How much innovation is needed to protect the ocean from plastic contamination?

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Mateo Cordier*, [1, 2] and Takuro Uehara[3]

[1] Research Centre Cultures–Environnements–Arctique–Représentations–Climat (CEARC), Université de Versailles-Saint-Quentin-en-Yvelines, UVSQ, 11 Boulevard d'Alembert, 78280 Guyancourt, France; mateo.cordier@uvsq.fr

[2] Centre d'Etudes Economiques et Sociales de l'Environnement-Centre Emile Bernheim (CEESE-CEB), Université Libre de Bruxelles, 44 Avenue Jeanne, C.P. 124, 1050 Brussels, Belgium.

[3] College of Policy Science, Ritsumeikan University, 2-150 Iwakura-Cho, Ibaraki City, 567-8570 Osaka, Japan.

* Corresponding author: Mateo Cordier, 11 Boulevard d'Alembert, 78280 Guyancourt, France. Email address: mateo.cordier@uvsq.fr

Abstract

Plastics are non-biodegradable, and increasing accumulation of plastic debris in the ocean is a major cause for concern. The World Economic Forum, Ellen MacArthur Foundation, and McKinsey & Company claimed in 2016 that technological innovations can solve the plastic problem. Such a claim raises an as yet unanswered question: how much technological innovation is needed and is it economically feasible? We offer answers to this question via a system dynamics model that we developed to simulate different scenarios aimed at controlling plastic debris entering the global ocean. Our results show that ocean cleanup technologies could achieve a 25% reduction in the level of plastic debris in the ocean below 2010 levels in 2030. However, this would require removing 15% of the stock of plastic debris from the ocean every year over the period 2020-2030, which equates to 135 million tons of plastic in total (metric tons). The implementation cost of such an ocean cleanup effort would amount to €492 billion-€708 billion, which represents 0.7%-1.0% of the world GDP in 2017 – this calculation is based on unit costs in €/kg estimated in The Ocean Cleanup project feasibility study. The Ocean Cleanup project alone is designed to collect 70320 tons of plastic debris over a 10 year period. Removing 135 million tons of plastic debris would require investing in 1924 similar cleanup projects. These results help to assess the economic feasibility of removing such large volume of plastics. Moreover, our results provide quantitative confirmation that technological solutions alone are not sufficient to solve plastic pollution issues. A portfolio of diverse solutions – not only technological ones – is likely to have greater technical, political and economic feasibility. Our model shows that such a combined portfolio implemented over the period 2020-2030 could reduce the ocean plastic stock to 2013 levels (94 million tons) by 2030.

Key words: marine ecosystem, waste management, ocean cleanup, system dynamics, decoupling GDP, marine litter.

1. Introduction

Plastics have become increasingly dominant in the consumer marketplace since their commercial development in the 1930s and 1940s (Jambeck et al., 2015). Global plastic production – that is, global polymer resin and fiber production – reached 381 million tons per year in 2015, an 8-fold increase from 1975 (data from Geyer et al., 2017, supplementary material). (All ton units used hereinafter are metric tons). In 1960, plastics made up less than 1% of municipal solid waste by mass in the United States (the United States Environmental Protection Agency, 2011). By 2000, this proportion increased by one order of magnitude (Jambeck et al., 2015).

The release of plastics into the marine environment occurs from land through a variety of sources, including atmospheric transport, littering, and illegal dumping, as well as discharge from rivers, storm drains, and sewage outflows. Plastic waste is sometimes also directly discarded at sea by fishing, aquaculture, and shipping activities (Lebreton et al., 2017; Horton et al., 2017). Since 2014, scientists have succeeded in providing gross estimates of the ecological, social and economic impacts of plastic pollution (UNEP, 2014; Jaacks and Prasad, 2017; McIlgorm et al., 2011). Plastics in the marine ecosystem are of increasing concern because of their persistence in the environment (Li et al., 2016) and their effects on the oceans and wildlife (Barnes et al., 2009; Baztan et al., 2017; da Costa et al., 2016), and, potentially, on human health (Trasande et al., 2015; Thompson et al., 2009; Shea and Committee on Environmental Health, 2003).

Plastic debris input volumes from land to the global ocean are closely correlated with the world economy as shown in Figure 1. Several authors have studied the possibilities of decoupling contaminant generation from economic growth (Jackson, 2009; Sjöström and Östblom, 2010). However, the close relationship between plastic contaminants and global Gross Domestic Product (GDP) in Figure 1 suggests that decoupling is a challenge. A report from the MacArthur Foundation (World Economic Forum et al., 2016) claimed that technological innovation can solve the plastic problem. However, the report does not say how much innovation is needed and does not analyze the feasibility of such interventions. Moreover, *"waste management has not proven to be a 'one size fits all' solution. If we look all over the world we see a diversity of strategies to reduce, reuse, recycle and clean up our waste"* (Rochman, 2016). In addition, historical studies show that technological innovations alone cannot solve ecological issues in an ever growing economy. To date, improvements in terms of reduction in contaminant and waste generation through cleaner technology innovation are often offset by increases in consumption and production levels driven by economic growth (Haberl et al., 2006; Jackson, 2009; Victor, 2008; Krausmann et al., 2009). This means that although cleaner technology innovations have succeeded in reducing contaminant and waste generation per unit of GDP, the continuous growth of GDP has overtaken improvements made in the ways in which each unit of GDP is produced. In this paper, we develop a world model that simulates plastic waste emission by human activities, transport from land to the ocean and accumulation in the marine ecosystem. The model is designed in Powersim following the system dynamics method (Sterman, 2000).

To date, there are no estimations of the overall global technological and economic effort required to reduce the annual flow of plastics entering the global ocean (estimated to 4.8-12.7 million tons/year by Jambeck et al., 2015) as well as the total stock accumulated in the ocean. And yet, this is quite important, since without waste management infrastructure improvements, the cumulative quantity of plastic waste entering the ocean from land (i.e., mismanaged waste) is predicted to double 2010 levels by 2025 (Jambeck et al., 2015).

Jambeck et al. (2015) use their estimations to evaluate potential global mitigation strategies in terms of mismanaged waste. They propose mitigation strategies in the 20 top countries ranked by the mass of mismanaged plastic waste. The top 20 countries' mismanaged plastic waste encompasses 83% of the total in 2010. They define mismanaged waste as material that is either littered or inadequately disposed of. Inadequately disposed waste is not formally managed and includes disposal in dumps or open, uncontrolled landfills, where it is not suitably contained. Mismanaged waste could eventually enter the ocean via inland waterways, wastewater outflows, and transport by wind or tides. With the world model developed in this paper, we assess the impact of three mitigation strategies proposed by Jambeck et al. (2015) on the plastic stock in the global ocean. Our aim is to verify, using the model, whether the simultaneous implementation of a portfolio of strategies (Table 1) could better achieve environmental targets than individual solutions.

The remainder of the paper is organized as follows. Section 2 outlines the methodology. In that section, we develop the model used to simulate scenarios of various environmental measures. We also describe each scenario. Section 3 is devoted to the simulation results showing the potential impact of each scenario. Section 4 is reserved for discussion of the results, and Section 5 for the conclusions.

[Insert Figure 1 here]

[Insert Table 1 here]

2. Method

All scenarios presented in Section 3 include a world population annual growth rate that varies between 1.0% and 1.2% depending on the year considered, based on forecasts from the United Nations (2017). The simulation model is based on System dynamics (SD) (Sterman, 2000) to capture the dynamics of marine plastic debris from their origin (their generation on land) to their fate (when they enter the ocean). System dynamics is a computer-aided approach to a system of coupled, nonlinear, first-order differential (or integral) equations (Richardson, 1991). System dynamics is suitable because it describes the complex dynamics of a system with a specific emphasis on flows and stocks. Marine plastic debris involves complex, dynamic social-ecological systems where stock is a key variable. Marine plastic debris flows from the land to the ocean where it accumulates, generating a stock of floating plastics in the water and depositing plastic on the seabed.

2.1 System dynamics model

Figure 2 shows the stock and flow diagram of the system dynamics model for marine plastic wastes. We used Powersim Studio 10 (http://www.powersim.com) to build the model.

[Insert Figure 2 here]

There are two critical stocks in the model: coastal population and plastic waste in the ocean (the full model in Powersim format can be provided upon request). The dynamics of the coastal population is defined as follows (more equations can be found in supplementary material online):

$$Coastal\ population^{t} = \int_{t_0}^{t_n} (Changes\ in\ coastal\ population^{t})dt + Coastal\ population^{t_0} \qquad (1)$$

The model focuses on the dynamics of the coastal population. Changes in the coastal population are assumed to be the same as changes in the world population using global population growth rate forecasts of the United Nations (2017).

Waste generation is proportional to the coastal population and is defined as follows:

$$Waste\ generation^{t} = Waste\ generation\ rate \times Coastal\ population \times 365\ days \qquad (2)$$

Plastic waste in the ocean is defined as:

$$Plastic\ waste\ in\ the\ ocean^{t} = \int_{t_0}^{t_n} (Entering\ rate^{t} - Cleanup\ rate^{t})dt + Plastic\ waste\ in\ the\ ocean^{t_0} \qquad (3)$$

The model assumes that the volume of plastic waste in the ocean accumulates in the ocean. It does not decline unless ocean cleanup operations are implemented. The entering rate is determined by mismanaged plastic waste and fractional entering rate (Figure 2).

In addition to the cleanup rate, there are primarily three variables related to environmental policies that can influence the entering rate: *Waste generation rate*, *% Plastic waste in stream*, and *% Inadequately managed waste* (Figure 2). The model allows environmental targets to be set for each of these three variables. The time taken to achieve the environmental targets can be modified by changing the variable adjustment time in the model. The equations for each of the variables have the same structure. For example, *Waste generation rate* is modelled as:

$$Waste\ generation\ rate^{t} = \int_{t_0}^{t_n} (Change\ in\ waste\ generation\ rate^{t})dt + Change\ in\ waste\ generation\ rate^{t_0} \qquad (4)$$

$$Change\ in\ waste\ generation\ rate^{t} = \frac{(Target\ waste\ generation\ rate^{t} - Waste\ generation\ rate^{t})}{Adjustment\ time\ 3^{t}} \qquad (5)$$

Therefore, *Waste generation rate* is equalized to *Target waste generation rate* in the next period when *Adjustment time 3* = 1. The greater an adjustment time, the longer a variable takes to achieve the target level.

2.2 Scenario simulation

Using the model, we simulate four sets of scenarios that describe the possible evolution of plastic stock in the world's ocean from 2010 to 2030. Scenarios 2 to 4 simulate the implementation of plastic solutions over the period 2020-2030. Each scenario is simulated by changing relevant variable values in the model (e.g., change in *% Inadequately managed waste* and *Fractional cleanup rate whole term*). To determine values consistent with scenarios, we use the evolutionary search algorithm (Powersim Solver 2.5), which enables calculation of the optimal *Fractional cleanup rate whole term* which realizes a target level of *Plastic waste in the ocean*. Technically, the model derives the *Fractional cleanup rate whole term* (called *Decision* in Powersim) that minimizes *deviation from target* (called *Objective* in Powersim), which is the difference between *Target plastic waste level in the ocean* and *Plastic waste in the ocean* in the model.

Technical details of all the scenario calculations can be found in supplementary material online as well as the values of the model parameters used in the scenarios (Supplementary Table S2). Table 2 below summarizes the values for several key variables.

[Insert Table 2 here]

Scenario 1 – Business As Usual

The *Business As Usual* scenario (BAU) is a reference scenario against which all the other scenarios can be compared. This scenario assumes that no additional environmental measures are implemented beyond those implemented in 2010, the reference year of the model. We assume the ocean cleanup effort to be very low. We arbitrarily set the cleanup effort at an annual removal percentage of 0.10 % of the total stock of plastics in the oceans worldwide (plastics floating at the water surface, in the water column, and deposited on the seabed).

Scenario 2.1 –"Ocean cleanup for 2020 stabilization"

The second set of scenarios are aimed at stabilizing the total plastic stock in the oceans at 2020's level by 2030. The model parameters described below in scenarios 2.1-2.4 have been estimated using an optimization technique, the evolutionary search algorithm *Powersim Solver 2.5,* to achieve stabilization. In this scenario, 4.22% of the stock of plastic debris in the ocean is removed every year between 2020 and 2030. This percentage is the *Fractional cleanup rate whole term*, i.e., one of the variables of the model from Figure 2. This is a curative “end-of-pipe” solution (i.e., solutions 18-20 in Table 1). Such technological solutions are currently in the testing phase in the ocean, for example the Ocean Cleanup Project (Slat, 2014).

Scenario 2.2 – “Zero inadequately managed waste”

This scenario simulates improvements made to waste collection infrastructure, a preventive “middle” solution (i.e., solutions 13-17 in Table 1) such as developing landfill sealing and improving collection of wastes, installing public plastic recycling bins, etc. in a way that 100% of waste collection infrastructure is managed properly. This strategy would require substantial infrastructure investment primarily in low- and middle-income countries, where it is lacking. In the absence of additional contributions by high-income countries (e.g., implementation of plastic solutions in high-income countries such as in scenario 2.3 or 4.2), there will be low social and political acceptability at the international level, which might reduce the likeliness of implementation.

Scenario 2.3 – “Waste management & ocean cleanup”

This scenario simulates the same preventive “middle” solutions as in scenario 2.2 (i.e., solutions 13-17 in Table 1) except that the effort has been halved (only 50% of inadequately managed waste collection infrastructure is improved) and combined with a curative “end-of-pipe” solution: plastic removal from the ocean (i.e., solutions 18 to 20 in Table 1). In this scenario, 2.33% of the stock of plastic debris in the ocean is removed every year between 2020 and 2030 in order to stabilize the level of plastic in the global ocean to the2020 levels.

Scenario 2.4 – "Zero plastic litter"

This scenario simulates preventive "middle" solutions to reduce the number of people who litter plastic wastes to zero – i.e., solution 14 in Table 1 – that could be achieved through awareness raising campaigns and/or encouraging collaborative strategies, based on the approaches proposed by Benkler (2011) and Ostrom (2010).

Scenario 2.5 – "Combined strategy I"

This scenario combines several solutions: ocean cleanup as in scenario 2.1, waste management as in scenario 2.3 and zero plastic litter as in scenario 2.4. This scenario assumes that 4.22% of the stock of plastic debris in the ocean is removed every year between 2020 and 2030 (scenario 2.1); 50% of inadequately managed waste are improved and turned into properly managed waste (scenario 2.3), and the percentage of plastic waste litter is reduced to zero (scenario 2.4).

Scenario 3.1 – "Ocean cleanup for 25% reduction"

This scenario is designed as scenario 2.1 except that the optimization process achieves a 25% reduction in the level of plastic debris in the ocean below 2010 levels in 2030. The optimization results from the model show that to achieve this target, 15.16% of plastic debris in the ocean must be cleaned up every year between 2020 and 2030.

Scenario 3.2 – "Ocean cleanup for 50% reduction"

This scenario is similar to the previous one except that the optimization process achieves a 50% reduction in the level of plastic debris in the ocean below 2010 levels in 2030. The optimization results from the model show that to achieve this target, 21.14% of plastic debris in the ocean must be cleaned up every year between 2020 and 2030.

Scenario 4.1 – "Waste management in 20 countries"

The fourth set of scenarios simulate some of the environmental measures proposed by Jambeck et al. (2015). Scenario 4.1 simulates a preventive "middle" solution similar to scenario 2.2 with only two differences: inadequately managed wastes are reduced only by 50% and exclusively *in the 20 top countries ranked by mass of mismanaged plastic waste.* Selecting a limited amount of countries should ease the implementation of such an ambitious target.

Scenario 4.2 – "Capping wastes"

This scenario simulates preventive "at-the-source" solutions based on the first 12 solutions (in Table 1) from the following three categories: *i*) avoid and reduce waste production, *ii*) reuse or repair old products, *iii*) recycle in closed-cycles and extend producer responsibility. Individual waste generation is capped at 1.2 kg/day/capita (the world average in 2010 for all kinds of wastes, plastic and non-plastic ones). Such an environmental measure would target higher-income countries and might require smaller global investments. Most of the low- and middle-income countries generate less waste per capita than high-income countries.

The percentage of plastics in the waste stream are capped at 11.1% (the world average in 2010). Such an environmental policy would universally target low-, middle- and high-income countries which exceed this world average.

Scenario 4.2 could be achieved through awareness raising campaigns and encouraging collaborative strategies based on approaches proposed by Benkler (2011) and Ostrom (2010). Such approaches might help to incite people to mitigate overconsumption behaviors in general (plastic products included). Installing public recycling bins and developing returnable bottle systems also helps in achieving the target in this scenario.

Scenario 4.3 – "Zero inadequately managed waste in 10 countries & capping plastic wastes"

In this scenario, full waste management is achieved, as in scenario 2.2, except that the requirement for reducing the volume of mismanaged plastic waste is limited to the top-10 ranked countries in Jambeck et al. (2015). These top 10 countries are all low- and middle-income countries. Such plastic waste management is a preventive "middle" solution (solutions 13-17 in Table 1). Simultaneously, plastic waste generation is capped at 11% in all countries, as described in scenario 4.2, which universally targets low-, middle- and high-income countries. Such a cap is a preventive "at-the-source" solution based on changing consumer and producer behaviors (solutions 1 to 12 in Table 1).

Scenario 4.4 – "Combined strategy II"

This scenario combines *waste management in the 20 top countries* (as in scenario 4.1), *capping wastes* (as in scenario 4.2), and *ocean cleanup for 2020 stabilization* (as in scenario 2.1). This means it simulates a preventive "middle" solution, a preventive "at-the-source" solution and a curative "end-of-pipe" solution.

2.3 Estimating plastic flows entering the ocean

The first estimations of the quantity of plastic entering the ocean from waste generated on land were calculated in 1975 (National Research Council, 1975). Jambeck et al. (2015) proposed new estimations in 2015 by linking worldwide data on solid waste, population density, and economic status to estimate the mass of land-based plastic waste entering the ocean. They calculated for the year 2010 that 275 million tons of plastic waste was generated by coastal populations (i.e., populations living within 50 km of a coast) in 192 coastal countries, with a total of 4.8 to 12.7 million tons entering the ocean annually at the global scale.

Since then, other studies have quantified the amount of plastic entering the ocean from land via rivers. Schmidt et al. (2017) estimate for the period 2004-2016 that 0.41 to 4.00 million tons of plastics were probably entering the global ocean every year from rivers. Lebreton et al. (2017) estimate this range to be between 1.15 and 2.41 million tons a year for the period 2005-2015. If rivers are the main pathway for plastic debris to the ocean from land, this would mean that the range proposed by Jambeck et al. (2015) might be overestimated (at least for their higher margin, 12.7 million tons/year). However, plastic wastes within coastal areas do not only enter the oceans through rivers. They can also reach oceans by other processes, such as direct littering near beaches by tourists or at sea by fishermen and aquaculture activities, storm water runoff, tidal or wind transport, illegal dumping, and sewage outflows during heavy rains (Lebreton et al., 2017; Schmidt et al., 2017; GESAMP, 2016). It is also important to note that the river models from Schmidt et al. (2017) and Lebreton et al. (2017) are limited to buoyant plastics found on river surface waters, whereas Jambeck et al. (2015) consider all types of plastics found in municipal waste. Finally, river models only consider a limited range of the full spectrum of plastic debris, as particles smaller than the mesh size of the sampling nets are not accounted for and debris larger than the aperture size of the trawl devices are under-represented (Lebreton et al., 2017). For these reasons, the estimates of Lebreton et al. (2017) and Schmidt et al. (2017) should be considered conservative.

Moreover, Jambeck et al. (2015) limited their assessment to plastic wastes generated by populations living within 50 km of a coast (assuming that they are those likely to generate most of the waste becoming marine debris). Although coastal populations are a key factor directly affecting the input of plastic into the ocean, populations living along large rivers, travelers to the beaches, etc. may also contribute to marine plastic debris.

Some researchers estimate that terrestrial waterways are the main transport processes by which debris is transported from the land to the coast (Willis et al., 2017). A very rough estimation predicts that 70% to 80% of marine litter, most of it plastics, originates from inland sources and are transported by rivers to the oceans (Bowmer and Kershaw, 2010; Wagner et al., 2014; Jambeck et al., 2015). This means that the higher range estimated by Schmidt et al. (2017) (4.0 million tons/year) represents about 75% (the middle of the range 70-80% mentioned above) of the total annual mass of plastic debris reaching the ocean from land. A simple rule of thumb allows us to estimate the total flow of plastics entering the ocean at 5.3 million tons/year: 4.0/75 * 100 = 5.3. In this way, we corrected the annual flows from Schmidt et al. (2017) and also those from Lebreton et al. (2017), which are mentioned in the legend of Figure 3, before entering them into Eq. (6). The higher estimate given by Schmidt et al. (2017), after correction, is close to 4.8 million tons/year, which is the value we chose as a starting parameter for the reference year in our model (i.e., the lower range calculated by Jambeck et al. (2015)).

Using the parameters from Jambeck et al. (2015) corresponding to their lower range and applying them to the estimations of Geyer et al. (2017), we obtained a total stock of ocean plastic debris of 79.24 million tons in 2010 (Figure 3). Our calculation is based on the total volume of plastic wastes generated in the world over the 1950-2015 period, i.e.

5700 million tons (Geyer et al., 2017), from which we subtracted the flows from 2011-2015 to obtain the stock of plastic debris cumulated from 1950-2010. We then applied the parameters from Jambeck et al. (2015) to account for the percentage of the world population living within 50 km of the coast (29%), the share of plastic wastes that is inadequately managed (30%) and littered (2%) as well as the share of mismanaged waste (i.e., inadequately managed waste and littered waste) that enters the ocean (15%). Calculation details are available in supplementary materials in Eq. (S1).

Our estimation of the total stock of plastics accumulated in the oceans from 1950-2010 correlate with the annual flow calculated in other studies for the year 2010. We extrapolated this annual flow for the year 2010 into an accumulated flow over 1950-2010. To do so, we recalculated the total stock of plastic in the ocean using an alternative method. First, we estimated annual flows of land-based plastic entering the ocean every year ($Ocean\ plastic\ input_{t-1}$ in Eq. (6)) over the period 1950-2010 assuming the growth rate is proportional to the growth rate in the world plastic industrial production ($Plastic\ production_t$ in Eq. (6), data provided by Geyer et al. (2017), supplemental materials). This translates into the following equation:

$$Ocean\ plastic\ input_{t-1} = Ocean\ plastic\ input_t \frac{Plastic\ production_{t-1}}{Plastic\ production_t} \quad (6)$$

Using Eq. (6) to calculate the ocean plastic input, for example in 2009, we enter in the equation $Plastic\ production_{t-1=2009}$ = 288 million tons, $Plastic\ production_{t=2010}$ = 313 million tons (Geyer et al., 2017, in supplemental materials) and $Ocean\ plastic\ input_{t=2010}$

= 4.8 million tons/year, for example, the lower estimation from Jambeck et al. (2015). The result gives $Ocean\ plastic\ input_{t-1=2009}$ = 4.42 million tons/year in 2009. Second, applying Eq. (6) for each year back to the year 1950 and summing the annual results from 1950 to 2010 gives a total stock of plastic debris in the ocean of 92.9 million tons. This is quite close to our estimation based on Eq. (S1) (79.24 million tons).

Figure 3 also shows that the result from Eq. (S1) is quite close to the estimation obtained when entering in Eq. (6) for 2010, after correction, the higher range from Lebreton et al. (2.41 million tons/year) or from Schmidt et al. (4.0 million tons/year). It gives a total stock of plastic debris in the global ocean in 2010 of 62.21 and 103.26 million tons, respectively. Obtaining relatively similar results with completely different methods indicates that we are approaching an accurate estimation. The likely range might be 62-103 million tons in 2010.

[Insert Figure 3 here]

3. Results

We simulated four sets of scenarios that describe the evolution of plastic stock in the world's ocean from 2010 to 2030. All environmental scenarios (scenarios 2 to 4) simulate the implementation of plastic solutions over the period 2020-2030.

The first set of scenarios displayed in Figures 4-6 is Scenario 1 *Business As Usual* (BAU). Figure 4 and Table 3 suggest that, in the absence of environmental measures, the stock of plastic debris accumulated in the world ocean might reach 183 million tons in 2030 (plastics floating at the surface, in the water column and deposited on the seabed).

The second set of scenarios displayed in Figure 4 are scenarios 2.1 to 2.5. *Scenario 2.1 Ocean cleanup for 2020 stabilization* succeeds in stabilizing the ocean plastic stock in 2030 at 134 million tons, at 2021 levels. This means removing a total of 57.5 million tons of plastic debris over a 10-year period. Figure 4 shows that if *Scenario 2.2 Zero inadequately managed waste* is implemented, the amount of plastic stock in the ocean would stabilize at 138 million ton, at 2022 levels. *Scenario 2.3 Waste management & ocean cleanup* succeeds in stabilizing the ocean plastic stock in 2030 at 134 million tons, at 2021 levels. Regarding *Scenario 2.4 Zero plastic litter,* Figure 4 suggests that if such a scenario were implemented, the stock of plastic debris in the ocean would reach 177 million tons by 2030, i.e. only 3.6% below the BAU level. *Scenario 2.5 Combined strategy I* might lead to a reduction of plastic debris in the world ocean in 2030 to 110 million tons, that is, corresponding to 2016-2017 levels.

[Insert Table 3 here]

The third set of scenarios is displayed in Figure 5. *Scenario 3.1 Ocean cleanup for 25% reduction* succeeds in reducing plastic debris in the world ocean in 2030 to 2002 levels (59 million tons), which means removing a total of 135.3 million tons of plastic debris over a 10 year period. *Scenario 3.2 Ocean cleanup for 50% reduction* succeeds in reducing plastic debris in the world ocean in 2030 to 1996 levels (40 million tons), which means removing a total of 154.5 million tons of plastic debris over a 10 year period.

The fourth set of scenarios is displayed in Figure 6. In *scenario 4.1 Waste management in 20 countries*, the stock of plastic debris in the world ocean reaches a level of 164 million tons in 2030, i.e., 10.4% below the BAU level. *Scenario 4.2 Capping wastes* seems to succeed in stabilizing the stock of plastic debris in the ocean at 138 million tons by 2030, i.e. 24% below the BAU level. *Scenario 4.3 Zero inadequately managed waste in 10 countries & capping plastic wastes* may succeed in stabilizing the stock of plastic debris in the ocean at 136 million tons by 2030, i.e. 26% below the BAU level. *Scenario 4.4 Combined strategy II* succeeds in reducing plastic debris in the world ocean in 2030 to 2013 levels (94 million tons), i.e., 49% below the BAU scenario.

[Insert Figure 4 here]

[Insert Figure 5 here]

[Insert Figure 6 here]

4. Discussion

Inciting citizens to stop plastic littering could theoretically help to reduce plastic flows from land to the ocean. However, simulation results for the scenario *Zero plastic litter* (scenario 2.4) suggest that even if all inhabitants in the world stop littering waste, plastic flows entering the world ocean would continue to increase. This suggests that focusing all efforts on reducing plastic littering will contribute little to solving the plastic problem. The final consumer's environmental responsibility is quite limited. Solutions should be focused on collective efforts for a significant positive impact to be observed in terms of abatement of plastic ocean contamination.

Simulation results of the scenario *Zero inadequately managed waste* (scenario 2.2) strengthen this assumption since it succeeds in stabilizing the ocean plastic stock, whereas scenario *Zero plastic litter* does not. Scenario 2.2 simulates a future where the world would have achieved zero inadequately managed waste, which means huge investments in low- and middle-income countries in terms of collective management of wastes, to avoid plastic leakages caused by wind or by rains from dumps or open, uncontrolled landfills.

The scenarios *Waste management & ocean cleanup* (scenario 2.3) and *Ocean cleanup for 2020 stabilization* (scenario 2.1) succeed in stabilizing the ocean plastic stock in 2030 at 2021 levels with less pressure on low- and middle-income countries. To achieve this environmental target, scenario 2.3 plans to simultaneously implement ocean cleanup and a 50% reduction of inadequately managed waste systems in all countries. This puts greater pressure on countries with high levels of inadequately managed waste. In scenario 2.1, the environmental target is exclusively achieved through ocean cleanup. However, this would require removing 4.22% of the global ocean plastic stock (plastics floating on the surface, in the water column and deposited on the seabed) every year between 2020 and 2030. For scenario 2.3, this percentage is reduced to 2.33%. A feasibility study could help to assess if such cleanup targets are technically and economically feasible.

In Boyan Slat's feasibility study (Slat, 2014, pp. 30-32 and 241), they plan to remove 70320 tons of plastics from the oceans over a period of 10 years, which might cost 3639 €/ton (base case), 4511 €/ton (best case) or 5236 €/ton (worst case). These costs include: (i) the required investment in capital expenditures; (ii) the estimated operating expenses over ten years, (iii) the replacement cost of equipment that has a useful life of 5 years and (iv) decommissioning costs after 10 years (Slat, 2014, pp. 32 and 435).

In the scenario *Ocean cleanup for 2020 stabilization* (scenario 2.1), removing 4.22% of ocean plastic stock every year over 10 years will remove a total of 57.49 million tons of plastics. The total cost of this scenario might amount to €209.21 billion (base case), € 259.34 billion (best case) or € 301.02 billion (worst case) – own calculation based on unit costs from Slat (2014) mentioned above. This would represent respectively 0.29%, 0.36% or 0.42% of the world GDP in 2017 (World Bank, 2018). These cost estimations are based on an estimation of plastic stock in the world's ocean in 2010, amounting to 79.24 million tons – own calculation based on data from Geyer et al. (2017) and Jambeck et al. (2015); calculation details are available in supplementary materials (Eq. S1). Using the lower ranges of Schmidt et al. (2017) or Lebreton et al. (2017) (Figure 3) could drastically reduce the cost estimations as well as the total amount of plastics to be cleaned up in scenarios 2.1 and 2.3. This should be investigated in further research. Moreover, calculating allocation rules (Cordier et al., 2018) for these costs to be spread over time as well as across economic sectors and countries could also significantly reduce the GDP percentages estimated above.

For more stringent environmental targets, such as aiming to achieve the mid-2000s levels, additional measures must be undertaken. Simulation results for the *Combined strategy I* (scenario 2.5 displayed in Figure 4) show that a combination of strategies is more likely to achieve that goal. Scenario 2.5 combines ocean cleanup for 2020 stabilization (scenario 2.1), improved waste management to reduce inadequately managed waste systems by 50% in all countries (part of scenario 2.3), and individual behavior changes to incite people to stop littering plastic products (scenario 2.4). This suggests that combining different kinds of environmental measures downstream and upstream across social-ecological systems ("end-of-pipe" and "at-the-source" solutions – Table 1) as well as downstream and upstream across plastic contamination causal chains ("curative" and "preventive" solutions) is more successful than scenarios where only one type of environmental measure is undertaken.

The scenarios *Waste management in 20 countries* (scenario 4.1), *Capping wastes* (scenario 4.2) and *Zero inadequately managed waste in 10 countries & capping plastic wastes* (scenario 4.3) are intended to be more realistic and achievable. Scenario 4.1 proposes to improve only 50% of the inadequately managed waste – not 100% – in only 20 countries – not the entire world. The idea is to obtain a marine ecological improvement with the minimum effort required in order to make plastic solutions more feasible. However, scenario 4.1 shows poor results in terms of ecological impact. That is, there is not much of an improvement in the level of plastic stock in the ocean compared to the BAU level. Scenario 4.2 performs better and succeeds in stabilizing the stock of plastic debris in the ocean by 2022 via two strategies: capping individual waste generation at 1.2 kg/day/capita (the world average in 2010) in all countries and capping plastics in the waste stream at 11.1% (the world average in 2010). Scenarios 4.3 also succeeds in stabilizing the stock of plastic debris in the ocean by 2022 via two strategies: improving waste management systems in 10 countries to achieve zero inadequately managed waste in those countries and capping plastics in the waste stream at 11.1% in all countries.

The combined strategy implemented in Scenario 4.3 combines a 100% reduction in inadequately managed waste in the 10 top countries with the capping of plastics in the waste stream at 11.1%. This combined strategy could be regarded as more equitable and socially and politically acceptable because low-, middle- and high-income countries would all participate in plastic solutions on the basis of the principle of their common but differentiated responsibilities. That is, they would all bear a common environmental responsibility but their contribution to plastic solutions would be differentiated according to their level of responsibility and to their affordability (i.e. their ability to pay for plastic solutions). This makes the implementation of this scenario more likely. However, capping plastics in waste stream at 11% would require changes in consumer behavior. This is not easy to achieve unless awareness raising campaigns are designed appropriately to encourage consumers/citizens to behave collectively towards a common target, a plastic-free ocean. Specific approaches are required to change individual mentality and switch from individualistic to collaborative behaviors (Benkler, 2011; Ostrom, 2010).

The scenario *Combined strategy II* (scenario 4.4) is another combined strategy since it merges scenarios *Waste management in 20 countries* (scenario 4.1), *Capping wastes* (scenario 4.2) and *Ocean cleanup for 2020 stabilization* (scenario 2.1). Scenario 4.4 involves three categories of solutions: a preventive "middle" solution (scenario 4.1), a preventive "at-the-source" solution (scenario 4.2) and a curative "end-of-pipe" solution (scenario 2.1). Implementation of avoid, reduce, reuse strategies, improvements in waste collection infrastructure, and ocean cleanup encourage changes in behavior in addition to technological solutions. Scenario 4.4 follows a similar approach as scenario 2.5 but it performs better and succeeds in achieving 2013 levels. This strengthens our assumption from scenario 2.5 that combining different kinds of environmental measures downstream and upstream (Table 1) is more successful than scenarios where only one type of environmental measure is undertaken. This scenario also combines environmental measures in different categories of countries. Improving waste management infrastructure in developing countries (Scenario 4.1 *Waste management in 20 countries*) is paramount and will require substantial resources and time. While such improvements in infrastructure are being implemented, industrialized countries can take immediate action by reducing waste and curbing the use of single-use plastics (scenarios 4.2 *Capping wastes* and 4.3 *Zero inadequately managed waste in 10 countries & capping plastic wastes*) as well cleaning-up the ocean (scenario 2.1) (Jambeck et al., 2015).

The combined upstream and downstream solutions simulated in *Combined strategy I* (scenario 2.5) and *Combined strategy II* (scenario 4.4) could either come from the top (political and economic decision makers) or the bottom of the society (citizens, environmental associations, small size enterprises). These solutions will require a change in mentality to encourage individuals to act collectively. Ostrom (2010) and Benkler (2011) have identified about 10 conditions required to create a context in which people are willing to self-organize at multiple levels and collaborate to find a solution to a common problem, such as achieving a plastic-free ocean.

Given the current marine biodiversity crisis in the world (Pauly and Zeller, 2017; Halpern et al., 2008; Worm et al., 2006), it might be interesting to test scenarios that allow for greater plastic abatement. Figure 5 shows that cleanup effort alone – scenario 3.2 *Ocean* *cleanup for 50% reduction* – could reduce the amount of plastic stock in the global ocean to 50% of 2010 levels in 2030. However, this would require removing 21.14% of the plastic stock from the ocean every year over the period 2020-2030. Scenario 3.1 *Ocean cleanup for 25% reduction* shows that reducing this target by half (achieve a 25% reduction in the level of plastic stock in the ocean below 2010 levels in 2030) would require removing 15.16% of plastic stock from the ocean every year over the same period.

In the scenario *Ocean cleanup for 50% reduction* (scenario 3.2), removing 21.14% of ocean plastic stock every year over 10 years results in removal of a total of 154.45 million tons of plastics. The total cost of this scenario might amount to € 562.04 billion (base case), € 696.72 billion (best case) or € 808.70 billion (worst case) – own calculation based on unit costs from Slat (2014, pp. 30-32 and 241). This would represent respectively 0.79%, 0.98% and 1.13% of the world GDP in 2017 (World Bank, 2018). In the scenario *Ocean cleanup for 25% reduction* (scenario 3.1), these percentages drop to respectively 0.69%, 0.85% and 0.99% of the 2017 world GDP.

In further research, scenarios simulated in Figure 5 could be improved by taking into account other cleanup strategies, such as addressing plastic waste directly dumped or lost in the ocean through aquaculture and fishing activities, and implementing cleanup activities on beaches.

5. Conclusions

Our paper demonstrates that combining multiple strategies to solve ocean plastic contamination provides better results than individual solutions. Focusing all efforts on a single solution, such as innovation in ocean cleanup technologies, would require huge volumes of plastic debris to be removed from the global ocean. The economic feasibility of small scale cleanup projects is being demonstrated by The Ocean Cleanup Project (Slat, 2014). However, extending this project to the global ocean would require investing in 1924 similar projects to achieve a 25% reduction in the total ocean plastic stock below 2010 levels by 2030. The cost of achieving such a target is estimated at between 0.7% and 1.0% of the world GDP in 2017.

In addition, focusing exclusively on ocean cleanup technologies does not reduce the plastic waste inputs from land to the ocean, which would necessitate continuous ocean cleanup effort. Can we afford a never-ending cleanup, and would this effort be economically feasible, as well as socially and politically acceptable? Is it sustainable given that cleanup effort will probably have to be increased in order to offset the exponential growth of plastic product consumption based on current trends? What will be the impact in terms of plastic debris ultimately reaching the ocean? Moreover, technology cannot solve all the problems also because plastics will degrade into microplastics and even nanoplastics. Cleanup technologies are currently unable to remove such small particles from the ocean.

The most effective mitigation strategies focus on source reduction, not on ocean cleanup technologies (Rochman, 2016; Sherman and van Sebille, 2016). This could be achieved through improving waste management infrastructure (Jambeck *et al*., 2015), preventing microfibers from clothing and small plastic fragments and beads from entering wastewater by putting filters on washing machines (Browne, 2015), removing plastic microbeads from personal care products (Rochman *et al.,* 2015), etc. Sherman and van Sebille (2016) argue that marine plastic pollution will persist unless we stop plastic input altogether.

Further research is required to assess the economic feasibility of the proposed solutions to plastic contamination in the global oceans. Economic principles must be designed or adapted to overcome financial, social and political difficulties, for example, the polluters pays principle (OECD, 1972; OECD, 1974), the extended producer responsibility (OECD, 2004), and the shared environmental responsibility principle (Cordier et al., 2018). The shared environmental responsibility principle might be a promising strategy in contrast to the conventional polluter pays principle, which might be less affordable. The long term ecological impacts of each scenario (beyond 2030) should be assessed to ensure that short term plastic solutions are feasible on the mid- to long term.

In further work, the quantification of flows and stocks of plastics from land to the global ocean in our model could be improved, through incorporating values derived from other models, such as Lebreton et al. (2017) and Schmidt et al. (2017).

Data availability statement

The datasets and materials generated and analyzed during the current study are available from the corresponding author on request.

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Author Contributions Statement

M.C and T.U wrote the manuscript text. T.U designed the Powersim model displayed in Figure 2. M.C conducted the simulation in the Powersim model to produce results displayed in Figures 4 and 6. T.U conducted the simulation in the Powersim model to produce results displayed in Figure 5. MC carried out calculations to design Figures 1 and 3. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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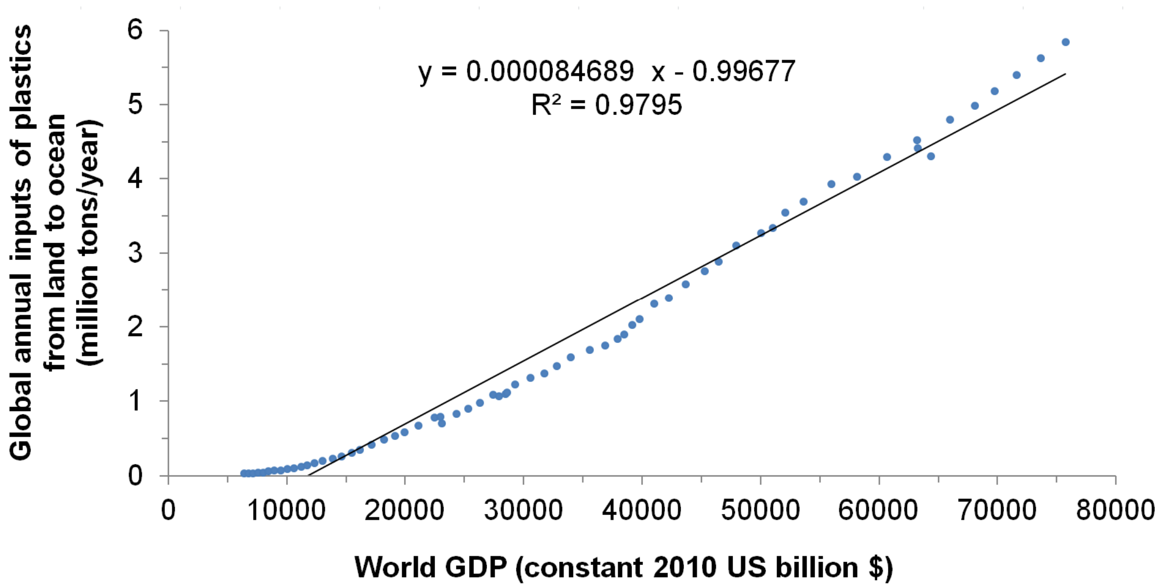


Figure 1. Correlation between annual inputs of plastic debris from land into the global ocean and world gross domestic product (GDP) over the period 1950-2015. In the equation of the linear regression (black continuous line), y = global plastic debris annual inputs from land to world's ocean (million tons/year), x = world GDP (constant 2010 US billion $) and - 0.99677 is the constant (i.e., the intercept with the vertical axis). Data on the vertical axis are our own calculations based on Eq. (6) in which we entered data from Jambeck et al. (2015) and Geyer et al. (2017). Data on the horizontal axis comes from the World Bank (2018) and are available in supplementary material online (Table S1).

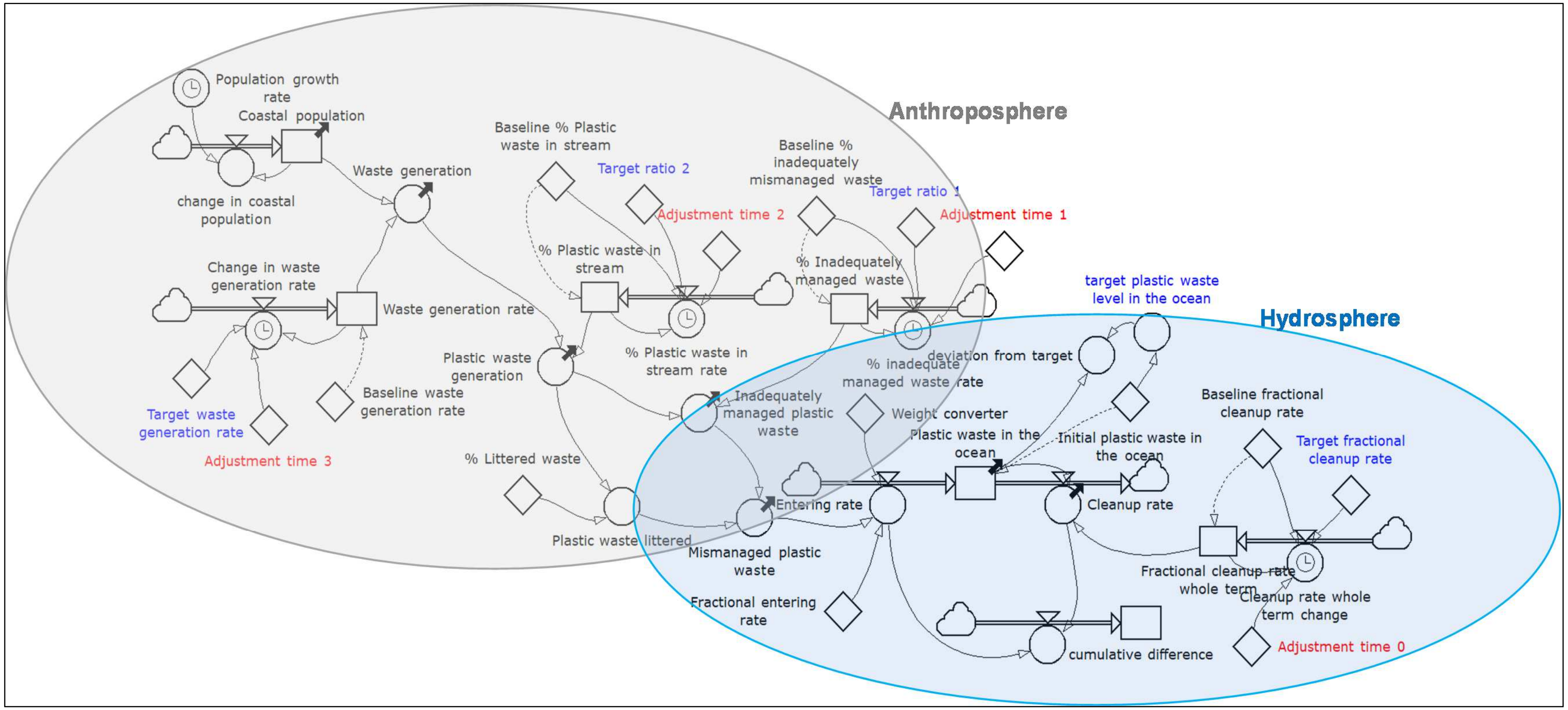


Figure 2. Stock and flow diagram of the system dynamics model for marine plastic wastes (designed in Powersim).

Stocks and flows are represented by boxes and double arrows, respectively. Circles and diamonds denote auxiliary variables and constants. Clouds indicate infinity and mark the model boundaries.

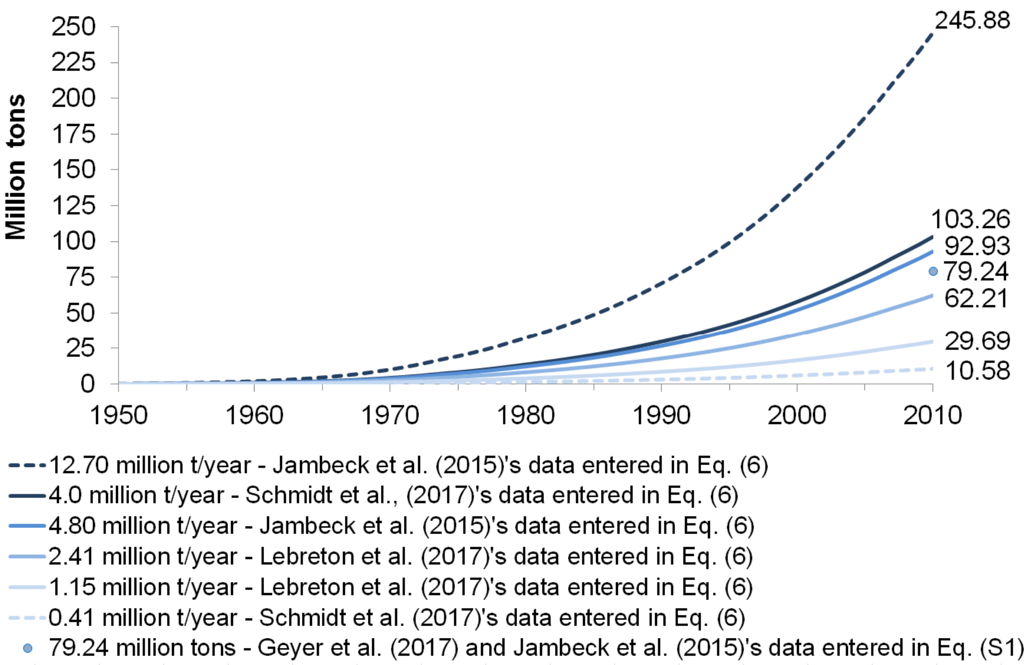


Figure 3. Total stock of plastic debris in the world ocean computed using different estimations of annual plastic flows entering the ocean from land. The 6 curves are cumulated values over 1950-2010 computed by summing the annual results of Eq. (6).

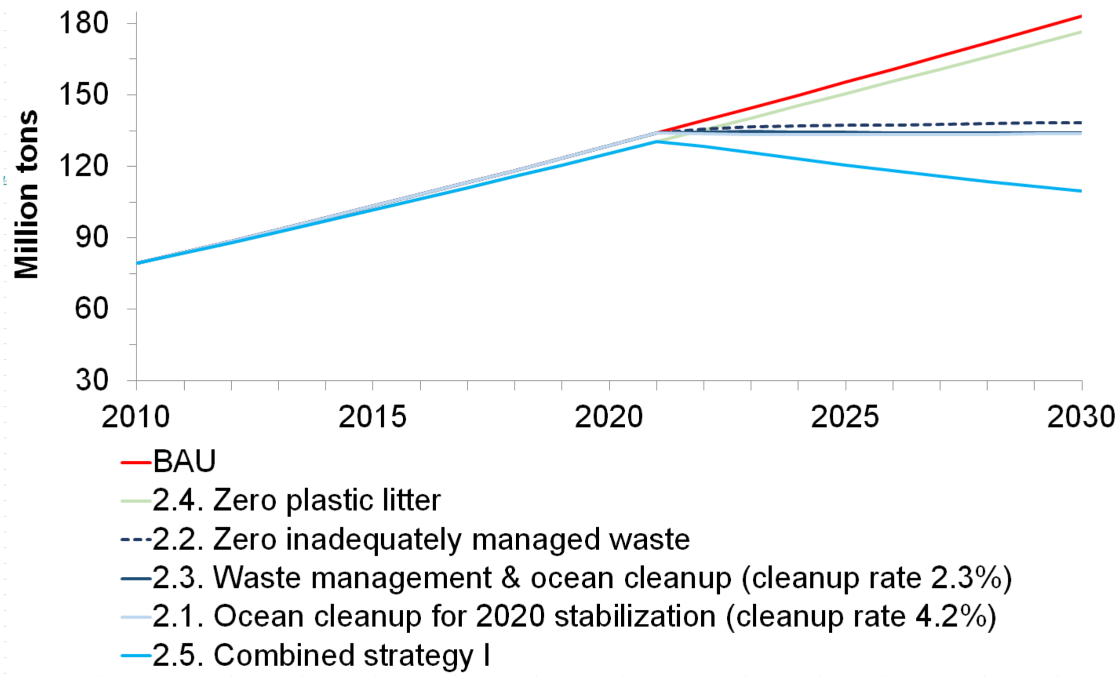


Figure 4. Impact of the second set of scenarios on total stock of plastic debris in the global ocean. Scenarios 2.1 to 2.4 have been designed with the aim of stabilizing the amount of plastic debris in the ocean to 2020 levels by 2030. In Figures 4 to 6, the stock of plastics in the world oceans includes plastics originating from land that are floating at the water surface, in the water column and deposited on the seabed.

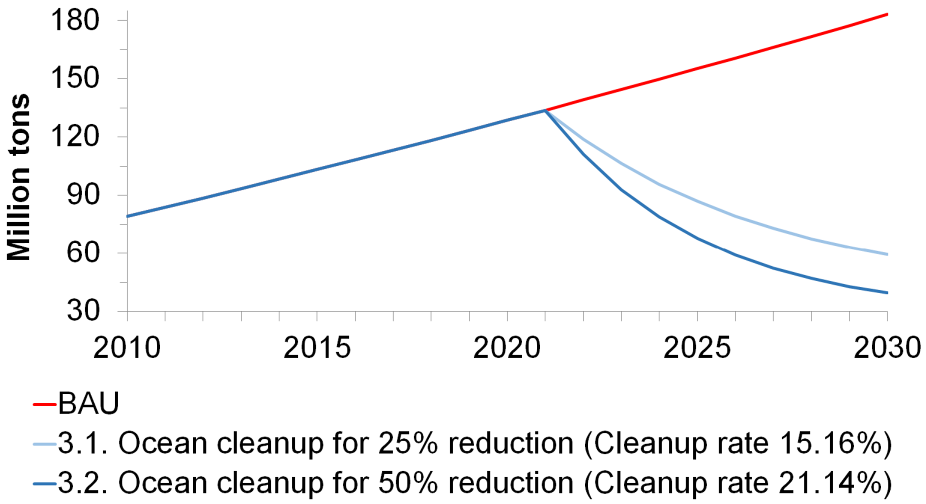


Figure 5. Impact of the third set of scenarios on total stock of plastic debris in the global ocean. Scenarios 3.1 and 3.2 simulate ocean cleanup efforts designed to reduce the amount of ocean plastic debris below 2010 levels.

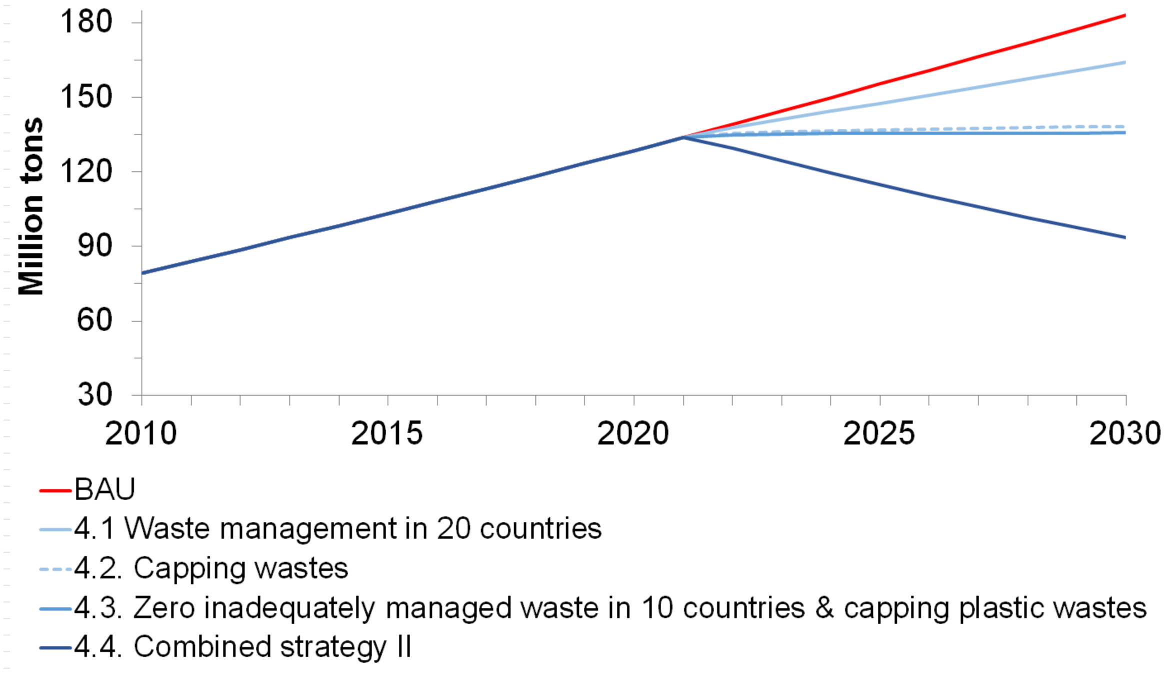


Figure 6. Impact of the fourth set of scenarios on total stock of plastic debris in the global ocean. Scenarios 4.1 to 4.3 are adapted from Jambeck et al. (2015) and are assumed to be more realistic and feasible scenarios.

Table 1. Categorization of environmental solutions to solve plastic issues

Location across the social-ecological system	Location across the problem causal chain	Solution categories	Examples of solutions
Upstream Solutions at the source of the problem	**Preventive measures**	Avoid and reduce waste production	1. Awareness raising campaigns and collaborative strategies (Benkler, 2011; Ostrom, 2010) to encourage households to reduce waste generation and overconsumption behaviors in general. 2. Inciting industries to substitute plastic materials with aluminum, glass, bio-plastics, etc. 3. Nurdle spillage prevention in plastic factories (nurdles are pre-production microplastic pellets). 4. Fiscal instruments and compulsory legislation to reduce the amount of packaging. 5. Compulsory legislation to ban micro beads in cosmetics or in toothpastes, or to ban single-use plastic products, etc.
		Reuse or repair old products	6. Returnable glass or PET bottle systems. 7. Moving from an economy of ownership to one of service functionality. 8. Online systems designed to help to share, trade, exchange, lend or rent second-hand products between neighbors, including plastic products. 9. Legislation forbidding planned obsolescence of products. 10. Fiscal rules that favor longer lasting products, etc.
Middle solutions		Recycling	11. Recycling in closed cycles (e.g., recycling of plastic bottles, plastic bags, etc.). 12. Legislation for compulsory extended producer responsibility in the plastic industry.
		Improvement in waste collection infrastructure	13. Invest in landfill sealing to avoid plastic waste leakages through rain, waterways or wind, from dumps or open, uncontrolled landfills, where waste is not suitably contained. 14. Invest in public garbage cans, waste collection system, awareness raising to reduce littering, etc.
		Incineration	15. Plastic waste incineration.
		Energy recovery	16. Plastic waste incineration with energy cogeneration.
		Composting biodegradable plastic bottles	17. Biodegradable (compostable) plastics made of starch that meet standards for biodegradability and compostability.
End-of-pipe solutions	**Curative measures**	Restore, e.g., remove plastics from ecosystems	18. Collection of plastic debris in oceans, for example the Ocean Cleanup Project (Slat, 2014). 19. Beach cleanups. 20. River interception techniques before plastic wastes enter the ocean, or filters in water treatment plants, etc.
		Health measures	21. Medical services to cure health impacts due to consumption of chemicals in plastic (e.g., Bisphenol-A and other endocrine disruptors).
Downstream	**Palliative measures**	Averting behaviors to avoid exposure to plastic chemicals	22. Final consumers purchasing glass bottles instead of plastic ones, switching from plastic bottles of mineral water to public tap water, etc.

Table 2. Main assumptions for key variables entered in the model.
Further details are available in the supplementary material online.

	Scenario 1. Business As Usual	Scenario 2.1. Ocean cleanup for 2020 stabilization	Scenario 2.2. Zero inadequately managed waste	Scenario 2.3. Waste management & ocean cleanup	Scenario 2.4. Zero plastic litter	Scenario 2.5. Combined strategy I	Scenario 3.1. Ocean cleanup for 25% reduction	Scenario 3.2. Ocean cleanup for 50% reduction	Scenario 4.1. Waste management in 20 countries	Scenario 4.2. Capping wastes	Scenario 4.3. Zero inadequately managed waste in 10 countries & capping plastic wastes	Scenario 4.4. Combined strategy II
Percentage of littered waste (%)[1]	2.0	2.0	2.0	2.0	0.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0
Percentage of plastic waste in stream (%)[2]	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	9.9	9.9	9.9
Percentage of inadequately managed waste (%)[2]	30.0	30.0	0.0	15.0	30.0	15.0	30.0	30.0	17.3	30.0	8.6	17.3
Ocean cleanup rate (%)[3]	0.1	4.2	0.1	2.3	0.1	4.2	15.2	21.1	0.1	0.1	0.1	4.2
Individual waste generation rate (kg/ person/day)[2]	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0.9	1.2	0.9

[1] Jambeck et al. (2015) supplementary data.

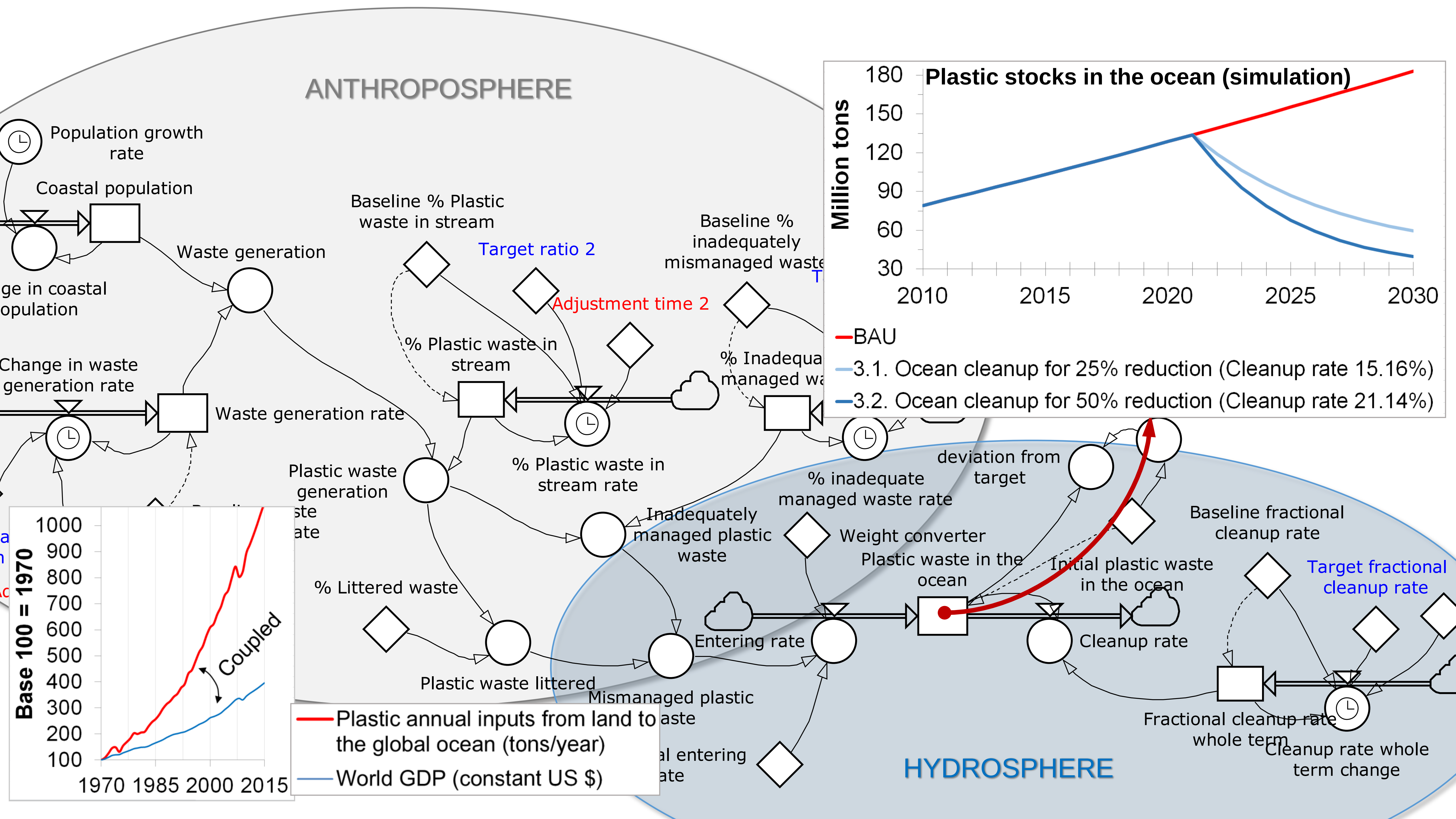
[2] Own calculation using supplementary data of Jambeck et al. (2015).

[3] Except the baseline value of 0.1%, which has been chosen arbitrarily at a very low level to reflect that current ocean cleanup operations are scarce and occur at very small scales, the ocean cleanup rates are calculated with the SD model via an optimization technique operated in Powersim, the *evolutionary search algorithm Powersim Solver 2.5*.

Table 3. Summary of simulation results: total stock of plastic debris in the global ocean (million tons).

The data in this table includes plastics originating from land that are floating at the water surface, in the water column and deposited on the seabed.

Years	Scenario 1. Business As Usual	Scenario 2.1. Ocean cleanup for 2020 stabilization	Scenario 2.2. Zero inadequately managed waste	Scenario 2.3. Waste management & ocean cleanup	Scenario 2.4. Zero plastic litter	Scenario 2.5. Combined strategy I	Scenario 3.1. Ocean cleanup for 25% reduction	Scenario 3.2. Ocean cleanup for 50% reduction	Scenario 4.1. Waste management in 20 countries	Scenario 4.2. Capping wastes	Scenario 4.3. Zero inadequately managed waste in 10 countries & capping plastic wastes	Scenario 4.4. Combined strategy II
2010	79.24	79.24	79.24	79.24	79.24	79.24	79.24	79.24	79.24	79.24	79.24	79.24
2011	83.94	83.94	83.94	83.94	83.64	83.64	83.94	83.94	83.94	83.94	83.94	83.94
2012	88.70	88.70	88.70	88.70	88.09	88.09	88.70	88.70	88.70	88.70	88.70	88.70
2013	93.50	93.50	93.50	93.50	92.60	92.60	93.50	93.50	93.50	93.50	93.50	93.50
2014	98.36	98.36	98.36	98.36	97.15	97.15	98.36	98.36	98.36	98.36	98.36	98.36
2015	103.27	103.27	103.27	103.27	101.75	101.75	103.27	103.27	103.27	103.27	103.27	103.27
2016	108.24	108.24	108.24	108.24	106.40	106.40	108.24	108.24	108.24	108.24	108.24	108.24
2017	113.26	113.26	113.26	113.26	111.10	111.10	113.26	113.26	113.26	113.26	113.26	113.26
2018	118.34	118.34	118.34	118.34	115.86	115.86	118.34	118.34	118.34	118.34	118.34	118.34
2019	123.46	123.46	123.46	123.46	120.66	120.66	123.46	123.46	123.46	123.46	123.46	123.46
2020	128.64	128.64	128.64	128.64	125.51	125.51	128.64	128.64	128.64	128.64	128.64	128.64
2021	133.87	133.87	133.87	133.87	130.40	130.40	133.87	133.87	133.87	133.87	133.87	133.87
2022	139.15	133.64	135.77	134.47	135.35	128.29	118.99	110.99	137.72	135.37	134.93	129.42
2023	144.49	133.47	136.54	134.53	140.35	125.72	106.41	93.00	141.11	136.06	135.24	124.49
2024	149.87	133.36	136.94	134.42	145.38	123.10	95.80	78.86	144.38	136.48	135.36	119.58
2025	155.29	133.31	137.22	134.28	150.47	120.55	86.85	67.77	147.62	136.81	135.43	114.82
2026	160.77	133.32	137.46	134.15	155.60	118.12	79.31	59.07	150.87	137.11	135.49	110.23
2027	166.30	133.38	137.68	134.04	160.78	115.80	72.97	52.27	154.14	137.40	135.54	105.84
2028	171.87	133.49	137.91	133.97	165.99	113.61	67.65	46.96	157.44	137.69	135.60	101.63
2029	177.48	133.64	138.13	133.91	171.25	111.53	63.18	42.82	160.77	137.99	135.65	97.61
2030	183.14	133.84	138.36	133.89	176.56	109.56	59.43	39.61	164.12	138.29	135.70	93.75



ANTHROPOSPHERE
Population growth rate
Coastal population
ge in coastal opulation
Waste generation
Change in waste generation rate
Waste generation rate
Baseline % Plastic waste in stream
Target ratio 2
Adjustment time 2
% Plastic waste in stream
% Plastic waste in stream rate
Baseline % inadequately mismanaged waste
% Inadequa managed wa
Plastic waste generation
Inadequately managed plastic waste
% inadequate managed waste rate
deviation from target
% Littered waste
Plastic waste littered
Mismanaged plastic
Entering rate
Weight converter
Plastic waste in the ocean
Initial plastic waste in the ocean
Cleanup rate
Baseline fractional cleanup rate
Target fractional cleanup rate
Fractional cleanup rate whole term
Cleanup rate whole term change
HYDROSPHERE
Plastic stocks in the ocean (simulation)
Million tons
180
150
120
90
60
30
2010
2015
2020
2025
2030
BAU
3.1. Ocean cleanup for 25% reduction (Cleanup rate 15.16%)
3.2. Ocean cleanup for 50% reduction (Cleanup rate 21.14%)
Base 100 = 1970
1000
900
800
700
600
500
400
300
200
100
1970 1985 2000 2015
Coupled
Plastic annual inputs from land to the global ocean (tons/year)
World GDP (constant US $)