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► To cite this version:

Mateo Cordier, Takuro Uehara. Will innovation solve the global plastic contamination: how much innovation is needed for that?. 2024. hal-04437786

HAL Id: hal-04437786

<https://hal.uvsq.fr/hal-04437786>

Preprint submitted on 31 May 2024

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1 **Will innovation solve the global plastic**
2 **contamination: how much innovation is needed**
3 **for that?**

4
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Abstract

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

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80 Introduction

81 Plastics have become increasingly dominant in the consumer marketplace since their
82 commercial development in the 1930s and 1940s (Jambeck et al., 2015). Global plastic
83 resin production reached 288 million metric tons in 2012 (MT is used hereinafter for
84 Metric Tons), a 620% increase since 1975 (Jambeck et al., 2015; PlasticsEurope, 2013).
85 The largest market sector for plastic resins is packaging (PlasticsEurope, 2013), that is,
86 materials designed for immediate disposal (Jambeck et al., 2015). In 1960, plastics made
87 up less than 1% of municipal solid waste by mass in the United States (EPA, 2011). By
88 2000, this proportion increased by one order of magnitude (Jambeck et al., 2015).

89
90 Plastic contamination is found everywhere in the world's oceans, coastal areas,
91 freshwater bodies and terrestrial environments (Baztan et al., 2017, p. 171). Since 2014,
92 scientists have succeeded to provide gross estimated of their ecological, social and
93 economic impacts (UNEP, 2014; Trasande et al., 2015; Gallo et al., 2018; Jaacks and
94 Prasad, 2017; McIlgorm et al., 2011). Plastics in the marine environment are of
95 increasing concern because of their persistence and effects on the oceans, wildlife, and,
96 potentially, humans (Jambeck et al., 2015; Thompson et al., 2009; Attina et al., 2016;
97 Trasande et al., 2015; Shea and Committee on Environmental Health, 2003; Barnes et al.,
98 2009; Obbard et al., 2014; Baztan et al., 2016; Da Costa et al., 2016).

99
100 A report by the MacArthur Foundation (Ellen MacArthur Foundation et al., 2016)
101 claimed that innovation can solve the plastic problem. However, it does not say how
102 much innovation is needed and does not analyse if it is feasible. In this working paper, we
103 propose to bring about answers to this question by developing an ecological-economic
104 world model that simulates plastic waste emission by human activities, transport from
105 land to the ocean and accumulation into the marine ecosystem. Innovations will be
106 simulated in an economic sub-model¹ integrated to the ecological-economic world model
107 as one of its components. The model, in its current development stage, is capable of
108 quantifying the impacts of innovations on the total amount of plastics accumulated in the
109 ocean at the world scale. The ecological-economic world model is designed in Powersim
110 following system dynamics programming. The economic sub-model will be designed in
111 Excel following input-output matrix equations. We will follow the technique developed
112 in Cordier et al. (2017) where more explanations can be found on the way the architecture
113 of the ecological-economic model and its economic sub-component are built and how
114 they interact one with another.

115
116

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).

117 **Materials & methods**

118

119 *Case study*

120

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

136

137 Jambeck et al. (2015, p. 770) use their estimations to evaluate potential mitigation
138 strategies. They propose to apply their mitigation strategies to the 20 top countries ranked
139 by the mass of mismanaged² plastic waste. The top 20 countries' mismanaged plastic
140 waste encompasses 83% of the total in 2010 and include, in order: China, Indonesia,
141 Philippines, Vietnam, Sri Lanka, ..., Morocco, North Korea, and United-States (full list
142 available in Jambeck et al. (2015, p. 769)). If considered collectively, coastal European
143 Union countries (23 total) would rank eighteenth on the list instead of Morocco. Jambeck
144 et al. propose the following mitigation strategies (the categorization below into three
145 categories is ours, see Table 1):

146

147 1. Preventive “middle” solutions based on plastic waste management:

148

- 149 - If the fraction of mismanaged waste were reduced by 50% in the 20 top countries
150 ranked by mass of mismanaged plastic waste, this mass would decrease by 41%
151 by 2025.
- 152 - This falls to 34% if the reduction is only applied to the top 10 countries.
- 153 - 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.

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

158

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

160

161 - A 26% decrease in the amount of mismanaged plastic waste would be achieved by
162 2025 if per capita waste generation were reduced to the 2010 average (1.2
163 kg/day)³ in the 91 coastal countries that exceed this average, and the percent
164 plastic in the waste stream were capped at 11% (the 192-country average in 2010).
165 This strategy would target higher-income countries and might require smaller
166 global investments. Changes in consumer behaviours would be required to reduce
167 plastic waste generation, which could encompass awareness rising campaigns on
168 the social and environmental problems caused by the hyper-consumption society,
169 taxes on plastic products to increase purchasing prices and hence to reduce
170 consumption, recycling systems, systems of returnable plastic or glass bottles,
171 online systems designed to help particulars to share, sell, exchange, borrow or rent
172 second-hand products (plastic products included), etc.

173

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

176

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

182

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

190

191

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.

192 **Table 1. Categorization of plastic solution types**
 193

Location across the problem causal chain	Location across the social-ecological system	Environmental solutions	Examples of concrete solutions
↓ Solutions at the source of the problem Middle solutions End-of-pipe solutions ↓	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.)
		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
	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.

194

195

196

197

198 *Scenarios*

199

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

211

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

214

215 *1. Business as usual scenario (BAU):* the current trend keeps on up to 2030 with no
216 additional environmental measures addressing plastics than those implemented in the
217 reference year, 2010. At the current stage of the model development, we assume the
218 ocean cleanup effort to be very low since only few cleanup initiatives have been
219 undertaken in the world and at extremely small scales. This is why we arbitrarily set
220 the cleanup effort at annual removal percentage of 0.10 % of the total stock of
221 plastics in the oceans worldwide. This percentage will be estimated more accurately
222 later. Regarding the other variables of the BAU scenario, they have been set based on
223 Jambeck et al. (2015) supplemental materials: the percentage of plastic waste that is
224 littered is set at 2% of plastic waste generation, the plastic waste inadequately
225 managed is set at 30.017% of plastic waste generation, individuals generate 1.216 kg
226 of wastes per day and per person, the share of plastics is set at 11.08 % of waste
227 generation; the world population annual growth rate varies between 1.0% and 1.2%.
228 According to the BAU scenario, if current trends keep on, the 2030's level of plastic
229 in the oceans (floating and deposited plastics on the seabed) will exceed the level of
230 2020 by 36.5% (Figure 2).

231

232

233

234

235

236

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

241

242 2.1. “*Cleanup effort only*” scenario: this scenario simulates curative “end-of-pipe”
243 solutions such as collecting plastics in the ecosystem (Table 1), for example the
244 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
245 optimization techniques with the world ocean plastic model in Powersim (Figure 1) in
246 a way to achieve a stabilization of plastic stocks in the world ocean by 2020.
247

248

249 2.2. “*Zero inadequately managed waste only*” scenario: this scenario simulates
250 preventive “middle” solutions (Table 1) such as developing landfill sealing to avoid
251 plastic leakages taken away by rains and winds, developing collective collect of
252 wastes in low- and middle income countries, installing plastic recycling bins in the
253 streets, etc. This strategy would require substantial infrastructure investment
254 primarily in low- and middle income countries. Without support from high income
255 countries (e.g., financial support) or additional measures (e.g., implementation of
256 additional plastic solutions in high-income countries also – such as in scenario 2.3),
257 this scenario will suffer low social and political acceptability at the international
258 level, which might reduce its likeliness. The level of inadequately managed waste has
259 been estimated by optimization techniques with the model (Figure 1) in a way to
260 achieve a stabilization of plastic stocks in the world ocean by 2020. The optimization
261 results show that the model variable “% Inadequately managed waste” used in the
262 BAU scenario ($0.300168 = 30.0168\%$)⁵ must be replaced by 0% (which is the level
263 achieved in developed countries such as France, Sweden, Australia, Japan, United-
264 States, etc.).

265

266 2.3. “*Reducing by 50% inadequately managed wastes and cleanup effort*” scenario: this
267 scenario simulates curative “end-of-pipe” solutions (e.g., cleanup projects to remove
268 plastics from ecosystems) combined to preventive “middle” solutions (e.g.,
269 developing landfill sealing to avoid plastic leakages, development of collective
270 collect of wastes in low- and middle income countries, installing plastic recycling
271 bins in the streets, etc.). This scenario has been designed in two steps:
272

272

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).

- 273 • First, to simulate the preventive “middle” solution (e.g., developing landfill
274 sealing to avoid plastic leakages), the level of inadequate waste management has
275 been reduced by half, that is, the variable “% Inadequately managed waste”
276 (Figure 1) in the BAU scenario (0.30017)⁶ has been replaced by 0.15008.
277
- 278 • Second, to simulate the curative “end-of-pipe” solution, after setting the variable
279 at the first step, we applied an optimization technique in Powersim to the variable
280 “cleanup rate” (Figure 1) in a way that the level of plastic in oceans in 2030 is
281 stabilized to the level of 2020. The optimization of the cleanup rate gives the
282 following results: cleanup rate = BAU effort + optimized cleanup effort = 0.10%
283 + 1.0387% = 1.1387% of the stock of plastic waste in the ocean is removed.
284
- 285 2.4. “Zero plastic litter only” scenario: this scenario simulates preventive “at-the-source-
286 of-the-problem” solutions (Table 1) such as awareness rising campaigns to reduce the
287 number of people who litter plastic wastes on the ground, to increase the number of
288 people that put plastic wastes in recycling bins as well as purchase glass bottles and
289 returnable bottles (PET or glass), to mitigate overconsumption behaviours in general
290 and specifically for plastic products, etc. The model shows that even reducing the
291 powersim variable “% Littered waste” (Figure 1) from 2% of plastic waste generation
292 (BAU scenario) to 0% (scenario 2.4) will not succeed to stabilize the level of plastic
293 in the oceans in 2030 to 2020’s level. The 2030’s level of plastic in the oceans will
294 exceed the level of 2020 by 15.4%.
295
- 296 2.5. Combined strategy 2.1 + 2.3 + 2.4: this scenario combines scenarios 2.1, a part of
297 2.3 and 2.4, which means the following values are entered in Powersim: baseline
298 cleanup effort (BAU) + optimized cleanup effort = 0.10% + 1.81% = 1.91% (scenario
299 2.1); “% Inadequately managed waste” = 15.008% (environmental measure from
300 scenario 2.3); the % Littered waste = 0% (scenario 2.4).
301

302 The third set of scenarios considers cleanup-effort-only scenarios similarly to scenario
303 2.1 except that they are designed to reduce the total plastic stock in the oceans below the
304 level of 2010:
305

- 306 3.1. Cleanup scenario for 25% reduction: this scenario is designed the same way
307 scenario 2.1 except that the optimization process is run to achieve in 2030 a level of
308 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).

309 from the model show that to achieve that level, 7.18% of plastic wastes in the ocean
310 must be cleaned up⁷.

311

312 3.2. *Cleanup scenario for 50% reduction*: this scenario is designed the same way
313 scenario 2.1 except that the optimization process is run to achieve in 2030 a level of
314 plastic waste in the ocean that is below 2010's level by 50%. The optimization results
315 from the model show that to achieve that level, 11.89% of plastic wastes in the ocean
316 must be cleaned up⁸.

317

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

319

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

323

324 7.1. *Reducing by 50% inadequately managed wastes by 2025 in the 20 top countries*
325 *ranked by mass of mismanaged plastic waste*: it simulates a preventive “middle”
326 solution similar to the one of scenario 2.3 except that in scenario 7.1, inadequately
327 managed wastes⁹ are reduced by half in a limited amount of countries in order to ease
328 the implementation of such an ambitious measure. Scenario 7.1 is thus a preventive
329 “middle” solution since only landfilling techniques are improved (see Table 1 above).
330 It is not a preventive “at-the-source” solution since awareness rising campaigns are
331 not implemented to reduce the number of people littering plastics on the ground. We
332 made this assumption for this scenario because it is difficult (but probably not
333 impossible) to convince all people in every country to never litter plastic products in
334 the street or on the beaches. Thereby, we calculated in the Excel file from Jambeck et
335 al. supplemental material that if the top 20 countries had an “Inadequately managed
336 plastic waste [kg/day]” reduced by 50%, the “% Inadequately managed waste” would
337 be 0.17265 instead of 0.300168 ($0.17265 = \text{Inadequately managed plastic waste}$
338 $[\text{kg/day}] / \text{Plastic waste generation} [\text{kg/day}] = 47\,077\,041.9 \text{ kg/day} / 272\,676\,238.6$
339 kg/day). So, to simulate scenario 7.1, we modified in Powersim the parameter
340 “Baseline % inadequately mismanaged waste” and replace the value of 0.300168 by
341 0.17265 (starting from 2020, assuming there is a delay between the time the measure
342 is designed and the time it is effectively implemented and result in concrete impacts).

343

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.

344 7.2. *Capping per capita waste generation to 1.2 kg/day¹⁰ by 2025 and capping the*
345 *percentage of plastics in waste stream at 11%¹¹*: it simulates preventive “at-the-
346 source” solutions (Table 1) based on changes in consumer behaviours. This strategy
347 would mainly target higher-income countries and might require smaller global
348 investments (most of the poor and emerging countries emit an amount of waste per
349 person and per day lower than 1.2 kg whereas rich countries often exceed this
350 amount). Several measures would be needed to motivate consumers to reduce their
351 plastic waste generation: awareness rising campaigns on the social and environmental
352 problems caused by the current consumption society, taxes on plastic products to
353 reduce plastic consumption, recycling systems, systems of returnable plastic or glass
354 bottles, online systems designed to help particulars to share, sell, exchange, borrow or
355 rent second-hand products (including plastic products), etc. This scenario is
356 calculated as follows:

357

- 358 • Calculation for capping the per capita waste generation to 1.2 kg/person/day:
359 We calculated in the Excel file from Jambeck et al. supplemental material that if
360 the countries with “waste generation rate” above the world average (1.2
361 kg/person/day) would reduce it to 1.2 kg/person/day, the world average “waste
362 generation rate” would be 0.92 kg/person/day. So, we simulated this cap by
363 modifying in Powersim the variable “waste generation rate” and replace 1.2 by
364 0.92 kg/person/day.
365
- 366 • Calculation for capping plastics in the waste stream at to 11%:
367 We calculated in the Excel file from Jambeck et al. supplemental material that if
368 the countries with “% Plastic in waste stream” higher than the world average
369 (11.09%) would reduce it to 11.09%, the world average “% Plastic in waste
370 stream” would be 9.88%. So, we simulated this cap by modifying in Powersim the
371 variable “% Plastic in waste stream” and replace 11.09% by 9.88%.

372

373 7.3. *Reducing by 100% inadequately managed waste by 2025 in the 10 top countries and*
374 *capping plastics in waste stream at 11%*: in this scenario, full waste management is
375 achieved (that is, 0% mismanaged waste) in the 10 top-ranked countries ranked in
376 Jambeck et al. (2015, p. 769) by mass of mismanaged plastic waste (poor and
377 emerging countries) and plastic waste generation is capped at 11% as described in
378 scenario 7.2 (rich countries). It simulates a preventive “middle” solution and an “end-
379 of-pipe” one based on both, plastic waste management and changes in consumer
380 behaviors. This scenario is calculated as follows:

381

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.

- 382 • Calculation to reduce waste mismanagement to 0 % in the top 10 countries:
383 For the same reason as in scenario 7.1, we assume that mismanagement
384 improvements devised by Jambeck et al. address only inadequately managed
385 waste, not littering. This measure is thus a preventive “middle” solution since only
386 landfilling techniques are improved (see Table 1 above). It is not a preventive “at-
387 the-source” solution since awareness rising campaigns are not implemented to
388 reduce the number of people littering plastics on the ground. We calculated in the
389 Excel file from Jambeck et al. supplemental material that if the top 10 countries
390 had an “Inadequately managed plastic waste [kg/day]” reduced to zero percents,
391 the “% Inadequately managed waste” at the global scale would be 8.56% instead
392 of 30.017% ($8.56\% = 100 * \text{Inadequately managed plastic waste [kg/day]} / \text{Plastic}$
393 $\text{waste generation [kg/day]} = 100 * 23\,341\,306.0 \text{ kg/day} / 272676238.6 \text{ kg/day}$).
394 Thus, we simulated this by modifying in Powersim the variable “Baseline %
395 inadequately mismanaged waste” and replace the value of 0.300168 by 0.085601.
396
- 397 • Calculation for capping plastics in the waste stream at to 11%:
398 Calculations are the same as in the 11% capping described in scenario 7.2
399

400 *7.4. Combined strategy: 7.1 + 7.2. + 2.1:* this scenario combines scenarios 7.1, 7.2 and
401 2.1, which means it simulates a preventive “middle” solution, a preventive “at-the-
402 source” solution and a curative “end-of-pipe” solution. This scenario consists in
403 entering the following values in Powersim: “Baseline % inadequately mismanaged
404 waste” = 0.17265 (scenario 7.1), “waste generation rate” = 0.92 kg/person/day and
405 “% Plastic in waste stream” = 9.88% (scenario 7.2), cleanup total effort = baseline
406 cleanup effort (BAU) + cleanup scenario effort = 0.10% + 1.81% = 1.91%.

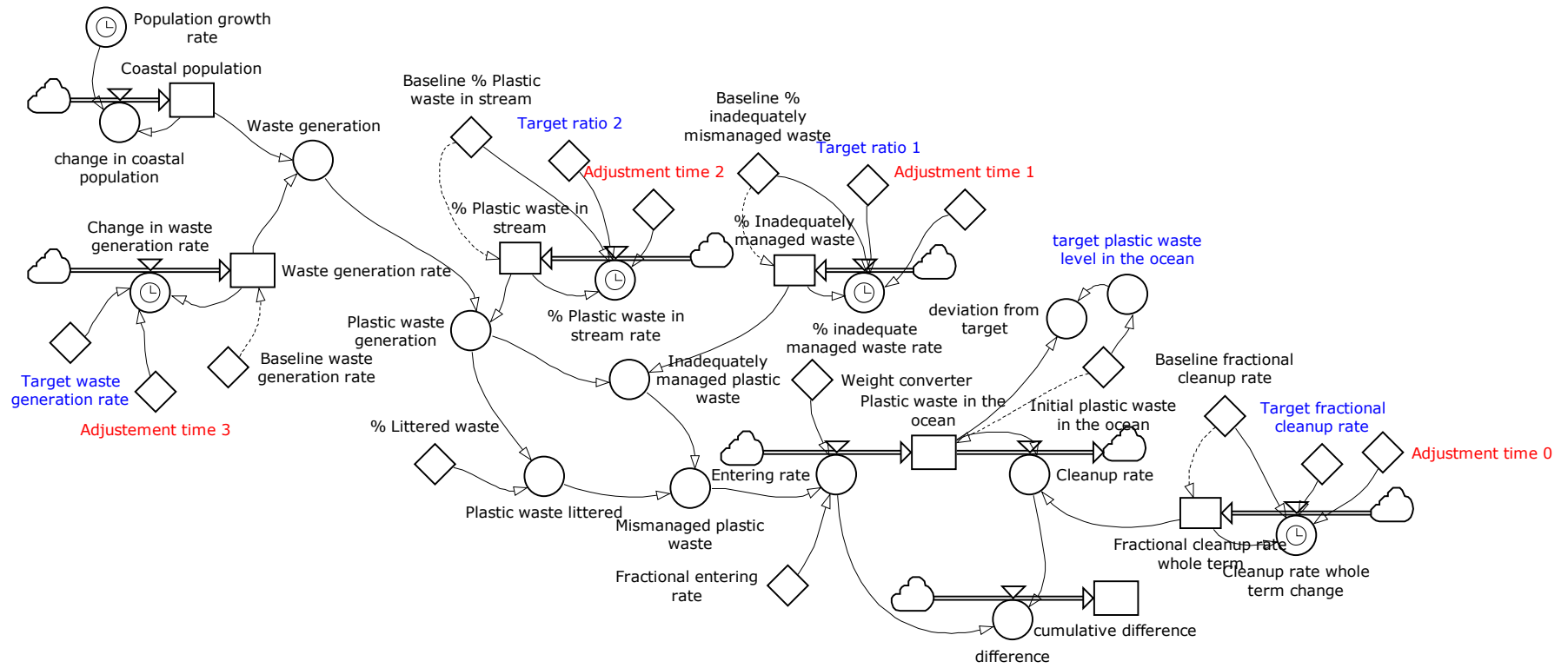
407

408 *Model description*

409

410 We adopted System dynamics (SD) (Sterman, 2000) for the design of our model to
411 capture the dynamics of marine plastic wastes from their origin (their generation on land)
412 to their fate (when they enter into the ocean). System dynamics is suitable because it
413 describes the complex dynamics of a system with a specific emphasis on flows and
414 stocks. Marine plastic wastes involve complex dynamics of social-ecological systems
415 where stock is a key variable. Indeed, marine plastic wastes flow from the land to the
416 ocean where they accumulate generating a stock of floating plastics in the water and
417 deposited plastic on the seabed. Figure 1 shows the stock and flow diagram of the system
418 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).

424 There are two critical stocks in the model: Coastal population and Plastic waste in the
 425 ocean (the full model in Powersim format can be provided upon request). The dynamics
 426 of coastal population is defined as follows:

427

$$428 \quad \text{Coastal population}^t =$$

$$429 \quad \int_{t_0}^{t_n} (\text{Changes in coastal population}^t) dt + \text{Coastal population}^{t_0} \quad (1)$$

430

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

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

436

$$437 \quad \text{Waste generation}^t = \text{Waste generation rate} \times \text{Coastal population} \times 365 \text{ days}$$

$$438 \quad (2)$$

439

440 Plastic waste in the ocean is defined as:

441

$$442 \quad \text{Plastic waste in the ocean}^t =$$

$$443 \quad \int_{t_0}^{t_n} (\text{Entering rate}^t - \text{Cleanup rate}^t) dt + \text{Plastic waste in the ocean}^{t_0} \quad (3)$$

444

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

454

455 **Results and discussion**

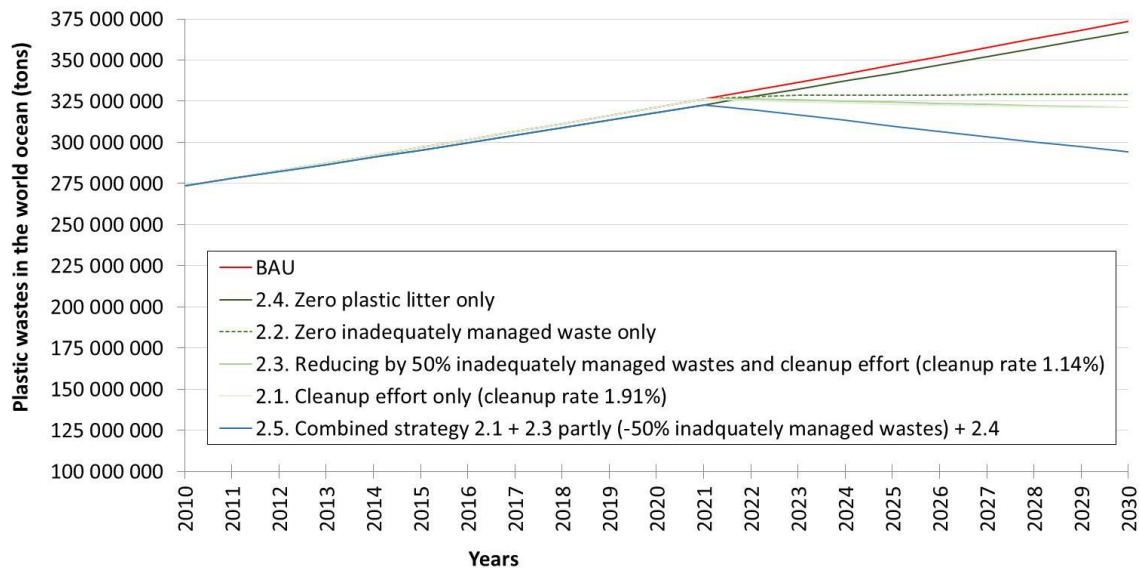
456 The first set of scenarios is made of the BAU scenario, which is used as a reference
 457 aimed at comparing all other scenarios. This helps us to assess how many environmental
 458 measures (scenarios 2 to 7) could help to improve the marine ecosystem compared to a
 459 situation without any environmental measures (BAU) other than those already existing in
 460 2010.

461

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

492
493 However, for more stringent environmental targets such as for example, recovering the
494 situation of 2015, additional measures must be undertaken. Scenario 2.5 (Figure 2) shows
495 that a combining strategy is likelier to achieve that goal. Scenario 2.5 succeeds to reduce
496 plastic wastes in the world ocean in 2030 to a level corresponding to 2015' level (294
497 million tons), which is 21.2% lower than the BAU scenario. This suggests that
498 combining different kinds of environmental measures across the social-ecological system,
499 downstream and upstream of the social-ecological system ("end-of-pipe" and "at-the-
500 source" solutions) as well as upstream and downstream of the plastic contamination

501 causal chain (“curative” and “preventive” solutions) is more successful than scenarios
 502 where only one type of environmental measure is undertaken.
 503



504 **Figure 2. Scenarios with environmental efforts designed to stabilize the amount of plastic**
 505 **wastes in the ocean at 2020’s level by 2030 (floating plastics and deposited on the seabed).**
 506

507
 508 Scenarios 7.1 to 7.3, inspired by Jambeck et al. (2015, p. 770), are interesting because
 509 they are intended to be more realistic and achievable. For example, scenario 7.1 proposes
 510 to improve only 50% of the inadequately managed waste, not 100%. And this is to be
 511 made in only 20 countries, not the entire world. The idea is to obtain a marine ecological
 512 improvement with the minimum effort required in order to make plastic solutions more
 513 feasible and likelier to happen. However, scenario 7.1 shows poor results in terms of
 514 ecological impact. The amount of cumulated plastic waste in the ocean achieves a level
 515 of 355 million tons in 2030 (Figure 3), i.e. barely 5.1% below the BAU level. Scenarios
 516 7.2 and 7.3 succeed to stabilize the stock of cumulated plastic wastes in the ocean by
 517 2022 at 327 million tons (Figure 3), i.e., 12% below the BAU in 2030.

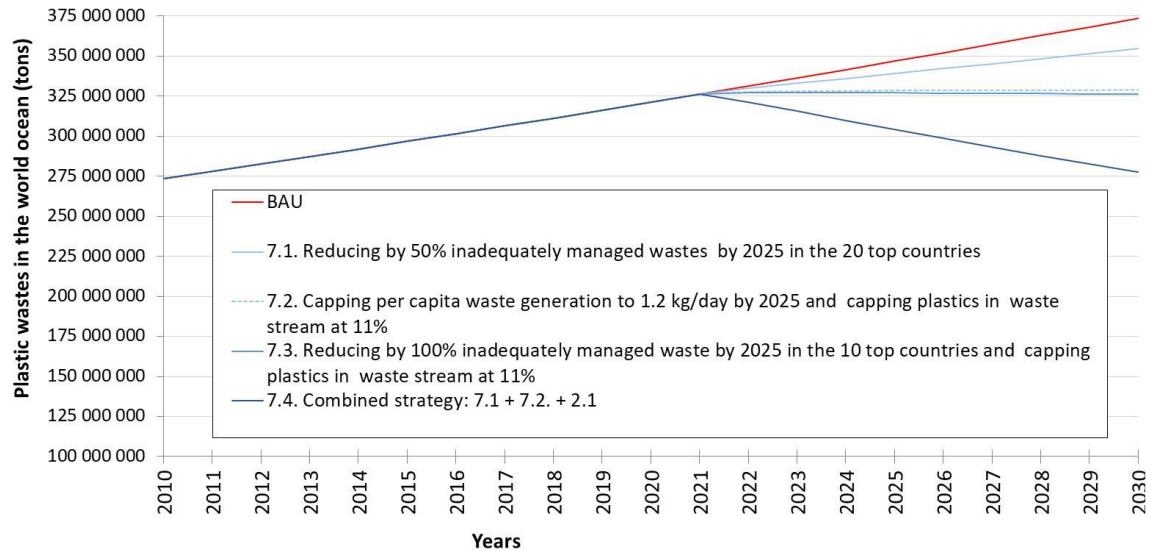
518
 519 The combined strategy implemented in Scenario 7.3 – that is, reducing by 100%
 520 inadequately managed waste by 2025 in the 10 top countries and capping plastics in
 521 waste stream at 11% – could be appreciated by stakeholders in terms of equity as well as
 522 social and political acceptability because poor, emerging and rich countries would
 523 participate to plastic solutions on the basis of the principle of common but differentiated
 524 responsibilities. That is, they would all bear a common environmental responsibility but
 525 their contribution to plastic solutions would be differentiated according to their level of
 526 responsibility and to their affordability (i.e., their ability to pay for plastic solutions). This
 527 makes the implementation of this scenario likelier. However, capping plastics in waste
 528 stream at 11% would require changes in consumer behaviours. This is not easy to achieve

529 unless awareness rising campaigns are designed appropriately to spur cooperation in the
530 mind of consumers and reduce individualistic behaviours. Peculiar designs are required
531 for that – read, inter alia, Benkler (2011) and Ostrom (2010c) – otherwise the change in
532 mentalities and behavior is extremely difficult to achieve.

533

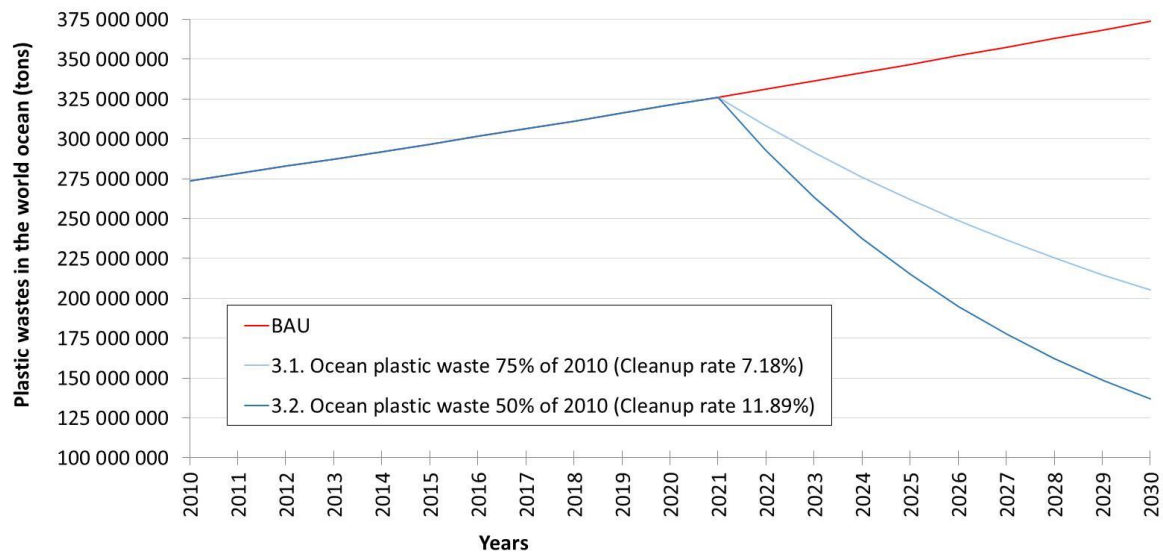
534 Scenario 7.4. is another highly combined strategy since it merges scenarios 7.1, 7.2 and
535 2.1, which involves three categories of solutions: a preventive “middle” solution
536 (scenario 7.1), a preventive “at-the-source” solution (scenario 7.2) and a curative “end-of-
537 pipe” solution (scenario 7.3). Scenario 7.4 follows thus a similar approach as scenario 2.5
538 but it performs better. Figure 3 shows that scenario 7.5 succeed to achieve a level of
539 cumulated plastic waste in the ocean of 277 million tons by 2030, i.e, 26% below the
540 BAU. This means recovering the situation of the year 2011. This strengthen our
541 assumption that combining different kinds of environmental measures downstream and
542 upstream the social-ecological system (“end-of-pipe” and “at-the-source” solutions) as
543 well as upstream and downstream of the plastic contamination causal chain (“curative”
544 and “preventive” solutions) is more successful than scenarios where only one type of
545 environmental measure is undertaken. Keeping on scenario 7.4 up to 2069 would allow
546 the amount of cumulated plastic waste in the ocean to achieve half the value of 2010, i.e.
547 137 million tons. Given the emergency of the situation for marine biodiversity, it might
548 be interesting to test scenarios that are quicker to reduce by 50% the level of 2010. Figure
549 4 is a first attempt in that sense. It shows that cleanup effort only (scenario 3.2) could
550 achieve that goal but would require removing from the ocean 11.89% of plastic every
551 year starting from 2020 up to 2030. Assuming that current levels of plastic annual
552 removal in the ocean is 0.10% (this is a first preliminary assumption that will be
553 improved later), this would require a technological progress 119 times higher than
554 nowadays. Scenario 3.1 is an intent to simulate quite an ambitious ecological target and at
555 the same time a bit more realistic. It shows that to reducing 2010’s level by 25% would
556 require removing from the ocean 7.18% of plastic every year starting from 2020 up to
557 2030 this would require to multiply 72 times current efforts in ocean cleanup
558 technologies. In further versions of this paper, we will assess if such a technological
559 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).



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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).

577 **Conclusion**

578 Our results suggest that to reach significant abatement of plastic wastes accumulated in
579 the ocean, a panel of diverse types of solutions is required. One type of environmental
580 measure alone will never succeed. Upstream and downstream solutions must be
581 combined across the social-ecological system (i.e., “end-of-pipe” and “at-the-source”
582 solutions from Table 1) as well as across the plastic contamination causal chain (i.e.,
583 “curative” and “preventive” solutions from Table 1). According to Jambeck et al. (2015),
584 long-term solutions will also likely include waste reduction and “downstream” waste
585 management strategies such as expanded recovery systems and extended producer
586 responsibility, i.e., plastic products used by consumers would be recovered by producers
587 for recycling purposes (Braungart, 2013; OECD, 2004; Lifset, 1993; Kalimo et al.,
588 2012). Also, Jambeck et al. assert that improving waste management infrastructure in
589 developing countries is paramount and will require substantial resources and time. While
590 such infrastructure is being developed, industrialized countries can take immediate action
591 by reducing waste and curbing the growth of single-use plastics (Jambeck et al., 2015).

592

593 All these upstream and downstream solutions could either come from the top (political
594 and economic decision makers) or the bottom of the society (citizens, environmental
595 associations, small size enterprises). But in any case, several of these solutions will
596 require a change in mentalities to spur individuals to act collectively. Trying to solve the
597 problem of providing a common good such as a plastic-free ocean is a classic collective
598 action dilemma (Kollock, 1998)¹². The classic theory of collective action predicts that no
599 one will change behavior and reduce their plastic consumption unless an external
600 authority imposes enforceable rules that change the incentives faced by those involved
601 (Hardin, 1968; Benkler, 2011). This is why many analysts call for a change in institutions
602 at the global level. However, the presumption that a collective action problem that has
603 global effects can only be solved globally is not relying on strong empirical support. A
604 large number of individuals facing collective action problems have self-organized to
605 cooperate and develop solutions to common pool resource problems at a small to medium
606 scale without external top-down authority from national or international levels (Poteete et
607 al., 2010; Agrawal, 2000; Schlager et al., 1994; Ostrom, 1992, 1994, 2001; NRC,
608 2002; Dietz, 2003). Plastic as many other problems conceptualized as “global
609 problems” are the cumulative result of actions taken at diverse levels, i.e., at the level of
610 individuals, families, small groups, communities, private firms, and local, regional, and
611 national governments (Ostrom, 2010a). Solving this problem requires collective action
612 and many actors at diverse levels need to change their day-to-day activities to avoid
613 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).

614 enforceable global treaty. However, if global solutions negotiated at a global level are not
615 backed up by a variety of efforts at national, regional, and local levels, they are not
616 guaranteed to work well (Ostrom, 2010a, c). Attempts to foster multiple-scale actions and
617 benefits rely on the concept of polycentric governance in which many centers of
618 decision-making are formally independent of each other but can undertake many
619 activities at diverse scales that cumulatively make a difference (Ostrom, 2010a; Gruby
620 and Basuro, 2014). Ostrom (2010c), Benkler (2011) and others have identified about 10
621 conditions required to create a context in which people are willing to self-organize at
622 multiple levels and collaborate to find a solution to a common problem.

623

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

632

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