Will innovation solve the global plastic contamination: how much innovation is needed for that?

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PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.27371v1 | CC BY 4.0 Open Access | rec: 20 Nov 2018, publ: 20 Nov 2018

Abstract

Plastics have become increasingly dominant in the consumer marketplace since their commercial development in the 1930s and 1940s. Global plastic production reached 335 million tons in 2016, a 640% increase since 1975. In 1960, plastics made up less than 1% of municipal solid waste by mass in the United States. By 2000, this proportion increased by one order of magnitude. As a result, plastic contamination is found everywhere in the world's oceans, coastal areas, freshwater bodies and terrestrial environments. Plastics in the marine environment are of increasing concern because of their persistence and effects on the oceans, wildlife, and, potentially, humans. A report by the MacArthur Foundation published in 2016 claimed that innovation can solve the plastic problem. However, it does not say how much innovation is needed and does not analyse if it is feasible. In this working paper, we propose to bring about answers to this question by developing an ecological-economic world model that simulates plastic waste emission by human activities, transport from land to the ocean and accumulation into the marine ecosystem. Innovations will be simulated in an economic sub-model integrated to the ecological-economic world model as one of its components. The model, in its current development stage, is capable of quantifying the impacts of innovations on the total amount of plastics accumulated in the ocean at the world scale. The ecological-economic world model is designed in Powersim following system dynamics programming. In a further work, the economic sub-model will be designed in Excel Following input-output matrix equations. Our preliminary results suggest that to reach a significant abatement of plastic in the global ocean, a panel of diverse types of solutions is required. One type of environmental measure alone will not succeed. Upstream and downstream solutions must be combined: (i) across the social-ecological system, that is, "at-the-source" but also "middle" and "end-of-pipe" solutions; (ii) as well as across the plastic contamination causal chain as well, that is, "preventive" but also "curative" solutions. Only combined solutions succeed to reduce the amount of plastic stock accumulated in the oceans since the 1950's to the level of 2010. Our model suggests that solutions which would be able to go further and reduce plastic stocks to 50% of 2010's level would require intense ocean cleanup. To achieve such an ambitious environmental target, 11.89% of total plastic wastes should be removed from the ocean every year between 2020 and 2030. The technical feasibility of such a solution is highly questionable knowing that current technologies remove only floating plastic at the surface of the water and that such floating plastic represent a very small percentage of all plastics accumulated in the global ocean at the surface of the water, in the water column and deposited on the seabed.

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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 resin production reached 288 million metric tons in 2012 (MT is used hereinafter for Metric Tons), a 620% increase since 1975 (Jambeck et al., 2015; PlasticsEurope, 2013). The largest market sector for plastic resins is packaging (PlasticsEurope, 2013), that is, materials designed for immediate disposal (Jambeck et al., 2015). In 1960, plastics made up less than 1% of municipal solid waste by mass in the United States (EPA, 2011). By 2000, this proportion increased by one order of magnitude (Jambeck et al., 2015).

Plastic contamination is found everywhere in the world's oceans, coastal areas, freshwater bodies and terrestrial environments (Baztan et al., 2017, p. 171). Since 2014, scientists have succeeded to provide gross estimated of their ecological, social and economic impacts (UNEP, 2014; Trasande et al., 2015; Gallo et al., 2018; Jaacks and Prasad, 2017; McIlgorm et al., 2011). Plastics in the marine environment are of increasing concern because of their persistence and effects on the oceans, wildlife, and, potentially, humans (Jambeck et al., 2015; Thompson et al., 2009; Attina et al., 2016; Trasande et al., 2015; Shea and Committee on Environmental Health, 2003; Barnes et al., 2009; Obbard et al., 2014; Baztan et al., 2016; Da Costa et al., 2016).

A report by the MacArthur Foundation (Ellen MacArthur Foundation et al., 2016) claimed that innovation can solve the plastic problem. However, it does not say how much innovation is needed and does not analyse if it is feasible. In this working paper, we propose to bring about answers to this question by developing an ecological-economic world model that simulates plastic waste emission by human activities, transport from land to the ocean and accumulation into the marine ecosystem. Innovations will be simulated in an economic sub-model[1] integrated to the ecological-economic world model as one of its components. The model, in its current development stage, is capable of quantifying the impacts of innovations on the total amount of plastics accumulated in the ocean at the world scale. The ecological-economic world model is designed in Powersim following system dynamics programming. The economic sub-model will be designed in Excel following input-output matrix equations. We will follow the technique developed in Cordier et al. (2017) were more explanations can be found on the way the architecture of the ecological-economic model and its economic sub-component are built and how they interact one with another.

[1] The economic sub-model is a work in progress. It will be finalized in early 2019. Regarding the ecological model used to simulate plastic accumulation in the ocean, the first version is ready and developed in this working paper. Its architectures and its parameters will be further improved in 2019, after discussion with plastic scientists at the Micro 2018 international conference held in Lanzarote (Canary Island, Spain).

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Materials & methods

Case study

The first estimations of the quantity of plastic entering the ocean from waste generated on land was calculated in 1975. Since then, no recent calculations had been provided until Jambeck et al. (2015) proposed new estimations 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 that 275 million metric tons (MT) of plastic waste was generated in 192 coastal countries in 2010, with 4.8 to 12.7 million MT entering the ocean annually at a global scale. This range might be an underestimate as other studies suggest a range between 10 and 20 MT a year (Raveender Vannela, 2012; European Commission, 2013; UNEP, 2017). However, up to know, there are no estimations of the technological and financial effort required to reduce the annual flow of plastics into the ocean as well as the total stock accumulated in the ocean. And yet, this is quite important since according to Jambeck et al. (2015), without waste management infrastructure improvements, the cumulative quantity of plastic waste available to enter the ocean from land (i.e., mismanaged waste) is predicted to double in 2025 compared to the situation in 2010.

Jambeck et al. (2015, p. 770) use their estimations to evaluate potential mitigation strategies. They propose to apply their mitigation strategies to the 20 top countries ranked by the mass of mismanaged[2] plastic waste. The top 20 countries' mismanaged plastic waste encompasses 83% of the total in 2010 and include, in order: China, Indonesia, Philippines, Vietnam, Sri Lanka, …, Morocco, North Korea, and United-States (full list available in Jambeck et al. (2015, p. 769)). If considered collectively, coastal European Union countries (23 total) would rank eighteenth on the list instead of Morocco. Jambeck et al. propose the following mitigation strategies (the categorization below into three categories is ours, see Table 1):

1. Preventive "middle" solutions based on plastic waste management:

    - If the fraction of mismanaged waste were reduced by 50% in the 20 top countries ranked by mass of mismanaged plastic waste, this mass would decrease by 41% by 2025.
    - This falls to 34% if the reduction is only applied to the top 10 countries.
    - This falls to 26% if applied to the top 5 countries.

[2] Jambeck et al. (2015) defined mismanaged waste as material that is either littered or inadequately disposed. Inadequately disposed waste is not formally managed and includes disposal in dumps or open, uncontrolled landfills, where it is not fully contained. Mismanaged waste could eventually enter the ocean via inland waterways, wastewater outflows, and transport by wind or tides.

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- To achieve a 75% reduction in the mass of mismanaged plastic waste, waste management would have to be improved by 85% in the 35 top-ranked countries. This strategy would require substantial infrastructure investment primarily in low- and middle-income countries.

2. Preventive “at-the-source” solutions based on changes in consumer behaviours:

- A 26% decrease in the amount of mismanaged plastic waste would be achieved by 2025 if per capita waste generation were reduced to the 2010 average (1.2 kg/day)[3] in the 91 coastal countries that exceed this average, and the percent plastic in the waste stream were capped at 11% (the 192-country average in 2010). This strategy would target higher-income countries and might require smaller global investments. Changes in consumer behaviours would be required to reduce plastic waste generation, which could encompass awareness rising campaigns on the social and environmental problems caused by the hyper-consumption society, taxes on plastic products to increase purchasing prices and hence to reduce consumption, recycling systems, systems of returnable plastic or glass bottles, online systems designed to help particulars to share, sell, exchange, borrow or rent second-hand products (plastic products included), etc.

3. Preventive “middle” and “end-of-pipe” based on both, plastic waste management and changes in consumer behaviors:

- A 77% reduction in the amount of mismanaged plastic waste could be realized with a combined strategy, in which total waste management is achieved (0% mismanaged waste) in the 10 top-ranked countries and plastic waste generation is capped as described above (per capita waste generation reduced to 1.2 kg/day in the 91 coastal countries that exceed this average.

With the ecological-economic world model developed in this paper, we assess the ecological impact of the three mitigation strategies proposed by Jambeck et al. (2015). Economic impacts will be estimated in a further work once the economic sub-model will be ready. The economic sub-model will also help us to design economic strategies – such as the shared environmental responsibility principle (Cordier et al., 2018) to make affordable plastic solutions that might be disproportionately expensive under the conventional polluter pays principle.

[3] Average calculated on the world population. It differs from Jambeck et al. (2015, p. 770) – 1.7 kg/day – because they calculated it on a country basis, not on a global population basis.

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Table 1. Categorization of plastic solution types

Location accross the problem causal chain	Location across the social-ecological system	Environmental solutions	Examples of concrete solutions
Solutions at the source of the problem	Preventive measures	Avoid waste production	Inciting households to reduce the generation of wastes through awareness rising campaigns aimed at mitigating overconsumption behaviours in general Inciting industries to substitute plastic materials by aluminium or glass for example
		Reuse old products	Returnable glass or PET bottles
		Recycling	Recycling in closed cycles (e.g., recycling of plastic bottles, plastic bags, etc.)
Middle solutions		Disposal in landfilling	Invest in waste management such as landfill sealing to avoid plastic waste leakages through rains, waterways, wind, etc.
		Incineration	Plastic waste incineration
		Energy recovery	Plastic waste incineration with energy cogeneration
		Composting biodegradable plastic bottles	Biodegradable (compostable) plastics made of starch that meet standards for biodegradability and compostability
End-of-pipe solutions	Curative measures	Collecting plastics in ecosystems	Collection of plastic wastes in oceans (e.g., Boyan Slat's Ocean Clean-up Project (Slat, 2014)
		Health measures	Health care due to plastic chemicals consumption (e.g., Bisphenol-A and other endocrine disruptors)
	Palliative measures	Averting behaviours to avoid exposure	Final consumers purchasing glass bottles instead of plastic ones, switching from plastic bottles of mineral water to public tap water, etc.

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Scenarios

We simulate three sets of scenarios that describe the evolution of plastic stock in the world's ocean from 2010 to 2030. All scenarios include the evolution of the world population based on forecasts from the UN (The United Nations, n.d.) . In a further version of the model, we will also add economic growth rate to take into account that every year, each individual consumes a greater amount of products than previous year. Economic growth explains that even if there were no population growth, plastic product and plastic waste generation would keep increasing. Once the IO sub-model will be coupled to the SD general model displayed in Figure 1, we will test several principles to allocate the implementation cost of plastic solution scenarios to countries and economic sectors (e.g., the polluter pays principle, the shared environmental responsibility principle, the common but differentiate responsibility principle, etc.).

The first set of scenarios simulates the evolution of plastics as if no environmental measures were implemented in addition to those already undertaken:

1. *Business as usual scenario (BAU):* the current trend keeps on up to 2030 with no additional environmental measures addressing plastics than those implemented in the reference year, 2010. At the current stage of the model development, we assume the ocean cleanup effort to be very low since only few cleanup initiatives have been undertaken in the world and at extremely small scales. This is why we arbitrarily set the cleanup effort at annual removal percentage of 0.10 % of the total stock of plastics in the oceans worldwide. This percentage will be estimated more accurately later. Regarding the other variables of the BAU scenario, they have been set based on Jambeck et al. (2015) supplemental materials: the percentage of plastic waste that is littered is set at 2% of plastic waste generation, the plastic waste inadequately managed is set at 30.017% of plastic waste generation, individuals generate 1.216 kg of wastes per day and per person, the share of plastics is set at 11.08 % of waste generation; the world population annual growth rate varies between 1.0% and 1.2%. According to the BAU scenario, if current trends keep on, the 2030's level of plastic in the oceans (floating and deposited plastics on the seabed) will exceed the level of 2020 by 36.5% (Figure 2).

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The second set of scenarios simulates environmental measures aimed at stabilizing the total plastic stock in the oceans by 2020. This means that the stock stops increasing and remains constant after 2020 but it is not reduced (except in scenario 2.5. "Combined strategy"):

2.1. "Cleanup effort only" scenario: this scenario simulates curative "end-of-pipe" solutions such as collecting plastics in the ecosystem (Table 1), for example the Boyan Slat's Ocean Cleanup Project (Slat, 2014). The level of cleanup total effort (= 1.91% of the stock of plastic waste in the ocean is removed)[4] has been estimated by optimization techniques with the world ocean plastic model in Powersim (Figure 1) in a way to achieve a stabilization of plastic stocks in the world ocean by 2020.

2.2."Zero inadequately managed waste only" scenario: this scenario simulates preventive "middle" solutions (Table 1) such as developing landfill sealing to avoid plastic leakages taken away by rains and winds, developing collective collect of wastes in low- and middle income countries, installing plastic recycling bins in the streets, etc. This strategy would require substantial infrastructure investment primarily in low- and middle income countries. Without support from high income countries (e.g., financial support) or additional measures (e.g., implementation of additional plastic solutions in high-income countries also – such as in scenario 2.3), this scenario will suffer low social and political acceptability at the international level, which might reduce its likeliness. The level of inadequately managed waste has been estimated by optimization techniques with the model (Figure 1) in a way to achieve a stabilization of plastic stocks in the world ocean by 2020. The optimization results show that the model variable "% Inadequately managed waste" used in the BAU scenario (0.300168 = 30.0168%)[5] must be replaced by 0% (which is the level achieved in developed countries such as France, Sweden, Australia, Japan, United-States, etc.).

2.3. "Reducing by 50% inadequately managed wastes and cleanup effort" scenario: this scenario simulates curative "end-of-pipe" solutions (e.g., cleanup projects to remove plastics from ecosystems) combined to preventive "middle" solutions (e.g., developing landfill sealing to avoid plastic leakages, development of collective collect of wastes in low- and middle income countries, installing plastic recycling bins in the streets, etc.). This scenario has been designed in two steps:

[4] Cleanup total effort = baseline cleanup effort (BAU) + optimized cleanup effort = 0.10% + 1.81% = 1.91% of plastic wastes in the ocean are removed.
[5] This value has been calculated in Jambeck et al. (2015)'s supplemental materials providing national data for the year 2010 for 192 countries (almost the entire world).

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- First, to simulate the preventive "middle" solution (e.g., developing landfill sealing to avoid plastic leakages), the level of inadequate waste management has been reduced by half, that is, the variable "% Inadequately managed waste" (Figure 1) in the BAU scenario (0.30017)[6] has been replaced by 0.15008.

- Second, to simulate the curative "end-of-pipe" solution, after setting the variable at the first step, we applied an optimization technique in Powersim to the variable "cleanup rate" (Figure 1) in a way that the level of plastic in oceans in 2030 is stabilized to the level of 2020. The optimization of the cleanup rate gives the following results: cleanup rate = BAU effort + optimized cleanup effort = 0.10% + 1.0387% = 1.1387% of the stock of plastic waste in the ocean is removed.

2.4."Zero plastic litter only" scenario: this scenario simulates preventive "at-the-source-of-the-problem" solutions (Table 1) such as awareness rising campaigns to reduce the number of people who litter plastic wastes on the ground, to increase the number of people that put plastic wastes in recycling bins as well as purchase glass bottles and returnable bottles (PET or glass), to mitigate overconsumption behaviours in general and specifically for plastic products, etc. The model shows that even reducing the powersim variable "% Littered waste" (Figure 1) from 2% of plastic waste generation (BAU scenario) to 0% (scenario 2.4) will not succeed to stabilize the level of plastic in the oceans in 2030 to 2020's level. The 2030's level of plastic in the oceans will exceed the level of 2020 by 15.4%.

2.5. Combined strategy 2.1 + 2.3 + 2.4: this scenario combines scenarios 2.1, a part of 2.3 and 2.4, which means the following values are entered in Powersim: baseline cleanup effort (BAU) + optimized cleanup effort = 0.10% + 1.81% = 1.91% (scenario 2.1); "% Inadequately managed waste" = 15.008% (environmental measure from scenario 2.3); the % Littered waste = 0% (scenario 2.4).

The third set of scenarios considers cleanup-effort-only scenarios similarly to scenario 2.1 except that they are designed to reduce the total plastic stock in the oceans below the level of 2010:

3.1. Cleanup scenario for 25% reduction: this scenario is designed the same way scenario 2.1 except that the optimization process is run to achieve in 2030 a level of plastic waste in the ocean that is below 2010's level by 25%. The optimization results

[6] 0.30017 means that 30.017% of the plastic waste generation in 2010 is inadequately managed (this is the value in 2010 taken from Jambeck's supplemental materials).

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from the model show that to achieve that level, 7.18% of plastic wastes in the ocean must be cleaned up[7].

3.2. Cleanup scenario for 50% reduction: this scenario is designed the same way scenario 2.1 except that the optimization process is run to achieve in 2030 a level of plastic waste in the ocean that is below 2010's level by 50%. The optimization results from the model show that to achieve that level, 11.89% of plastic wastes in the ocean must be cleaned up[8].

[… Other sets of scenarios will be simulated in a further version of this working paper].

The seventh set of scenarios covers some of the environmental measures proposed by Jambeck et al. (2015, p. 770) in order to assess their potential global impacts on plastics in the ocean:

7.1. Reducing by 50% inadequately managed wastes by 2025 in the 20 top countries ranked by mass of mismanaged plastic waste: it simulates a preventive "middle" solution similar to the one of scenario 2.3 except that in scenario 7.1, inadequately managed wastes[9] are reduced by half in a limited amount of countries in order to ease the implementation of such an ambitious measure. Scenario 7. 1 is thus a preventive "middle" solution since only landfilling techniques are improved (see Table 1 above). It is not a preventive "at-the-source" solution since awareness rising campaigns are not implemented to reduce the number of people littering plastics on the ground. We made this assumption for this scenario because it is difficult (but probably not impossible) to convince all people in every country to never litter plastic products in the street or on the beaches. Thereby, we calculated in the Excel file from Jambeck et al. supplemental material that if the top 20 countries had an "Inadequately managed plastic waste [kg/day]" reduced by 50%, the "% Inadequately managed waste" would be 0.17265 instead of 0.300168 (0.17265 = Inadequately managed plastic waste [kg/day] / Plastic waste generation [kg/day] = 47 077 041.9 kg/day / 272 676 238.6 kg/day). So, to simulate scenario 7.1, we modified in Powersim the parameter "Baseline % inadequately mismanaged waste" and replace the value of 0.300168 by 0.17265 (starting from 2020, assuming there is a delay between the time the measure is designed and the time it is effectively implemented and result in concrete impacts).

[7] Cleanup total effort = baseline cleanup effort (BAU) + optimized cleanup effort = 0.10% + 7.08% = 7.18% of plastic wastes in the ocean are removed.
[8] Cleanup total effort = baseline cleanup effort (BAU) + optimized cleanup effort = 0.10% + 11.79% = 11.89% of plastic wastes in the ocean are removed.
[9] Jambeck et al. (2015, p. 770) use the term "waste mismanagement improvements" without specifying what kind of action it encompasses. Thus, we consider in scenario 7.1 that mismanagement improvements address only inadequately managed waste, not littering.

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7.2. Capping per capita waste generation to 1.2 kg/day[10] *by 2025 and capping the percentage of plastics in waste stream at 11%*[11]*:* it simulates preventive "at-the-source" solutions (Table 1) based on changes in consumer behaviours. This strategy would mainly target higher-income countries and might require smaller global investments (most of the poor and emerging countries emit an amount of waste per person and per day lower than 1.2 kg whereas rich countries often exceed this amount). Several measures would be needed to motivate consumers to reduce their plastic waste generation: awareness rising campaigns on the social and environmental problems caused by the current consumption society, taxes on plastic products to reduce plastic consumption, recycling systems, systems of returnable plastic or glass bottles, online systems designed to help particulars to share, sell, exchange, borrow or rent second-hand products (including plastic products), etc. This scenario is calculated as follows:

- Calculation for capping the per capita waste generation to 1.2 kg/person/day:
  We calculated in the Excel file from Jambeck et al. supplemental material that if the countries with "waste generation rate" above the world average (1.2 kg/person/day) would reduce it to 1.2 kg/person/day, the world average "waste generation rate" would be 0.92 kg/person/day. So, we simulated this cap by modifying in Powersim the variable "waste generation rate" and replace 1.2 by 0.92 kg/person/day.

- Calculation for capping plastics in the waste stream at to 11%:
  We calculated in the Excel file from Jambeck et al. supplemental material that if the countries with "% Plastic in waste stream" higher than the world average (11.09%) would reduce it to 11.09%, the world average "% Plastic in waste stream" would be 9.88%. So, we simulated this cap by modifying in Powersim the variable "% Plastic in waste stream" and replace 11.09% by 9.88%.

7.3. Reducing by 100% inadequately managed waste by 2025 in the 10 top countries and capping plastics in waste stream at 11%: in this scenario, full waste management is achieved (that is, 0% mismanaged waste) in the 10 top-ranked countries ranked in Jambeck et al. (2015, p. 769) by mass of mismanaged plastic waste (poor and emerging countries) and plastic waste generation is capped at 11% as described in scenario 7.2 (rich countries). It simulates a preventive "middle" solution and an "end-of-pipe" one based on both, plastic waste management and changes in consumer behaviors. This scenario is calculated as follows:

[10] 1.2 kg/day is the world average in 2010. In that year, 91 coastal countries exceeded that amount.
[11] 11% is the 192-country average in 2010.

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- Calculation to reduce waste mismanagement to 0 % in the top 10 countries:
  For the same reason as in scenario 7.1, we assume that mismanagement improvements devised by Jambeck et al. address only inadequately managed waste, not littering. This measure is thus a preventive “middle” solution since only landfilling techniques are improved (see Table 1 above). It is not a preventive “at-the-source” solution since awareness rising campaigns are not implemented to reduce the number of people littering plastics on the ground. We calculated in the Excel file from Jambeck et al. supplemental material that if the top 10 countries had an “Inadequately managed plastic waste [kg/day]” reduced to zero percents, the “% Inadequately managed waste” at the global scale would be 8.56% instead of 30.017% (8.56% = 100 * Inadequately managed plastic waste [kg/day] / Plastic waste generation [kg/day] = 100* 23 341 306.0 kg/day / 272676238.6 kg/day). Thus, we simulated this by modifying in Powersim the variable “Baseline % inadequately mismanaged waste” and replace the value of 0.300168 by 0.085601.

- Calculation for capping plastics in the waste stream at to 11%:
  Calculations are the same as in the 11% capping described in scenario 7.2

7.4. Combined strategy: 7.1 + 7.2. + 2.1: this scenario combines scenarios 7.1, 7.2 and 2.1, which means it simulates a preventive “middle” solution, a preventive “at-the-source” solution and a curative “end-of-pipe” solution. This scenario consists in entering the following values in Powersim: “Baseline % inadequately mismanaged waste” = 0.17265 (scenario 7.1), “waste generation rate” = 0.92 kg/person/day and “% Plastic in waste stream” = 9.88% (scenario 7.2), cleanup total effort = baseline cleanup effort (BAU) + cleanup scenario effort = 0.10% + 1.81% = 1.91%.

Model description

We adopted System dynamics (SD) (Sterman, 2000) for the design of our model to capture the dynamics of marine plastic wastes from their origin (their generation on land) to their fate (when they enter into the ocean). System dynamics is suitable because it describes the complex dynamics of a system with a specific emphasis on flows and stocks. Marine plastic wastes involve complex dynamics of social-ecological systems where stock is a key variable. Indeed, marine plastic wastes flow from the land to the ocean where they accumulate generating a stock of floating plastics in the water and deposited plastic on the seabed. Figure 1 shows the stock and flow diagram of the system dynamics model for marine plastic waste.

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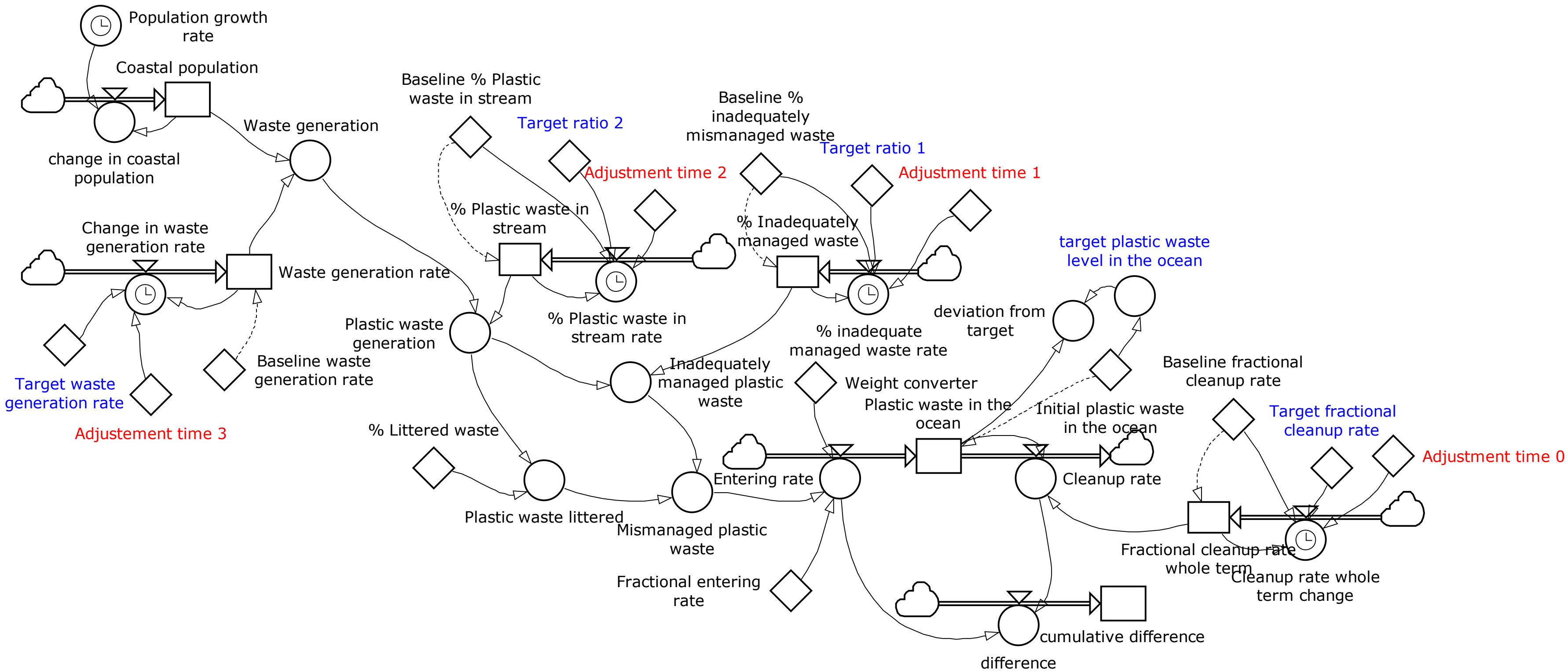

Figure 1. Stock and flow diagram of the system dynamics model for marine plastic waste (designed in Powersim).

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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 coastal population is defined as follows:

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

Following Jambeck et al. (2015), the model focuses on the dynamics of coastal population. Changes in coastal population are assumed to be the same as changes in the world population by using the prediction of population by the United Nations (The United Nations, n.d.).

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

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

Plastic waste in the ocean is defined as:

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

The model assumes that plastic waste in the ocean does not decline unless it is cleaned up by people. It does not disappear but stays somewhere in the ocean. Entering rate is determined by mismanaged plastic waste and fractional entering rate (Figure 1). In addition to clean up rate, there are primarily three variables in which environmental policies can intervene to reduce the entering rate: Waste generation rate, % plastic waste in stream, and % Inadequately managed waste (Figure 1). The model allows environmental targets to be set for each of these three variables. The speed required to reach the environmental targets can be modified by changing the variable adjustment time in the model.

Results and discussion

The first set of scenarios is made of the BAU scenario, which is used as a reference aimed at comparing all other scenarios. This helps us to assess how many environmental measures (scenarios 2 to 7) could help to improve the marine ecosystem compared to a situation without any environmental measures (BAU) other than those already existing in 2010.

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As expected, without any additional environmental measures (BAU scenario), the stock of plastic wastes accumulated in the ocean at the global scale will be the highest in 2030 reaching 374 million tons (Figure 2). Inciting citizens to stop littering plastic products could theoretically help. However, the model results suggest that such an environmental measure would be far to be enough. If citizens would change their behavior and succeed to never litter plastics on the ground (either because of a spontaneous change of mentalities or thanks to awareness rising campaigns from public authorities or environmental associations), the cumulated stock of plastic waste in the ocean in 2030 would reach an amount of 367 million tons in 2030 (scenario 2.4). This is slightly below the BAU scenario but not much. The amount of plastic waste entering the ocean annually would keep growing quite fast any way. This suggests that focusing all efforts on plastic littering by citizen will never help to solve the plastic problem. Their environmental responsibility is quite limited. Solutions should probably be developed in a collective thinking, not an individual one if we want a significant positive impact to be observed in terms of plastic flow abatement. Results from scenario 2.2 simulations strengthen this assumption. In that scenario, investments are made in every country in all landfills that are inadequately managed to reduce plastic leakages by wind or rains. Plastic recycling bins are also installed in the streets to spur citizen to recycle plastic products, and collective collect of wastes are installed in low- and middle-income countries in all cities and villages where it was lacking. This scenario simulates a future where the world would have achieved zero inadequately managed waste. If such an idealistic future would happen, the model suggests that the amount of cumulated plastic waste in the ocean would stabilize by 2024 at a level of 329 million tons (i.e., 12% below the BAU scenario). Scenarios 2.3 and 2.1 might be more realistic and succeed to stabilize the ocean cumulated plastic stock in 2030 at the level of 2020, that is, 321 million tons. To achieve this environmental target, ocean cleanup must be implemented in addition to improving inadequately managed waste systems. A feasibility study could help to assess if cleaning of 1.14% (scenario 2.3) to 1.91% (scenario 2.1) of ocean plastic waste stock every year is technically and financially achievable. Probably the feasibility study written by Boyan Slat's team (Slat, 2014) could help to answer that question.

However, for more stringent environmental targets such as for example, recovering the situation of 2015, additional measures must be undertaken. Scenario 2.5 (Figure 2) shows that a combining strategy is likelier to achieve that goal. Scenario 2.5 succeeds to reduce plastic wastes in the world ocean in 2030 to a level corresponding to 2015' level (294 million tons), which is 21.2% lower than the BAU scenario. This suggests that combining different kinds of environmental measures across the social-ecological system, downstream and upstream of the social-ecological system ("end-of-pipe" and "at-the-source" solutions) as well as upstream and downstream of the plastic contamination

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causal chain ("curative" and "preventive" solutions) is more successful than scenarios where only one type of environmental measure is undertaken.

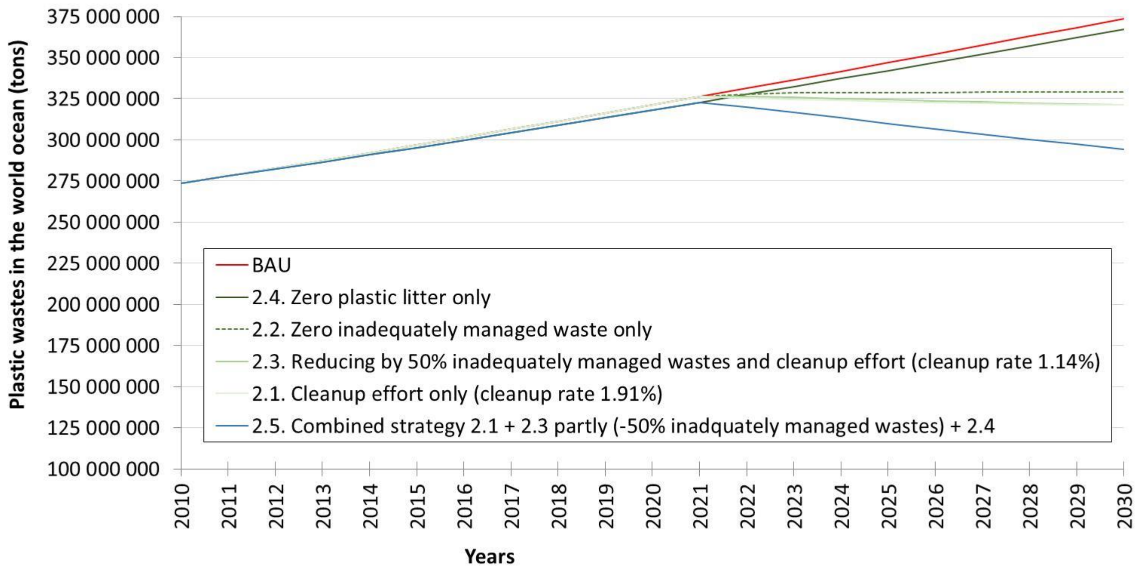

Figure 2. Scenarios with environmental efforts designed to stabilize the amount of plastic wastes in the ocean at 2020's level by 2030 (floating plastics and deposited on the seabed).

Scenarios 7.1 to 7.3, inspired by Jambeck et al. (2015, p. 770), are interesting because they are intended to be more realistic and achievable. For example, scenario 7.1 proposes to improve only 50% of the inadequately managed waste, not 100%. And this is to be made 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 and likelier to happen. However, scenario 7.1 shows poor results in terms of ecological impact. The amount of cumulated plastic waste in the ocean achieves a level of 355 million tons in 2030 (Figure 3), i.e. barely 5.1% below the BAU level. Scenarios 7.2 and 7.3 succeed to stabilize the stock of cumulated plastic wastes in the ocean by 2022 at 327 million tons (Figure 3), i.e., 12% below the BAU in 2030.

The combined strategy implemented in Scenario 7.3 – that is, reducing by 100% inadequately managed waste by 2025 in the 10 top countries and capping plastics in waste stream at 11% – could be appreciated by stakeholders in terms of equity as well as social and political acceptability because poor, emerging and rich countries would participate to plastic solutions on the basis of the principle of 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 likelier. However, capping plastics in waste stream at 11% would require changes in consumer behaviours. This is not easy to achieve unless awareness rising campaigns are designed appropriately to spur cooperation in the mind of consumers and reduce individualistic behaviours. Peculiar designs are required for that – read, inter alia, Benkler (2011) and Ostrom (2010c) – otherwise the change in mentalities and behavior is extremely difficult to achieve.

Scenario 7.4. is another highly combined strategy since it merges scenarios 7.1, 7.2 and 2.1, which involves three categories of solutions: a preventive “middle” solution (scenario 7.1), a preventive “at-the-source” solution (scenario 7.2) and a curative “end-of-pipe” solution (scenario 7.3). Scenario 7.4 follows thus a similar approach as scenario 2.5 but it performs better. Figure 3 shows that scenario 7.5 succeed to achieve a level of cumulated plastic waste in the ocean of 277 million tons by 2030, i.e, 26% below the BAU. This means recovering the situation of the year 2011. This strengthen our assumption that combining different kinds of environmental measures downstream and upstream the social-ecological system (“end-of-pipe” and “at-the-source” solutions) as well as upstream and downstream of the plastic contamination causal chain (“curative” and “preventive” solutions) is more successful than scenarios where only one type of environmental measure is undertaken. Keeping on scenario 7.4 up to 2069 would allow the amount of cumulated plastic waste in the ocean to achieve half the value of 2010, i.e. 137 million tons. Given the emergency of the situation for marine biodiversity, it might be interesting to test scenarios that are quicker to reduce by 50% the level of 2010. Figure 4 is a first attempt in that sense. It shows that cleanup effort only (scenario 3.2) could achieve that goal but would require removing from the ocean 11.89% of plastic every year starting from 2020 up to 2030. Assuming that current levels of plastic annual removal in the ocean is 0.10% (this is a first preliminary assumption that will be improved later), this would require a technological progress 119 times higher than nowadays. Scenario 3.1 is an intent to simulate quite an ambitious ecological target and at the same time a bit more realistic. It shows that to reducing 2010’s level by 25% would require removing from the ocean 7.18% of plastic every year starting from 2020 up to 2030 this would require to multiply 72 times current efforts in ocean cleanup technologies. In further versions of this paper, we will assess if such a technological advance is feasible.

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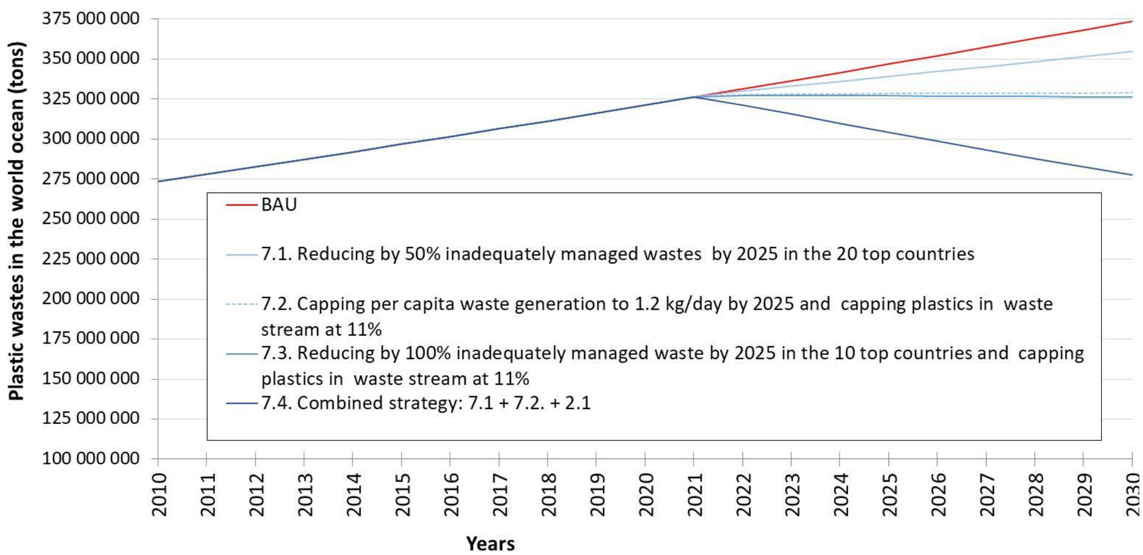

Figure 3. Impact of scenarios inspired by Jambeck et al. (2015, p. 770) on the amount of plastic wastes in the global ocean (floating plastics and deposited on the seabed).

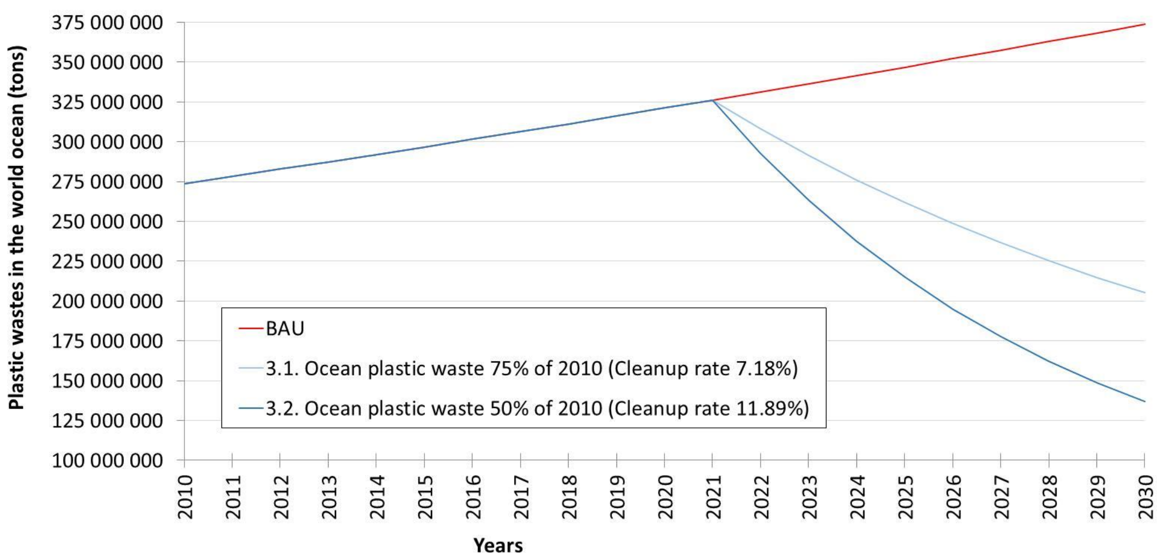

Figure 4. Scenarios with environmental efforts (ocean cleanup effort only) designed to reduce the amount of ocean plastic wastes below 2010 levels (floating plastics and deposited on the seabed).

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Conclusion

Our results suggest that to reach significant abatement of plastic wastes accumulated in the ocean, a panel of diverse types of solutions is required. One type of environmental measure alone will never succeed. Upstream and downstream solutions must be combined across the social-ecological system (i.e., "end-of-pipe" and "at-the-source" solutions from Table 1) as well as across the plastic contamination causal chain (i.e., "curative" and "preventive" solutions from Table 1). According to Jambeck et al. (2015), long-term solutions will also likely include waste reduction and "downstream" waste management strategies such as expanded recovery systems and extended producer responsibility, i.e., plastic products used by consumers would be recovered by producers for recycling purposes (Braungart , 2013; OECD, 2004; Lifset, 1993; Kalimo et al., 2012). Also, Jambeck et al. assert that improving waste management infrastructure in developing countries is paramount and will require substantial resources and time. While such infrastructure is being developed, industrialized countries can take immediate action by reducing waste and curbing the growth of single-use plastics (Jambeck et al., 2015).

All these upstream and downstream solutions could either come from the top (political and economic decision makers) or the bottom of the society (citizens, environmental associations, small size enterprises). But in any case, several of these solutions will require a change in mentalities to spur individuals to act collectively. Trying to solve the problem of providing a common good such as a plastic-free ocean is a classic collective action dilemma (Kollock, 1998)[12]. The classic theory of collective action predicts that no one will change behavior and reduce their plastic consumption unless an external authority imposes enforceable rules that change the incentives faced by those involved (Hardin, 1968; Benkler, 2011). This is why many analysts call for a change in institutions at the global level. However, the presumption that a collective action problem that has global effects can only be solved globally is not relying on strong empirical support. A large number of individuals facing collective action problems have self-organized to cooperate and develop solutions to common pool resource problems at a small to medium scale without external top-down authority from national or international levels (Poteete et al., 2010; Agrawal, 2000 ; Schlager et al., 1994 ; Ostrom, 1992, 1994, 2001 ; NRC, 2002 ; Dietz, 2003). Plastic as many other problems conceptualized as ‘‘global problems’’ are the cumulative result of actions taken at diverse levels, i.e., at the level of individuals, families, small groups, communities, private firms, and local, regional, and national governments (Ostrom, 2010a). Solving this problem requires collective action and many actors at diverse levels need to change their day-to-day activities to avoid plastics to end up in oceans. At the global level, reducing the threat requires an

[12] Plastic contamination is a global environmental problem with impacts at worldwide scale (Baztan et al., 2016, p. 178-179). However, the causes of plastic contamination operate at a much smaller scale. Billions of actors could benefit from reduced plastic emissions into the environment, whether they make any effort toward this goal or not (Ostrom, 2010a,b,c ; Kerber, 2017).

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enforceable global treaty. However, if global solutions negotiated at a global level are not backed up by a variety of efforts at national, regional, and local levels, they are not guaranteed to work well (Ostrom, 2010a, c). Attempts to foster multiple-scale actions and benefits rely on the concept of polycentric governance in which many centers of decision-making are formally independent of each other but can undertake many activities at diverse scales that cumulatively make a difference (Ostrom, 2010a; Gruby and Basuro, 2014). Ostrom (2010c), Benkler (2011) and others 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.

Further research is required to assess the technical and financial feasibility of the solutions proposed to solve plastic contamination of the global ocean. Direct and indirect economic impacts must be assessed to measure social and political feasibility. Economic principle must be designed for financial, social and political difficulties to be overcome (e.g., shared environmental responsibility principle, polluter pays principle, extended producer responsibility, etc.). The SD model must be improved and some parameters made more accurate. We need still to develop and couple the input-output model to the SD model also to assess long term ecological impacts (beyond 2030) of each scenario

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