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Using Stock and Flow Modeling to Address Knowledge Gaps in Marine Plastic Pollution Data

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USING STOCK AND FLOW MODELING TO ADDRESS KNOWLEDGE GAPS IN MARINE PLASTIC POLLUTION DATA

by

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ABSTRACT

USING STOCK AND FLOW MODELING TO ADDRESS
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As plastic becomes a ubiquitous part of society, its growth outpaces waste disposal infrastructure and enters the environment as physical and chemical pollution. Plastic can also erode during the use cycle and reach the environment without any chance of being arrested by collection efforts. Plastic is a hazard to many parts of the earth's life support system but there are many knowledge gaps regarding the processes by which plastic moves through the use cycle and environment. In particular, the ocean is generally regarded as a sink for plastic out of which it is difficult to escape, but plastic can sink into the benthic zone reaching a deeper and more permanent sink and affecting a different environment. Little is known about the rate plastic moves from the surface to the benthic zone, the time it spends on the surface, and the quantity already in the benthic zone. To address these knowledge gaps, a stock and flow model was constructed using FORTRAN to simulate as much of the plastic use, disposal, and pollution cycle as was feasibly possible. The constructed model allowed for a complex use of Residence Time Distributions (RTDs), with plastic exiting a stock at variable rates and percentages based on the quantity of plastic entering the stock. This model was then cross-referenced with real data on surface ocean plastic, plastic waste, and other known quantities to check the accuracy of the simulation. Once it was determined that the model's derived values for quantities that have

been accurately measured in real life were within acceptable margins, the model's values for the RTDs of plastic in the ocean were deemed reasonable. The model was also used to project plastic pollution into the future using several different scenarios to obtain estimates on future plastic production and pollution as well as the effects of RTDs on various stocks in the model. The model produced in this research could be scaled to different regions by changing the production value of the plastic entering the model and the plastic use quantities and waste disposal methods and rates.

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INTRODUCTION

1.1 PLASTIC PRODUCTION AND CONSEQUENCES

Humanity's increasing reliance on plastic in almost every aspect of life is creating a worrying and not well understood threat to the planetary support systems that sustain life on this planet. While plastic is widely utilized in consumer products globally, the understanding of and research into its impact on the ecosystems and individual health of the organisms that inhabit them has been vastly outpaced by the production of new plastic materials. Only recently have policymakers begun to consider issues such as the longevity of plastic polymers, the bioaccumulation of microplastic particles as a gradient that increases with higher trophic levels, or the adsorption (adherence of molecules to a surface) of toxins from the surrounding seawater.

Although these fields of study are not yet fully understood, human society continues to grow its production of plastic and to inadvertently introduce new plastic into aquatic and marine environment through raw production loss, mismanaged waste, slow degradation of plastic materials in, e.g., tires, buildings and synthetic clothing, and simple carelessness on the part of the consumer. This denotes a general discounting of the effects of human actions on the health of the earth's life support systems (ELSS) and future human generations, either through apathy towards or ignorance of the problem. Nanoplastics, which exist on the nanomolecular scale, are particularly worrying as they have a higher potential of entering the cellular structure of higher order animals, and have been found to

have the capability to cross cell boundaries and enter into cells, including those found in the brain.

At this point, any cleanup effort targeting plastic already in the environment has no hope of keeping up with the flows of plastic into the environment. For plastic removal efforts to be effective, the flow of mismanaged plastic waste must be reduced through the increase of removal efforts and reducing the amount of plastic produced. A thorough understanding of the primary sources and sinks of oceanic microplastic is necessary for any flow mitigation effort to be effective, which can be obtained through the coupling of physical oceanographic models with existing data on coastal topography, river output, watershed boundaries, degradation of plastic already present in the ocean, and plastic production.

The amount of plastic in the ocean depends on two basic principles: the amount of plastic flowing into the ocean and the residence time distribution (RTD) of the plastic currently in the ocean. While the plastic flow into the ocean has been reasonably measured in the past, little work has been done into determining the RTD of plastic once it has reached the ocean. By doing so, more accurate estimations of the quantity of plastic in the ocean can be determined.

1.2 PRODUCTION QUANTITIES, KNOWLEDGE GAPS

Currently, a lack of data in the amount of plastic entering and currently residing in the oceanic system means there are large gaps in knowledge regarding the exact amount of plastic pollution in the ocean. However, one study estimated that around 8 billion tons of plastic have been produced in the history of the world as of 2015, and 381 million tons per

year were produced in 2015 (Jambeck et al., 2015). Around 75% of the plastic produced in a year leaves its usage cycle the same year (Geyer et al, 2017). While it is difficult to estimate the amount of plastic that enters the ocean system, it is estimated by some studies that 80% of the plastic in the ocean came from mismanaged waste on land originally, with the rest coming primarily from the shipping, fishing, and aquaculture industry, although estimates may vary depending on the publication and the methods used to arrive at an estimate. For example, many papers focus on more highly visible sources of atmospheric plastic pollution and discount more complex sources such as the erosion of synthetic materials such as clothing, tires, and agricultural products, or the loss of preproduction plastic in the form of nurdles (Andrady, 2011).

One study estimates that the top 20 countries responsible for producing the largest amount of plastic waste contribute around 83% of the total plastic waste entering the ocean (Jambeck et al., 2015). These countries are either developing nations without the established infrastructure to deal with waste plastic, or countries with a high rate of production of new plastic that, while they may have a low percentage of mismanaged plastic waste, cause vast amounts of plastic debris due to the high volume of plastic they produce (Moore & Phillips, 2012). Developed nations can also reduce the recorded amount of plastic waste they manage by exporting it to developing nations with less strict plastic disposal laws (Law et al., 2020).

Once plastic waste enters the ocean, it can linger there for decades, as the conditions present in aquatic environments are not conducive to the breaking down of the molecules that make up plastic. These molecules do however provide a vessel for contaminants to latch onto, as well as living organisms that may become invasive species as these plastics

migrate through the ocean. Ocean-bound plastic is often mistaken by various organisms for their particular food of choice, such as long stringy green bits of plastic resembling the seaweed that some species of sea turtles like to eat, and brightly colored plastic lighters resembling the fish eggs that albatross parents feed their chicks. These plastics provide an immediate danger as a choking hazard, but also a more insidious threat through bioaccumulation.

Organisms that consume plankton as their primary diet may mistakenly consume microplastics or nanoplastics, especially in the center of gyres where plastic can seasonally outnumber plankton by ratios of 8 to 1, to as great as 45 to 1 (Moore & Phillips, 2012). As these organisms are consumed by predators, the plastic begins to bioaccumulate and grow in concentration up the food chain. At any stage, this may affect humans, who as the apex predator species of the globe consume animals from all trophic levels.

One of the major problems regarding risk estimations of plastic debris is the lack of knowledge concerning the amount of plastic actually in the ocean. Estimates have been made for the quantity of plastic entering the ocean and the percentages of plastic exiting the ocean into various sinks such as benthic sediment and coastal deposition, but these methods often produce inconsistent numbers, and the various components of the data have not been combined to determine an accurate amount of plastic in the ocean. The goal of this modeling project is to fill these knowledge gaps by using existing data and RTDs in a stock-and-flow model to test a range of RTDs in the ocean, then compare these RTDs and the quantities of plastic they with past published estimates of plastic in the ocean to see which previously published estimates could be explained by these tested RTDs.

Knowing the RTDs of plastic in the ocean allows for the solving of one of the great unknowns of plastic pollution research: why the projected inflow of plastic into the ocean is much greater than the amount of plastic in the ocean estimated by field studies of the ocean. In the past, the ocean has been treated like a stock into which plastic flows but does not exit. As more studies are done about atmospheric ejection of plastic, benthic settling of plastic, biofouling, and shoreline redeposition, we are coming to understand that plastic does in fact leave the ocean stock, but little is known about the quantities or time scale of this exodus.

This model will allow the testing of whether the flows of plastic into the ocean are more or less important than the flows out of the ocean for determining the amount of plastic in the ocean. There has long been known that there is an imbalance in the amount of plastic estimated to enter the ocean compared to the amount actually found/predicted in the ocean surface. Recently, Weiss et al. (2021) postulated that the imbalance was a result of drastically lessened flows into the ocean than previously thought, rather than comparatively fast RTDs for plastic in the ocean. This project will allow the testing of the validity of this theory by determining what importance the amount of plastic entering the ocean holds compared to the RTD of plastic in the ocean in relation to the amount of plastic that can be found on the surface of the ocean.

1.3 STRUCTURE OF THIS DOCUMENT

This thesis will in Chapter 2 present the history of synthetic plastics before discussing modern trends in plastic production and plastic waste management. It will, in sections 2.5-2.7, briefly discuss the state of plastic waste in the environment and the

physical and chemical threats to the earth's ecosystems posed by plastic. Next in sections 2.8 and 2.9, this thesis will introduce the concept of plastic RTDs and detail some permanent or semipermanent sinks of plastic, as well as past plastic modeling efforts. Next in section 2.10, the purpose of this model and the components necessary for it to run will be discussed. In chapter 3, the quantity of data that has already been gathered and will be necessary for the modeling will be discussed. In chapter 4, the plastic use cycle will be broken down into a system of stocks and flows, and the difference between managed and mismanaged waste will be discussed. Next, each of the different stocks will be discussed in detail and any relevant data will be discussed, as well as the flows into and out of these stocks. In chapter 5, the results of the modeling process will be discussed, and in chapter 6, the paper will discuss reducing inconsistencies in the estimated amount of plastic in the ocean and the estimation of RTDs, as well as the scientific knowledge gained from this work.

CHAPTER 2

BACKGROUND

2.1 HISTORY OF PLASTIC PRODUCTION

The use of synthetic or semi-synthetic polymers has been a part of human society in one form or another for hundreds of years, but only in recent decades has it begun to pervade every part of human life and every corner of the planet, whether that be seemingly pristine mountaintops, remote tropical beaches, the bottom of ocean trenches, or the very rain and air of the atmosphere. Some of the progenitors of the cultural phenomenon of polymer-based goods were the indigenous tribes of South America, who used the sap of the rubber tree in the construction of shoes and sports balls, early forerunners of the synthetic shoes and sports equipment that one can find in the sporting-goods aisle of any supermarket the world over. This use of rubber tree sap was copied by Charles Macintosh and Charles Goodyear in the early- to mid-1800's in an attempt to make waterproof clothing, with mixed success. Natural rubber is very reactive to temperature, a problem Goodyear attempted to solve using nitric acid and heat. In the process, he unwittingly discovered a process to link the polymers within the rubber into a three-dimensional chain, altering the rubber's properties (Moore & Phillips, 2012).

One of the first synthetic thermoplastics, Parkesine, was developed in the mid 1800's by Albert Parkes, who was attempting to develop a realistic looking replacement for the ivory used in billiard balls. Parkes fabricated proof-of-concept commercial items such as knife handles and pipe stems and exhibited them at the 1862 London International Exhibition, but his company failed before a meaningful impact could be made on the

market by the synthetic material that Parkes had developed to take the role in commercial goods typically filled by more natural materials such as wood, ivory, bone, or metal (Moore & Phillips, 2012).

Parkes and his contemporaries dealt primarily in semi-synthetic plastics, combining natural materials with chemicals to produce a new material with different properties. For example, Parkes' method involved combining cotton, wood fibers, castor bean oil, and sulfuric acid to create a pliable dough that hardened when it dried. Bakelite, developed by Leo Baekeland around the turn of the 20th century from a mixture of carbolic acid, formaldehyde, and other agents, is widely considered to be the first fully synthetic plastic resin, marking the advent of plastic entering the consumer market as a cheap, easily produced replacement for more expensive natural materials.

By the 1920's, Baekeland's factory was producing around 4 million kilograms of plastic annually, around the time the nature of polymers was first described by German scientist Hermann Staudinger, for which he was awarded the Nobel Prize (Moore & Phillips, 2012). By 1950, worldwide production of plastic had increased to 2 million tons of plastic annually, an increase of 3 orders of magnitude compared to the annual output of Baekeland's factory just 30 years earlier (Jambeck et al., 2015). This acceleration of production was partially caused by demand during the second World War, where plastic stepped in to fill the roles of harder to find natural materials such as rubber, silk, glass, and metal. In post-war America, this "proof-of-concept" combined with a slowly growing consumerism, a belief that the only way the economy was to survive was constant growth and consumerism, and desire for throwaway, disposable goods that would see the production of plastic skyrocket in the coming decades.

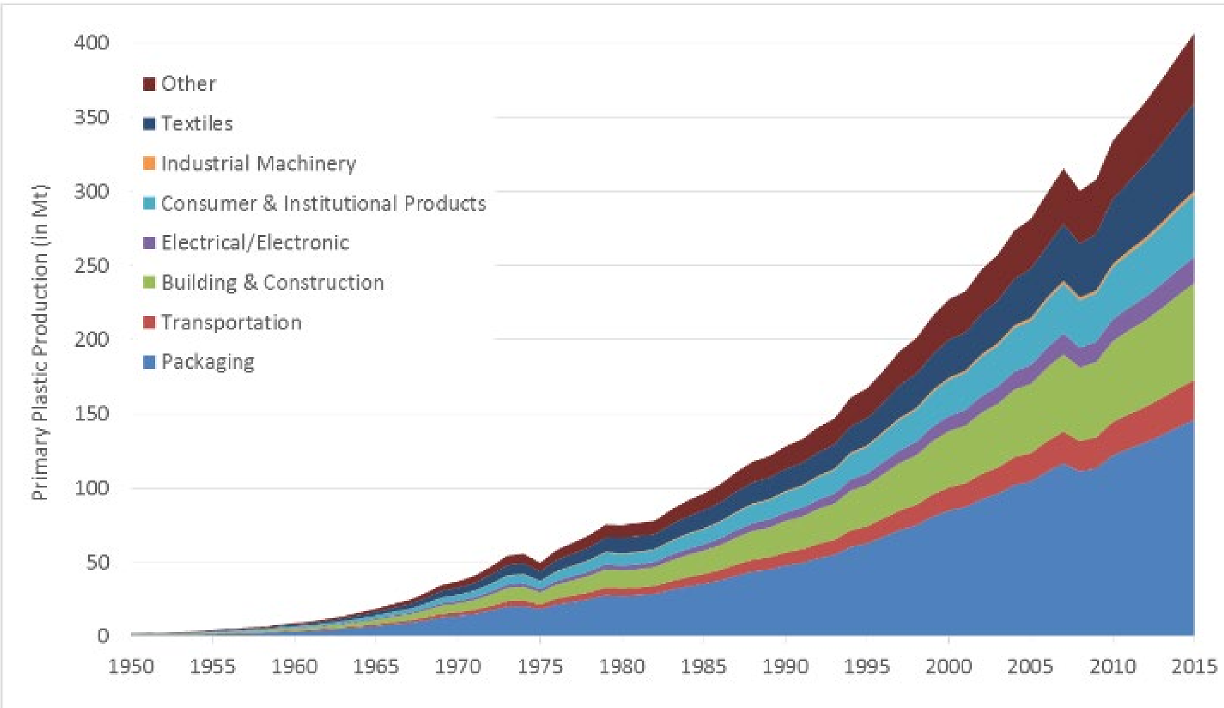
Items that were once constructed to be used for years or decades were replaced by cheaply made versions built for only a few uses at most. This coincided with lobbying and marketing campaigns by large manufacturing businesses and organizations to move the responsibility of the waste generated by this disposable goods culture from the manufacturer to the user, leading to an immense amount of plastic waste both properly managed and not (Moore & Phillips, 2012).

2.2 EARLY STUDIES IN PLASTIC POLLUTION

The first reports of plastic in the ocean began appearing in the early 1970's with such papers as Carpenter et al. (1972) who discussed gut obstructions in fish and the potential for chemicals in the water to accumulate onto plastic debris, and Carpenter & Smith (1972), who discussed plastic weathering in marine conditions, the prevalence of what in modern terms would come to be known as microplastics, and the process of biofouling by marine microorganisms. At this point according to Jambeck et al. (2015) and Ritchie & Roser (2018) approximately 331 million tons of plastic had been produced worldwide, and over 44 million tons of plastic waste had already entered the ocean at this point. Despite these early warning signs of plastic's threat to the wellbeing of the earth's oceans, plastic continues to this day to be produced at an alarming rate.

According to Jambeck et al. (2015), in 1950 an estimated 2 million tons of new plastic was produced worldwide. By 2015, this number had risen to 381 million tons of new plastic produced annually (Graph 1). A portion of this plastic is designed for multi-use purposes with intended lifespans that can range from several months to several decades

depending on the intended use, but Ritchie & Roser (2018) estimate that around 2% of the plastic produced annually enters the ocean that year.



Graph 1. Primary Plastic Produced in Different Use Categories in Millions of Tons Per Year (Geyer et al., 2017).

2.3 MODERN PLASTIC PRODUCTION

Modern plastic begins its life cycle in the form of small pellets known as nurdles, which are around 5mm in diameter. Nurdles are often lost during transit between the plant that produces them and the plant where they are molded into their final form, or inside the initial processing plant itself. Such an incident occurred in May 2021 in Sri Lanka when almost 1700 tons of raw plastic nurdles spilled from a tanker offshore; an estimated millions or billions of nurdles that have covered hundreds of miles of shoreline and have

been partially melted and absorbed toxins from the wreck of the ship that had been carrying them (Rathnayake, 2012).

While this is an extreme incident, loss of nurdles in the shipping or manufacturing process occurs daily and has the greatest opportunity for pollution when it happens in a location near a coast or major river (Moore & Phillips, 2012). It is uneconomical for the various production and shipping companies that deal with nurdles to recover these waste plastics and many enter the environment due to improper containment protocols. Nurdles comprise up to 10% of the plastic waste found on certain beaches around the world (Moore & Phillips, 2012). It is estimated that around 230,000 tons of nurdles enter oceanic systems every year.

Nurdle pollution is especially prevalent in manufacturing cities near coastlines, such as many cities in the United Kingdom or the city of San Francisco in the United States (Napper & Thompson, 2016). Nurdles have been found on every beach surveyed in Louisiana and Texas, and based on weathering patterns many of the nurdles collected were rather recent and appeared to be from many different sources, suggesting nurdle spills are a frequent problem (Baurick, 2020).

Raw plastic nurdles are primarily used to create plastic resins and plastic fiber, as well as other more novel forms. Geyer et al. (2017) estimated the life history of the entire population of plastic created by the entire human race. As of 2015, the annual amount of plastic produced was between 350-400 million tons. 65 years earlier, humans had only produced around two million tons. It is estimated that as of 2015, around 8 billion tons of plastic had been produced.

Polyethylene, polypropylene, and polyvinyl chloride are the most produced plastic resins, accounting for 69% of all resins produced. Polyester is the most produced plastic fiber and accounts for about 70% of all plastic fibers produced. The most common use for plastic is for packaging, accounting for 42% of all nonfiber plastics produced. The next most common use for plastic is in the construction industry, which accounts for around 19% of nonfiber plastic usage. The study estimates that around 350-400 million tons of new plastic were produced in 2015 (excluding plastic made from recycled materials) and that approximately 300 million tons of plastic left the usable stage of its life.

During the production process, different additives are introduced into the raw plastic to change its property. These additives may alter the plastic's shape, malleability, durability, color, or other properties. Due to patent laws in many countries, plastic manufacturers do not have to disclose the specific ingredients used in their proprietary plastic blends. The de jure purpose of this is to allow companies to prevent their competitors from copying their product, but it also prevents consumers from knowing about potentially harmful additives in the plastics they utilize. One confirmed instance of such a harmful additive being in plastic is the presence of bisphenol-A in many types of resins, which acts as an endocrine disruptor (NIEHS, 2021).

According to Geyer et al. (2017) most packaging plastics often are only used for less than a year, while construction plastics are used for around a decade or more on average. Around 12% of all plastics ever produced (around 800 million tons) have been incinerated, erasing the physical presence of the plastic but releasing carbon into the atmosphere unless captured by carbon traps. Around six hundred million tons, or 9% of all plastic ever produced, has been recycled. This leaves around 79% of all plastics ever produced still

existing in the world. Recycling and incineration have also only been a factor for around 40 years, meaning plastic had had a chance to accumulate for 30 years unchecked before preventative measures were put in place to arrest its unchecked growth.

In general, resin products are almost exclusively responsible for the bulk of recycled plastic while plastic fibers are rarely recycled and are primarily incinerated or discarded. The trend that Geyer et al. (2017) predict states that humanity will have produced around 35 billion tons of plastic by 2050, recycled 9 billion tons, incinerated 12 billion tons, and sent 12 billion tons into landfills or into the environment as litter. This would represent a compound annual growth rate of around 3% between 2017 and 2050. Table 1 shows the percentages of different plastic polymers in 2015.

Table 1

Common Plastic Polymers and the Percentage of Use in 2015

Polymer Type/Additive	2015 Primary Production Percentage
LD, LDPE	15%
HDPE	13%
PP	17%
PS	6%
PVC	9%
PET	8%
PUR	7%
PPA fibers	14%
Other	3%
Additives	4%

Source - Geyer et al. (2017).

As discussed above, loss in the manufacturing cycle and the erosion of plastic in its general use are some of the biggest hidden contributors to plastic waste entering the environment. If raw nurdles are lost during transport it is not economical to recover them, and if this loss occurs in a coastal or riverine environment, these nurdles can easily reach the ocean. As discussed above with the wreck of the cargo ship off the coast of Sri Lanka, nurdles can even escape from vessels in the ocean, leading to the direct pollution of marine ecosystems.

On a related topic that will be discussed below in much greater detail, plastic may also be lost through erosion during general use. Some of the more prevalent examples of this are the loss of plastic fibers off of synthetic garments during the washing process, erosion of tires during the normal operation of a vehicle, erosion of plastic mulch or plastic greenhouses when these products undergo thermodegradation during their normal use, and the erosion of fishing gear during the course of its lifespan undergoing stress in the ocean.

A primary difference between plastic leakage from the use cycle and plastic waste is that plastic waste is a primarily consumer and government-driven phenomenon, brought about by a lack of accountability for plastic companies to provide cradle-to-grave or cradle-to-cradle management for their harmful product. Through clever marketing and other means, they have shifted this burden to the consumer and the governmental bodies that manage waste in a particular region, which may not have the capability or inclination to properly dispose of plastic waste in a way that will not enter the environment.

On the other hand, plastic leakage from normal usage comes from inherent properties of the plastic itself and does not result from any conscious consumer or

governmental action, save for the rare occasion such as a driver intentionally burning out his tires recreationally. This leakage may result from a plastic's brittleness, repeated stress, weakness to heat, or other factors. These weaknesses are an inherent part of plastic products and often are a result of companies weighing the durability of their product against the cost it would take to produce it, and accepting a certain amount of erosion as an acceptable loss. The only way to stop this source of plastic pollution would be to engineer plastic that does not erode under the conditions the current types do, or to replace plastic in these use conditions with biodegradable or natural materials (Moore & Phillips, 2012).

2.4 PLASTIC WASTE MANAGEMENT

As plastic exits its use cycle, it can be recycled, incinerated, disposed of in a landfill, or discarded directly into the environment. Jambeck et al. (2015) discusses sources of plastics that are entering the ocean from coastal countries. According to this paper, 192 of the 195 countries of the world have coastal access to the ocean, accounting for 93% of the total population of the earth. Almost 80% of plastics enter the ocean from the land.

Intentionally discharging shipboard waste material into the ocean was banned in 1988 yet still continues at an alarming rate clandestinely. The primary contributors to this source of waste are cruise lines and fishing vessels. Often discarding fishing gear can be traced back to its country of origin by its construction, and accidental loss vs. intentional discarding can be determined by examining whether certain higher-durability components of the gear have been intentionally removed for reuse (Moore & Phillips, 2012).

The authors of Jambeck et al. (2015) estimate that coastal nations generate around 2.5 billion tons of solid waste every year. Plastic resin production was used to estimate

plastic waste generation. Around 100 million tons of plastic were generated in coastal communities within 50 km of the coast. The average coastal country mismanages one to eight million tons of their plastic waste every year.

The top 20 countries in terms of amount of mismanaged plastic waste are responsible for 83% of the total weight of mismanaged plastic globally (2010 estimate). The majority of the top 20 countries are nations experiencing a rapid developmental growth, resulting in a large increase in plastic production, but which lack the proper waste disposal infrastructure to deal with the production increase. Two of the top 20 countries have a mismanagement rate of less than 15%. These countries still rank among the top 20 nations in terms of amount of mismanaged plastic because of a high population and/or high amounts of plastic waste generated per capita.

The amount of plastic generated from 2015-2021 was expected to increase at the time of Jambeck et al. (2015). Developing nations are expected to double their percentage of mismanaged plastic waste, while developed nations are expected to also increase the percentage of plastic waste that is mismanaged, although at a smaller rate increase than developing nations. The authors also discuss potential mitigation strategies such as the effect of reducing mismanaged waste in the top 20 ranked countries who produce plastic waste.

Two possible solutions discussed to reduce the total amount of plastic waste in the ocean are a reduction in the percentage of mismanaged plastic waste and the reduction of overall plastic production. Targeted waste management seems to have a larger effect on the total amount of mismanaged plastic in the system than the reduction of total plastic production, but landfills are not a foolproof and permanent sink for refuse, especially older

ones. Landfills in coastal areas may also become contributors to the influx of plastic into the ocean system as sea level rises and landfills at low elevation are inundated and eroded.

By reducing mismanaged plastic waste by 50% in the top 5 countries with the highest mismanaged plastic waste percentage, a 26% decrease in the total mass of mismanaged plastic waste would be achieved. For a similar decrease in plastic waste to occur due to reduction of plastic waste, the top 91 plastic producing countries would have to reduce and cap their amount of plastic production to the levels present in 2010. This would require a much larger international effort and would have a significant impact on the economy of many nations and the economy of the world at large.

Jambeck et al. (2015) refutes the idea that the world will reach "peak waste" by 2100 and will see a decline in overall waste production and specifically plastic waste production. The assertion of the paper is that plastic production and mismanaged plastic waste will continue rising correlated to the economic and population growth of developing nations unless a concentrated global effort is undertaken to reduce the amount of plastic produced and to improve waste management strategies and infrastructure. These strategies will take time to employ in developing nations, but in industrialized nations these strategies can be employed much more rapidly for a much faster mitigation of total plastic waste mass while developing nations are working on improving their waste management strategies and infrastructure.

Another question would be whether developing or industrialized nations would be able or willing to invest the necessary capital to produce the infrastructure needed for long-term (century scale) storage of plastics. Mismanaged waste is defined by these authors as "material that is either littered or inadequately disposed." Inadequate disposal is

further expanded upon by being defined as waste that is deposited in a dump, whether legal or illegal, or a poorly constructed landfill that does not fully constrain the materials placed within it.

The difference between a dump and a landfill is a question of both construction and function (SWSSD1, 2017). Dumps are generally uncovered and poorly regulated, leading to a lack of regulation of the materials entering the dump, as well as an increase in pest problems for dumps with a prevalence of food waste. The lack of regulation means that individuals could deposit hazardous waste or chemicals into the dumps without any record of its presence being created. As many dumps were not constructed to prevent leachate from entering the groundwater system, these hazardous materials could then enter the hydrological cycle and contaminate local ecosystems, waterways, and aquifers. Dumps also often utilize unregulated trash burning to dispose of waste, which is a source of atmospheric pollution.

In contrast, landfills generally restrict access to monitor incoming waste and to discriminate against any incoming hazardous materials. Landfills often possess liners to prevent leachate from the contained waste from entering the environment, and are generally covered regularly to prevent pest access, reduce runoff from precipitation, and reduce odor pollution. If they do burn waste, landfills often do much more to contain the environmental impacts, and the constructors of modern landfills often have plans in place to maintain the landfill for a significant period of time after its closure.

Landfills are often used in developed countries instead of dumps but developing nations or regions may still use dumps to dispose of waste as the necessary infrastructure for proper waste removal in managed landfills is not yet in place. As our understanding of

waste disposal continues to grow and evolve, the methods and standards we use for waste disposal may change. Just as dumps were once considered an acceptable waste disposal solution in many developed nations, today's modern landfills may be viewed as inadequate and environmentally harmful in the future as new waste disposal solutions are devised.

2.5 PLASTIC LEAKAGE IN THE ENVIRONMENT

Plastics can also enter the environment directly from their use cycle as well. One instance of this would be fibers from synthetic garments entering water sources from the process of laundering clothes. Hartline et al. (2016) conducted a study of the effects of using mechanical washing machines to launder synthetic garments and the contribution of these effects to microplastics in waste laundry water. The paper states that over 40 million tons of polyester fibers are produced every year, with 54% of these fibers being used for clothing purposes.

Top loading washing machines were shown to produce around 7 times the microplastic fibers as front-loading washing machines. Aging the garments also resulted in an increase of fiber production. The fiber samples collected after each wash ranged from 0-2 grams. New garments occasionally failed to produce fibers large enough to be collected by the 333 μm filter, but all washing cycles produced fibers collected by the 20 μm filter.

The paper estimates that most microfiber plastic enters the environment from the washing of synthetic fiber garments. Microplastic particles have also been noted to erode from synthetic vehicle tires during normal use. In coastal areas these particles have a high chance of entering the ocean system through runoff of precipitation (Moore & Phillips, 2012).

Plastic can enter the ocean system from coastal runoff, riverine input, loss from marine industry, and aerosolization. Schmidt et al. (2017) dredged previously published data for quantities of microplastics gathered at certain rivers. They also applied sediment transport equations to determine the theoretical output of the rivers and gathered more data on the percentages of mismanaged waste by country. According to their numerical models, the 10 highest polluting rivers in the world likely contribute 88-94% of the total river input of plastic into the ocean.

Another important estimate they postulate is that rivers transport an average of around 80,000 to 150,000 tons of plastic from inland coastal areas per year, but the range measures from 10.7 kg/y/km^2 to 14 kg/y/km^2, with “kg” representing the mass of the plastic collected; “y” representing the time interval used, in this case years; and km^2 representing the size of the drainage basin for the river.

2.6 PHYSICAL THREATS FROM MARINE PLASTIC DEBRIS

Plastic can potentially remain relatively undegraded in a marine ecosystem for hundreds of years. Plastic may be degraded through thermooxidation, photodegradation, biodegradation, thermal degradation, and hydrolysis (Andrady, 2011). In the open ocean, thermodegredation, photodegradation, and thermooxidation are retarded due to the insulating and light absorbing capabilities of water and the relatively low access to free oxygen in relation to a terrestrial environment. However, biodegradation may still act as a driver of the fragmentation of plastic polymers into smaller pieces in a marine environment.

As plastic particles are exposed to seawater, they release dissolved organic carbon, which attracts heterotrophic microorganisms (Andrady, 2011). Plastic particles also provide a colonizable surface for many species of oceanic plankton, which would normally accumulate on naturally forming transparent exopolymer particles, or TEP (Yamada et al., 2017). This “biofouling” adds additional mass to the plastic particles, which occasionally overcomes their innate buoyancy and causes them to sink.

However, it is assumed that biofouling is not an effective sink of oceanic plastic, as the microbial load of the particles will abandon their perch either when the particle sinks below the euphotic zone and the microbes are no longer able to support themselves with photosynthesis, when the particle sinks into an area of the ocean with higher acidity, destroying the carbonate shells many species of marine microorganisms possess (Urbanek et al., 2018), or when the microbes residing on the plastic fragment are eaten by another microorganism. At this point, the particle would rise to the ocean’s surface again and begin reaccumulating microbes (Andrady, 2011).

It has also been well documented that oceangoing plastic debris tends to wash up in beach environments in areas within or adjacent to major ocean currents. This debris can interfere with the nesting habits of creatures like sea turtles, and can impersonate food items causing animal fatalities from ingestion injuries (Moore & Phillips, 2012). Ingestion of plastics by marine organisms has long been a field of interest in the marine science community. Studies were conducted as early as the 1960’s on the effect of plastic ingestion by seabirds (Moser & Lee, 1992).

For decades, while it was well known and studied that plastic consumption was prevalent among seabirds who mistook the plastic particles for their prey of choice, be it

fish eggs, squid, crustaceans, or fish, it was assumed that the consumption of plastics were generally nonharmful for many species of seabirds despite evidence suggesting the consumption of plastic in some cases resulted in obstruction of the afflicted birds' digestive tracts, damage to the internal organs, choking, and a false feeling of satiation resulting from a digestive system full of plastic instead of food.

Many seabirds are also unable to regurgitate the plastic they have swallowed as they have adapted to a diet without much waste to expel after a meal and thus do not possess the necessary reflexes and/or musculature. As a result, these birds will slowly accumulate more and more plastic as they mistake it for their regular diet until their bodies are unable to cope with the foreign bodies any longer (Moser & Lee, 1992).

New studies have found evidence that some seabird species such as albatross mistakenly target plastic particles when foraging for food to feed their offspring. Albatross have the ability to expel a bolus of undigestible material after feeding, but a newborn chick usually takes around five months to develop this reflex after hatching. If a chick ingests too much plastic before it possesses the ability to regurgitate it, the chick may choke to death or be unable to feed due to the plastic obstructing its digestive system. Around 90% of Laysan albatross chicks found dead in a study in the early 80's possessed evidence of having died from plastic ingestion, with an average mass of plastic ingested of 76.7 grams.

Plastic presents itself as a prime target for albatross parents looking for nourishment for their chicks. They target particles that are colorful and buoyant, resembling clumps of fish eggs on the surface of the water. As albatross are visual hunters, they prefer targeting these easy-to-see, easy-to-hunt meals. Research personnel stationed at Midway Island in the Pacific estimate that albatross parents nesting on the island may

remove up to five tons of plastic a year from the ocean to feed to their chicks (Moore & Phillips, 2012).

Around 43% of the members of the cetacean family, 38% of seabirds, the majority of fish species, and all extant species of turtles have been observed to mistakenly consume plastic. Plastic consumption may not always directly lead to mortality but oftentimes will reduce the overall fitness of the organism through toxins leaching from the plastic, malnourishment from clogged digestive systems, and other effects.

Green sea turtles are another species that shows preference for a certain type of microplastic when feeding. Members of this species often target clear, dark, or green plastic particles, and show a preference for longer, softer plastics over more compact and/or hard particles. These traits are identical to the turtle's natural diet of seagrass and algae. Green sea turtles also show bioaccumulation of plastic particles from their prey: macroplankton filter feeders that do not possess the capability to distinguish between plastic particles and plankton (Duncan et al, 2019).

Jamieson et al. (2019) discovered evidence of microplastic ingestion in crustaceans living at depths of 7,000 meters to 10,000 meters. 72% of the organisms sampled contained microplastic in some quantity. The paper denotes that marine plastic particles can negatively affect the organisms that come in contact with it by ingestion, by blocking digestive processes, and by impeding the organisms' movement. Plastics may also serve as a vector and a concentrator for toxins in the ocean as they are adsorbed to the synthetic surface. These toxins are then released when the plastic enters an organism's body and is exposed to the organism's body temperature which is often higher than the surrounding ocean.

The deepest sediments plastic particles have been confirmed to have been deposited in are in the Kuril-Kamchatka Trench at a depth of almost 5800 meters. While the full effects of plastic on surface ecosystems is not yet fully understood, the effects of plastic contamination on deep sea organisms is even less well understood as the scientific knowledge about hadal ecosystems is still severely limited by the remoteness and difficult accessibility of those environments.

Jamieson et al. (2019) also asserts that the deep-sea environment is the ultimate sink for many processes on earth, and the organisms there have adapted to maximize any available resource the surface world sends them. Thus, the organisms dwelling there are more likely to risk ingesting a synthetic or toxic substance in case it happens to be food. The authors of the paper sampled nine oceanic trenches and found plastic present in the guts of organisms at all nine. The lowest percentage of organisms with plastic present in their guts was 50% of those collected at a certain sample site, and the highest percentage of organisms with plastic in their guts was 100%.

Synthetic fibers had a much higher rate of appearance than synthetic particles implying that either the organisms sampled preferred ingesting the fibers to the particles, or that fibers were more easily able to reach the sampled depths. Nylon, polyethylene, polyamide, unidentified polyvinyls, and polyester were all identified.

2.7 CHEMICAL THREATS AND MICROPLASTICS

For decades, the scientific community has been aware of the potential of plastics to adsorb toxins from their environment. Plastics have the potential to collect chemicals, including carcinogens and other harmful compounds, concentrating them and potentially

worsening their effect on the organisms that come in contact with the plastic through ingestion as a result of mistaken identity, ingestion in drinking water, or bioaccumulation (Cook & Hartz, 1983).

Plastics also contain a number of additives that change different attributes of the plastic compound such as the color, the brittleness, the flexibility, the longevity, and others. Many plastic producers do not disclose the full list of chemical additives their plastic contains, citing “industry secrets.” These additives, and the chemicals plastics adsorb from their environment, have the potential to act as toxins, carcinogens, or endocrine disrupting chemicals (EDC).

EDCs are chemically similar to an organism’s natural hormones and can cause widespread disruptions to the organism’s biological systems. Organisms in the developmental or fetal stage are even vulnerable to the effects of EDCs present in the parent organism’s system.

Organisms in higher trophic levels are at a higher risk of being affected by the chemicals within or adsorbed to plastic particles as these toxins will collect in organisms in lower trophic levels as these organisms consume plastic contaminated with toxins and be transferred to other organisms that consume them. As humans consume animals from almost all trophic levels, including some otherwise apex predators such as sharks and tuna, humans are at a heightened risk of being affected by the bioaccumulation of these toxins (Moore & Phillips, 2012).

Andrady (2011) provides a useful discussion about the production and sources of microplastic particles and their potential impacts. Five categories of plastics are given that are widely used in packaging and have the potential to enter the ocean environment:

polyethylene, polypropylene, polystyrene, polyethylene terephthalate, and polyvinyl chloride.

At the time the paper was written, it was estimated that 80% of plastic debris in the ocean originated from land-based sources, including river inputs. 18% of the remaining percent was estimated to have come from the fishing industry, with aquaculture comprising a significant amount of the remaining 2%. Microplastics themselves are often operationally defined by size. Plastic can degrade to form microplastics in five ways: biodegradation, photodegradation, thermooxidative degradation, thermal degradation, and hydrolysis.

Thermal degradation is not a natural process and only occurs in artificial environments. Seawater also severely hinders the mechanisms of many other types of plastic degradation due to its unique chemical and physical properties. Its insulating nature prevents plastic from reaching the ideal temperature required for many types of degradation. The lower quantity of oxygen in the ocean compared to the atmosphere also hinders the thermooxidative degradation and biodegradation processes.

There is some slight evidence of the mineralization of plastic polymers in an oceanic environment, but the process is very slow, with less than 1.2% of the mass of most samples being degraded over a three-month period. With oceanic production of microplastic particles likely being insignificant, a large portion of the microplastics in the ocean likely come from direct microplastic import from terrestrial sources or degradation of plastics in a beach environment.

The beach provides an ideal environment to produce microplastics with the potential to enter the marine environment. Two features of beach environments that most

marine environments lack is high temperature and readily available oxygen. These two characteristics, combined with proximity to the ocean, make beaches prime sources for the generation of marine microplastic debris. Beaches are also largely comprised of quartz sediments or in the case of some coastlines, larger boulders. These provide a hard scouring medium to aid in the degradation of plastic debris into smaller homogeneous pieces.

Andrady (2011) also discusses the potential toxicity of microplastics. The particles themselves may possess toxic properties, can be a choking hazard for marine organisms mistaking them for food, and can also leach toxins out of their environment and concentrate them, leading to an intensified dose of toxins when an organism ingests them.

These toxins may be used to deduce the journey of a particular plastic particle by analyzing the chemical signature of various bodies of water and comparing them to the concentrations of toxins in the particle. This paper also contains an analysis of ingestion of microplastics by biota. Studied zooplankton would ingest algae and similarly-sized microplastic particles without bias, and lug worms collected from marine environments demonstrated tire tread particles and diesel soot. Both microplastics and the toxins they gather can move their way up the trophic levels of the ocean through bioaccumulation, although no definitive data on this had been determined at the writing of the paper.

Nanoparticles of plastic are also a concern, although Andrady (2011) did not have access to any definitive data on them either. However, the paper does mention the importance of studying them, as nanoplastics may interact with other nanoscale organisms in the ocean such as phytoplankton, which are the most important primary producer on earth.

2.8 PLASTIC RESIDENCE TIMES AND SINKS

Once plastics enter the ocean, they can remain on the surface or subsurface for a long time before being deposited in another environment. Cózar et al. (2014) analyzed surface plastic accumulation in the open ocean using direct observation techniques. Their estimate of the amount of plastics on the surface of the ocean was between 7,000-35,000 tons. They determined five different collection points of surface plastic: the North Pacific gyre, the South Pacific gyre, the North Atlantic gyre, the South Atlantic gyre, and the Indian Ocean gyre.

The centers of ocean gyres serve as collection points for ocean surface plastic because they are areas of relatively limited current activity compared to the rest of the ocean, and are bounded by strong currents that funnel marine debris into these areas, where the lack of current activity prevents the debris from being pushed elsewhere on the surface of the ocean. The paper estimates that around 50% of all plastic produced is buoyant on seawater, and that from the 1970's on around 0.1% of all plastic produced makes its way to the sea.

Around 60-64% of plastic in the ocean has made its way there from a terrestrial coastal environment, with the remaining amount of surface plastic presumably coming from such sources as river runoff, atmospheric transport, and shipboard waste. The majority of observed plastic particles occur in the range of 1-5 mm in diameter, with the highest concentration being an average of 2 mm in length. As plastics are constructed of uniform polymers, they tend to decompose in a fractal manner, with similar patterns of weathering being observed in plastics on both the macro- and microscopic scales.

When discussing sinks of floating plastic, Cózar et al. (2014) postulates four possibilities: redeposition in coastal areas, fragmentation into smaller particles, sinking due to biofouling, and ingestion by biota. The paper postulates that as plastic production increases, the efficiency of plastic sinks must increase as well.

Another possibility presented is that the removal rate of surface plastic is much faster than the input of surface plastic, and that the existing surface plastic of the ocean is a result of lag time between the input of plastic and its removal from the ocean. In the case of the ocean gyres, the sink of coastal deposition is not likely as the encircling currents makes it difficult for floating debris to reach a coastline, except in cases of islands located in the middle of gyres, such as Hawai'i.

It is also very unlikely to assume that plastic fragmentation, driven by heat input from solar radiation, is responsible for the apparent increase in plastic removal as a response to the increase in plastic input, as the amount of solar radiation has not increased proportionally to the increase in plastic production and pollution. Biofouling is also not a viable removal option in the deep open ocean, as the organisms responsible tend to vacate their plastic sanctuaries when they sink below a certain depth, either due to the plastic moving out of the euphotic zone and thus not becoming a viable perch for photosynthetic organisms or those who depend on them for nutrients, or because the increasing acidity in the deep ocean results in the fatal dissolution of the carbonate shells of many organisms.

Consumption by planktivorous organisms in the epipelagic and the mesopelagic is likely an increasingly important sink of microplastics. The paper found plastic in the stomachs of 1-29% of the epipelagic planktivorous fish sampled, and in 9-35% of the mesopelagic fish sampled. This presents worrying implications for the bioaccumulation of

microplastics up the trophic levels. Ingestion also allows plastic particles to reach the bottom of the ocean, as the organisms that consumed it die and sink or defecate.

Cózar et al. (2014) found a large discrepancy (several orders of magnitude) between the amount of plastic discovered in the surface waters of the gyres and the amount of plastic they predicted. One proposed reason for this was the fragmentation of plastics into nanoplastic particles that were too small to be picked up by the sampling methods used.

The deep ocean floor is a potential theorized sink for oceangoing plastic debris. Choy et al. (2019) used remotely operated vehicles and spectroscopy to study microplastic flux in the water column of Monterey Bay, California. The water column from 5 to 1000 m deep was analyzed. High concentrations were observed at a depth of around 200 to 600 m, just below the mixed layer in this area. The concentrations found at this range of depths were much higher than surface concentrations in the same area.

Choy et al. (2019) also postulates that larvaceans, which utilize a mucus-constructed structure similar to a spider's web to filter out particles from the water column for feeding, may provide an appreciable sink for microplastics in the environments they are native to. When larvacean nets become too clogged with inedible particles, the larvaceans will discard their nets and construct new ones. The discarded nets sink to the ocean floor. In the past, this has been noted as a large source of carbon flux to the ocean floor, and the paper postulates that this may serve as a sink for microplastic particles as well.

Choy et al. (2019) collected and analyzed discarded larvacean nets and found microplastic particles present in all samples collected. Pelagic crabs were also sampled and microplastic particles were discovered in the intestinal tracts of all samples collected. The samples collected from the intestinal tracts of the crabs showed a great deal more

weathering than the samples collected from the water column and the larvacean nets, potentially signifying that organism digestion of plastics may play a role in the weathering of oceanic plastic debris.

Although much is known about plastic concentrations in the upper levels of the water column, less is known about fluxes between the different layers, and of plastic concentrations at lower depths in the water column. The depths at which these fluxes occur, the size of the particles studied, and the varied conditions throughout the ocean contribute to the difficulty in collecting data on the subject. Modeling can be used as a substitute for direct data collection in some cases, when enough adjacent data is present for extrapolation.

2.9 PAST MODELING EFFORTS

Modeling has been used in the past to try to address similar questions about marine plastic debris. One potential modeling technique to simulate the activity of ocean-going plastic would be a Lagrangian approach, modeling individual instances of marine debris in an effort to discern the behavior of marine debris in the larger ocean system. This approach was taken by Sherman & van Sebille (2016), who studied plastic transport in the Pacific and hypothesized the optimal location for deploying plastic collectors. Ocean circulation data from the NOAA Global Drifter Program were mapped to a six-cell matrix and the probability of plastic moving between each cell was calculated. The amount of mismanaged plastic in a country was used to estimate the amount of plastic entering the system, which Jambeck et al. (2015) studied.

The model was calculated from 1965 to 2025, and population growth was considered and correlated to an increase in the amount of plastic going into the system. Because of the large number of cells in the ocean, it would be very difficult to model the entire ocean with the computing power available to the conductors of this study, so the researchers elected to estimate the most likely locations for high influxes of plastic into the ocean. 500 sink arrangements were tested, and a single computer was used to model these arrangements over the course of one real-world week. The authors of the paper estimate that there would be around 30,000*29 (29 sink locations with 30,000 grid cells in the model) possible arrangements of sink locations to model.

A secondary goal of the study was discovering a method of reducing the amount of microplastics without heavily affecting the number of plankton in the same area. The locations of each sink were randomized, and the amount of plastic removed was calculated for each cell. This process was repeated 500 times. The optimal locations for potential plastic collectors were determined to be in the North Pacific, because of the large population and poor waste management practices of many Asian nations.

Mass flux was also discovered to be a better determinant for effective plastic removal than total plastic mass, as hypothetical plastic collection devices would require large plastic flux into the area in which they are located to be effective. This would also reduce the flow of plastic into other areas of the ocean. Thus, targeting large areas of plastic mass flux was determined to be the most effective manner of removing plastic waste.

A difficulty using the Lagrangian approach for modeling large masses of particles in a chaotic system like the world ocean is the computing power required to simulate the movement of these particles in a realistic manner, which is key for an effective modeling

study. The goal of any modeling project is to produce a simplified approximation of a complex real-world system so the system can be studied and useful inferences can be made.

The complexity of a Lagrangian style model of plastic movements is impractical with current levels of computing. The behavior of ocean currents, which possess a combination of predictable movements and randomness, can also be difficult to model. This is compounded by the heterogeneity of plastic debris in the ocean. Plastic has a myriad of different densities, durability, and other characteristics that alter how they behave in an aquatic system.

Another work that utilized Lagrangian style modeling was Coppini et al. (2018), which focused on 3D modeling of plastic in the Mediterranean Sea, in the Adriatic Sea region. The authors denote five primary processes by which plastics are removed from a body of water (defined in the Eulerian sense). Plastics may be washed onto a beach and deposited or washed back into the ocean, they may move vertically in the water column, they may settle to the bottom or be resuspended, they may fragment into smaller particles and change their properties, or they may be eaten or excreted by biological organisms.

Coppini et al. (2018) hypothesized that the Adriatic Sea primarily experienced plastic loss from beaching events. A 2D Markov chain model was used to estimate plastic flux. The average half-life of a plastic particle in this model (the amount of time half of the given plastic particles in the model at a certain time took to enter a sink and leave the model) was around 43.7 days. The primary influence on plastic particle movement was the Western Adriatic Coastal Current and the South Adriatic Gyre.

Coppini et al. (2018) assumes that 100,000 tons of plastic enter the Mediterranean Sea annually, and that 50% of plastics comes from oceanfront cities, 30% comes from river influx, and 20% comes from shipping lanes (compared to the 40/40/20 global ration). They then examined the number of coastal cities (495), rivers (110), and shipping lanes (332) in the Adriatic to determine average rate influx for each. The largest river influence was determined to be the Nile River, with Alexandria being the largest coastal city influence. Shipping lanes were determined to be the highest contributor to plastic waste pollution.

A Lagrangian model was used that incorporated 6000 virtual particles of plastic and accounted for current drift models to calculate the motion of the virtual particles. The top 10 sources of plastic influx were responsible for 46% of the total plastic waste influx. Plastic influx from the Atlantic Ocean through the Strait of Gibraltar and from the Black Sea through the Dardanelles Strait were discounted. A spin up period of 90 days was sufficient to populate the virtual Mediterranean environment with plastic particles.

If the only sink is plastic beaching, the plastic particles have a half-life of 100 days. If sedimentation is added in addition to plastic beaching, the half-life becomes 80 days. Primary points of accumulation are in the Catalan Sea in the West Mediterranean and the Cilician sub-basin in the Northeast Mediterranean. The model was run to simulate the period of 2013-2017. Overall, around 107 plastic particles flowed through the model during this time period. The model discovered the above two primary points of accumulation for plastic particles.

Coppini et al.'s (2018) use of Markov chain modeling was certainly more processor-efficient than the study conducted by Sherman & van Sebille (2016), but may have been

less accurate. Markov chain modeling assigns probabilities for the different actions a particle can take given their current position, and may be a less accurate method of estimating the motion of particles in ocean currents as the burden of movement is placed on the particles rather than the currents that in real life would be responsible for the motion of marine debris.

To its credit, this model did account for potential sources of plastic rather than merely propagating the model with an even number of particles and studying their motion as Sherman & van Sebille (2016) did. Although the primary focus of this model was estimating potential sinks of marine plastic in the Mediterranean, it illustrated a good principle for a model seeking to estimate sources of oceangoing plastic to utilize, which is accounting for all the various sources of ocean plastics.

2.10 KNOWLEDGE GAPS AND RESEARCH QUESTIONS

Some knowledge gaps that emerge from the field of plastic pollution research are the quantities of plastic pollution entering the environment before waste disposal technology was available, the quantities of plastic that continue to enter the environment through illegal disposal practices, the amount of plastic eroding off of plastic products during normal usage cycle, and the RTD of plastic in the ocean.

For millennia, humans used midden heaps near their settlements to deposit waste items out of sight and smell of the rest of the community. This practice has allowed archaeologists to study early humans and still occurs today in some areas, such as more rural parts of the Occident or areas in historically exploited nations that do not have adequate access to waste disposal infrastructure.

From the time when plastic was introduced as a manufacturing material to the present day, people in some communities are still using these open-air waste dumping sites to dispose of their trash. These sites are often poorly contained and poorly recorded, thus any plastic rubbish that enters them has the opportunity to escape and enter the environment unrecorded. It would be quite difficult to obtain data on the plastic entering these unregulated dumping grounds and estimates of how much is exiting these sites and entering the environment except by abstracting from a higher level of data.

In a similar vein, plastic that enters the environment illegally is understandably hard to quantify. While there is some amount of onshore dumping and littering, a large portion comes from ships on the sea. Cruise liners have been documented dumping plastic waste into the ocean, and fishing vessels have been documented discarding plastic fishing gear into the ocean after removing the expensive portions to reuse later. Discarded fishing gear that has been recovered has sometimes been tied back to certain countries or ports based on their construction, but this debris must actually be recovered in order to quantify them.

A hard-to-quantify source of plastic that is recently beginning to be considered is the amount of plastic that enters the environment from the normal use of plastic products. Many types of plastic such as car tires, agricultural plastic, or synthetic clothing are used in high-impact roles that result in the erosion of microplastics off of their larger structure. For tires, the plastics they shed are one of the larger pollutants in large urban cities and pose a large risk to the ocean environment in coastal cities and highways.

Agricultural plastic has a lifespan of around 3 years and is often buried directly in the soil rather than being discarded properly. The high-temperature, high solar exposure conditions agricultural plastic is used under results in a large amount of microplastic

production, which can later adversely affect the nearby soil and aquifer and the plants grown in the area. Synthetic clothing often loses a percentage of its mass during the wash cycle as microplastic fibers are removed from the garment by the washing process. Quantifying these sources of plastic would be essential for knowing values such as atmospheric microplastic and microplastic in the water cycle, but unfortunately are very difficult to directly measure in any meaningful way.

Coinciding with the research question of this paper, a large knowledge gap is the RTD of plastic in the ocean. There is vast heterogeneity in the physical properties of the individual pieces of litter that enter the ocean environment, and this diversity leads to different RTDs for different categories of plastic marine debris. For example, a heavier piece of high-density polyethylene might become biofouled and negatively buoyant, sinking to the benthic sediments faster than a lighter piece of polystyrene; but the weaker polystyrene might break apart and disintegrate into smaller pieces of microplastic to then be consumed by organisms.

To determine solid RTDs, different categories must be determined using differentiating factors such as resinous vs. fibrous composition or the different chemical compositions. These can be determined by looking at the different manufacturing percentages for each category of plastic and either generalizing from one year of data or finding as many data points as possible and looking at the change in manufacturing practices over time. Then, the percentage of the total amount of plastic entering the ocean from each category of plastic represents must be determined. This must be determined by looking at the behavior of plastic "upstream," both in controlled flows such as the use cycle and uncontrolled flows such as waste or erosion.

By looking at the data on RTDs for different uses of plastic, the lag between plastic entering and exiting different parts of the use cycle can be determined. Next, the types of plastic entering the ocean must be categorized in terms of their physical characteristics. Important factors to examine would be the average density, resistance to weathering, size, and shape of plastic entering the ocean from each usage category. Then, each of these categories must be analyzed to estimate what the individual RTDs for each type of plastic passing into the ocean would be.

Each previous analysis must be combined to determine these RTDs as they would depend on the amount of plastic entering the ocean, the percentage of each type of plastic entering the ocean, and the resilience to the ocean those different types of plastic would have to an oceanic environment. After this, an average global RTD for all plastic can be estimated, with individual RTDs used for more precise estimations. Using a model to fill this research gap is one of the primary goals of this paper.

CHAPTER 3

DATA

3.1 PRODUCTION

According to Geyer et al. (2017), by 2015 around 8.3 billion tons of plastic had been produced worldwide since plastic had begun to be produced commercially on a significant scale (their model had an R^2 value of 0.9968). Also, by 2015, around 6.3 billion tons had left the use cycle, around 75%. Of these 6.3 billion tons, around 9% had been recycled, or around 567 million tons. Only 10% of this recycled plastic, 56.7 million tons, had been recycled more than once. 12% of the plastic ever produced had been incinerated: around 756 million tons. This leaves 79%, around 4.98 billion tons, in either landfills or the environment.

By 2050, an estimated 12 billion more tons of plastic waste will be in landfills or the environment. Around 30% (2.5 billion tons) of all plastic that has ever been produced is still in the use cycle. In 1960, plastic consisted of 1% of all waste. 55 years later it had risen to 10%. More than half of the plastic resin ever produced has been produced since 2002 (Geyer et al., 2017). A table detailing the difference between plastic waste data in 2015 and projected numbers for 2050 can be found in Table 2.

Table 2

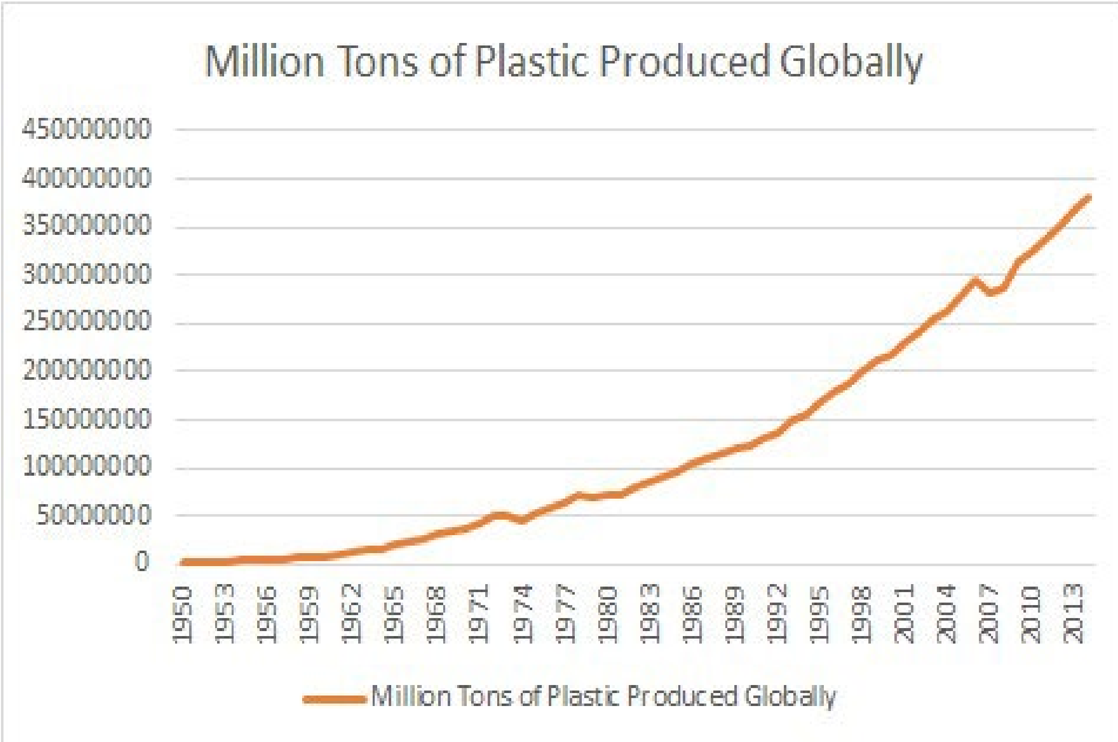
Plastic Production, Recycling, Incineration, and Discarding in Both 2015 and 2050

	2015	2050
Produced	8,300	34,000
Recycled	600	9,000
Incinerated	800	12,000
Discarded	4,900	12,000

All Values in Mt. from - Geyer et al. (2017).

In an ideal situation, the stocks of the model would be able to be populated using existing data from throughout the entire history of mass plastic manufacturing, and the flows of the model would be able to be calculated from this data as well. However, the desired data is often limited in its scope. Sometimes this limitation is temporal, with some years being left out of the data. Sometimes the limitation is spatial, where some areas have deficient data. Data may also be conflicting between two sources, and in this case, there may not be enough sources presenting the same type of data to determine which source is more accurate.

Regarding the flow of plastic into the system, there are a good number of papers that present a record of plastic production data since 1950. These sources all get their data from an industry group called PlasticsEurope, who publishes an annual "Plastic – The Facts" document with a number of figures regarding plastic production and pollution obtained from the organization's in-house research group, with no further information on how this data is collected. Nevertheless, these publications are cited by almost every academic source on plastic that needs a data source for global plastic production annually (Graph 2).



Graph 2. Plastic Production Since 1950 Based on the Data in (Geyer et al., 2017) Citing PlasticsEurope as the Data Source.

Flows into the various stocks generally need to be extrapolated from known percentages of plastic use data for years in which this data was not being measured. This is not the most accurate form of measurement as use ratios change over time, but by gathering as many data points as possible, a somewhat accurate picture of the amount of plastic entering various usage stocks can be determined.

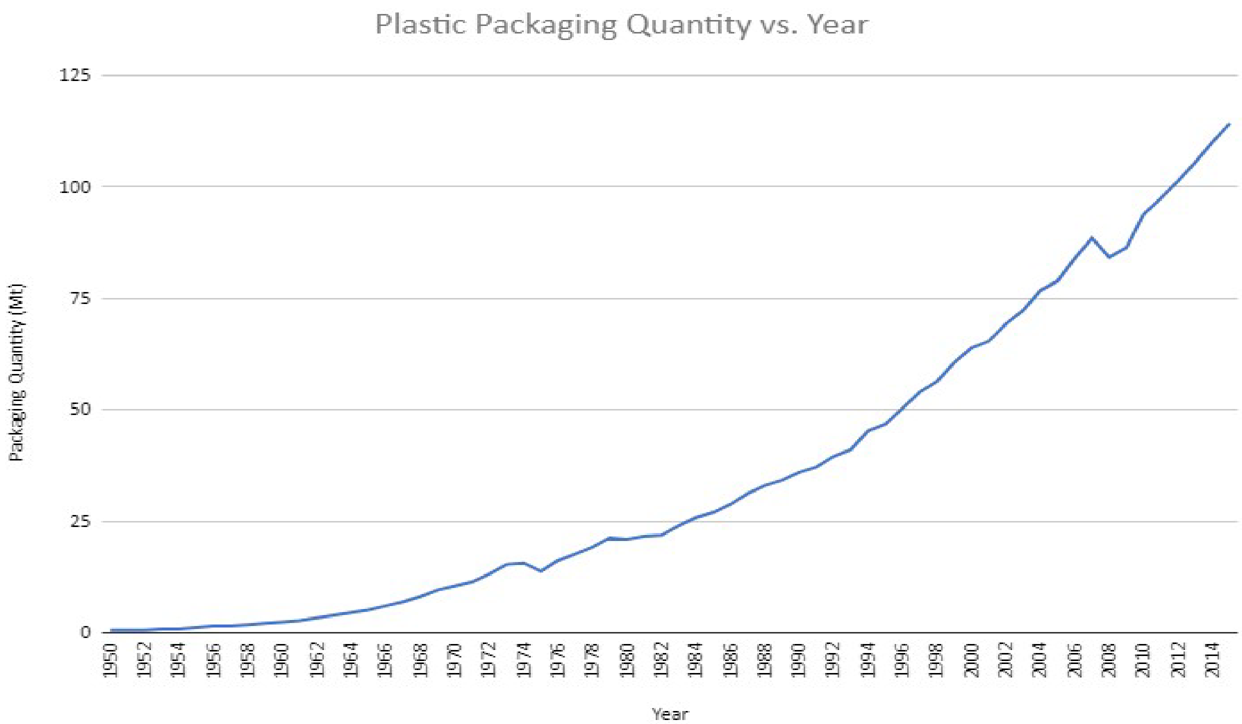
For example, Andrady (2011) estimates that around a third of the plastic resin used every year is used for the production of single use plastic packaging. This may not have held true in the 1950’s when single-use plastic was not as ubiquitous in food preservation and consumer good packaging as more natural materials like metal, glass, and wood. This

estimate is also not as high as the one made by Geyer et al. (2017) in 2017 when they assert that half of all new plastic resin is used to produce single use plastic packaging.

3.2 PACKAGING

As discussed above, the most accurate estimate of the amount of plastic resin that is used annually for single use packaging production puts the number at around 75-80 million tonnes. This is around one-third of the total plastic produced the year of study, which was 2011 (Andrady, 2011). Another source estimates this number much higher, at around half of all plastic production used for single use packaging (Geyer et al., 2017). These estimates may be accurate for the 2000's-2010's, but most certainly has changed over time and likely still is fluctuating. For example, in 1950 when plastic production began to first be a noticeable presence on the market, many products were still made out of more natural materials such as metal, wood, glass, and animal byproducts (Moore & Phillips, 2012).

We can poorly extrapolate by assuming a 0% plastic packaging production rate in 1950 and calculating a uniform growth rate for plastic packaging production between 1950 and 2014 as a percentage of the total amount of plastic produced that year, using the average of Andrady (2011) and Geyer et al. (2017) in terms of packaging production percentage and year of estimate. If we continue to assume a uniform growth rate, we can also continue the estimation through to 2015. Then we can apply the range of percentages obtained between 1950 and 2015 to the plastic production data between 1950 and 2015 to estimate the amount of plastic production used for single use plastic packaging since 1950. A graph showing this data can be found on the next page in Graph 3.



Graph 3. Packaging Production Since 1950 Based on the Data in Geyer et al. (2017) and Andrady (2011).

3.3 CONSUMER GOODS

The category of consumer goods is one of the most heterogeneous classifications of plastic use and includes products made from many different types of plastic, products that are a composite of or have components made from several different types of plastic or plastic and another material, and products that have varied lifespans, depending on their intended use and the user. For example, a cellphone made from plastic, glass, metal, and other materials may be intended to be used for several years, while a disposable pen may have a lifespan of several years. The lifespan of consumer plastic goods may also depend on the culture of the population that is using them, as more frugal or judicious cultures may

stretch the lifespan of their plastic products as long as possible through careful use and repair, either to keep them from becoming waste as long as possible or to prolong their usage to prevent the necessity of purchasing new household goods on a potentially limited budget.

On the other hand, some cultures that have the resources necessary to purchase new long-term products at will may not be as judicious at using their consumer products to their intended lifespan, let alone attempting to extend its lifespan. Waste may even be directly or indirectly glorified in certain circumstances. In the cellphone example earlier, a consumer from a culture where social status relies on perceived wealth may see purchasing a new cell phone every year as preferable to saving resources and making one cellphone last until planned obsolescence necessitates purchasing a new model. Nevertheless, generalizations can be made. Geyer et al. (2017) notes that plastic consumer products have an average lifespan of 3 years, with a standard deviation of 1 year.

3.4 CONSTRUCTION

It is estimated that around 19% of all nonfiber plastic ever produced has been used for construction. We can estimate from the total amount of plastic ever produced, around 8.3 billion tons, that around 1.58 billion tons of plastic has been used for construction purposes (Geyer et al., 2017). We can further narrow the estimate down by applying this 19% number to annual plastic production values since 1950. This will not be entirely accurate as the not only the amount but also the percentage of plastic in construction has risen since the 1950's, but it is a good estimate if more precise numbers are unable to be found. Construction is a stock in which plastic tends to linger for far longer than other,

more impermanent areas such as packaging. It is estimated that only around 5% of the plastic waste leaving the use cycle every year is construction, which is far lower than the 19% of plastic that enters the use cycle in the construction stock.

3.5 AGRICULTURE

Agricultural plastic accounts for around 2% of the total amount of annual plastic production. In agriculture, plastic is primarily used for shade netting, artificial mulch, and greenhouse construction. The shade netting and artificial mulch prevent the growth of weeds, predation by pests, and sun damage, but also prevent access to pollinators and are prone to degradation. 60-80% of the 1.5 million tons of plastic film produced annually is used in the People's Republic of China (Zhang et al., 2020).

It is estimated that in 2019, over 40,000 square kilometers in Europe were covered by plastic shade netting or artificial mulch. Around 131-627 kg/ha of waste is produced annually from shade netting and artificial mulch usage (Maraveas, 2020). While first application of plastic mulch on a field can increase productivity as much as 25-42%, productivity can decrease as much as 3% per 100 kg/ha of plastic pollution from plastic mulch and netting (Zhang et al., 2020). Plastic greenhouses can have a lifespan of 1-4 years and generate anywhere from 800 kg/ha/yr to 2398 kg/ha/yr (Briassoulis et al., 2013).

3.6 SYNTHETIC CLOTHING

In the washing cycle, around 0.3% of a synthetic garment's mass is lost and becomes microplastic in the sewage system (Hartline et al., 2016). The vast majority of this microplastic is in the form of microfibers, which range from 11.9 to 17.7 micrometers in

diameter and 60 to 78 millimeters in length. It is estimated that for every 1g of synthetic clothing that is washed, around 117 of these fibers are released. An average wash load is around 6kg of material, meaning over 700,000 microplastic fibers could be released into the sewage system per washing cycle, if the percentage of synthetic garments in the wash load was 100% (Napper & Thompson, 2016).

3.7 FISHING INDUSTRY AND AQUACULTURE

For the majority of human history, natural materials were used in fishing for both pleasure and industry. Recently, synthetic materials have begun to supplant natural ones in items such as floats, lines, rods, and other essential fishing tools. Plastic materials are used for properties such as their longevity, increased strength, lower weight, etc. As in many other cases, the longevity of plastic fishing equipment ensures that it becomes a long-lasting pollutant if it is accidentally or purposefully discarded into the ocean (Moore & Phillips, 2012). At this point, it is safe to assume that every commercial vessel uses fully plastic gear.

Most commercial fishing gear used presently consists of polyolefins such as polyethylene and polypropylene, as well as nylon. While regulations are in place to try and prevent the intentional discarding of broken fishing gear into the ocean, losses of plastic gear may still occur through illegal dumping or accidental losses. It is estimated that these losses are high enough to be responsible for 18% of the plastic currently in the ocean (Andrady, 2011). This ”18%” figure can be used to estimate the amount of plastic fishing gear by working backwards from the amount of plastic estimated to be in the ocean, which can be used to roughly calculate loss rates.

3.8 TIRES

Tires are one of the most prolific sources of microplastic pollution in the ocean, especially from coastal environments. It is estimated that the per capita microplastic particle production from car tires is around 0.23-4.7 kg/year, with a global average of 0.81 kg/year. 3-7% of particulate matter in the air is estimated to be tire particles, making them a significant health hazard in cities. It is estimated that around 5-10% of the microplastic in the ocean is from tire wear (Kole et al., 2017).

3.9 MANAGED WASTE

The amount of waste that is managed versus mismanaged varies widely by country and by region, and depends on the legislation regarding waste management, the enforcement of and obedience to this legislation, the population of that area, and the amount of plastic generated or imported. According to Geyer et al. (2017), a figure that is cited in many sources, around 12% of plastic ever produced has been recycled and around 9% has been incinerated. These would be considered to managed waste categories, with the other managed waste category being properly constructed landfills. Plastic waste deposited in dumps, eroded, or littered would qualify as mismanaged waste.

3.10 TERRESTRIAL WASTE

Terrestrial waste as the name implies is waste that has not been properly managed, and enters the terrestrial environment. For the sake of modeling simplicity, we are considering freshwater bodies of water such as rivers, lakes, and glaciers as part of the

terrestrial environment. It is estimated by Jambeck et al. (2015) that around 2% of plastic waste worldwide enters the environment as mismanaged waste from being discarded in improperly constructed landfills, from being intentionally littered, or from being eroded from plastic products due to their use cycle being unusually rigorous. Examples of this last point would include tire rubber, synthetic fishing gear, and synthetic agricultural gear such as plastic greenhouses and mulch.

3.11 ATMOSPHERIC WASTE

Microplastics in the atmosphere are a form of pollution that has begun to be studied rather recently. Deposition rates around the globe from plastic in precipitation range from 50-700 particles of plastic per square meter year. These particles are generally fibrous in shape and because of their low density relative to their length, are able to be carried by air currents similar to a spiderling using its silk to parachute (Brahney et al., 2021). Other particle types are smaller, similar in size and density to more naturally forming varieties of dust that have been known to travel in a transatlantic fashion (Nogueira et al., 2021). Little research has been done on how plastic enters the atmosphere. Speculation and modeling has included wave action from the ocean and large lakes, roads, and agricultural dust production.

Atmospheric plastic has the insidious nature of being able to pollute even the most remote and unsettled locations. It is estimated that around 22,000 tons of plastic falls on just the mainland United States every year (Brahney et al., 2021). The mainland of the United States is around 9.834 million square kilometers. If the rate of precipitation is uniform, then around 2.24 kilograms of plastic fall annually on every square kilometer of

the United States. If this rate is uniform across the globe, then the earth experiences over its 510 million square kilometers of surface, around 1.14 million tons of plastic precipitation.

3.12 OCEANIC WASTE AND RESIDENCE TIMES

Plastic waste in the ocean may come from terrestrial sources or from ships including shipping, cruise ships, and fishing vessels. Coppini et al. (2018) notes that the global average for plastic debris sources is that 80% of the ocean's plastic enters from terrestrial sources and 20% enters from the land. Cózar et al. (2014) states that around 0.1% of plastic produced enters the ocean, which one can use to gain a rough estimation of the amount of plastic entering the ocean annually, but without taking into account RTDs in different plastic stocks this number would vary greatly from reality.

The primary focus of this research is examining the RTDs of plastic in the ocean. It is known that plastic is transported to the benthic zone, which can be considered one of the few true sinks of plastic in the ocean, and it is speculated that microplastic can be reaerosolized via wave action. Plastic may also temporarily leave the ocean through beach deposition. According to Cózar et al. (2014), around 50% of plastic is buoyant in seawater, meaning the other 50% that makes its way into a marine environment will quickly sink.

Bioaccumulation likely plays a large role in transporting plastics to the benthic zone. Choy et al. (2019) noted a large concentration of plastics at a depth of 200-600m, just below the mixed layer. It is speculated that ocean organisms will colonize a plastic's surface until it is negatively buoyant, then abandon it when it leaves a nutrient-rich or light-abundant area, causing the plastic to rise until it is within this zone again. Larvacean nets

have also been found clogged with plastic, and it is assumed that as these organisms discard their nets quite frequently when they become unusable for catching food, that these nets then become a transport for plastic to the deep ocean.

All of these permanent and temporary sinks help to explain the estimate from Cózar et al. (2014) of around 7,000 to 35,000 tons of plastics at the surface of the ocean. This is a far cry from the amount that should be in the ocean, which combining the data of Cózar et al. (2014) and Geyer et al. (2017) should be around 7.8 million tons, at least. Comparing this number with the Cózar et al. (2014) data for the amount of plastic in the ocean, it is clear that either some gross misestimations have occurred or not all of the plastic that enters the ocean stays on the surface. One of the goals of this study seeks to determine how long this plastic does stay on the surface.

CHAPTER 4

MODEL STRUCTURE

4.1 PURPOSE OF MODEL AND NECESSARY COMPONENTS

A key purpose of this study is to test whether a stock and flow model (SFM) combined with existing plastic production, use and pollution data can be used to improve estimates of RTD of plastic debris in the ocean. Knowing the RTD of plastic in the ocean will allow better estimates to be made on the amount of plastic waste currently in the ocean, and will allow more accurate forecasts to be made of quantities of oceanic plastic waste in the future.

The SFM is described in Plag et al. (2022). The design of this SFM is informed by the research presented in this thesis. This model is designed for simulations, for which the model is run with a fixed time steps over a simulation period (e.g., from 1950 to 2100). Data used in the SFM model comes from real world data collected from several sources. The structure of the model consists of stocks of plastic in various states of existence and flows between these stocks that alter the quantity of the stocks they flow into and out of. The stocks are scalar variables, with the units (metric tons) recording only the mass of plastic at each time step. The flow variables are also scalars quantifying the flows into and out of stocks. The main stock is the amount of plastic in the ocean, with all the flows in the model either ultimately terminating in the ocean or flowing out of the ocean into a plastic sink.

The stocks in the model either have a distribution of RTDs, or the RTD in the stock is infinite. For example, the stock of incinerated plastic has no flow out and RTD is infinite.

Since this model simulates the entire plastic production and waste system from raw plastic to disposal or pollution, adding RTDs to certain stocks allow a more accurate view of how much is in a given stock at any time and how much is leaving that stock in its flows.

For example, plastic that goes into the construction industry and is used in home construction has a long RTD, sometimes up to decades. On the other hand, plastic single-use packaging usually has a RTD of a few months. Since the model has a timestep of 1 year, plastic packaging would be treated as a stock without RTDs. If the model treated the construction and packaging stocks the same, all of the plastic going into building houses and long-term construction would be counted in the model as leaving the stock and becoming waste in the same year it entered the stock, which is not accurate to reality.

The RTDs for each stock that possesses them have a distribution that differs based on the method of usage for the plastics in their stock. A certain percentage of the stock that enters each year will exit one year later, another percentage for year two, and so forth. For example, the construction stock has a maximum RTD of 51 years, and each year from 1-51 has a different percentage of plastic that leaves during that year. When all the percentages of plastic exiting the stock from 1-51 are added up, they equal 100%. When the construction stock is calculating the amount of plastic exiting its stock, it must take into account every year from the previous year to 51 years prior and remember the amount of plastic entering in that year and what the RTD percentage is for that year.

Some stocks have no applicable RTDs. This is because they have maximum RTDs that are shorter than a year such as plastic packaging, sinks that just accumulate like the benthic zone, or there is not enough data to calculate or even estimate their RTDs accurately, such as the atmosphere.

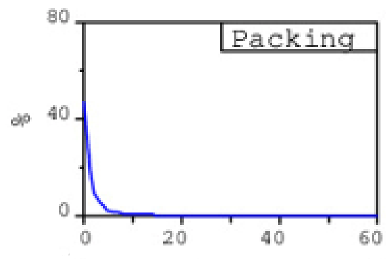
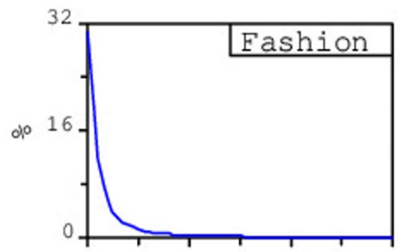
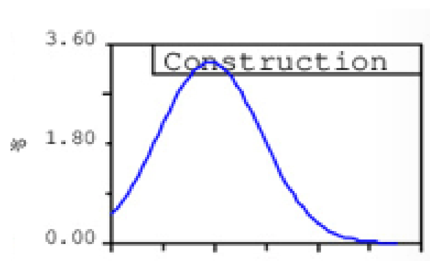
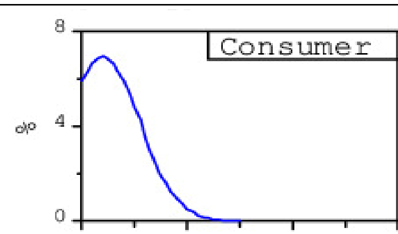
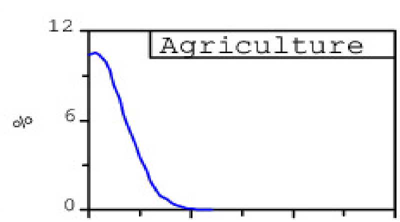
The parameters of the model, except for the flow of plastic into the model from the petroleum industry, are not time dependent. As the plastic entering the model is historical data and is necessary to track the increase of plastic throughout the entire system, it changes every timestep based on a preexisting series of numbers drawn from historical data. However, other parameters such as maximum RTDs, the percentage of plastic leaving each stock at each RTD, and the percentage of plastic entering each flow from each stock do not change. While they could be made fluid and some, such as the percentage of manufactured plastic entering each use category, do change over time historically, it was decided that this was beyond the scope of this research and that having static parameters was sufficient.

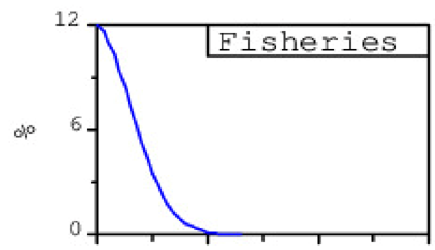
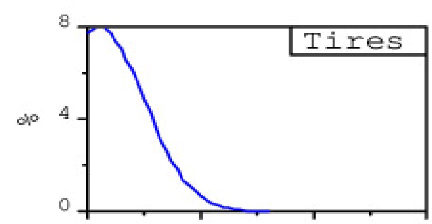
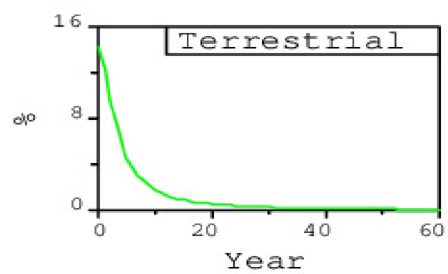
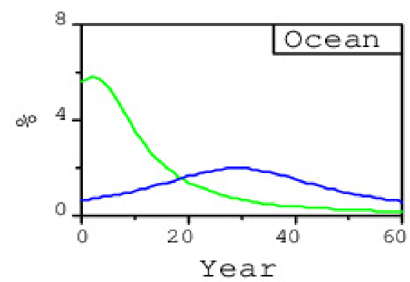
Since little actual data is available for the RTDs of plastic stocks, many had to be constructed from available data. Plastic single-use packaging is regularly described as having an average use cycle of less than a year. Taking into account potential outliers produced a curve that skewed heavily to the <1 value for the average residence time for plastic packaging, with a small percentage that were outside that predicted window. Data on the average lifespan of clothing was found, and plastic erosion during washing cycles was taken into account as a small but constant stream of plastic throughout the life of the garment. Construction has a high initial production of plastic during the construction of the buildings, but a very wide range of residence times spanning decades. Construction plastic residence times can be very heterogeneous due to the different use natures of the buildings the plastic is in. Consumer products are another widely varied stock, with around 2-4 years being a mean RTD but with notable quantities falling outside that range. Plastic mulch and plastic netting are the most widely used type of agricultural plastic and both have a lifespan

of 3 years maximum, but plastic greenhouses can be used longer. All agricultural plastic undergoes severe erosion due to the intense environmental conditions it is placed under. Fishing gear has a lifespan of 3 years maximum as well due to the high-stress usage, and much of this plastic enters the ocean directly as loss or intentional discard. Tires have a relatively long lifespan but undergo constant erosion due to the wear and tear of driving. Terrestrial plastic is another stock that is hard to quantify RTDs for due to the highly diverse nature of the environments that make up that stock, but a reasonable estimate was made. Surface ocean plastic has 35-50% of all of its plastic sink to the bottom almost immediately, with the rest potentially lasting on the surface for decades. Not much is known about plastic behavior in the water column other than its tendency to hover around the euphotic zone as biofouling increases and decreases its weight in response to sunlight or lack thereof.

Table 3 illustrates the different stocks with the name of the stock, a graph illustrating the distribution of RTDs for the stock, and the sources used to determine each set of RTDs. The y-axis of the graphs denotes the percentage of the total stock that is released in a particular year within the range of residence RTDs, and the x-axis of the graphs denotes the range of RTDs for that stock.

Table 3
Graphs Illustrating the Spread of RTDs for Each Relevant Stock, as Well as the Source Used for Each Set of RTDs.

Stock	**Residence Times**	**Source**
Packaging		Moore & Phillips (2012) Geyer et al. (2017)
Fashion		Hartline et al. (2016) Napper & Thompson (2016)
Construction		Geyer et al. (2017)
Consumer Products		Moore & Phillips (2012)
Agriculture		Briassoulis et al. (2013) Zhang et al. (2020) Maraveas (2020)

Tables 3, Continued. **Stock**	**Residence Times**	**Source**
Fisheries		Moore & Phillips (2012) Coppini et al. (2018) Andrady (2011)
Tires		Moore & Phillips (2012) Kole et al. (2017)
Terrestrial Waste		Andrady (2011) Jambeck et al. (2015)
Ocean		Jamieson et al. (2019) Choy et al. (2019) Cózar et al. (2014)

Note that the Ocean Stock has two residence times. The green line corresponds with the RTD for the surface ocean and the blue line corresponds with the RTD for plastic in the ocean water column.

Below are two simplified versions of the model, grouping the stocks into four different types: production, use, waste, and environment. One version, Figure 1, focuses on the flows in the system while the other, Figure 2, focuses on the stocks.

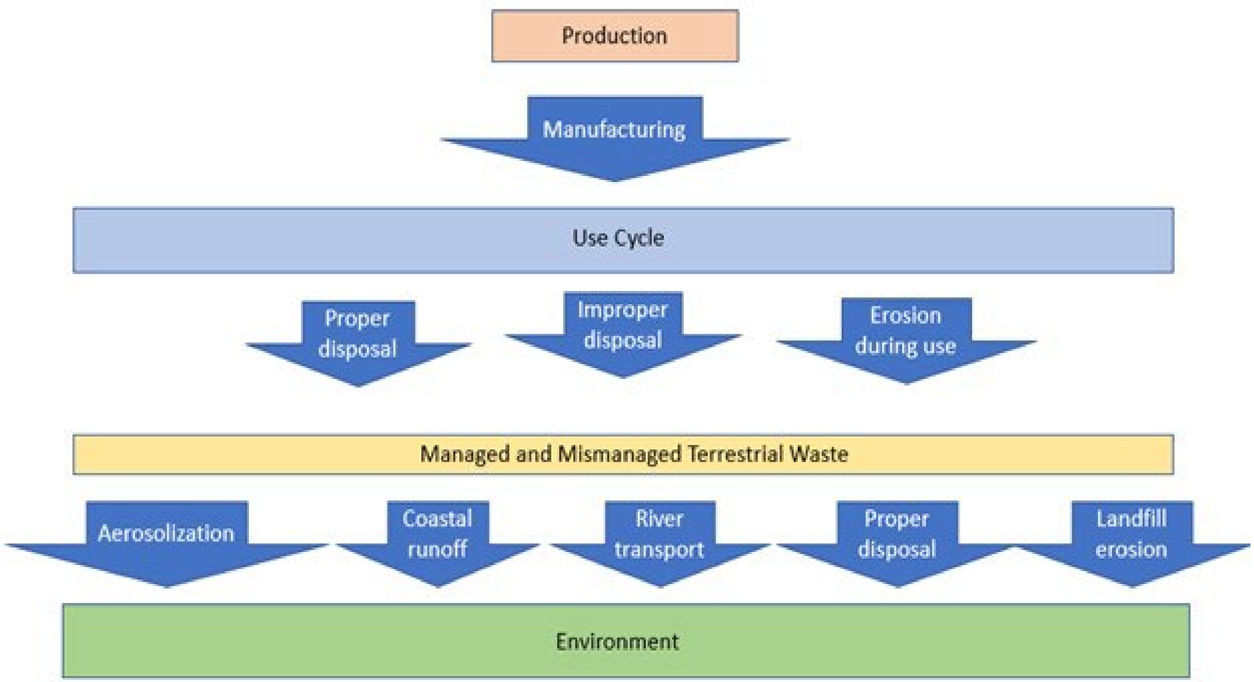


Figure 1. A Visual Model of the System of Plastic Production, Use, and Disposal. The arrows represent the flows into different categorical parts of the system.

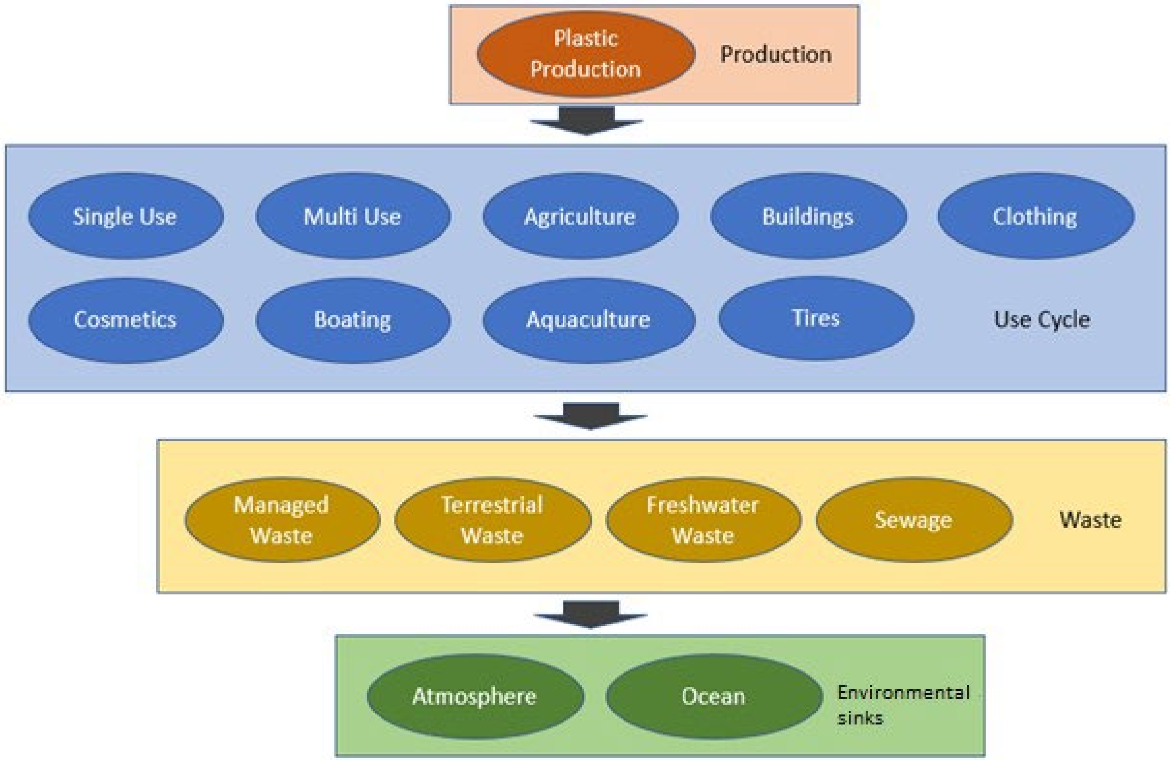


Figure 2. The System of Plastic Production, Use, and Disposal. The round bubbles represent stocks that plastic can accumulate in, and the rectangular boxes represent how the stocks are grouped together. The arrows represent flows between the stocks, although the flows have been greatly simplified for visual clarity.

A combined view can be seen in Figure 3 and wholly represents the various stocks and the flows between them.

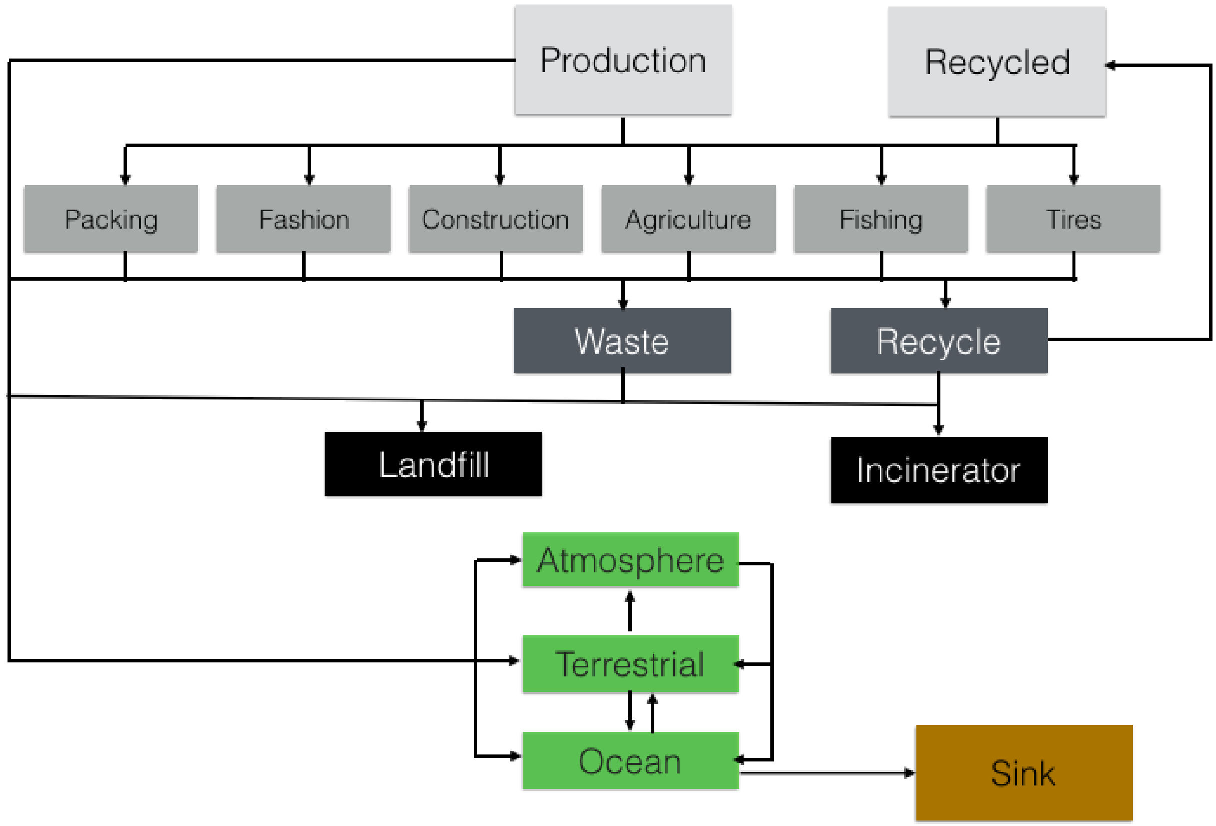


Figure 3. The Final SFM Used in the Program.

A flow matrix that numerically illustrates the flows between the different stocks can be seen in Table 4. The number in each row and column of the flow matrix determines the percentage of plastic that flows between the stock denoted in the vertical column and the stock denoted in the horizontal row every annual time step.

Table 4

A Matrix Depicting the Flow Between the Different Stocks in the Model

Stock	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Production
2	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	Recycled
3	33	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Single-Use Packing
4	10	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Fashion
5	20	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Construction
6	16	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Consumer
7	2	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Agriculture
8	10	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Fishing
9	4	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Tires
10	0	0	80	90	85	80	80	80	60	0	0	0	0	0	0	0	0	Collected
11	0	0	15	8	8	15	15	15	15	0	0	0	0	0	0	0	0	Recycle
12	0	0	0	0	0	0	0	0	0	50	25	0	0	0	0	0	0	Incineration
13	0	0	0	0	0	0	0	0	0	40	15	0	0	0	0	0	0	Landfill
14	1	1	0	0	0	0	0	0	4	0	1	0	0	0	25	0	0	Atmosphere
15	3	2	4	1	4	4	4	0	20	6	6	0	0	33	0	50	0	Terrestrial
16	1	1	1	1	3	1	1	5	1	4	3	0	0	67	75	0	0	Ocean
17	0	0	0	0	0	0	0	0	0	0	0	100	100	0	0	50	0	Sink
Sums	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0	

The ultimate flow into the model is fossil fuel from the petroleum industry, which flows into the stock of plastic production, to represent the total amount of new plastic produced in a year. This plastic production stock is fed by a recycling flow, coming from a managed waste stock which will be discussed later. From this stock, raw plastic flows into stocks representing significant usage categories. These categories include multi-use consumer goods, single-use packaging, agriculture, construction, synthetic clothing, vehicle tires, cosmetics, boating, and aquaculture. Flows out of these usage categories represent plastic goods that are exiting their use cycle. They are calculated based on the expected lifespan of the plastic in each stock. Flows out of plastic production can be seen in Figure 4.

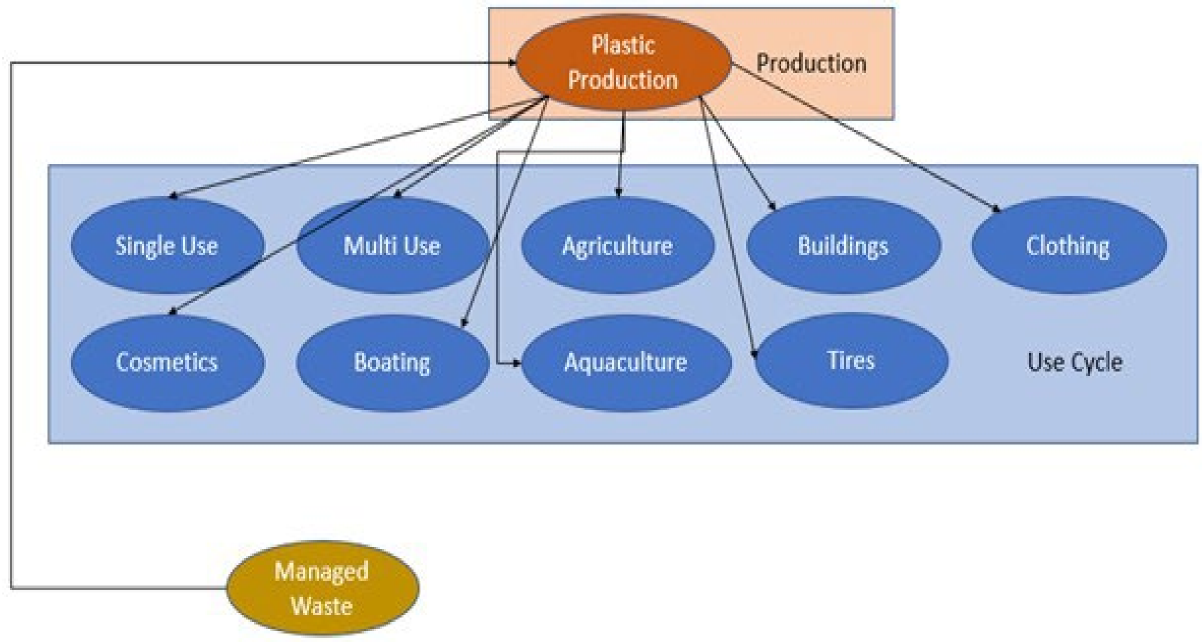


Figure 4. Flows Into and Out of Plastic Production. With plastic flowing into the plastic production stock from the managed waste category through recycling and out of the plastic production category into the various use cycle stocks.

4.2 USE CYCLE STOCKS AND FLOWS

The multi-use consumer good stock represents plastic products designed to be used by consumers over a period of time longer than one use. This is quite a wide-reaching categorization and covers a significant portion of the new plastic being produced each year. Flows of discarded plastic out of this stock flow into a managed waste stock and a mismanaged terrestrial waste stock in Figure 5.

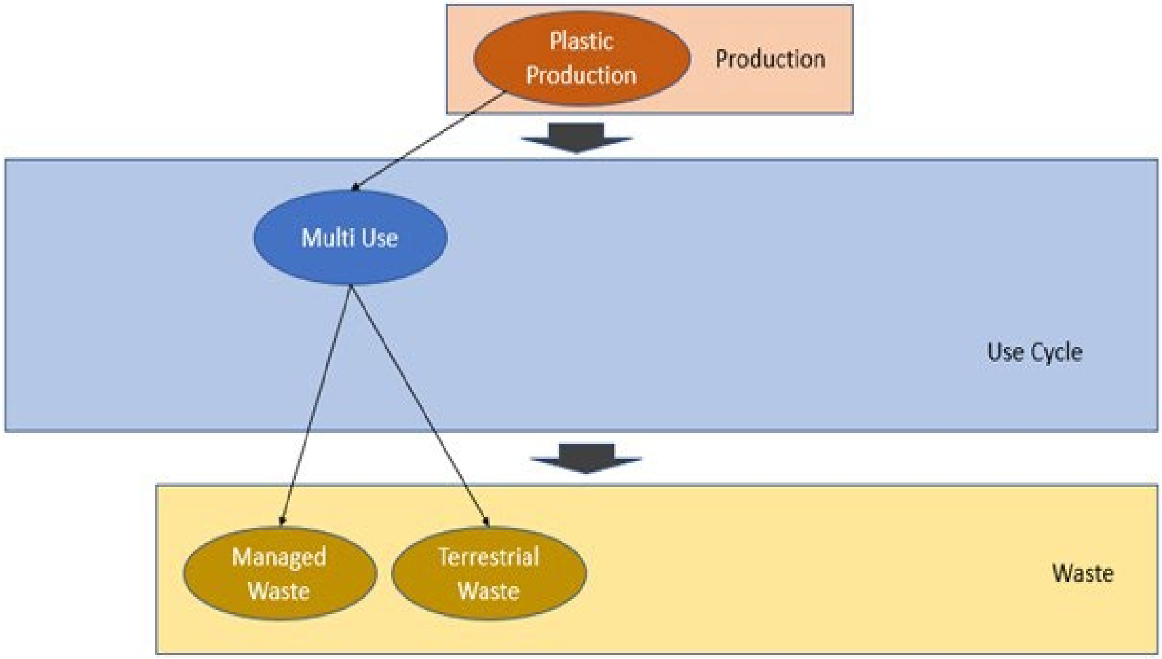


Figure 5. Flows Into and Out of the Multi-Use Plastic Category. Preservation of goods.

The single-use stock represents plastic designed to be used once for the preservation of goods during manufacturing and shipping or used once and discarded for sanitary purposes, such as bubble wrap, cling wrap, packing foam, plastic utensils, disposable diapers, and feminine hygiene products. This stock may be the single largest stock that newly produced plastic enters. Discarded plastic from this stock enters the managed waste stock and mismanaged terrestrial waste stock in Figure 6.

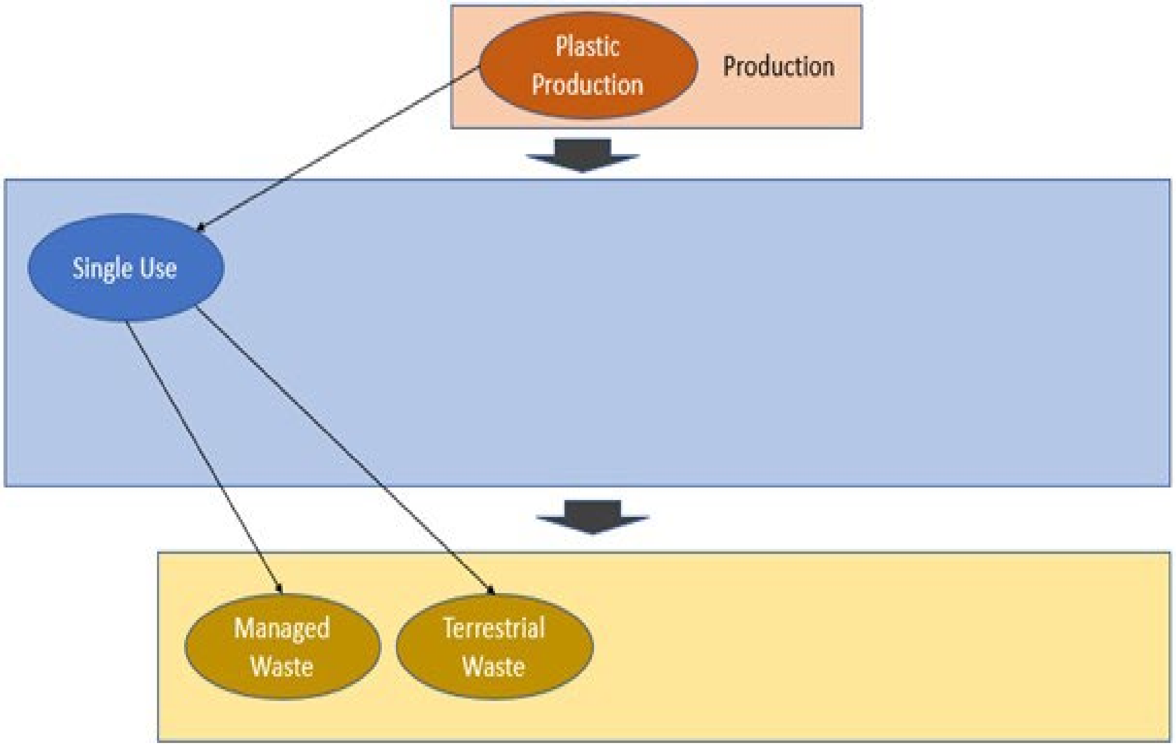


Figure 6. Flows Into and Out of the Single-Use Plastic Category.

The agriculture stock primarily encompasses plastic mulch sheeting deployed to protect crops from excessive precipitation, pests, and sun damage. This material is seeing increasingly widespread usage, especially in China. After the growing season, farmers may attempt to reuse the same netting, they may properly dispose of it, or they may simply bury it. These plastic mulch sheets are a significant source of microplastics as they undergo thermal degradation from the sun during their normal usage. These microplastics may enter the soil and eventually the groundwater of the area or they may be aerosolized by the wind and enter the atmosphere. Therefore, plastic leaving the agriculture stock may enter the managed waste stock, the atmosphere stock, or the terrestrial mismanaged waste, seen in Figure 7.

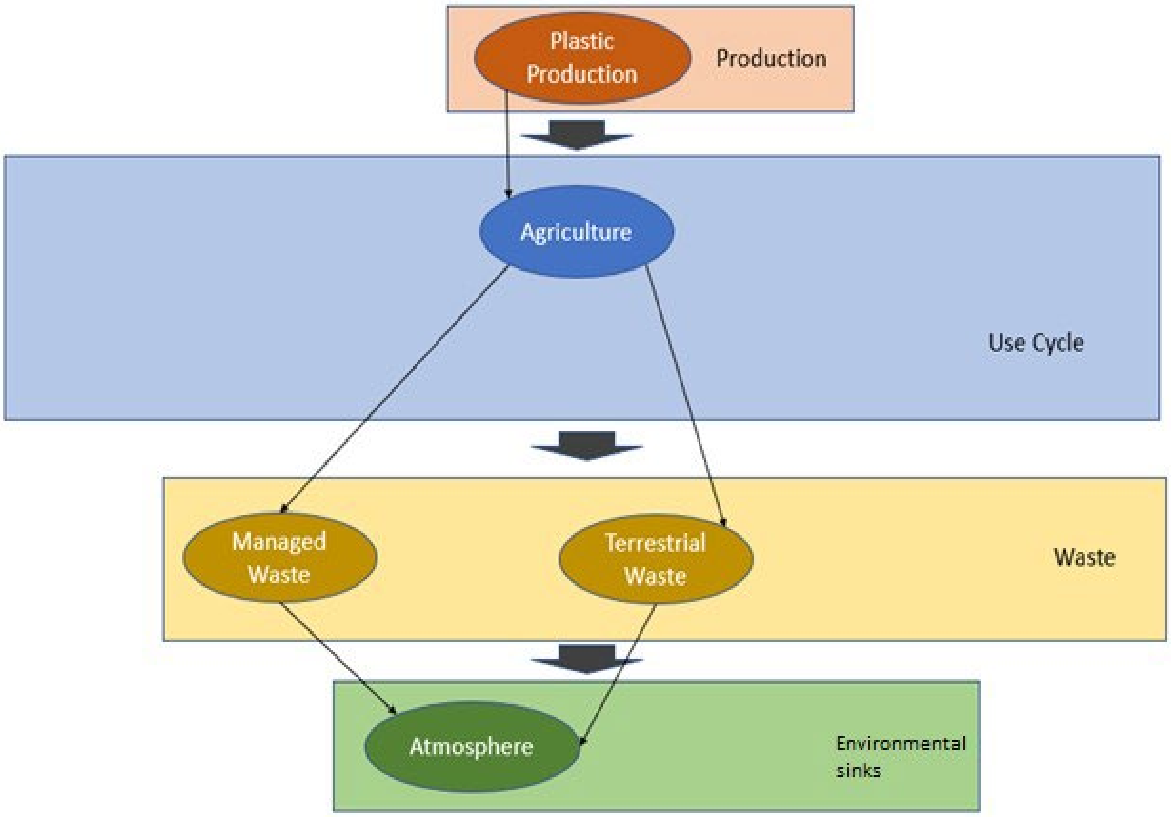


Figure 7. Flows Into and Out of the Agriculture Stock.

The construction stock represents plastic that is being used in any type of building construction. This is a stock with a long RTD, and a stock of which the flows in and out would vary wildly per country, as some regions use far less plastic in their buildings than others, some regions have fewer long-lived buildings than others, and some regions employ regulations for disposing of plastic waste that are stricter than others. The flows out of this stock will enter managed waste and terrestrial mismanaged waste, seen in Figure 8.

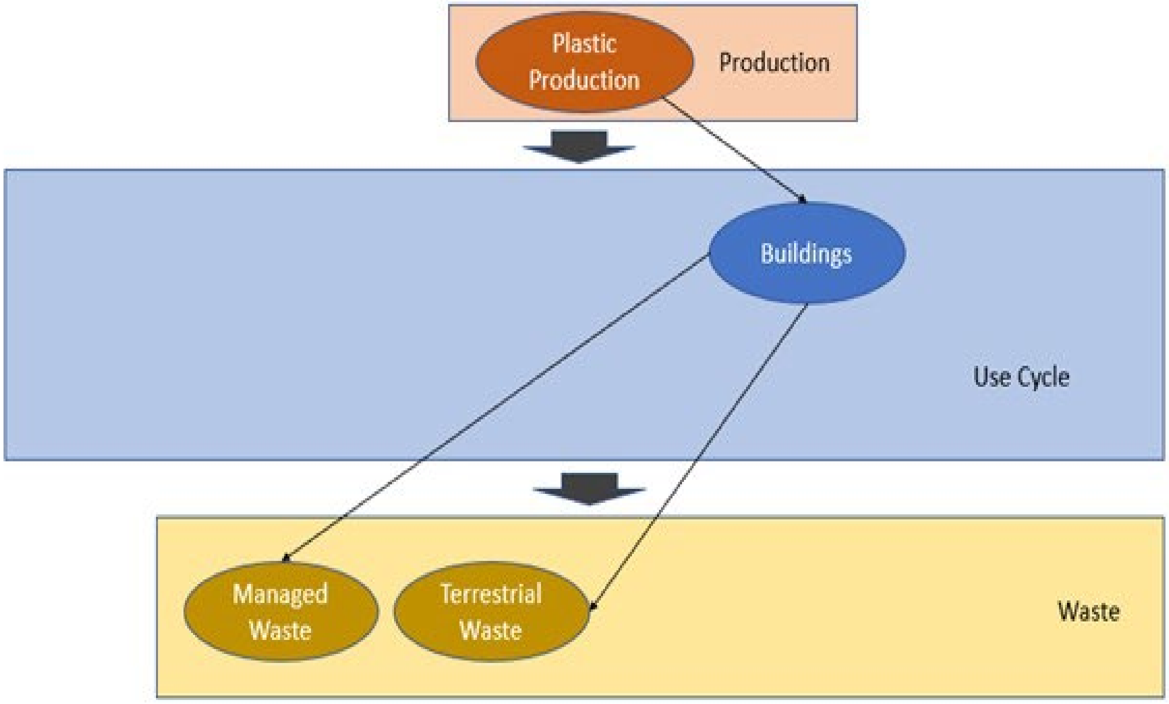


Figure 8. Flows Into and Out of the Construction Stock.

The synthetic clothes stock includes any synthetic garments. These garments may be intentionally discarded, and indeed many fashion houses discard large portions of their unsold inventory when it is no longer "in fashion," but the largest flow out of this source is the shedding of synthetic fibers during the normal wear and washing of these garments. These synthetic fibers will enter the sewer system and some will inevitably escape filtration and enter freshwater or saltwater systems. Thus, the flows out of this stock will include managed waste and sewage, Figure 9.

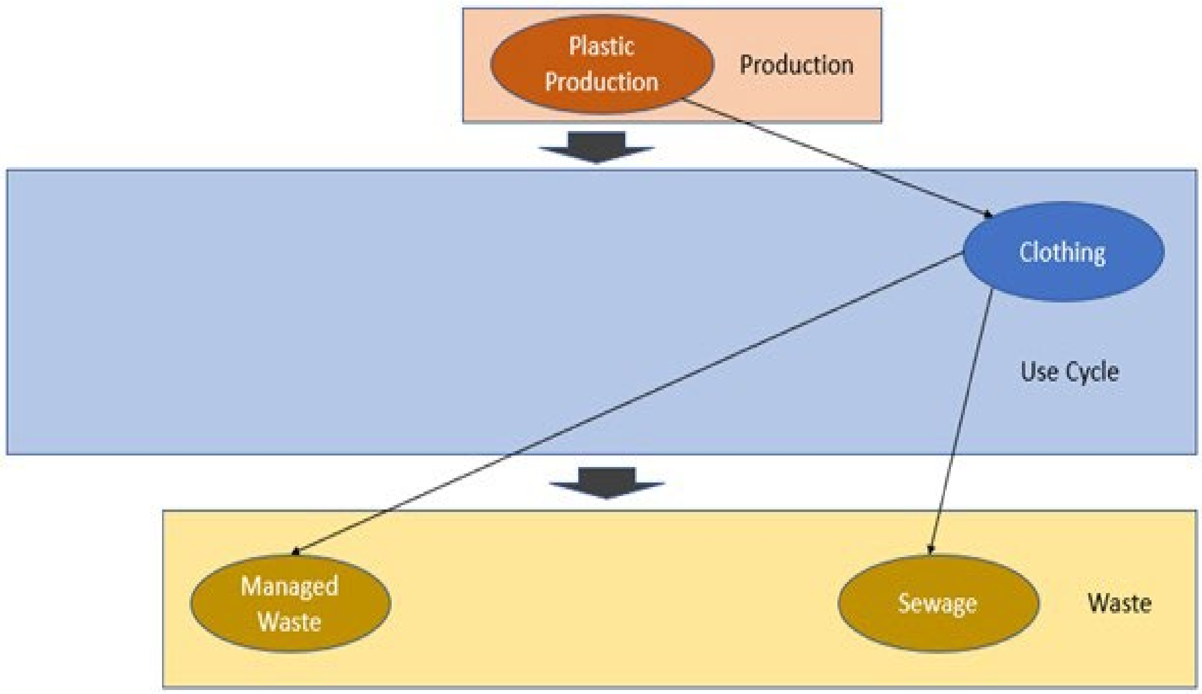


Figure 9. Flows Into and Out of the Clothing Stock.

The vehicle tire stock largely encompasses tires that are discarded once they reach the end of their lifespan and microplastic particles that flake off of the tires during normal usage. These microplastics, in addition to those produced by plastic mulch used by agriculture, are the primary source of microplastics in the atmosphere. Therefore, the vehicle tire stock has flows entering managed waste and the atmosphere, Figure 10.

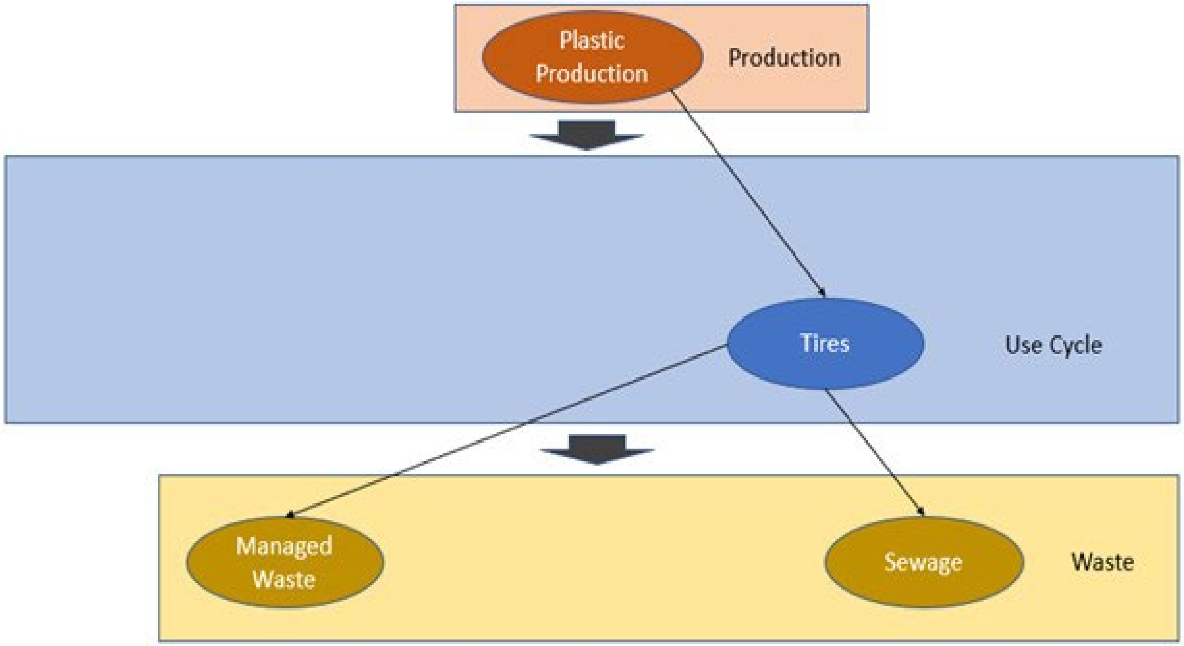


Figure 10. Flows Into and Out of the Tires Stock.

The cosmetics stock is an interesting example of a plastic stock that is decreasing in many regions. The usage of plastic microbeads in cosmetics have been banned in many countries around the world, but some still allow their usage. These microbeads are washed down the drain during their usage and end up in the sewage system and ultimately freshwater sources. Therefore, the sole flow out of the cosmetics stock is into the sewage stock, Figure 11.

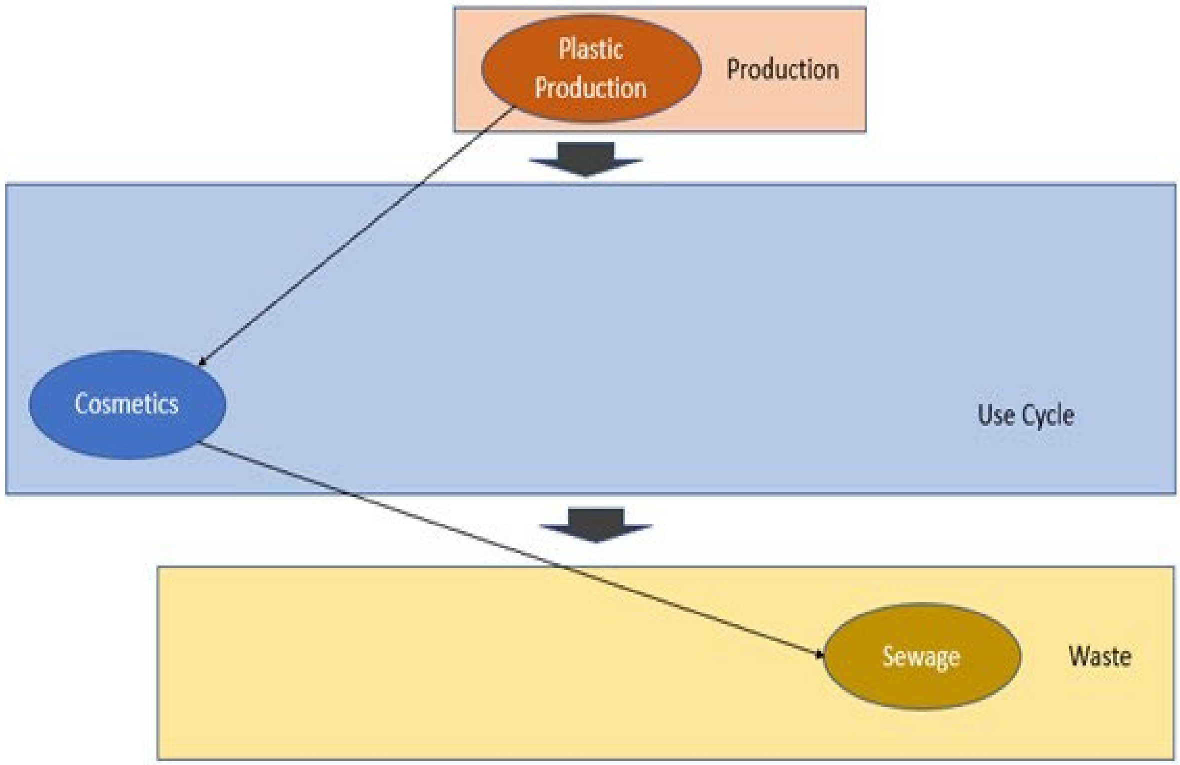


Figure 11. Flows Into and Out of the Cosmetics Stock.

Boating is a broad stock that covers losses from the fishing industry, shipping losses, fiberglass boat degradation, and synthetic paint chipping. Losses in this area could be the loss of fishing gear in fresh or saltwater, the loss of shipping containers containing plastic overboard, the slow erosion of plastic-hulled boats, and the chipping of synthetic paints. This stock will have a small flow into managed waste and larger flows into freshwater waste and the ocean itself, as seen in Figure 12.

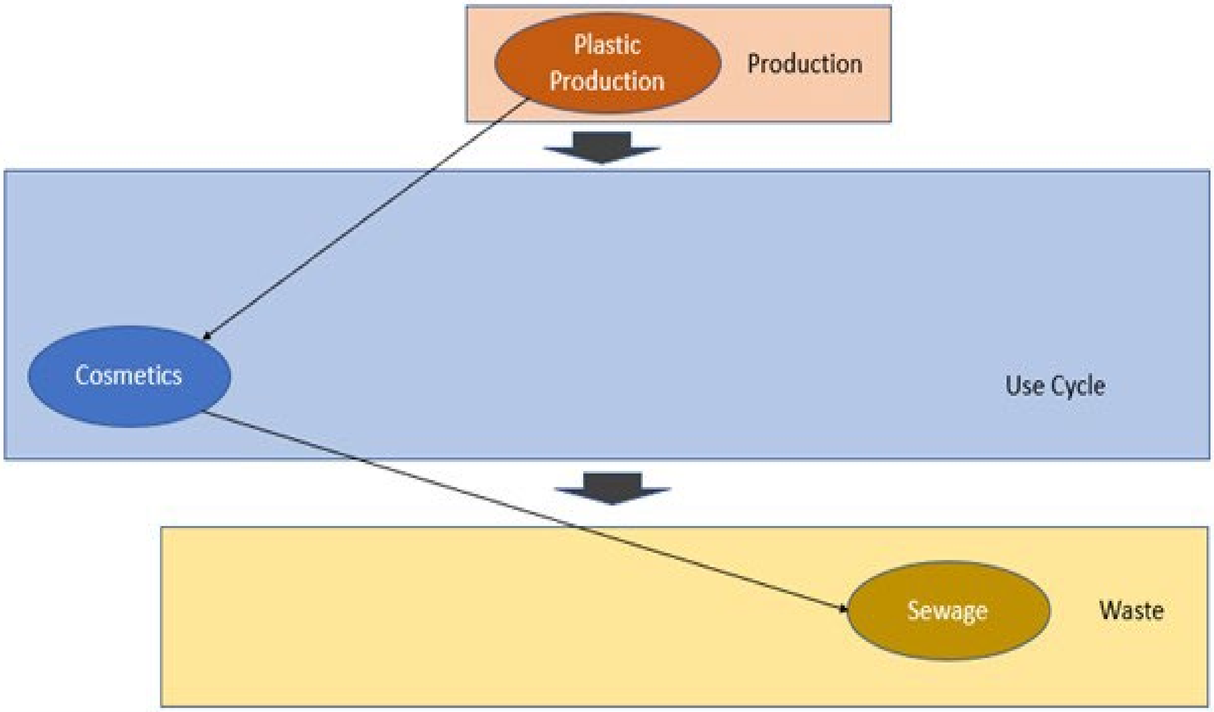


Figure 12. Flows Into and Out of the Boating Stock.

The aquaculture stock consists of equipment used in the aquaculture industry. Flows out of this stock represent equipment loss and erosion during the process of aquaculture. They flow into managed waste, freshwater waste, and the ocean, Figure 13.

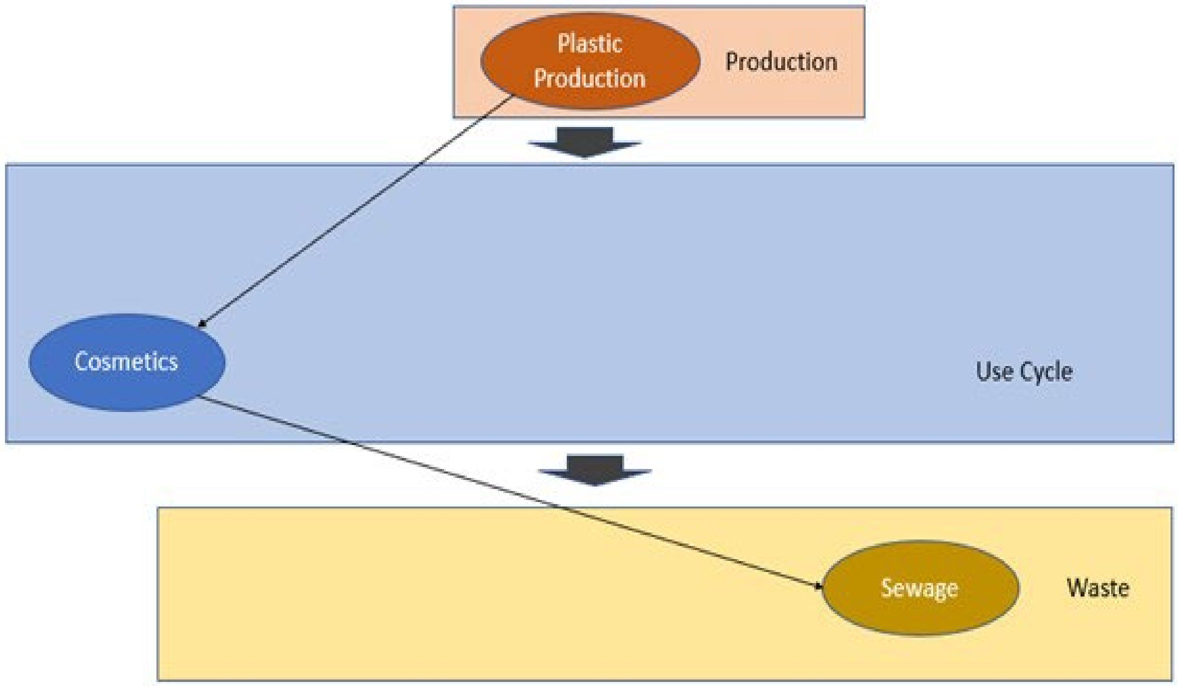


Figure 13. Flows Into and Out of the Aquaculture Stock.

4.3 MANAGED AND MISMANAGED WASTE

The managed waste stock represents plastic waste that has been adequately disposed of. Depending on their quality, plastics may be incinerated, recycled, or buried when they reach the end of their life cycle. Unfortunately, landfills may leak out into the environment especially if they have constructed using outdated standards. Thus, the managed waste stock may flow back into plastic production in the recycling process, into the incineration “stock” thereby exiting the system, or into the mismanaged terrestrial waste stock through landfill degradation, Figure 14.

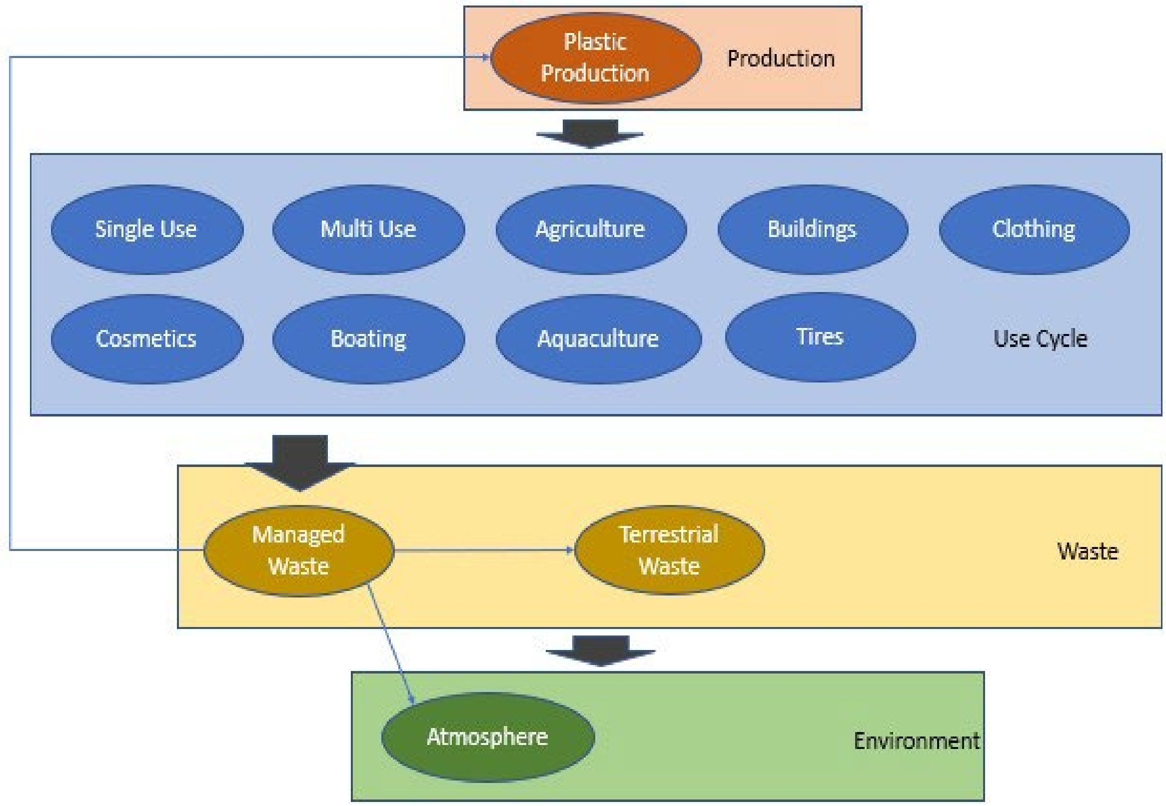


Figure 14. Flows Into and Out of the Managed Waste Stock.

4.4 TERRESTRIAL WASTE

The terrestrial waste stock represents all plastic littered or unintentionally discarded on the surface of the earth or into the groundwater system. Thus, this would include terrestrial pollution such as agriculture and tires but not marine pollution such as boating or aquaculture. Terrestrial waste may eventually enter the freshwater system through groundwater movement or storm runoff. Thus, the sole flow out of terrestrial waste is into freshwater waste, Figure 15.

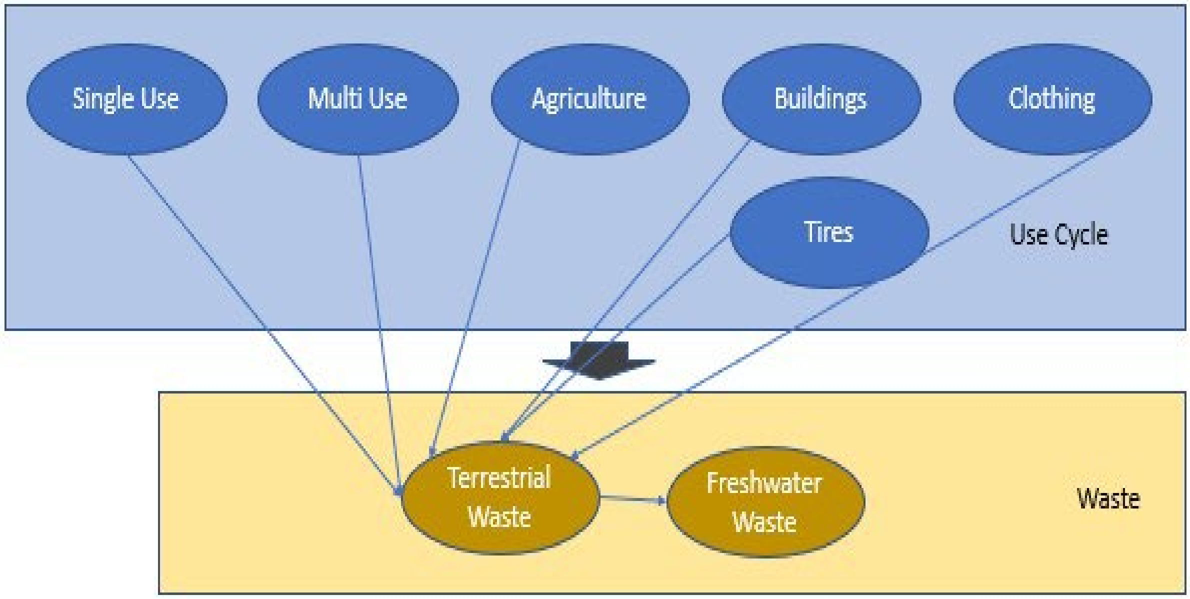


Figure 15. Flows Into and Out of the Terrestrial Waste Stock.

4.5 SEWAGE

The sewage stock is fed by microplastics from synthetic garments and cosmetics, and feeds into the freshwater waste stock through plastics that escape the filtration process. A portion of this stock also feeds into the managed waste stock, and the mismanaged terrestrial waste stock. The managed waste stock is fed by a flow of plastic that is caught by the filtration process and removed from the environment, and the mismanaged terrestrial waste stock is fed by microplastics in greywater that is used to water agricultural lands or municipal parks (Laws, 2017).

4.6 FRESHWATER WASTE

Freshwater waste represents plastic debris in rivers and lakes, which may one day enter the ocean as it follows the river's course into the sea. Thus, the flow of plastic from the freshwater stock into the ocean is the primary flow out of the freshwater stock.

4.7 OCEAN WASTE

The ocean stock is fed into by the atmosphere through precipitation, by the freshwater stock, by the terrestrial waste stock through coastal runoff, the construction stock through destruction of coastal buildings through natural disasters, and by the boating and aquaculture stocks. The outflows of this stock will flow back into the atmosphere, into the benthic sediment stock, and into the terrestrial waste stock through redeposition in beach environments. It is the stock of the most interest in this project.

4.8 ATMOSPHERIC WASTE

The atmospheric stock represents airborne microplastics and nanoplastics and is fed by the tire stock as microplastics are generated from the normal wear and tear on vehicle tires generated during use, and the agriculture stock as microplastics are created from the conditions formed by the heat and exposure plastic mulch is subjected to during its lifespan. There is also a small amount from the ocean stock by the reaerosolization of microplastics by wave action.

4.9 BENTHIC WASTE

The benthic sediment stock is one of the ultimate sinks for the ocean stock and is fed by marine plastic debris that is too heavy to float, due to inherent high density or biofouling from marine organisms. As this is one of the ultimate sinks, there are no flows out of this source.

4.10 PROGRAMMING STRUCTURE AND EQUATIONS

Several modeling scenarios were run, with a time series of plastic production by millions of tons ranging from 1950 to 2100. Data was projected from 2015 until 2100, and data from 1950 to 2015 was used from Geyer et al. (2017), who cited the PlasticsEurope market research group.

FORTRAN was used to program the model. The model can run on any time step, and for this thesis, it was run on one year time steps, with flows transporting plastic between stocks in a structured, cascading order to ensure calculations are performed correctly. For example, the flow from the recycled plastic stock flows to the production stock after the flows out of the production stock have been calculated. In the real world, recycled plastics reentering production would not affect the flow of plastic from the production stock into during the same time step they enter the production stock.

The basic stock equation used in the model to calculate the change in the amount of plastic in a given stock:

$$S_i^n = S_{i-1}^n + \sum_{m=1}^{N} F_i^{mn} - \sum_{m=1}^{N} F_i^{nm} \tag{1}$$

In this equation, S denotes the stock in question, i denotes the time step, F denotes a flow out or into the stock, and J and K denote the number of flows specific to that stock that move into and out of that stock. To account for RTDs, a series of equations can be used. One variant on the basic stock equation is

$$S_i^j = S_{i=1}^J + I_i^j - O_i^j \tag{2}$$

where j replaces the acronym as the identifier of the stock and I and O replace F as the inflows and outflows from a stock, respectively. I can be used to calculate inflows dependent on RTDs using

$$I_i^j = \sum_{j\cdot=1}^{N} f\,jk \cdot O_i^k \tag{3}$$

where f_{jk} represents the fraction of stock outflow from stock S^j into stock S^k.

Calculating the outflows of a stock dependent on RTDs can be written as

$$O_i^j = \sum_{i=0}^{R^j} r_l^j \cdot I_{i-1}^j \tag{4}$$

where r^j_l represents the percentage of the inflow that flowed into stock S^j at timestep l that will then flow during this timestep. R^j in this instance represents the maximum time in the list of RTDs contributing to this equation.

4.11 CALIBRATION AND VALIDATION

As there are few agreed-upon estimates for the mass of plastic in the ocean, it is difficult to use other published works to validate this model. Lebreton (2019) used scenario-based modeling to forecast plastic pollution in the ocean through 2050 and predicted a range of 3-10 million tons of plastic in the ocean surface. The results of the

model produced for this project showed 8 million tons of plastic in the ocean surface by 2050 with the shortest RTDs tested. Van Sebille et al. (2015) states that between 9.3 and 236 million tons of plastic entered the ocean in 2010. The model used in this project predicted around 250 million tons of plastic entering the entire ocean in 2010. While the model tends to skew higher than some published estimates, the differences are slight.

CHAPTER 5

MODEL PROGRAMMING STRUCTURE AND EQUATIONS, SIMULATION RUNS, AND RESULTS

5.1 SIMULATION RUNS

Four scenarios have been successfully conducted using this model and program. All scenarios use the data from Geyer et al. (2017) for the plastic produced from 1950 to 2015 and used different predictive parameters to simulate plastic production data until 2100. The first scenario simulates a compound increase of 3% annually in plastic production from 2015 to 2100. This number is in sequence with the recent growth rate of plastic production around the world and simulates a scenario in which plastic production is not reduced by market forces, petroleum production, environmental concerns, or other mitigating factors.

The second scenario modeled involved new plastic production sharply decreasing to 0% at 2020, with the recycling flow from managed waste back up to production still running. With no new plastic entering the cycle from the petroleum industry, the only source of plastic for the production stocks would be the limited amount recovered from plastic waste. It is recognized that this is not a realistic scenario, but merely designed to showcase the minimal role that recycling plays in the plastic production cycle and how in its current state it cannot truly be considered a sustainable method for dealing with the plastic waste problem.

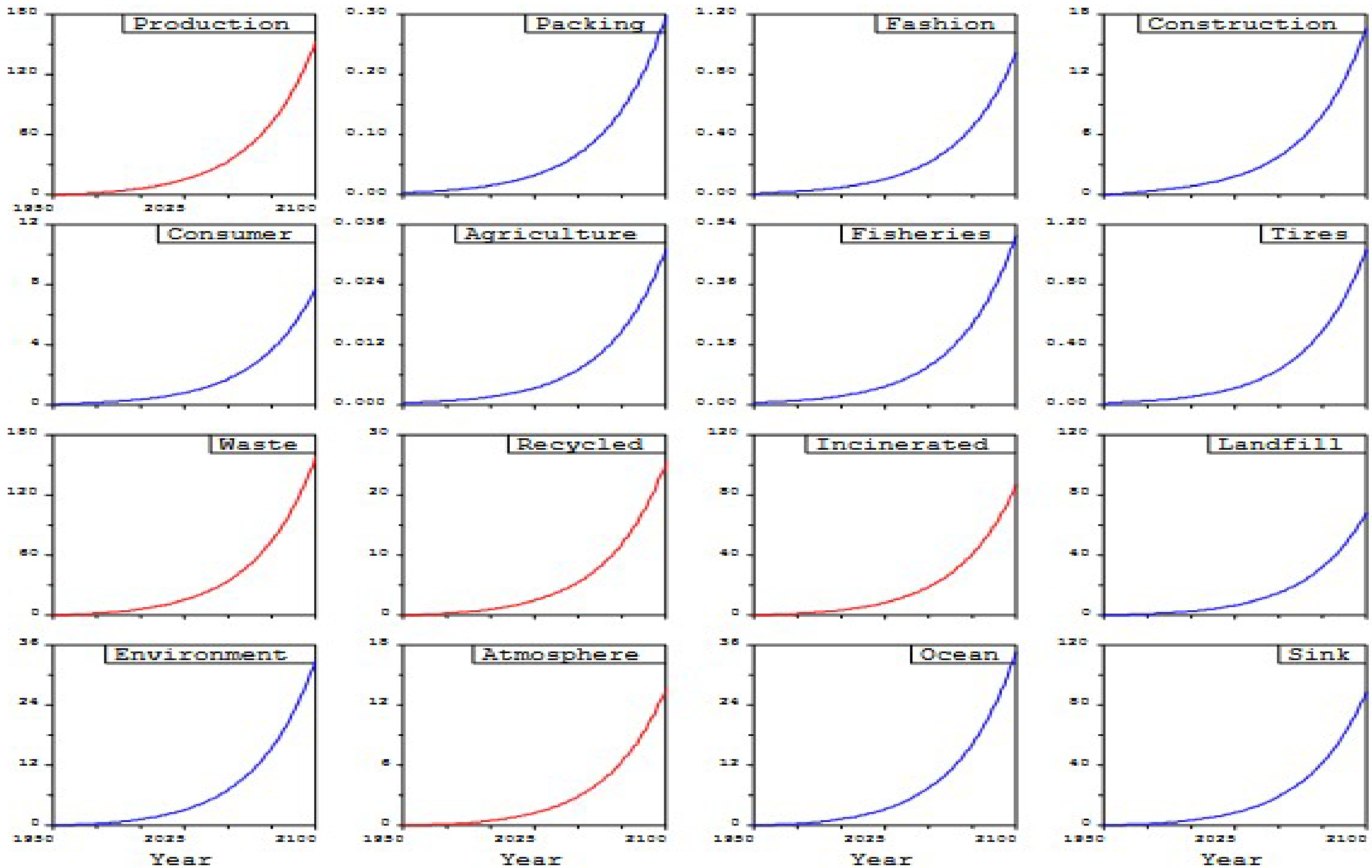
The third scenario models an increase by 3% annually until 2025, then a period of no growth until 2050, then a decrease in plastic production by 3% annually until the year

2100. This situation simulates a scenario in which a conscious effort is made to reduce plastic usage.

The fourth scenario is similar to the second scenario in which plastic production increases by 3% annually until 2025, and then drops to no plastic production. The purpose of this scenario is to test the effects of an extra 5 years of production on the plastic in the system before a system shutdown, compared to the shutdown conditions in scenario two.

5.2 RESULTS

In the first scenario, the modeling occurred as expected for a projection in which production increased 3% annually for 85 years. The graphs of the stocks can be found in Graph 4.



Graph 4. Graphs for the Quantity of Plastic in Each Stock in the First Modeled Scenario.

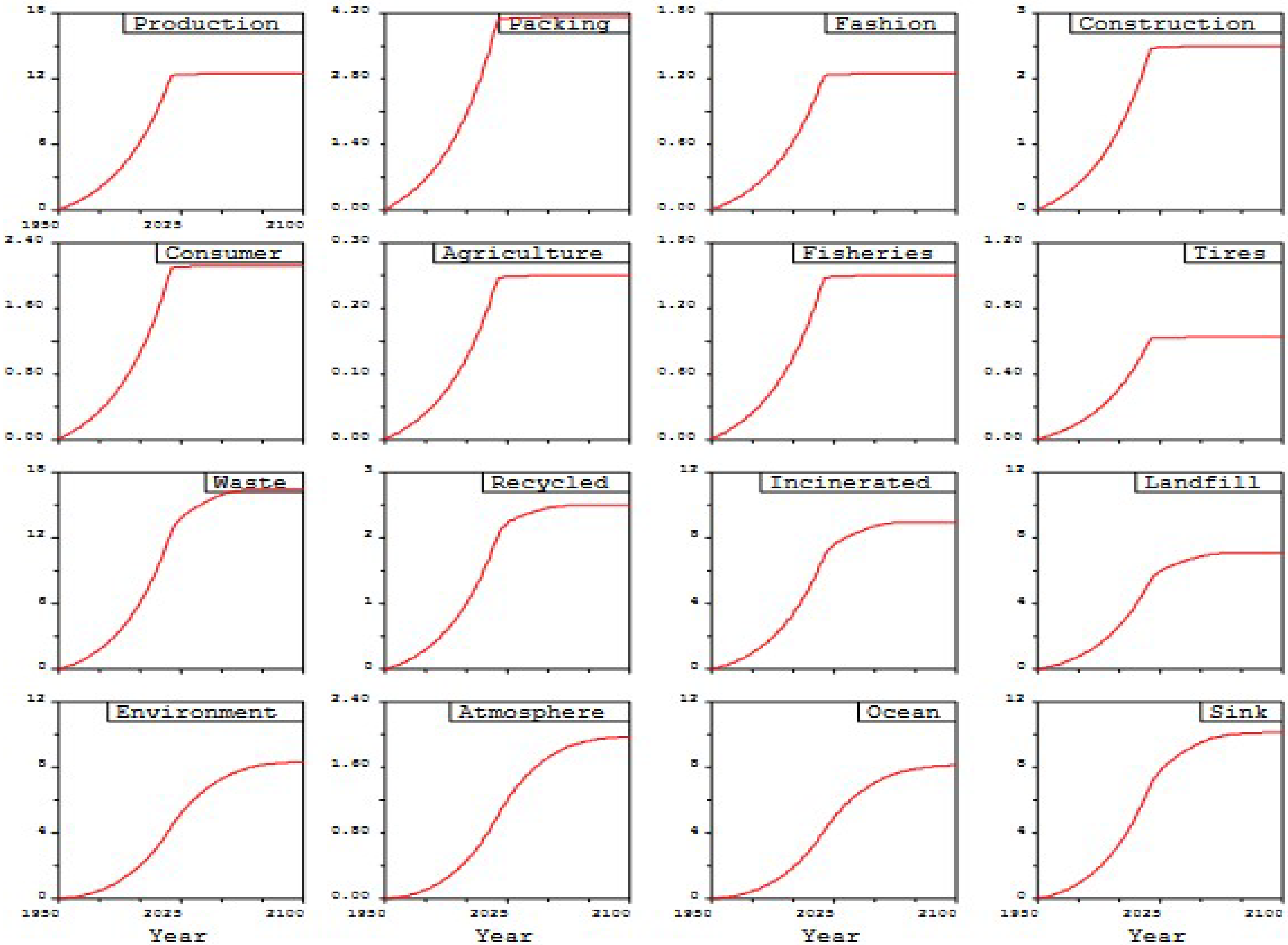
The graphs with blue curves represent stocks that can have plastic accumulating in them due to having flows with nonzero RTDs, and the graphs with red curves represent stocks with flows that have no RTD. The red curve measures the amount of plastic that has flowed through the stock at that point, while the blue curve represents the amount of plastic in the stock at the time on the y-axis. As can be seen, each stock shows an increase in the amount of plastic, whether the amount of plastic contained or the amount of plastic passing through. Stocks with RTDs show a growth curve that appears exponential as plastic collects in them faster than can be disposed of through outflows, while stocks without RTDs also show an increase in the plastic flowing through them due to an increase in flows from ”upstream” in the model.

Of the stocks with continuous flows with no RTDs, plastic production and waste were both high at approximately 150 million tons total. Incinerated plastic was also high at about 90 million tons total. Recycled plastic was a little lower at about 25 million tons total and atmospheric plastic was the lowest at roughly 13 million tons total. For plastic stocks that showed accumulation through RTDs, the stock that showed the most accumulation was the benthic zone or oceanic sink at approximately 90 million tons of plastic.

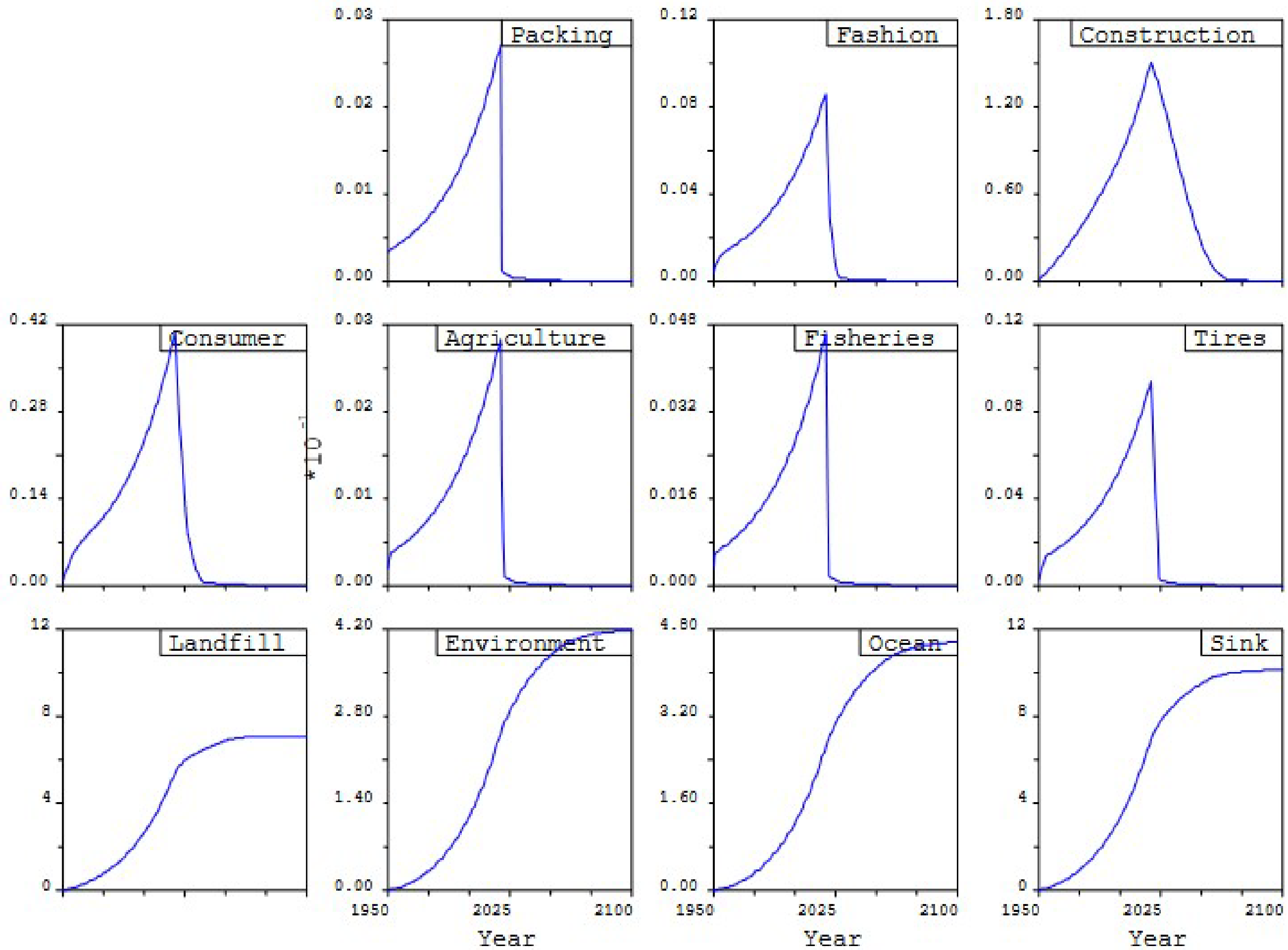
Compared to the amount of plastic entering the ocean this number is much higher, suggesting that according to this model, most of the plastic on the surface of the ocean sinks to the benthic zone. In fact, the plastic recorded in the oceanic stock at around the year 2015 is less than one million tons, around the estimate of tens to hundreds of thousands of tons given by Weiss et al. (2021). This suggests that the majority of plastic does not stay on the surface of the ocean but migrates to the benthic zone, which is captured by this model. After the benthic zone, landfills were also quite high at around 70

million tons of plastic, followed by the ocean and environment both around 30-40 million tons. There is then a sharp drop to construction at 14 million tons, and consumer plastic at 5 million tons. Every other stock accumulates less than a million tons by the year 2100. Packaging, fisheries, and agriculture are all very low, denoting their low RTDs and high turnover.

In the second modeled scenario, plastic production is ceased in the year 2020 but recycling continues until the stocks it draws from are depleted. The stocks without stored RTDs can be seen in Graph 5, and the stocks with RTDs can be seen in Graph 6.



Graph 5. Graphs for the Quantity of Plastic Passing Through Each Non-RTD Stock in the Second Modeled Scenario.



Graph 6. Graphs for the Quantity of Plastic Contained in Each RTD Stock in the Second Modeled Scenario.

As can be seen, the records of the amount of plastic that has passed through each non-RTD stock initially follow a similar trend to the non-RTDs in the first modeled scenario, but change when plastic production ends in the year 2020. The stocks Production, Packing, Fashion, Construction, Consumer, Agriculture, Fisheries, and Tires all plateau almost immediately as the amount of plastic passing through them quickly drops to zero.

These stocks, except for the Production stock itself, are usage stocks that receive their inflows directly from production. The stocks that are two or three degrees of

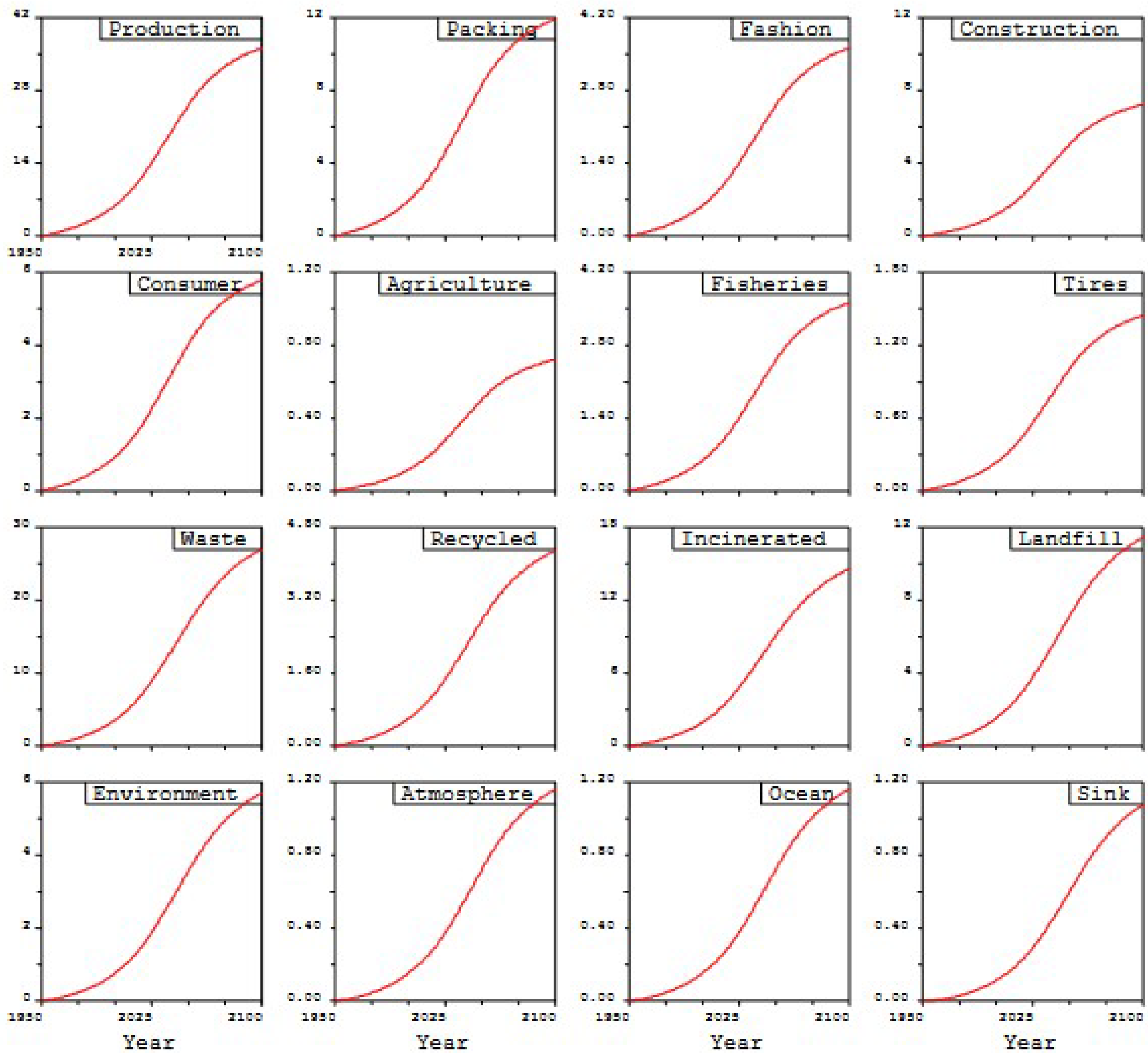
separation away from the Production stock have curves that more gradually plateau, some continuing to accrue plastic until the end of the modeling run due to stocks ”upstream” with longer RTDs.

In Graph 6, showing the amount of plastic in stocks with RTDs over the course of the model run, the effect of RTDs on the amount of plastic in these stocks can be seen. When the plastic production flow is reduced to zero, stocks with lower RTDs like packaging, agriculture, fisheries, fashion, and tires fall to almost zero plastic in a very short time as these plastics exit via the outflows from these stocks. Stocks such as the consumer stock and construction stock take longer to fully ”drain,” as they possess longer RTDs. Sinks like the landfill, environment, ocean, and sink stocks show no such decrease in content as a nonzero portion of their stock is retained infinitely, or on a scale so long as to not be captured by the model.

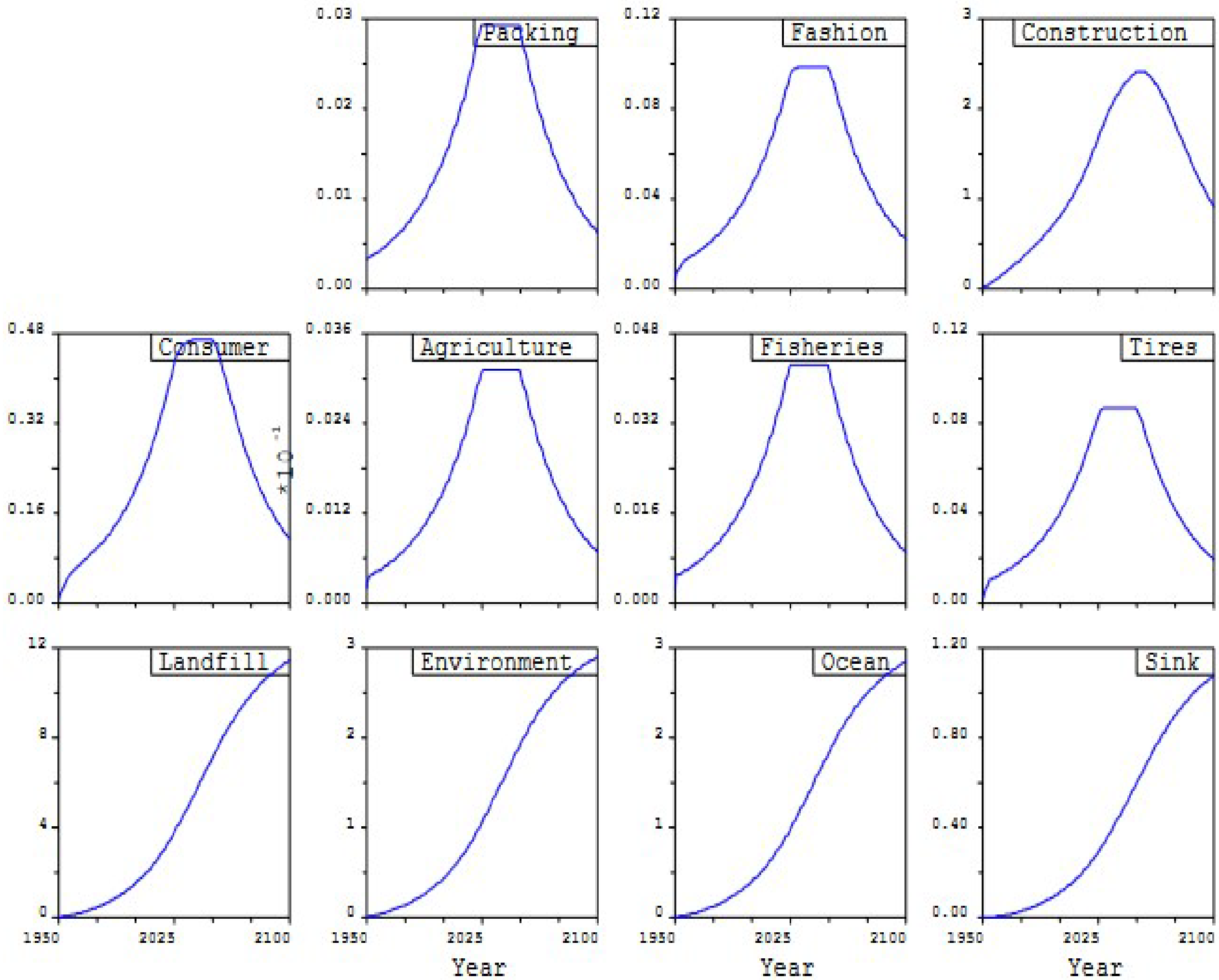
While this scenario may not be realistic, it is useful in a number of ways. First, it allows for a testing of the accuracy of the model’s RTDs. Using a common-sense visual analysis of the data backed up by real world studies, one can see if the model’s behavior is accurately displaying the results of a scenario where plastic production suddenly ceased. Second, a modification to the parameters of this model can produce a scenario in which a reduction of plastic production occurs rather than a total shutdown. This is useful for modeling scenarios like the COVID-19 pandemic, when an economic downturn caused a temporary reduction in the production of plastic, or a gas shortage, which would reduce the raw petroleum needed to produce plastic goods.

In the third modeled scenario, plastic production increases at a rate of 3% annually until 2025, followed by a period of no growth until 2050, then a decrease in plastic

production by 3% annually until the year 2100. The quantities of plastic recorded moving through these stocks during this time period, and the quantities of plastic in measurable stocks, can be found in Graphs 7 and 8.



Graph 7. Accumulated Flows in Gt Plastic Into the Stocks for Scenario 3.

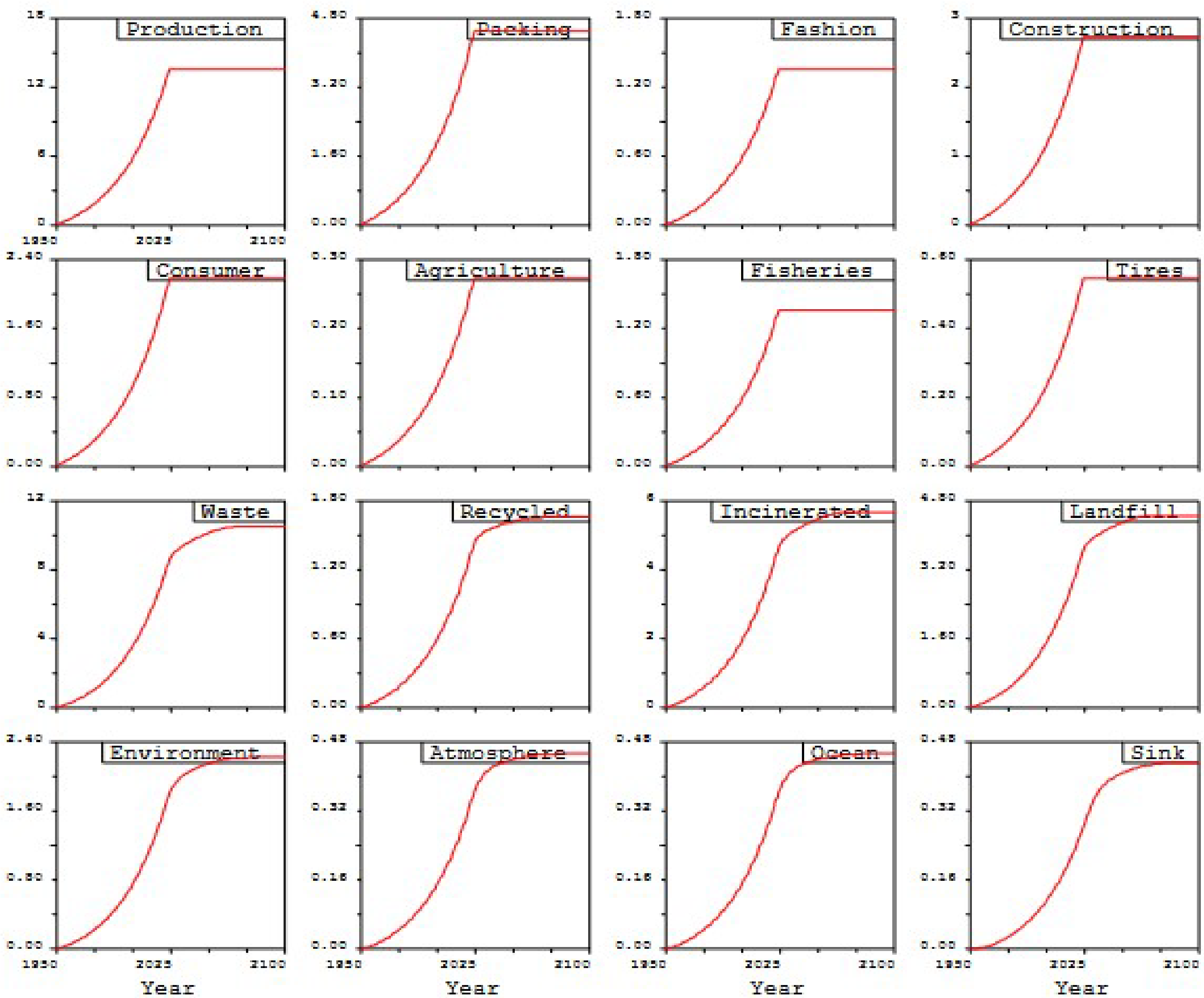


Graph 8. Graphs for the Quantity of Plastic Contained in Each RTD Stock in the Third Modeled Scenario.

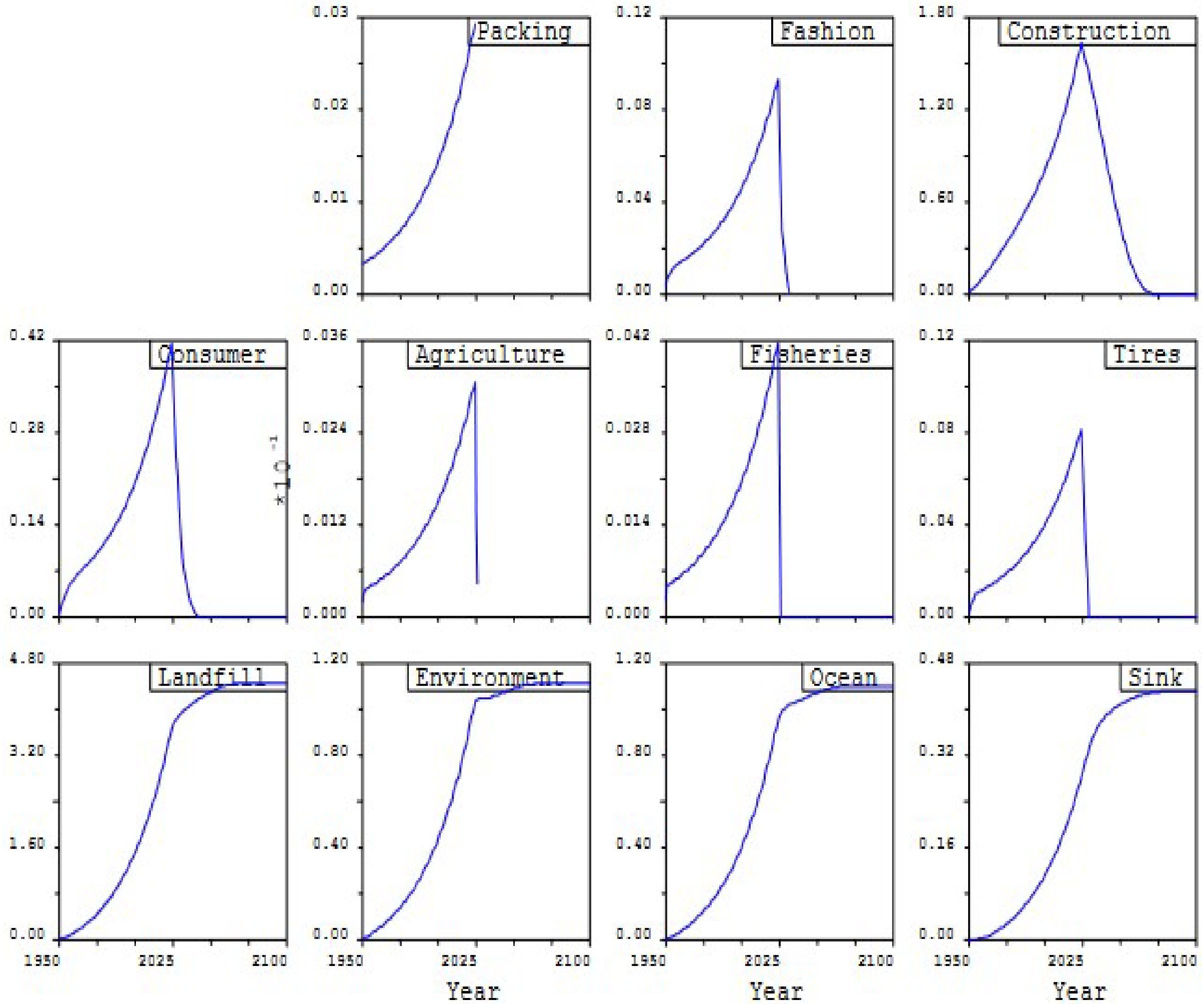
Graph 7 shows much more tapered data curves for the amount of plastic moving through each stock during the model run compared to Graph 4, the data from the run in which a 3% increase continued throughout the length of the model run. In addition, Graph 8 shows data curves in the plastic use stocks that peak, plateau, and then slowly taper off in a less dramatic fashion than those in Graph 6. The sink stocks still slowly plateau as well.

This modeling scenario with some adjustments would work well for modeling the effects of a steady, planned decrease in the amount of plastic being used by a population.

Model run four addresses a scenario in which plastic production continues to grow until 2025 and then immediately stops. This is very similar to model run two and will test the model's ability to show delicate changes. The results from this model run can be seen in Graphs 9 and 10.



Graph 9. Graphs for the Quantity of Plastic Passing Through Each Non-RTD Stock in the Fourth Modeled Scenario.



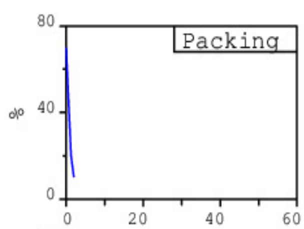
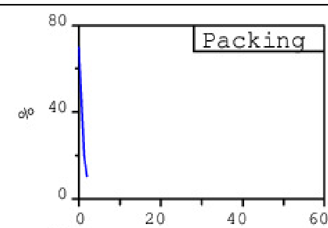
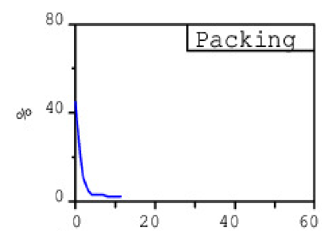
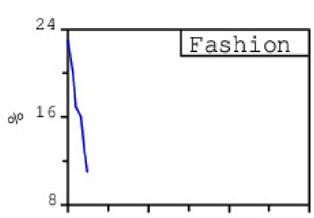
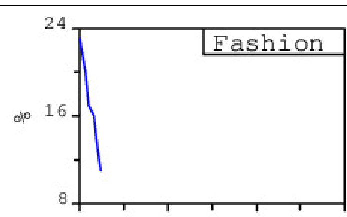
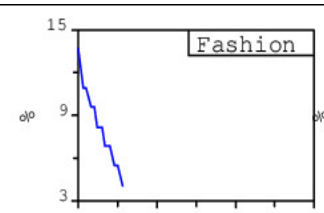
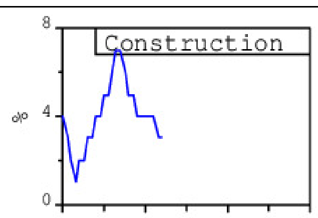
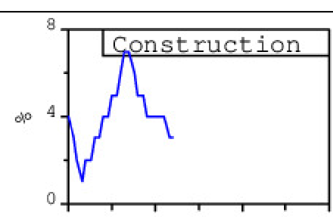
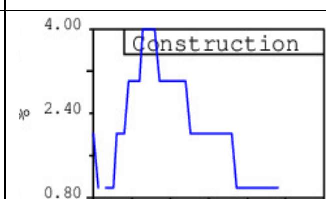
Graph 10. Plastic Stocks in Gt for Scenario 4.

Although the changes are slight and the curves are very similar, both the figures from modeling run two and the figures from modeling run four are distinct. The figures from modeling run four show slight increases in the data curves for the amount of plastic retained in RTD stocks as well as the amount of plastic passing through stocks through the course of the model run. This shows that even a 5-year wait in plastic reduction can have a large, cascading impact throughout the system.

Next, three different sets of RTDs were tested using the first plastic production scenario. The first set of RTDs (Table 5) were half of the RTDs predicted by the already-gathered data presented earlier in this work. The next scenario (Table 6) halved the RTDs in all stocks except for the RTDs in the ocean, which were doubled. The last set of RTDs (Table 7) tested left the RTDs in the ocean doubled, and also doubled the rest of the RTDs in the model. The purpose for this spread of RTDs is to determine, in the context of this model, whether RTDs "upstream" or RTDs in the ocean have more effect on the total quantity of plastic in the ocean.

Table 5

Table Showing Half the RTDs Used for the Three Tested Scenarios

RTDs	**All Short**	**Short Upstream, Long Ocean**	**Long All**
Packaging			
Fashion			
Construction			

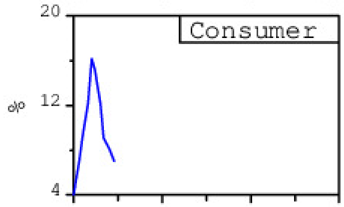
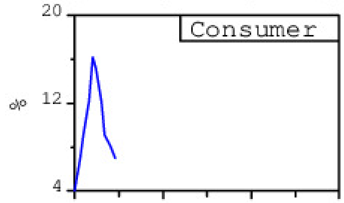
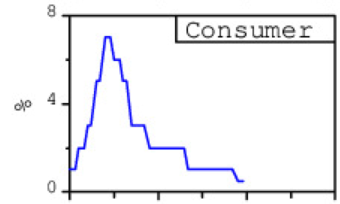
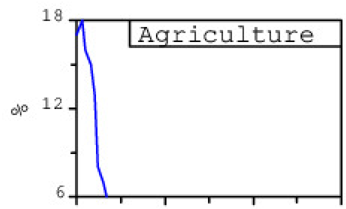
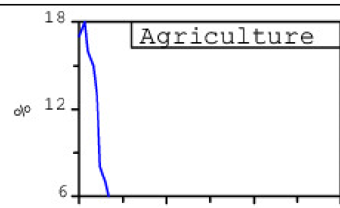
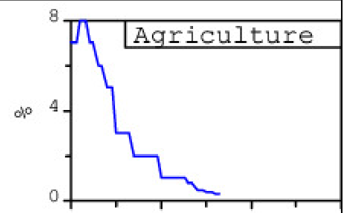
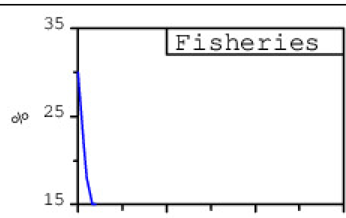
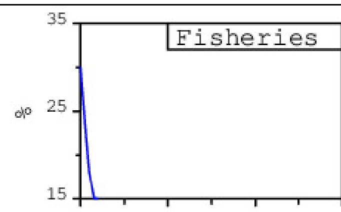
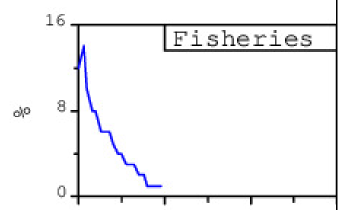
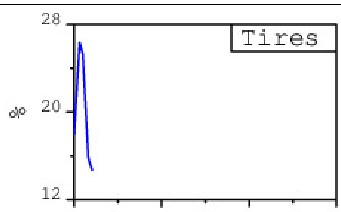
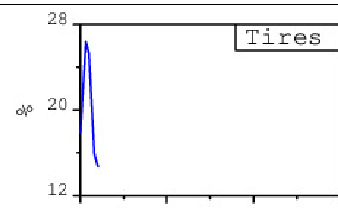
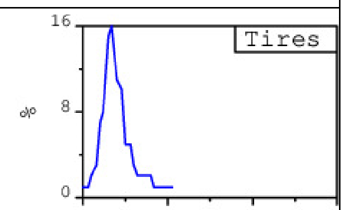
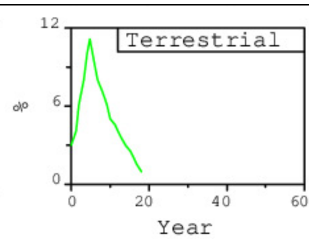
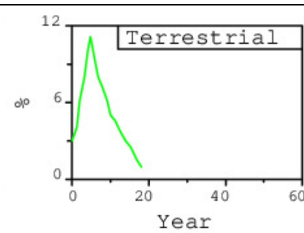
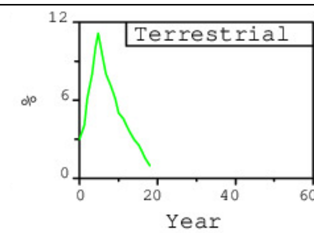
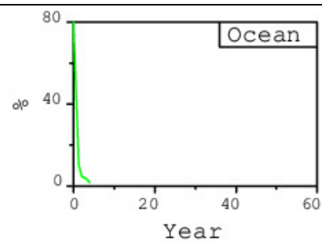
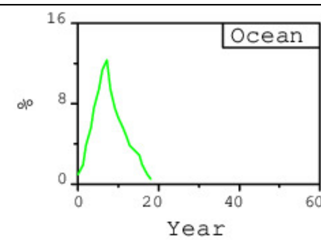
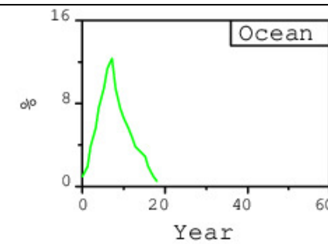
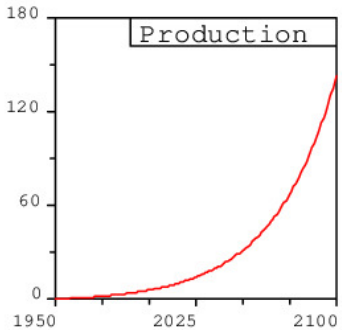
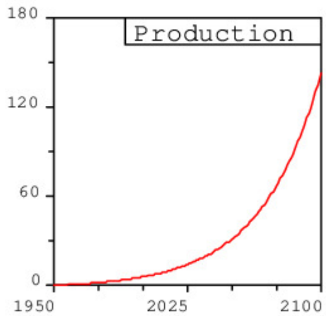
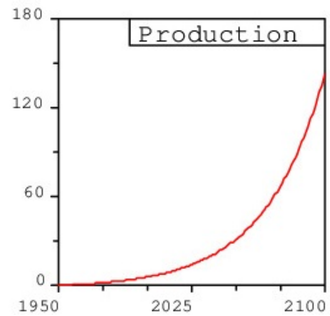
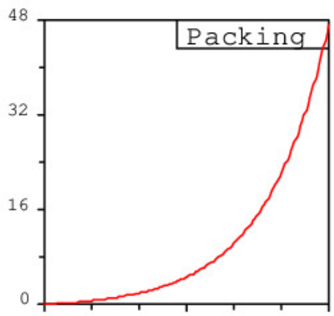
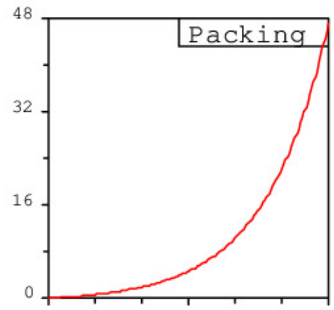
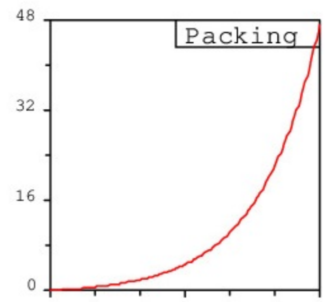
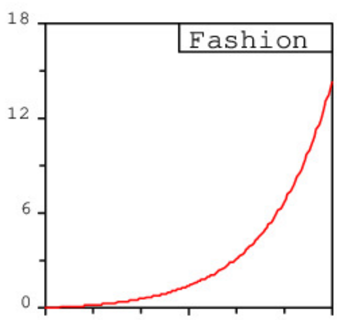
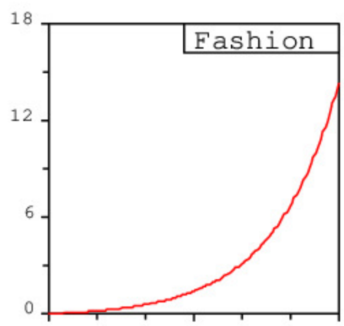
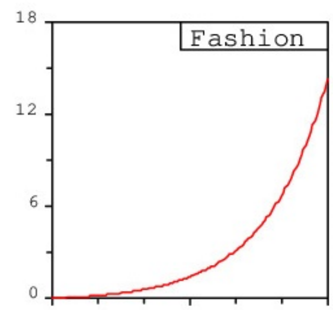
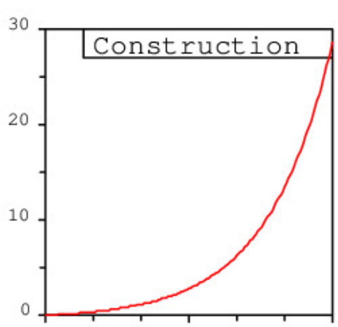
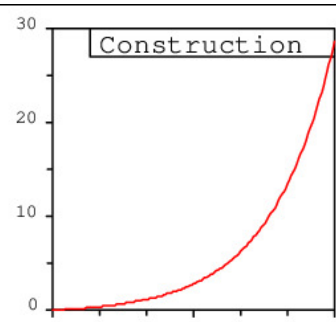
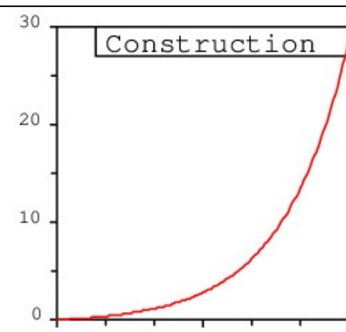
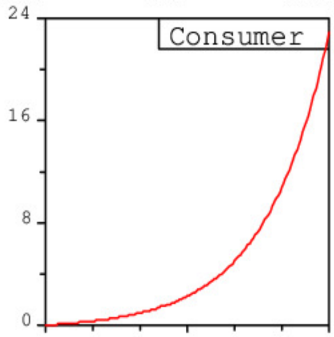
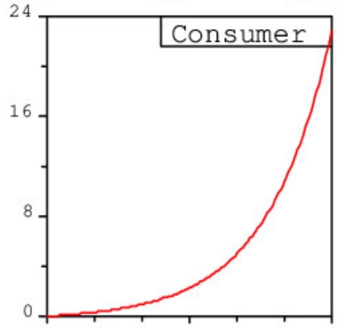
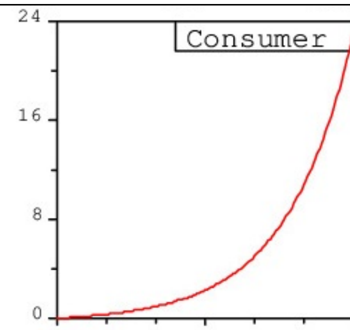
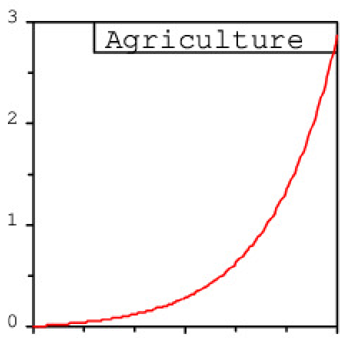
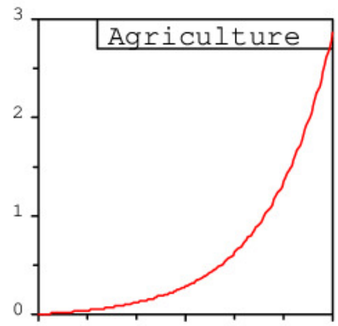
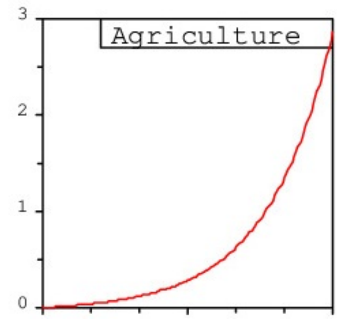
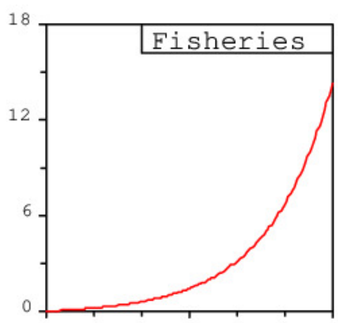
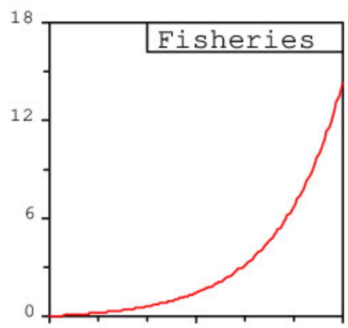
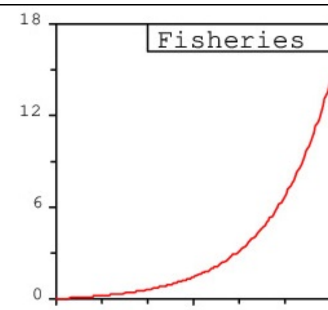
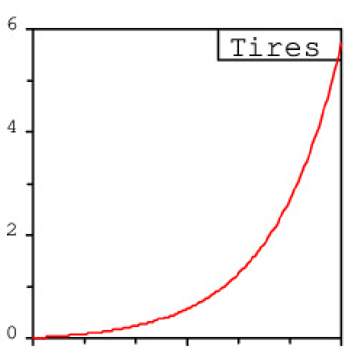
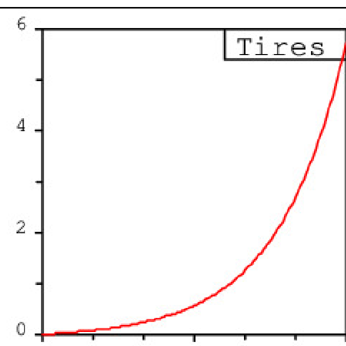
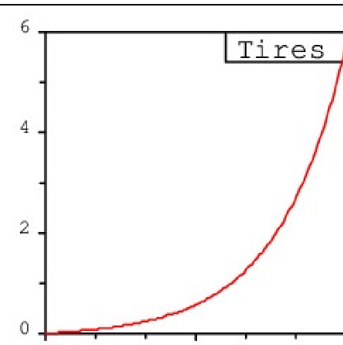
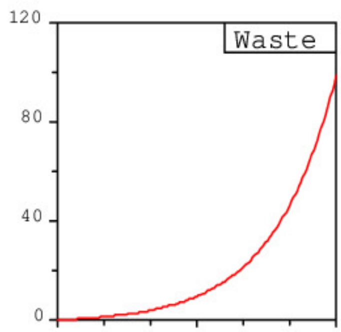
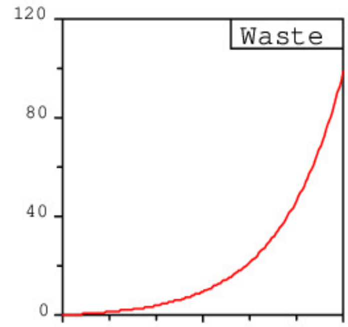
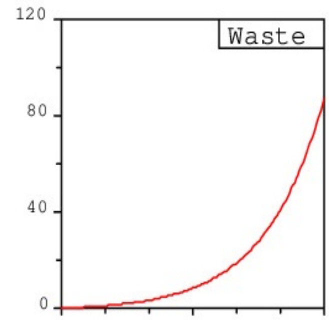
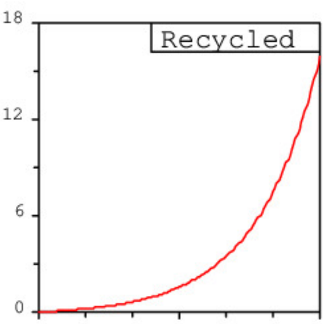
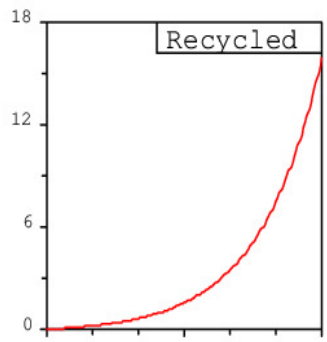
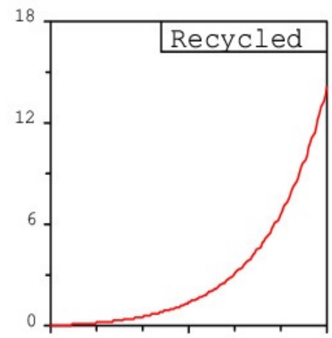
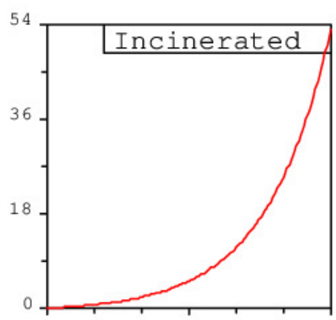
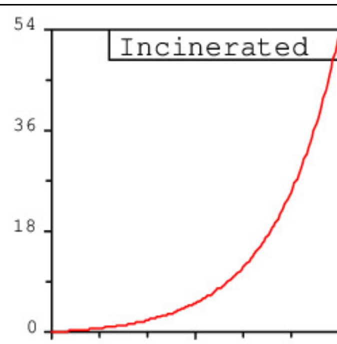
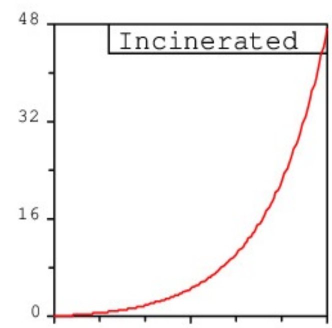
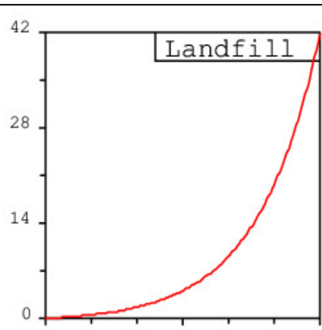
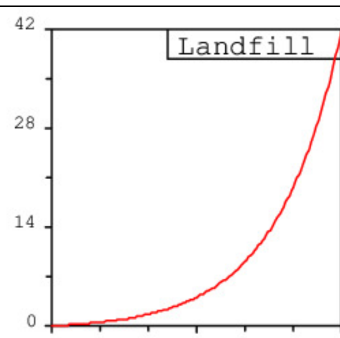
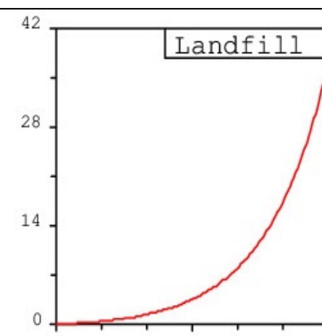
RTDs	Table 5, Continued. All Short	Short Upstream, Long Ocean	Long All
Consumer			
Agriculture			
Fisheries			
Tires			
Terrestrial			
Ocean			

Table 6

Table Showing the Flows Passing Through Different Stocks for the Three Tested Scenarios at Half the RTDs in All Stocks Except the Oceans, Which Were Doubled

Flows	All Short	Short Upstream, Long Ocean	Long All
Production			
Packaging			
Fashion			
Construction			

Flows	Table 6, Continued. All Short	Short Upstream, Long Ocean	Long All
Consumer			
Agriculture			
Fisheries			
Tires			

Flows	Table 6, Continued. All Short	Short Upstream, Long Ocean	Long All
Waste			
Recycled			
Incinerated			
Landfill			

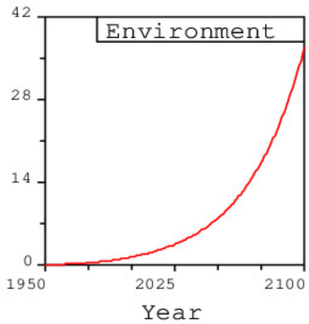
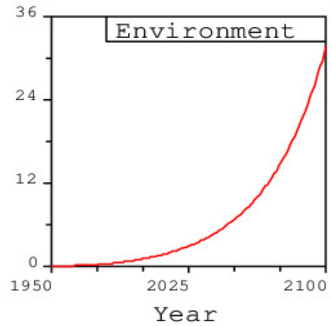
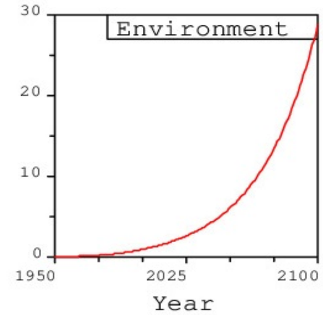
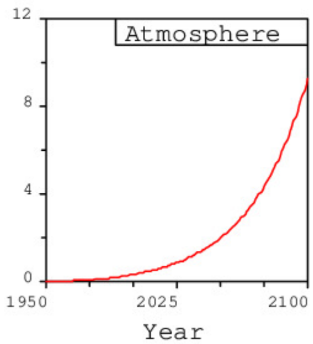
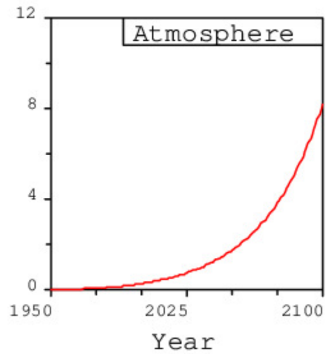
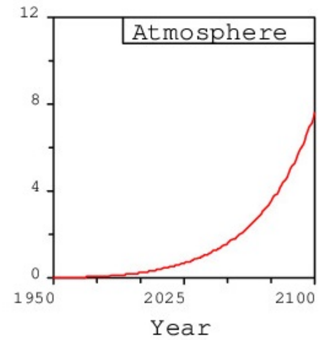
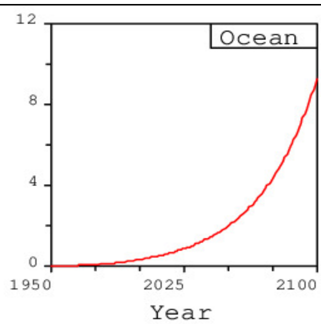
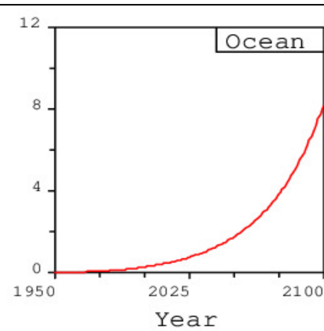
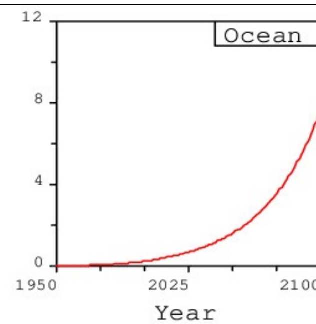
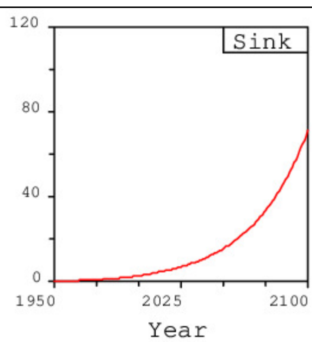
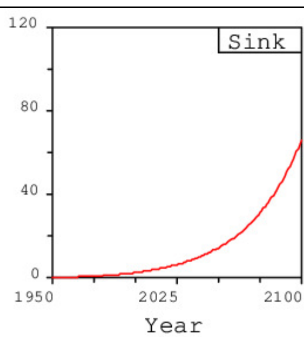
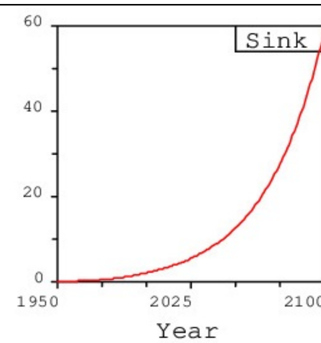
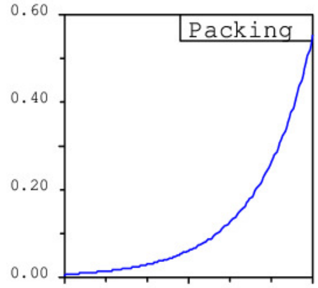
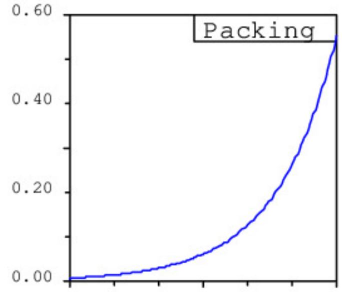
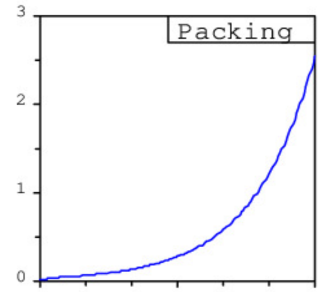
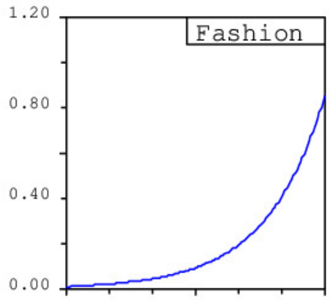
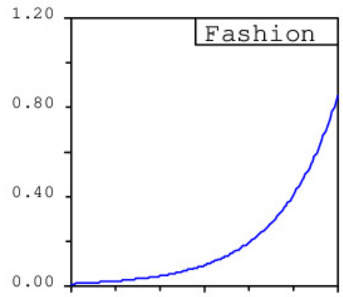
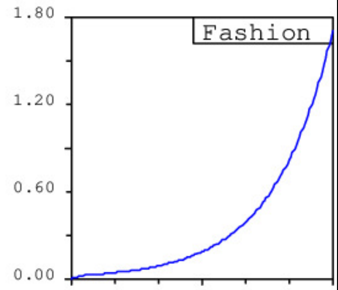
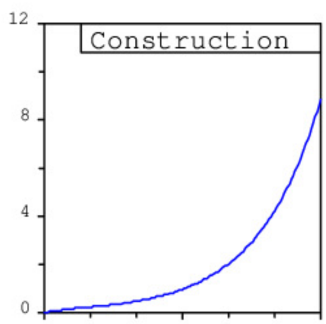
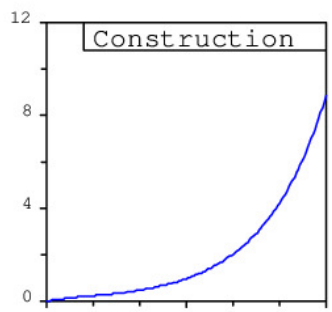
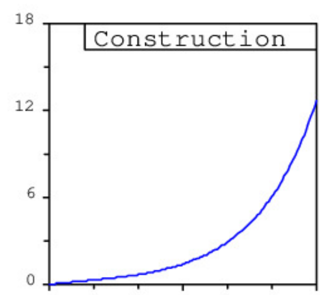
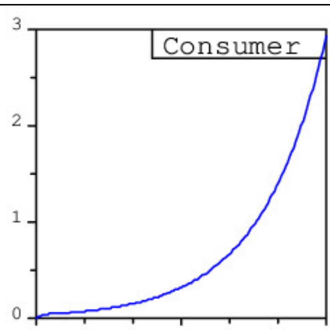
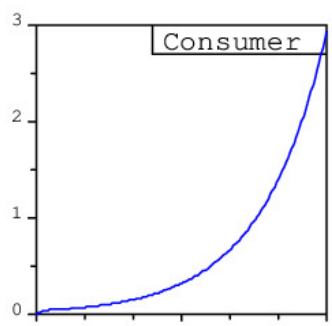
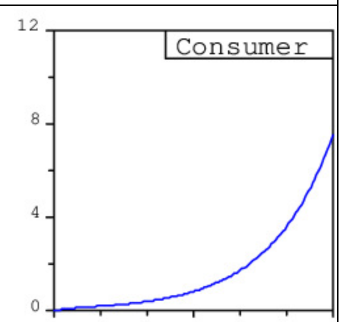
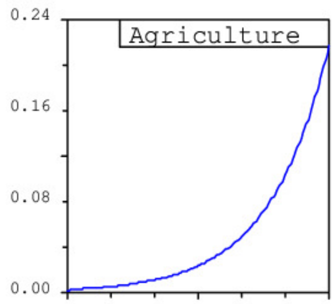
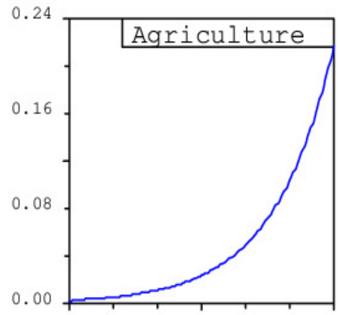
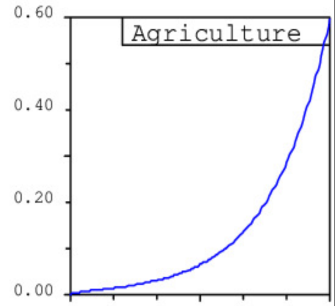
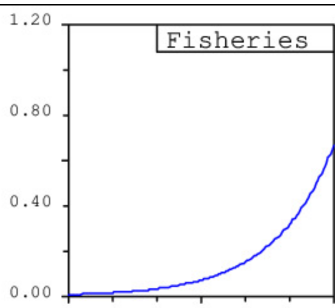
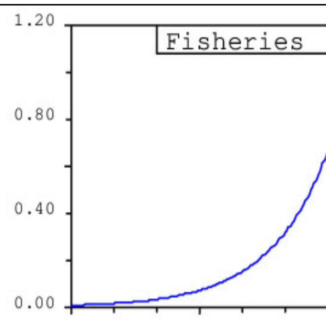
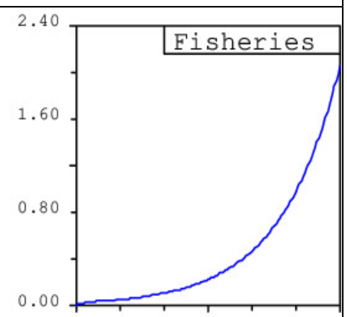
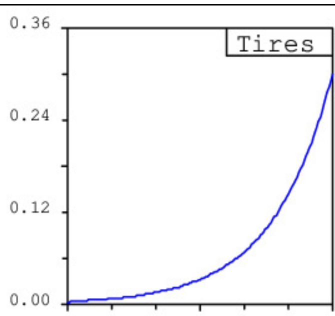
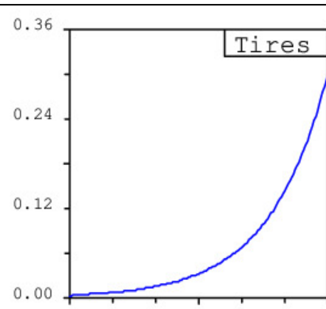
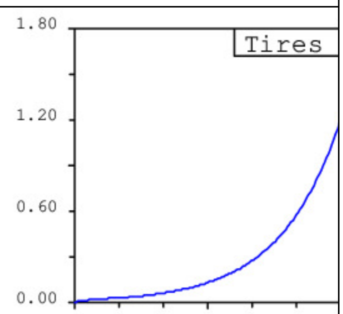
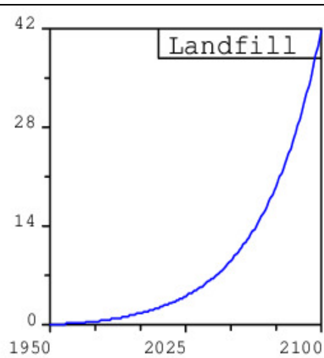
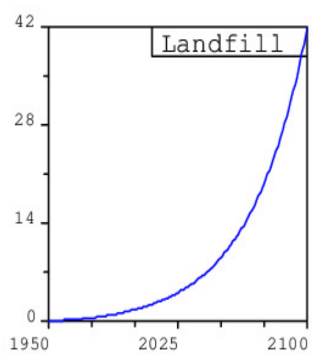
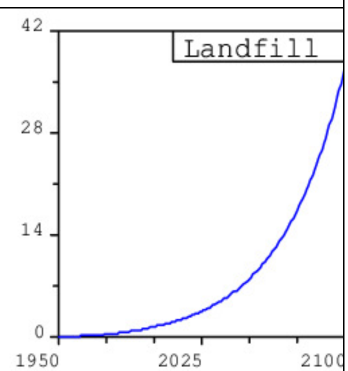
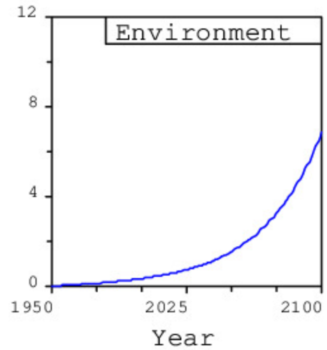
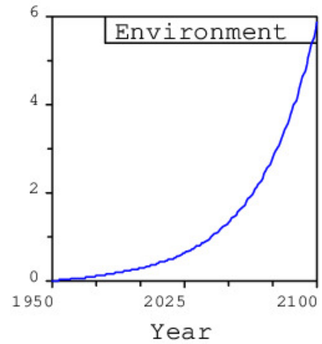
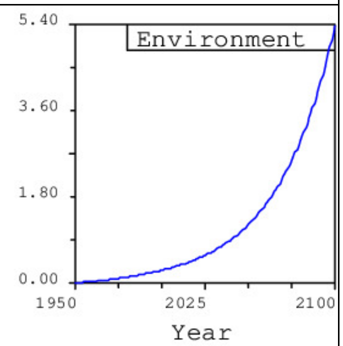
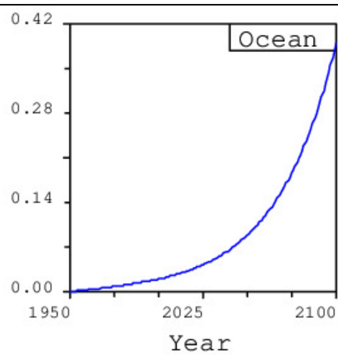
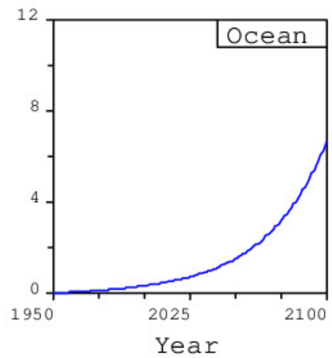
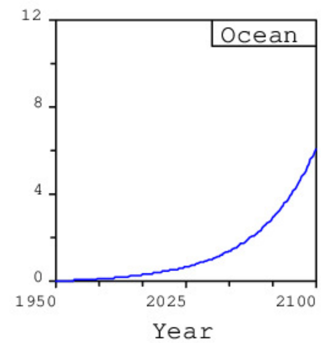
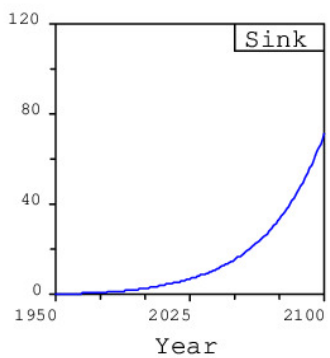
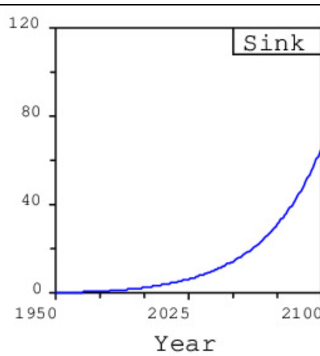
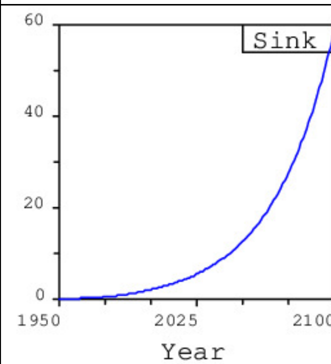
Flows	**Table 6, Continued.** **All Short**	**Short Upstream, Long Ocean**	**Long All**
Environment			
Atmosphere			
Ocean			
Sink			

Table 7

Table Showing the Quantity of Plastic in the Stocks of the Model for the Three Tested Scenarios at Double the RTDs in All Stocks Including the Ocean

Stocks	**Control**	**Short Upstream, Long Ocean**	**Long All**
Packaging			
Fashion			
Construction			
Consumer			

Stocks	Table 7, Continued. Control	Short Upstream, Long Ocean	Long All
Agriculture			
Fisheries			
Tires			
Landfill			

Stocks	**Table 7, Continued.** Control	Short Upstream, Long Ocean	Long All
Environment			
Ocean			
Sink			

CHAPTER 6

DISCUSSION

6.1 OVERVIEW OF FINDINGS

There was little change in the amount of plastic present in the ocean between the scenario in which only the ocean RTDs were large and the scenario in which all the RTDs were large, but there was a significant change between the scenario in which all the stocks were halved and the scenario in which all the stocks except the ocean were halved and the ocean was doubled. It seems that increasing the RTD of the stocks upstream does little to decrease the amount of plastic in the ocean, while increasing the RTD of the ocean causes the amount of plastic present in the ocean to increase greatly over time. This means that in the context of the model, ocean RTDs have a much greater impact on the plastic present in the ocean than the flows into the ocean.

6.2 MODEL CAPABILITIES

The model constructed during this project has shown to be adequate at projecting future plastic scenarios using real-world data. By using data about the same phenomenon from conflicting sources, such as the percentage of plastic entering the ocean annually, or by using a range of estimates about an uncertain phenomenon, this model can be used to produce a range of values for the entire system in a way that takes into account and accurately depicts the systemic nature of the plastic production and disposal system. By addressing inconsistencies in estimates through testing them in relation to known

quantities, these inconsistencies can be reduced and an understanding of the most accurate data estimates can be synthesized.

Similarly, by using known RTDs and known percentages of plastic moving between the various stocks in the plastic production system, unknown RTDs can be tested and determined based on the effect that occurs when they are tested in this model. For example, the amount of plastic on the surface ocean calculated by the model while running under ”real world” conditions was concurrent with the amount of plastic estimated to be in the surface ocean at the same time period as simulated in the model. This likely means that, since the ”upstream” flows were generally known quantities, the RTDs in the surface ocean that were estimated for the purposes of simulation were generally correct compared to settling rates of plastic into the benthic zone in the real world.

This model is easily scalable to different plastic production and pollution scenarios that simulation is needed to analyze. By changing the amount of plastic production to match a country's or region's instead of the globe's, and changing the values for the country's or region's plastic usage and waste management, this model has the capability to simulate gaps in data where data collection is difficult or had not been undertaken for a period of time. In concert with known quantities, this approach will allow a further closing of the knowledge gaps that exist in plastic production and pollution.

CHAPTER 7

CONCLUSIONS

7.1 RESEARCH IMPLICATIONS

In regard to the effect ocean RTDs have on the amount of plastic in the ocean, the findings of this model show that the system of waste plastic in the ocean is very sensitive to changes in the RTDs of the usage, waste, and environmental stocks, and is particularly sensitive to changes to the RTDs in the ocean itself. Halving or doubling the predicted RTDs retrieved from other published research caused changes in the amount of plastic in the ocean on the scale of orders of magnitude. The greatest influence was seen when altering the RTD for the ocean.

7.2 SUGGESTIONS FOR FUTURE RESEARCH

Potentially, downward actions such as biofouling, ingestion, and larvacean net capture play a much larger role in the downward transport of plastic than previously thought. To test this theory, a good next step for this line of research would be to more closely quantify the different expected flows out of the ocean surface and run similar tests to determine which flow or combination of flows was the most influential in reducing the amount of plastic on the ocean surface. Another next line of inquiry for this model would be to make it more complex by accounting for different terrestrial features such as rivers and coastal cities, and different features of ocean basins. More complexity could be added to the stocks as well, and a more focused, agent-based model could be constructed to observe how distinct instances of plastic in the system behave based on their individual properties,

using Lagrangian techniques in a stock and flow model. Both these techniques are beyond the scope and computing power of this project but could be good goals for future endeavors.

REFERENCES

Andrady, A. L. (2011). Microplastics in the marine environment. *Marine Pollution Bulletin, 62*(8), 1596-1605. https://doi.org/10.1016/j.marpolbul.2011.05.030

Baurick, T. (2020). 'Nurdle patrol' survey finds plastic pellets on almost every Louisiana and Texas beach. In *nola.com*. Last modified September 19, 2020. https://www.nola.com/news/environment/article_a0c43db8-fa9a-11ea-862e-874fec025dbe.html

Brahney, J. Mahowald, N., Prank, M., Cornwell, G., Kilmont, Z., Matsui, Hitoshi., & Prather, K. A. (2021). Constraining the atmospheric limb of the plastic cycle. *Proceedings of the National Academy of Sciences, 118*(16), e2020719118. https://doi.org/.1073/pnas. 2020719118

Briassoulis, D., Babou, E., Hiskakis, M., Scaarascia, G., Picuno, P., Guarde, D., & Dejean, C. (2013). Review, mapping and analysis of the agricultural plastic waste generation and consolidation in Europe. *Waste Management & Research: The Journal for a Sustainable Circular Economy, 31*(12). https://doi.org/10.1177/0734242X13507968

Carpenter, E., Anderson, S., Harvey, G., Milkas, H., & Peck, B. (1972). Polystyrene spherules in coastal waters. *Science, 172*(4062), 749-750. https://doi.org/10.1126/science.178 .4062.749

Carpenter, E., & Smith Jr., K.. (1972). Plastics on the Sargasso sea surface. *Science, 175*(4027), 1240-1241. https://doi.org/10.1126/science.175.4027.1240

Carr, S., Liu, J., & Tesoro, A. (2016). Transport and fate of microplastic particles in wastewater treatment plants. *Water Research 91*, 174-182. https://doi.org/10.1016/ j.watres.2016.01.002

Choy, A., Robison, B., Gagne, T., Erwin, B., Firl, E., Halden, R., Hamilton, A., Katija, K., Lisin, S., Rolsky, C., & Van Houtan, K. (2019). The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. *Scientific Reports 9*(7843), 1-10. https://doi.org/10.1038/s41598-019-44117-2

Cook Jr., F., & Hartz, K. (1983). Adsorption of chlorinated methanes from aqueous solution on selected plastic adsorbents. *American Water Works Association 75*(8), 423-426.

Coppini, G., Lyubartseva, S., Lecci, R., & Creti, S. (2018). *Proceedings of the International Conference on Microplastic Pollution in the Mediterranean Sea*. Switzerland: Springer International Publishing.

Cózar, A., Echevarria, F., González-Gordillo, J. I., Irigoien, X., Úbeda, B., Hernández-León, S., Palma, A. T., Navarro, S., García-de-Lomas, J., Ruiz, A., Fernández-de-Puelles, M. L., & Duarte, C. M. (2014). Plastic debris in the open ocean. *Proceedings of the National Academy of Sciences of the United States of America 111*(28), 10239-10244.

Duncan, E. M., Arrowsmith, J. A., Bain, C. E., Bowdery, H., Broderick, A. C., Chalmers, T., Fuller, W. J., Galloway, T. S., Lee, J. H., Lindeque, P. K., Omeyer, L. C. M., Snape, R. T. E., & Godley, B. J. (2019). Diet-related selectivity of microplastic ingestion in green turtles (*Chelonia mydas*) in the eastern Mediterranean. *Scientific Reports 9*(11581). https://www.nature.com/articles/s41598-019-48086-4

Geyer, R., Jambeck, J., & Law, K. (2017). Production, use, and fate of all plastics ever made. *Science Advances 3*(7). http://doi.org/10.1126/sciadv.1700782

Hartline, N., Bruce, N., Karba, S., Ruff, E., Sonar, S., & Holden, P. (2016). Microfiber masses recovered from conventional machine washing of new or aged garments. *Environmental Science Technology 50*(21), 11532-11538. https://doi.org/10.1021/acs.est.6b03045

Jambeck, J., Geyer, R., Wilcox, C., Siegler, T., Perryman, M., Andrady, A., Narayan, R., & Law, K. (2015). Plastic waste inputs from land into the ocean. *Science 347*(6223), 768-771. https://doi.org/10.1126/science.1260352

Jamieson, A., Brooks, L., Reida, W., Piertney, S., Narayanaswamy, B., & Linley, T. (2019). Microplastics and synthetic particles ingested by deep-sea amphipods in six of the deepest marine ecosystems on earth. *Royal Society Open Science 6*(2). https://doi.org /10.1098/rsos.180667

Kole, P., Lohr, A., Van Belleghem, F., & Ragas, A. (2017). Wear and tear of Tyres: a stealthy source of microplastics in the environment. *International Journal of Environmental Research and Public Health 14*(10). https://dx.doi.org/10.3390\%2Fijerph14101265

Law, K., Starr, N., Siegler, T., Jambeck, Jenna., Mallos, N., & Leonard, G. (2020). The United States' contribution of plastic waste to land and ocean. *Science Advances 6*(44). https://doi.org/10.1126/sciadv.abd0288

Laws, E. (2017). *Aquatic Pollution: An Introductory Text* (4th ed.). Hoboken, NJ: Wiley & Sons, Ltd.

Lebreton, L., 2019. The Quest to Find the Missing Plastic. The Ocean Cleanup. https://theoceancleanup.com/updates/the-quest-to-find-the-missing-plastic/

Maraveas, C. (2020). Environmental sustainability of plastic in agriculture. *Agriculture 10*(8). https://doi.org/10.3390/agriculture10080310

Moore, C., & Phillips, C. (2012). *Plastic Ocean: How a Sea Captain's Chance Discovery Launched a Determined Quest to Save the Oceans* (2nd ed.) (Avery, 2012). New York: Avery.

Moser, M., & Lee, D. (1992). A fourteen-year survey of plastic ingestion by western north Atlantic seabirds. *Colonial Waterbirds 15*(1), 83-94. https://doi.org/10.2307/1521357

Napper, I., & Thompson, R. (2016). Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. *Marine Pollution Bulletin 112*(1-2), 39-45. https://doi.org/10.1016/j.marpolbul.2016.09.025

National Institute of Environmental Health Sciences. (2021). Bisphenol A (BPA). Accessed September 14, 2021. https://www.niehs.nih.gov/health/topics/agents/sya-bpa/index.cfm

Nogueira, J., Evangelista, H., Valeriano, C. de M., Sifeddine, A., Neto, C., Vaz, G., Moreira, L., Cordeiro, R., Turcq, B., Aniceto, K. C., Neto, A., Martins, G., Barbosa, C., Godoi, R., & Shimizu, M. (2021). Dust arriving in the Amazon basin over the past 7,500 years came from diverse sources. *Communications Earth and Environment 2*(5). https://doi.org/10.1038/s43247-020-00071-w

Plag, H., Martin, D., 2022. A Comprehensive Stock and Flow Model of the Plastic Use Chain to Quantify Plastics in the Environment and Ocean. In preparation.

Rathnayake, Z. (2022). Nurdles are everywhere: how plastic pellets ravaged a Sri Lankan paradise. *The Guardian.* January 25, 2022. https://www.theguardian.com/environment/2022/jan/25/nurdles-are-everywhere-how-plastic-pellets-ravaged-a-sri-lankan-paradise

Ritchie, H., & Roser, M. (2018). Plastic pollution. *Our world in data.org.* https://ourworldindata.org/plastic-pollution

Schmidt, C., Krauth, T., & Wagner, S. (2017). Export of plastic debris by rivers into the sea. *Environmental Science Technology 51*(21), 12246-12253. https://doi.org/10.1021/acs.est.7b02368

Sherman, P., & van Sebille, E. (2016). Modeling marine surface microplastic transport to assess optimal removal locations. *Environmental Research Letters 11*(1). https://doi.org/10.1088/1748-9326/11/1/014006

Solid Waste Special Service District 1, Moab, Utah. (2017). *Dump or landfill? Is there a difference? A resounding yes!* Published December 8, 2017. https://swssd1.org/dump-or-landfill-is-there-a-difference-a-resounding-yes/

The problem. *The Great Nurdle Hunt: Tackling Worldwide Nurdle Pollution.* Accessed September 14, 2021. https://www.nurdlehunt.org.uk/the-problem.html

Tiseo, I. (2022). Global plastic production 1950-2020. *Statista.* Accessed February 12, 2022. https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/

Urbanek, A., Rymowicz, W., & Mironczuk, A. (2018). Degradation of plastics and plastic-degrading bacteria in cold marine habitats. *Applied Microbiology and Biotechnology 102*(1), 7669-7678. https://doi.org/10.1007/s00253-018-9195-y

Van Sebille, E., Wilcox, C., Lebreton, L., Maxmenko, N., Hardesty, B., van Franeker, J., Eriksen, M., Siegel, D., Galgani, F., & Law, K. (2015). A global inventory of small floating plastic debris. Environmental Research Letters 10(12). https://doi.org/10.1088/1748-9326/10/12/124006

Weiss, L., Ludwig, W., Huessner, S., Canals, M., Ghiglione, J.-F.., Estournel, C., Constant, M., & Kerherve, P. (2021). The missing ocean plastic sink: gone with the rivers. *Science 373*(6550). https://www.science.org/doi/10.1126/science.abe0290

Yamada, Y., Tokokawa, T., Uchimiya, M., Nishino, S., Fukuda, H., Ogawa, H., & Nagata, T. (2017). Transparent exopolymer particles (TEP) in the deep ocean: full-depth distribution patterns and contribution to the organic carbon pool. *Marine Ecology Progress Series 583*(1), 81-93. https://doi.org/10.3354/meps12339

Zhang, D., Ng, E., Hu, W., Wang, Hongyuan., Galaviz, P., Yang, H., Sun, W., Li, C., Ma, X., Fu, B., Zhao, P., Zhang, F., Jin, S., Zhou, M., Du, L., Peng, C., Zhang, X., Xu, Z., Xi, B., Gong, L., Kou, C., Li, Y., Ma, Y., Huang, D., Zhu, J., Yao, J., Lin, C., Qin, S., Zhou, Q., Wu, S., Zhang, Y., Pan, J., Gu, B., & Liu, H. (2020). Plastic pollution in croplands threatens long-term food security. *Global Change Biology 26*(6), 3356-3367. https://doi.org/10.1111/gcb.15043

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