycling, it was estimated that 22% of the BDEs from electronic waste and 17% of BDEs from automotive waste could end up in recycled plastics (Leslie *et al.*, 2016). Similarly, phthalates are also thought to re-enter the product cycle through the use of recycled plastic, potentially increasing consumer exposures (Pivnenko *et al.*, 2016; Lee *et al.*, 2014). This may pose difficulties for the use of recycled plastics by manufacturers in some applications where phthalate content is regulated – such as in children's toys (Ionas *et al.*, 2014). Given the increasing need to drive greater resource efficiency through recycling in a circular economy, it is important that this is not achieved at the expense of consumer safety (Leslie *et al.*, 2016).

There are also applications for plastics where biopolymers from plant based feedstock, such as starch or cellulose, can be used as an alternative to petrochemical based polymers. Some (but not all) bioplastics can be considered biodegradable or compostable, being converted into CO_2, methane, water, inorganic compounds and biomass. However, these must be coupled with the right waste management process, such as industrial composting or anaerobic digestion to provide conditions for them to successfully biodegrade and to utilise methane for energy production (Song *et al.*, 2009). In addition, although some bioplastics are recyclable, effective waste separation and appropriate labelling is required to avoid them contaminating the recycling stream for petrochemical based plastics. It is also worth noting that plastics marked as “biodegradable” or “compostable” are unlikely to rapidly degrade in environmental conditions in the oceans, which differ significantly from conditions in industrial or home composters and anaerobic digesters (UNEP, 2016). As such, biodegradable plastics can still be expected to fragment slowly over time and biodegradability should therefore not be an excuse for littering.

Biopolymers present an opportunity to manufacture plastics from a renewable feedstock with reduced CO_2 emissions as long as they are properly managed, preferably by recycling. There is therefore the potential for them to play a role in packaging and single use products in the future and consequently this is projected to be a growing market (European Bioplastics, 2016; Song *et al.*, 2009). Indeed, as their mechanical properties have improved some bioplastics are now equivalent to their petroleum based counterparts and are being used in agricultural films, consumer packaging and personal care disposables, such as nappies (Hopewell *et al.*, 2009). The Coca-Cola company also introduced a 100% bio-PET bottle in 2009 and plans to switch entirely to bio-based plastics by 2020 (Carey, 2017). It is worth noting here that these bottles are designed to be recyclable and not biodegradable and so responsible disposal, collection and waste management is required to maintain them within a circular economy and out of the environment.

Bioplastic polymers are also being used for some more long term applications, where their biodegradable properties are controlled, such as textiles, automotive parts and building and construction material (Hopewell *et al.*, 2009). However, there is a need to consider impacts of land use for food crops and biodiversity from intensive agriculture required to grow the feedstock crops (World Economic Forum *et al.*, 2016). Currently, they only represent a small proportion of arable land (European Bioplastics, 2016).

7.2.4 Re-use and Recycle

Product re-use and recycling presents more opportunities to reduce the production of virgin plastic and its associated resource use and emissions in comparison to single use products disposed of to landfill. It gives end of life plastics a value that will divert them from landfill and our surrounding environment by increasing their usable lifespan. Because of its durability, plastic as a material lends itself well to reuse. Indeed, reusable plastic crates and pallets are used for transporting goods on an industrial scale (Thompson *et al.*, 2009), whilst domestically there has been an increase in the use of reusable plastic shopping bags by the public following the introduction of tariffs and restrictions on single use bags in countries such as the UK. The energy and resource efficiency of reuse is high since it avoids producing multiple single use products. In the case of non-alcoholic beverage sales in Germany, a life cycle assessment has estimated that if 100% of these came in refillable bottles (20% in glass, 80% in PET plastic) it could save over 1.2 million tons of CO_2 annually in comparison to if they were 100% non-refillable (R3 Consulting Group *et al.*, 2009).

Recycling aims to provide a process for effective material recovery in which plastic can be reprocessed into a similar product (closed loop recycling) or a product with lower quality properties (downcycling) (reviewed in Hopewell *et al.*, 2009). As such, end of life material can be regarded as valuable feedstocks for new production instead of waste (Thompson *et al.*, 2009). Through these processes, plastic products can be reprocessed into new products, clothing or even construction material, where plastic with a short lifespan can be recycled into a long life application. This can be driven by the development of effective collection infrastructure to provide an economy of scale in the plastic waste feedstock for recyclers. Here, public support is required to provide the feedstock by separating out from their own waste stream to divert it from landfill and litter through their own waste disposal practices. There are also options for recovering chemical constituents, but these have so far lacked economic viability (Hopewell *et al.*, 2009).

Thermoplastics, such as PET, PE and PP all have high recyclable potential, whilst thermoset plastics do not since they cannot be re-melted and reformed. For example, PET bottles can be recycled in a closed loop into new bottles or reprocessed and downcycled into polyester fibres for clothes. In the UK, Axion Polymers are also taking advantage of a closed loop recycling opportunity by taking plastics from end of life cars to produce more vehicle components for the automotive sector (Axion Polymers, 2017). Their recycled polymers have been used to produce air vents and headlamp casings for BMW and MINI cars (**Figure 16**).

Figure 16: An automotive headlamp casing made using recycled plastic (Photo: David Jones)

However, the recycling process faces a number of challenges in both supply and demand. It requires sufficient feedstock to be economically viable and it needs to produce a high quality product that can compete in demand with virgin polymer. One of the greatest challenges is that of separation. It is easier to produce high quality recycled polymer equivalent to virgin polymer from a waste stream of single polymer products (Hopewell *et al.*, 2009). However, many waste streams contain a mix of plastic products with a variety of polymers and composite materials. There is a wide range of plastic polymer formulations on the market and some products will contain a mix of polymers. Plastic packaging is also particularly notable as a composite material, which can also contain paper, metals and dyes and therefore cannot always be economically recycled. As a result this has gained interest as a feedstock for energy recovery instead.

The risk is that contamination of the feedstock for a recycling process can reduce the quality of the recycled polymer in comparison to virgin plastic, leading to reduced demand. Although there are still applications for resins made from mixed polymers, such as producing plastic bags, this is limited to downcycling rather than closed loop (Hopewell *et al.*, 2009). With appropriate labelling, this separation process can be assisted by the public separating out recyclable plastic materials in their own waste stream. Ideally re-design could move us towards a more limited range of polymers in products in the waste stream to decrease the amount of rejected material and to increase the quality of the final product (Hopewell *et al.*, 2009). Indeed, high quality recycled plastic is vital in the context of the declining price of oil, which has made it difficult for recyclers to compete with virgin polymers (Szaky, 2015). Indeed, the low cost of oil has made it cheaper to produce virgin plastic than to use a recycled feedstock, which presents a significant challenge to plastic recycling and a need to rebalance the economic incentive towards the use of recycled plastic. Such intervention may require intervention from policymakers to redress this issue.

Current recycling rates of plastic vary extensively between countries and there is much scope for improvement. Focussing on the three largest areas for plastics manufacture there is an average of 30% recycling of plastic in Europe, which varies extensively between member states, only 9% in the US and 25% for China, which imports a lot of its material from other countries (UNEP, 2016). There is a need for policymakers to promote recycling to drive up these rates and to support recycling within the waste management infrastructure. However, there is also scope for the involvement of industry in managing the waste that their products create. One example of policy action to drive up recycling has been seen in Germany through their Ordinance on Avoidance of Packaging Waste, a policy of Extended Producer Responsibility (EPR). EPR requires manufacturers to be financially responsible for the costs of waste collection and management at the end of their products life, shifting the cost away from local governments and public funding. Indeed, EPR schemes in France have reduced public spending on waste management by almost 15% (Nash and Bosso, 2013). In doing so it aims to create economic incentive for manufacturers to make their products more re-usable, recyclable, less resource intensive and less toxic, and to make waste management systems more cost effective (Nash and Bosso, 2013). In Germany, this was initiated in 1991 to reduce packaging waste that was being generated when the country was facing severe landfill shortage and packaging was accounting for around 30% of municipal solid waste (Hanisch, 2000). As a result of this policy, between 1991 and 1998 the per capita consumption of packaging reduced by 13.4%, although critics point out that this was achieved at a high investment cost in the waste management system (Hanisch, 2000). There may be applications of EPR in helping to fund waste management infrastructure in low and middle income countries through finance from the foreign manufacturers who sell their products in these markets.

Figure 17: Craig Leeson using a reverse vending machine in Germany to return a plastic water bottle

In addition to packaging waste, bottle deposit legislation for single use bottles was introduced in 2003 under the packaging ordinance in Germany. This applies to single use bottles for water, alcoholic drinks, dietetic drinks and carbonated and non-carbonated drinks, on which there is a small levy (€0.25) that is refunded to the consumer when the bottle is returned to the manufacturer through the use of reverse vending machines (**Figure 17**). There is also a voluntary bottle deposit scheme in place for refillable bottles to encourage consumers to return them for reuse and recycling at their end of life, which also provides financial incentive. These schemes have resulted in the collection of 95-98% of all single use beverage bottles (R3 Consulting Group *et al.*, 2009) and 98.5% of all refillable bottles sold (Zero Waste Europe, 2014). By giving the bottles a value, it has also reduced them littering the streets (Zero Waste Europe, 2014). Bottle deposit schemes have also been introduced in other European countries, some US states, Canada and Australia and there are currently campaigns to introduce it in the UK to drive up recycling rates and reduce litter.

This principle of placing a financial value on plastic waste for consumers is also being employed by the Plastic Bank in Haiti (**Figure 18**) to help clean up the local environment, reduce input to the ocean and to provide an income to locals to help alleviate poverty. They have set up 30 recycling markets where local people can bring recyclables and earn an income by exchanging it for solar phone charging, sustainable cook stoves and cooking fuel or cash. The Plastic Bank then recycles it to sell as “Social Plastic” to corporations for use in their products as an innovative ways to be environmentally responsible (Field, 2016). For example, Norton Point have partnered with the Plastic Bank to produce a range of sunglasses from Social Plastic, which they are currently crowdfunding (Taylor, 2016). This has demonstrated that there can still be a role for scavengers and waste pickers within a waste management system in low and middle income countries to collect and separate high value plastic in return for income. However, there is clearly a dramatic need to significantly improve their working conditions, standards of living and to offer opportunities to improve their skill set for alternative employment (Ocean Conservancy, 2015).

Figure 18: The Plastic Bank team at one of their recycling markets in Haiti

7.2.5 Recovery and Advanced Thermal Treatment Technologies

Plastic waste that is not easily or economically recyclable can still be a valuable as a feedstock for thermal treatments that can process it to produce energy. This also has the benefit of significantly reducing the mass or volume of waste to transfer to landfill, the associated chemical leaching and it avoids putrefaction of waste, which has adverse implications for sanitation. Currently, combustion by incineration is most commonly integrated into waste management infrastructure. Whilst some countries, such as Switzerland, Japan and Denmark, incinerate over 65% of their waste this option has been disregarded in other countries, although there are plants under construction or being planned in the UK and USA (Damgaard *et al.*, 2010).

Such technologies contrast with open burning of waste with no emission control, which is practiced particularly in areas lacking waste management infrastructure to dispose of waste and can release a range of toxic chemicals, as previously discussed. Concerns about polluting emissions, such as dioxins and furans, particulate matter and acid rain precursors, have also been raised for incineration technologies. However, it is worth noting that air pollution control systems have been introduced to comply with tightened legislation and emissions standards in areas such as the EU (Vehlow, 2015). Nonetheless there has been interest in in alternative treatment technologies that avoid or reduce these emissions further (Byun *et al.*, 2010). Indeed, more advanced waste to energy technologies, such as pyrolysis and gasification, including some of their sub-types, are gradually being integrated into the waste management infrastructure in a range of niche and medium-scale applications. These have the added benefits of producing useful materials and avoiding or reducing toxic emissions (Li *et al.*, 2016a; Lombardi *et al.*, 2015; Byun *et al.*, 2010).

Pyrolysis is an advanced thermal treatment process that can be used to thermally degrade plastic waste in the complete absence of oxygen. By melting and heating plastics to high temperatures (between 300 and 850ºC) in the absence of oxygen, they do not burn but degrade into smaller hydrocarbon chains (Butler *et al.*, 2011). These are vaporised and can be condensed, distilled and collected as usable liquid oils and waxes. The process also produces a solid char of carbon and other non-combustible compounds, as well as synthetic gas (syngas), which is predominantly carbon monoxide and hydrogen and can be used to fuel the heating process (Lombardi *et al.*, 2015). As such, it has been referred to a method of *"feedstock recycling"* as opposed to just energy recovery since it uses plastics as a resource to produce alternative products. In fact, the liquid fuel from pyrolysis may have a greater economic value than the electricity generated by combustion incineration (Butler *et al.*, 2011).

Appropriate feedstock for pyrolysis is limited to a few waste flows. Indeed, municipal solid waste is not appropriate and needs to be separated beforehand to collect the most suitable material, including some end of life plastics, for processing (DEFRA, 2013). At the Plastic Energy Ltd (formally Cynar PLC)'s pyrolysis plant in Ireland, which was shown in *A Plastic Ocean*, this process is being used to transform plastic waste into fuel, with light oil, kerosene and diesel fuels being produced from the condensed liquids, giving plastic waste a second life. As a feedstock they can use plastics from products that are not easily or economically recycled, such as single use packaging, which would normally be diverted to landfill. They use high and low density polyethylene, polypropylene and polystyrene but they do not process polyethylene tetraphthalate (PET) or polyvinyl chloride (PVC) products so this technology would not reduce recycling rates for these types of plastic. At Plastic Energy Ltd, they estimate that they can produce 18,000 L of alternative diesel fuel from 20 tons of plastic per day and if they applied their technology to the UK's 1.2 million tons of end of life plastic produced every year, they could produce 840 million litres (Plastic Energy Limited, 2017).

As well as fuels, other companies can use pyrolysis to convert polypropylene and polyethylene plastics into chemicals such as olefin gases (e.g. ethane, propene and butadiene), which are used as the synthesis of a range of chemicals useful to society (Butler *et al.*, 2011). There are also potential applications for pyrolysis in disposing of waste wood, cooking oil, lubricating oil and sewage sludge. A plant in Japan also uses rubber tyres as a feedstock, producing gas, oil, steel wire and carbon, which are reused by the steel industry (Lombardi *et al.*, 2015).

Gasification also uses high temperatures to process solid waste into syngas fuel, of which yields and purity can be increased through the controlled input of oxygen, air or steam to the process (Lombardi *et al.*, 2015; Ruj and Ghosh, 2014). This can be achieved using thermal plasma treatment, which can provide a high energy density and reach temperatures of over 20,000ºC, allowing the process to achieve high throughput of a wide range of wastes from a small reactor (Li *et al.*, 2016a; Byun *et al.*, 2010; Gomez *et al.*, 2009). The process breaks down waste into its base elements, which are converted into hydrogen and carbon monoxide for syngas, whilst inorganics (such as metals) and minerals that are not broken down are converted into a glassy, vitrified slag that traps remaining hazardous chemicals in its matrix (Li *et al.*, 2016a). Metal recovery is also possible through this process and both the syngas and the solid slag have commercial value as energy and construction material (Gomez *et al.*, 2009). It has also been shown to reduce the mass or volume of waste by up to 95%, reducing the volume that is sent to landfill (Li *et al.*, 2016a).

So far thermal plasma treatment has only been used successfully in specific niche applications, such as PyroGenesis Canada Inc.'s technology (**Figure 19**) on board the US Navy's USS Gerald R Ford (CVN 78) Supercarrier for disposal of their solid waste. Perhaps its most important use so far has been in the destruction of hazardous wastes including radioactive waste, medical waste and asbestos (Byun *et al.*, 2010; Gomez *et al.*, 2009).

Both technologies have the potential to reduce the volume of end of life plastics disposed of to landfill and to transform them into a profitable resource. At present, pyrolysis only has a very small role in the waste management infrastructure of the EU but there is scope for this technology to be incorporated for both large and small scale applications alongside recycling (Butler *et al.*, 2011). This may have substantial economic benefits with a scoping report by the American Chemistry Council finding that the development of plastics to oil facilities in the US could produce an economic output of $8.9 billion in oil production and employment annually (American Chemistry Council, 2014). In comparison, whilst thermal plasma treatment has the potential to be applied to a wider range of wastes, it is very energy intensive and economically costly. At this point it is not clear whether it will be economically viable at a larger scale than the niche applications it is currently used in. However, avoiding the costs associated with disposal to landfill and the commercial value of syngas energy production, construction material and metal recovery may improve its economic viability (Gomez *et al.*, 2009). Nonetheless, there is a need to significantly decrease its running costs to improve the economic viability of this technology.

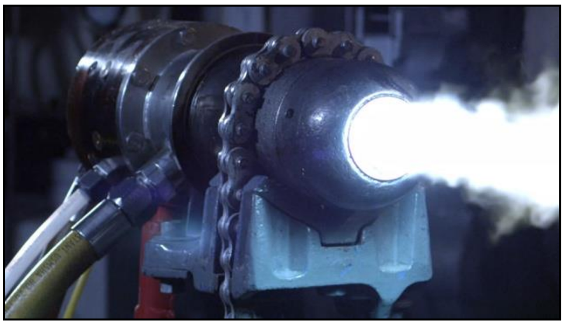

Figure 19: The plasma torch from PyroGenesis Canada's thermal plasma treatment technology

Both technologies have a number of adjustable parameters in place to reduce toxic emissions to the environment. In pyrolysis for example, the absence of oxygen and avoiding the use of chlorinated feedstocks, such as polyvinylchloride plastics, should minimise the formation of toxic compounds like dioxins. In addition, the use of high temperatures in these technologies followed by rapid cooling further minimises dioxin formation, whilst further treatment of gaseous by-products prior to emission to the environment can reduce other toxic substances and particulates (DEFRA, 2013). However, they are still a source of CO_2 emissions and greater resource efficiency and lower carbon footprint can be achieved with interventions higher up the waste hierarchy (reduction, re-use and recycling), which reduces the demand on raw materials for plastic production. In addition, since the financial viability of thermal treatments depends on a constant supply of waste plastic, it may not provide incentives to reduce our waste output in the long term.

7.3 Can we clean up our environment?

Given the impacts of plastic in the environment, there is unsurprisingly much interest in cleaning up the oceans of plastic waste. However, there are a number of major challenges to this and clean ups will only be possible in some areas where plastics are accessible. Where clean ups are feasible, there are a range of benefits even if they are at a small scale compared to the magnitude of the plastic pollution problem. Beach cleaning can remove plastics that come ashore, making beaches more attractive for tourism and local people. They can be used to raise public awareness and produce valuable data on the types of plastics in the environment and trends in their abundance (**Figure 20**) (Thompson *et al.*, 2009). In doing so, they can have a valuable role in promoting consumer responsibility and increasing pressure on governments and manufacturers. They also stop the plastics they collect from re-entering the ocean and can help protect wildlife. Indeed, the removal of entangling debris on beaches and disentangling of monk seals in the Northwest Hawaiian Islands is one of the intervention strategies being employed to aid population recovery of this species, whose numbers have increased 3% annually in the last three years (NOAA Fisheries, 2017). Another example was seen after the spillage of Sinopec nurdles in Hong Kong, as shown in *A Plastic Ocean*, where a large clean-up campaign was initiated and conducted largely by members of the public and NGOs through social media. This was estimated to have recovered around 70% of the lost pellets from the environment (UNEP, 2016).

In the case of fishing debris, there can be substantial economic benefits to cleaning up local environments. In the Chesapeake Bay, USA it was estimated that removing 34,408 derelict crab pots led to an increase in catch with a value of US$21.3 million, 24% higher than would have been expected without this intervention (Scheld *et al.*, 2016). However, even after plastic is removed from a local environment more is likely to flood in on the ocean currents, as well as from rivers and land based sources, as long as it is still released from across the globe. This makes maintaining a clean environment a constant and ongoing challenge.

Figure 20: Beach cleaning in the UK (Photo David Jones)

The fact is that it is simply impossible to clean up the entire ocean due to its sheer vastness, the widespread distribution of plastic, and the difficulties in accessing remote areas, particularly the deep sea. This has led to interest in cleaning up hotspots for plastic pollution, such as the Great Pacific Garbage Patch, instead. Perhaps the best known project is that of the Ocean Clean-up, which aims to develop a series of 1-2 km wide passive, floating barrier systems that use the natural ocean currents of the gyre to collect and remove half of the Great Pacific Garbage Patch in 5 years (The Ocean Cleanup, 2017). However, concerns have been raised by experts of the ecological impact of such an array, which could cause the bycatch of free-floating organisms (UNEP, 2016). A recent modelling exercise has also found that their initial array design would be more effective closer to shore and the source of plastic waste, off the coast of China and in the Indonesian archipelago, to prevent plastic travelling to the gyre (Sherman and Van Sebille, 2016). Free floating barriers such as this may also have application at the mouths of rivers to collect plastic before it can flow out to sea to begin its degradation into microplastics (UNEP, 2016). Other schemes for collecting plastic from the ocean have involved small financial incentives for fishermen in Korea to return marine debris to port that they encounter (Morishige, 2010). A similar scheme in Europe provides fishing fleets with hardwearing bags to collect marine litter caught in their nets for disposal in ports at no cost to the fishermen, with Scottish fishermen recently landing their 1000th metric ton of litter (Fishing for Litter, 2017).

Whilst it is possible to recover larger macroplastics, particularly on beaches where they are accessible, the microplastics that make up over 90% of all marine plastics are another story. Small and widely distributed at the ocean surface, mixed in with plankton and other fauna, removing them has been described as *"economically and ecologically prohibitive, if not completely impractical"* (Eriksen *et al.*, 2014). As such the greatest gains can be achieved by prevention at source, avoiding the input of primary microplastics and the macroplastics that generate microplastics as they degrade.

> *"You can't possibly filter out these tiny particles from the entire ocean, you can't filter the entire ocean, in fact so much plastic is in the ocean now in a form that we really can't get to it that I feel the emphasis needs to immediately shift to stop putting it in."*
>
> **Mike deGruy, Marine Biologist and Filmmaker**

The inherent issue with cleaning up the plastic from our environment is that this presents only treatment of the problem and not a cure, which is why there is a need to prioritise global, preventative strategies on land and financial investment to stop the flow of plastic into the waterways and the ocean in the first place (Newman *et al.*, 2015). The higher up the plastics life cycle the more effective and ecologically sound the solutions will be. This is where a reduction in the production and use of single use plastics, improved waste management and the promotion of a circular economy comes into play to avoid plastic emissions to the environment. Doing so will bring substantial benefits, aid clean-up strategies in the long term and will be assisted by improvements in our understanding of the sources and pathways of plastics to the environment to help us identify the best prevention strategies. The case of industrial plastic pellets demonstrates that interventions at source can have a positive impact on plastic in the environment and effects on wildlife. There has been a significant reduction (around 75%) in industrial plastic pellets recovered in both the North Atlantic subtropical gyre and in the stomachs of fulmars in the North Sea, thought to be as a result of such interventions (Van Franeker and Law, 2015; Van Franeker *et al.*, 2011). A reduction has also been observed in other bird species in the North Pacific, South Atlantic and Indian Oceans and since plastic ingestion is correlated with exposure, reduced exposure should be leading to less ingestion (Wilcox *et al.*, 2016; Ryan, 2008; Vlietstra and Parga, 2002). These findings also suggest that microplastics at the sea surface disappear to other environmental compartments in relatively short time spans (a matter of decades) if preventative interventions are enacted (Van Franeker and Law, 2015). It has been suggested that this is linked to a general reduction in losses of pellets from industry to the environment through improved practices and the economic incentive to avoid losing valuable product (Van Franeker and Law, 2015; Van Franeker *et al.*, 2011). Indeed, the plastic industry's international initiative, Operation Cleansweep, which was set up in the US in 1991 aims for zero loss of pellets, flakes and powders and is now conducted at thousands of factories globally (Operation Cleansweep, 2016). This is not to say that this voluntary scheme is perfect, as pre-production pellets are still being emitted and found in the marine environment globally. Unfortunately, the reduction in pellets ingested by birds has also been compensated for by an increase in their ingestion of user plastic recovered, demonstrating the need for further intervention (Van Franeker *et al.*, 2011; Vlietstra and Parga, 2002). In addition, the disappearance of plastics from the sea surface indicates transport to other environmental compartments, including beaches, biota and the deep sea.

8. Moving forward

> *"No one knows how much plastic has accumulated in the sea over the last 50 years. But pace has picked up."*
> **Dr Sylvia Earle, Marine Biologist and Explorer**

It is anticipated that the rising global population combined with increasing urbanisation, economic development and consumerism will substantially increase the amount of waste that we generate (Ruj and Ghosh, 2014; Hoornweg and Bhada-Tata, 2012; Gomez *et al.*, 2009). In a business as usual scenario, without improvements in waste management, it has been estimated that the 8 million metric tons generated by coastal countries and released into the ocean in 2010 will increase by an order of magnitude by 2025 (Jambeck *et al.*, 2015). Even if we stop releasing plastic into the ocean today, the continued degradation of the plastic debris that is already in the ocean will leave a microplastic legacy that could persist in the environment for centuries (GESAMP, 2015; Barnes *et al.*, 2009).

We are now presented with an opportunity to make a real, positive difference to the quality of our surrounding environment and to avert an increasing risk to wildlife and ourselves. Now that the problem of our plastic ocean has been identified it is up to us to consider it a common concern for mankind and work towards implementing and innovating solutions, many of which are already within our grasp. It is important that we remember that the ocean connects us all, not just geographically, but by providing our food, employment, leisure and recreation, wellbeing and over half of the air that we breathe. A less polluted, healthier and more resilient ocean able to support biodiverse and abundant wildlife and withstand environmental change will better provide us with the ecosystem services that are crucial for the success of human society, economy, health and wellbeing.

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