Problem Chosen	2020 MCM/ICM Summary Sheet	Team Control Number
E		2021103

Plastic is everywhere. Due to its convenience and low cost, plastic is used in many settings before it is quickly disposed of. Unfortunately, much of this plastic makes its way into our oceans, where it wreaks havoc and contributes to the decline in populations of ocean creatures. Single-use plastic is undeniably convenient, but we must balance the benefits with the environmental costs. How does one quantify the environmental impact of consuming an additional unit of plastic? In this paper, we consider predicted future seabird populations as a metric for evaluating the future effect of our current plastic production. We model seabird population dynamics by considering births, natural deaths, and anthropomorphic deaths due to interactions with plastic debris. As a result, seabird population is expressed as a function of both time and the volume of accumulated plastic at a given time. Our decision to use seabirds as a proxy for the health of the marine environment is backed up scientific literature that establishes the usefulness of seabirds as a bioindicator.

Using this population model, we predict that, if global plastic production continues at its current pace, seabirds will become endangered by the year 2056 and will become critically endangered by 2062. From this, we can see that our current plastic production trend is causing rapid degradation of our marine ecosystem, which emphasizes the necessity of new policies regarding our production and management of plastic products. We describe these policies as functions of accumulated plastic over time. The environmental impacts of various policies are evaluated by simulating the seabird population model with plastic levels dictated by the policy function rather than their current trend. The economic cost of each policy is determined by considering the total magnitude of reduction in plastic consumption necessary to achieve the policy, as well as the rate of plastic reduction induced by the policy. We determined that an appropriate global policy would be to reduce accumulated plastic by a constant amount each year until the remaining volume of plastic is less than 3,750 million metric tons. This policy will allow the seabird population to recover while imposing the minimum economic cost to society.

After having found the global policy, we develop an equitable approach for distributing the costs of achieving the optimal policy's goals across different countries. Responsibility for the seabird population is divided across countries by taking into account each country's income, population, and accumulated plastic production. The burden of reducing plastic is placed more heavily on countries that currently produce plastic in excess to the required amounts. Through the above methods, our report summarizes our analysis on types of plastic reduction policies and its effects on preserving the marine environment.

Contents

1 Introduction

Since the large scale production of single-use disposable plastics began in the 1950s, there has been an accumulation of plastic waste in the environment, particularly our oceans [1]. Although the accumulation of this plastic pollution has gone unnoticed by many who enjoy the benefits of using single-use plastic products, the animal residents of our marine ecosystems have certainly felt the detrimental effects. It is estimated that 4-12 million metric tons of plastic waste end up in the ocean every year [2]. This problem is compounded by the fact that plastic degrades at a very slow rate, so plastic that is added to the ocean stays in the ocean in perpetuity if no human action is taken [4]. The lives of marine animals are put at risk when they encounter plastic debris in their habitats. In some cases, these encounters result in death. It is important to be able to balance the convenience of using single-use plastic with the damage to the marine environment that comes as a result.

In this report, we present a model to assess current trends in plastic waste growth and to suggest appropriate changes in global policy to efficiently mitigate plastic waste and protect our environment. To achieve this objective, we do the following:

- **Create a metric to assess marine environmental health** as a direct result from global plastic production at any given time.
- **Estimate plastic accumulation** since 1950 and assess current plastic production and consumption trends to predict plastic accumulation over the next few decades.
- **Reconcile conflicting economic and environmental incentives** of various plastic production policies by determining the associated environmental impacts and societal costs of each policy.
- **Recommend adjustments to global policy** to effectively spread responsibility to reduce plastic waste across each country without overburdening any one country in particular.

2 Model

The overall goals of our model are to (1) predict the point at which damage due to single-use plastic waste becomes irreparable, (2) evaluate environmental impacts of policies to reduce plastic production, and (3) determine an equitable division of the costs of plastic regulation across countries.

We quantify the health of the environment using seabird population as a proxy. Seabirds are a crucial part of marine ecosystems and are viewed as an effective bioindicator for evaluating the effects of disturbances (e.g., plastic pollution) on the environment [5]. Thus, we use predicted future seabird population as our metric to evaluate the effectiveness of potential policies. In this report, policies are represented as quantity of plastic, measured in million metric tons (Mt), that is produced over time. To quantify the costs of policies, we consider the total magnitude of reduction in plastic consumption necessary to achieve the policy, as well as how quickly plastic consumption levels have to be changed in order to achieve the policy. We later divide the global policy into policies for each individual country. Since some countries can take on a higher economic cost resulting from plastic reduction, relative income, population, and current plastic production per capita serve as metrics to evaluate each country's ability to reduce their plastic consumption.

2.1 Environmental Health

Assumption: Seabird population $S(t)$ is a useful proxy for estimating global marine environmental health at time t.

Remark: Seabirds are waterfowl that depend on the ocean and surrounding areas for survival. Since seabirds are well-integrated with the marine environment, they are sensitive to changes in the ocean environment. Seabirds have been shown to be a reliable bioindicator of the state of the marine environment for a variety of reasons including their wide-ranging area of habitation and their rapid response to changes in their environment [5].

In addition to being a good reflection of the general state of the health of the marine environment, sea birds are worthy of protection in their own right. As a top predator, seagulls play an important role in regulating population dynamics of marine species and are a critical for the normal functioning of the marine ecosystem [6]. A decrease in seabird population has the potential to cause cascading effects lower down in the food chain, which could have disastrous and far-reaching effects on the environment [7].

Studies have shown that seabird populations have been significantly impacted by plastic waste [8]. Seabirds are at risk of accidentally ingesting plastic that they encounter in marine waters, which can have detrimental health effects and may lead to death. As plastic production has increased, more and more plastic has ended up in the ocean, which has increased the risk posed to seabirds.

Assumption: Changes in seabird population over time are determined birth rates, natural death rates, and deaths caused by seabird interactions with marine plastic pollution.

We can model the seabird population S with the following differential equation:

$$\frac{dS}{dt} = (b - d_n)S - d_p S P_{trend}(t),$$

where b is the seabird birth rate, d_n is the natural seabird death rate, d_p is the number of seagull deaths due to plastic per seabird per Mt of plastic, and $P_{trend}(t)$ is the cumulative amount of plastic that has been produced globally.

We can analytically solve this differential equation, yielding a closed-form solution ($P(t)$ is an integrable function):

$$S(t) = S(0)\exp\left((b - d_n)t - d_p \int_0^t P(t')dt'\right)$$

2.1.1 Estimation of Parameters

In order to use our model of seabird population as a concrete metric of environmental health, we examined scientific literature to estimate model parameters, which allows us to provide concrete estimates of seabird population given a certain plastic production trend. We chose the razorbill as our reference seabird because breeding and survival rates and feeding behaviors are representative of the average seabird. Razorbills have a conservation status of ”near threatened,” and since they use the ocean as their feeding grounds, they are at risk of interactions with oceanic plastic waste [9].

We use the following parameter values:

- $b = 0.326$, which represents the number of births per seabird. This is obtained by multiplying the productivity of each pair of seabirds (0.895) by the fraction seabirds that are at breeding age (approximately $8/13$), as determined through observational studies [10].

- $d_n = 0.146$, which represents the fraction of seabirds that die. This is calculated as one minus the average of the survival rates of juvenile seabirds (0.630) and adult seabirds (0.895), weighted by the fraction of the population that are juveniles (approximately $2/13$) or adults (approximately $11/13$) [10].

- d_p = 8.395e-06, which is the number of seabird deaths due to plastic per seabird per million metric tons of cumulative plastic produced. This value was estimated by breaking down d_p as

  $$d_p = \frac{\text{\# of bird deaths}}{\text{\# of birds that ingested plastic}} * \frac{\text{\# of bird that ingested plastic}}{\text{Mt of cumulative plastic} * \text{seabird population}}$$

  Roman *et al.* (2019) found that 32.1% of seabirds have ingested plastic debris and 20.4% of seabirds die after ingesting a single piece of plastic [11]. Around the time the study was conducted, total cumulative plastic production was approximately 8300 Mt [12]. d_p was computed as $0.321(0.204)/8300$.

- $S(51) = 10e6$. For convenience, we choose $t = 0$ to correspond to the year 1950. A 2001 study by Chapdelaine *et al.* showed that the global razorbill population was approximately one million at the time of the study, so we estimate that in 2001 ($t = 51$, there were one million razorbirds [13]. Using this as our condition, we can solve for $S(0)$, the razorbill population in 1950.

It is useful to note that although razorbills were chosen as a our reference species, our model can be easily adapted to predict population sizes of other seabird species or even other animals by simply replacing b, d_n, and d_p with values that are appropriate for the chosen species.

2.2 Plastic Production

Assumption: In the absence of new plastic production policies, plastic production will continue along its current trend, which exceeds the level required to sustain the seabird population. As a result, global policy is required to limit plastic production worldwide.

Remark: Since the total volume of plastic produced prior to 1950s is negligible, we chose the year 1950 to correspond to $t = 0$ for the sake of convenience [2].

2.2.1 Modeling Plastic Production Policies

Assumption: The global accumulation of plastic under policy $P_{policy}(P_{trend}, P_r, t)$ can be modeled by a piece-wise differentiable function of both the total unencumbered accumulated global quantity of plastic $P_{trend}(t)$ (i.e., the cumulative plastic production following current trends) and time t.

Assumption: On time of policy activation (T_a), countries do not contribute to reducing accumulated global levels of plastic, i.e.:

$$P_r(T_a) = 0 \rightarrow P_{policy}(T_a) = P_{trend}(T_a)$$

Remark: Our global policy model has two primary objectives: (1) To account for time for policy activation (T_a) and (2) to be easily translatable to benchmarks for plastic reduction recommendations for world governments. We first define function $P_{policy}(P_{trend}, P_r, t)$, which is a function that represents the global accumulation of plastic under plastic reduction policy $P_r(t)$. Before policy activation time T_a, P_{policy} is equal to P_{trend}. After T_a, when plastic reduction plan P_r has come into effect, we express P_{policy} as P_{trend} with the cumulative reduction of plastic defined in P_r, or $P_{policy} = P_{trend} - P_r$. Thus, we arrive at a piece-wise formulation of P_{policy} as follows:

$$P_{policy}(P_{trend}(t), P_r(t), t) = \begin{cases} P_{trend}(t) & \text{if } t < T_a \\ P_{trend}(t) - P_r(t) & \text{if } t \geq T_a \end{cases}$$

To calculate the desirable P_r for the recovery of the environment (i.e. seabird population), we will first determine a P_{policy} that ensures seabird survival in the limiting case ($t \rightarrow \infty$). Upon finding a satisfactory P_{policy}, we can then determine P_r by computing the following:

$$P_r(t) = P_{trend}(t) - P_{policy}(t)$$

2.2.2 Costs of Plastic Production Policies

Assumption: Countries will more readily accept a policy that minimizes (1) the quantity of cumulative saved plastic from the ocean and (2) the rate of decrease of their plastic production.

Remark: Countries are shown to adopt and enact plastic reduction policies that are easy to achieve and do not change much over time [3]. We formulate a cost C of a particular plastic reduction policy over time interval $[t_0, t_f]$ as the sum of the total plastic saved from the ocean ($P_{trend}(t_f) - P_{policy}(t_f) = P_r(t_f)$) and the maximum year-to-year reduction of plastic ($\frac{d}{dt}P_r$). Thus, the cost of enacting a plastic production reduction $P_r(t)$ from $t = t_0$ to $t = t_f$ is defined as

$$C_{t_0,t_f}(P_r) = P_r(t_f) + \lambda \max_{[t_0,t_f]} \left\{ \frac{d}{dt} P_r \right\}$$

where λ is a constant that represents a country's hostility to extreme changes in plastic production levels form year to year.

2.3 Breakdown by Country

Assumption: Country-level dynamics can be modeled using the same framework as global-level dynamics.

Remark: To further characterize global plastic accumulation trends, we dive into plastic production by individual countries. We can break down cumulative global plastic, $P_{trend}(t)$, and express it as a sum across cumulative plastic $P_i(t)$ for each country i at time t. Yearly contributions to $P_{trend}(t)$ are denoted as $\Delta P_{trend}(t)$ such that $P_{trend}(t+1) = P_{trend}(t) + \Delta P_{trend}(t)$. $\Delta P_{trend}(t)$ corresponds to the volume of plastic produced globally in year t. Likewise, yearly contributions to $P_i(t)$, the cumulative plastic produced by country i, is denoted as $\Delta p_i(t)$ such that $P_i(t+1) = P_i(t) + \Delta p_i(t)$. $\Delta P_{trend}(t)$ corresponds to the volume of plastic produced by country i in year t.

In the absence of global policies, countries act as individual rational agents to produce the amount of plastic necessary to keep their local economies running at the optimal level. Since a country's economic output is maximized at market equilibrium, the quantity of plastic supplied for a country $\Delta p_i(t)$ must be equivalent to the quantity of plastic demanded by the consumers of that country. However, for many countries, $\Delta p_i(t)$ is far above the appropriate level for environmental preservation. $\Delta P_{trend}(t) = \sum_i \Delta p_i(t)$ contributes to a larger cumulative global plastic amount $P_{trend}(t)$ and a resulting depletion of seabird population $S(P_{trend}, t)$. While each country caters to the best interests of their economies, they have a collective responsibility to protect the global marine environment. The problem is that countries currently ignore this responsibility. If order to address this problem, global policies must be instituted as an agreement across countries to appropriately limit global plastic production and increase plastic cleanup. In Section 5.2, we explore how to equitably distribute the costs of plastic reduction and cleanup by requiring countries with large $\Delta p_i(t)$ to contribute more to these efforts.

3 Predicting the Point of Irreversible Damage

In this section, we answer the question: *If we do not change our current plastic production policies, when will the damage we cause to the environment reach an irreversible level?*

Future cumulative plastic volumes (in Mt) can be estimated by fitting a quartic polynomial to recent plastic data (Figure 1). The equation of the trend line is

$$P_{trend}(t) = 0.000262t^4 + 0.001772t^3 + 0.6967t^2 - 4.123t + 10.83;$$

with an R^2 value of 0.9999. We use chose to use a quartic polynomial fit for two reasons. The first reason is that an exponential curve did not fit as well ($R^2 = 0.9936$), with notable deviation between the trend line and the tails of the data. The second reason is that we plotted annual plastic production over time and found that it was cubic. Since cumulative plastic production is the integral of annual plastic production, it follows naturally that cumulative plastic production should be quartic.

Using $P_{trend}(t)$, we can predict the future cumulative plastic production if we follow the current trend determined by existing plastic production policies.

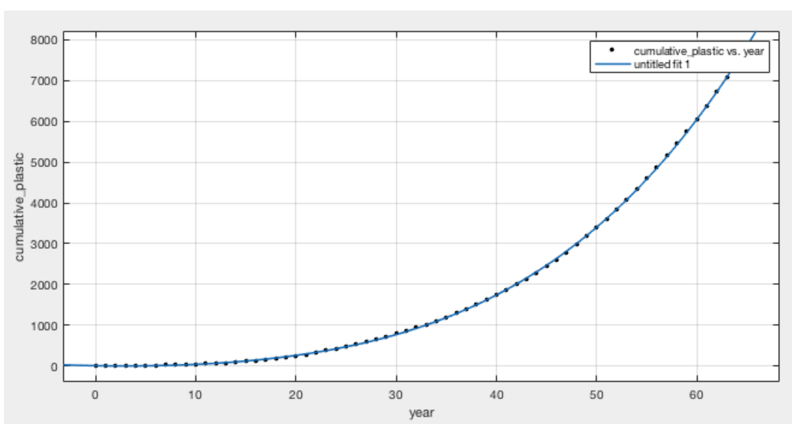

Figure 1: Plot of past and projected cumulative global plastic production

Assuming that plastic production continues as its current pace, we can project the future seabird population by setting $P_{trend}(t) = P_{trend}(t)$ in our equation for $S(t)$ that we derived above. Thus, the predicted seabird population given that we follow current plastic production trends can be written as

$$S^{trend}(t) = S(0)\text{exp}\left((b - d_n)t - d_p \int_0^t P_{trend}(t')dt'\right)$$

Plotting $S^{trend}(t)$ for the years 1950 to 2150, we see that seabird population was increasing when plastic production first took off in the 1950s, but the population peaks around the year 2000 and has been in a steady decline since (Figure 2). The initial increase is due to natural population dynamics. Since the birth rate is greater than the death rate ($b > d_n$), seabird population has a natural tendency to increase exponentially. However, the dangers of plastic waste impose a downward pressure on bird populations. As time goes by, more plastic accumulates in the ocean, and the threat of plastic to seabirds increases. According to our model, we are now at a point when the sum of natural deaths and deaths due to plastic are greater than the birth rate, so the seabird population is in decline.

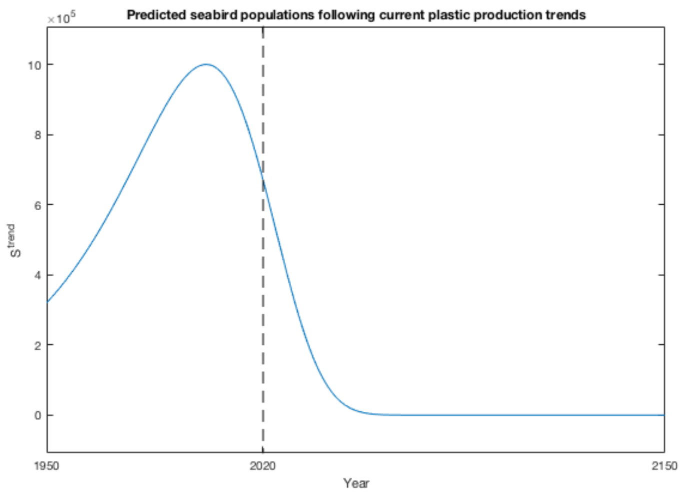

Figure 2: Projected seabird population given that global plastic production follows current trend.

According to the *The International Union for Conservation of Nature* (IUCN), a species is considered *endangered* if the population size is estimated to be fewer than 2,500 mature individuals and the population is expected to continue to decline[14]. Our model predicts that our reference seabird population, razorbills, will become endangered no later than the year **2056**. This is a slight overestimate of the time needed in order for razorbills to become endangered because, when our model predicts that there are 2,500 seabirds, there are actually fewer than 2,500 *mature* seabirds since some of the 2,500 birds are juvenile. Therefore, razorbills will mostly reach the 2,500 mature individuals threshold earlier than 2056.

Furthermore, IUCN considers a species to be *critically endangered* if the population size is estimated to be fewer than 250 mature individuals and the population is expected to continue to decline [14]. According to our model, our reference seabird population will reach this threshold no later than the year **2062**.

Assuming that current plastic production trends continue, cumulative plastic production by the year 2056 will be approximately 42,600 Mt, which is a 34,800 Mt increase from current cumulative plastic levels. By the year 2062, the cumulative amount of plastic produced will have reached approximately 53,100 Mt.

4 Evaluation of Global Plastic Policies

There are various policies we can consider for controlling plastic production. The first type of policy is one in which we reduce or terminate plastic production but engage in no additional cleanup efforts. We will show that this type of policy is insufficient if we want to save our environment from irreversible damage. The second type of policy requires a net reduction in accumulated plastic produced until all plastic is cleaned up. The third type of policy requires a net reduction in accumulated plastic until plastic volumes are below a calculated threshold. Both the second and third types of policies result in the recovery of seabird populations, but the third type of policy is more realistic to implement.

4.1 Policy Type 1: Reduce or Terminate Plastic Production with No Cleanup Efforts

One type of policy that is often proposed is to allow for the continuation of plastic production but at a reduced level. Examples of such policies are regulations that require plastic companies to reduce their production by some percentage every year or regulations that impose a cap on the maximum amount of plastic that can be produced. However, this type of policies not sufficient to save the environment.

In fact, even the immediate termination of plastic production is not enough to save the sea birds, as shown in Figure 3. Terminating plastic production prolongs the survival of the seabird population, as evidenced by the population under policy line (blue line) appearing slightly above for population without policy line (orange line) for several decades, but these lines ultimately converge to the same value, namely a population size of zero. The reason for this bleak outcome is that the amount of plastic waste that has accumulated in our oceans is already so high that, in the absence or cleanup efforts, seabirds will continue to die at an alarming rate.

Because policies with no cleanup actions are proven to be useless against the global plastic crisis, we will not compute their cost C, as they will not serve as a meaningful comparison to the policies below.

4.2 Policy Type 2: Termination of Plastic Production with Complete Cleanup

We showed above that the termination of plastic production alone is not enough to save the seabirds. In order to restore the health of the environment, cleanup efforts must be introduced. In this section, we model the effects of a policy that both terminates plastic production and mandates a constant amount of plastic waste to be cleaned up each year (e.g., each year, 10 Mt of plastic must be cleaned up from the ocean).

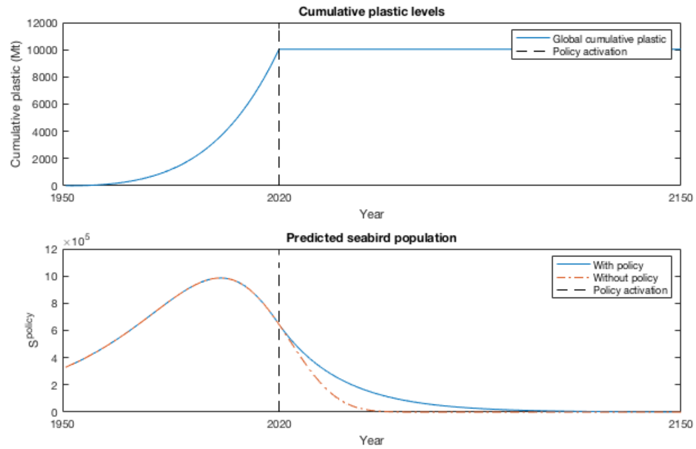

Figure 3: (Top) Cumulative plastic levels given that global plastic production is immediately terminated. (Bottom) The blue line is the predicted seabird population as a result of these policies, and the orange dotted line is the predicted seabird population in the absence of policies.

Figure 4 shows the environmental impacts of stopping plastic production and engaging in cleanup efforts that mitigate the environmental effects of 100 Mt of previously produced plastic (e.g., if, for each 100 Mt of plastic produced in previous years, 30 Mt ended up in the ocean, this policy would require that 30 Mt tons of plastic be cleaned up from the ocean every year going forward). These cleanup efforts are assumed to continue until all plastic waste is removed from the environment. We see that once plastic production stops and cleanup efforts begin, the decline in seabird population begins to slow and eventually starts to recover. Our model predicts that by the start of the next century, seabird populations will take off.

One should note that the tail end behavior of predicted bird population should be interpreted with caution. Since our seabird model was created to model the interactions of near endangered populations of sea birds with plastic waste, it does not precisely model seabird population dynamics for large populations (e.g. the model does not account for the carrying capacity of the marine environment). The important takeaway is termination of plastic production causes seabird population to recover, but the extent of this increase may not be accurately reflected by our model.

Additionally, it is useful to know that a complete termination of plastic production is not necessarily required for achieving the effects described above. If people wish to continue producing and consuming plastic, they can, provided that they engage in additional cleanup efforts that cancel out the environmental damage caused by their consumption.

Due to the sheer magnitude of effort required to enact such a policy, stopping plastic production and gradually removing existing plastic entirely would realistically never be adopted by any country. However, it is still important to quantify the cost of this policy for future comparison with more realistic plans.

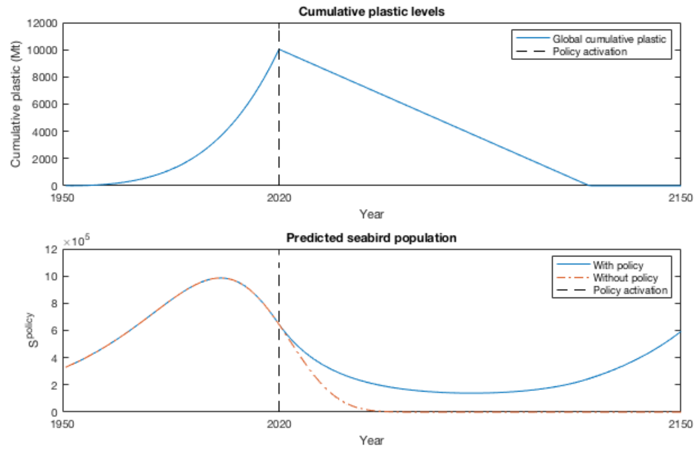

Figure 4: (Top) Cumulative plastic levels given that global plastic production is immediately terminated *and* an equivalent of 100 Mt of previously produced plastic is cleaned up from the environment each year until plastic pollution is completely removed. (Bottom) The blue line is the predicted seabird population as a result of these policies, and the orange dotted line is the predicted seabird population in the absence of policies.

We compute the cost C over time interval $[T_a, T_f]$ of this policy, $P_{aggressive}$, which cuts all plastic production and removes all cumulative global plastic by a constant amount year-to-year:

$$P_{aggressive}(t) = P_g(t) - P_g(T_a) - \frac{P_g(T_a)}{T_f - T_a}t$$

We chose a linear reduction policy, since any higher polynomial or exponential reduction policies would introduce maximum derivatives of higher magnitudes. We penalize the maximum derivative because more abrupt changes in production levels impose greater hardships on society as people are forced to adapt more quickly.

$$C_{T_a,T_f} = P_g(T_f) + \lambda\left(\frac{P_g(T_a)}{T_f - T_a}\right)$$

By setting the interval to $[2020, 2150]$ (eliminating plastic in 130 years), we find that $C_{2020,2150} = 1.6902\text{e}5 + \lambda 77.188$.

4.3 Policy Type 3: Termination of Plastic Production with *Incomplete* Cleanup

We saw above that the termination of plastic production paired with a complete cleanup of plastic results in the recovery of seabird populations. However, complete plastic cleanup is likely unrealistic due to limitation in technology for pollution cleanup. Here, we show that complete plastic cleanup is not a necessary condition to save the environment and that the environment is still able to recover even if some amount of plastic remains in the oceans.

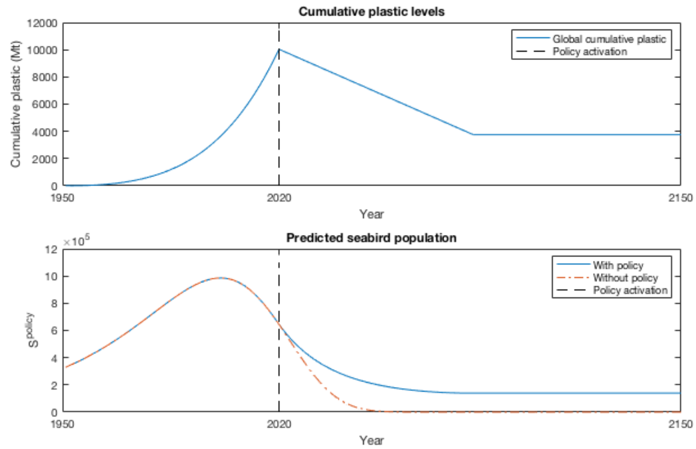

Figure 5: (Top) Cumulative plastic levels given that global plastic production is immediately terminated *and* an equivalent of 100 Mt of previously produced plastic is cleaned up from the environment each year until plastic levels become 3,753.7 Mt. (Bottom) The blue line is the predicted seabird population as a result of these policies, and the orange dotted line is the predicted seabird population in the absence of policies.

Furthermore, we calculate the maximum level of plastic that can remain not cleaned up without killing off seabird populations.

By setting $\frac{dS}{dt}$ from the seabird population model to 0, we can solve for the maximum allowable level of plastic P_{min} that will not pose any threat to the seabirds (e.g. the seabird population will no longer be in decline):

$$0 = (b - d_n)S - Sd_pP_{min}$$

$$P_{min} = \frac{b - d_n}{d_p}$$

If the global accumulated plastic is reduced to a level that is equal to P_{min}, seabird populations will stop declining and stabilize. If the quantity of global plastic is reduced below P_{min}, the seabird population stop declining, stabilize, and start growing again.

Figure 5 shows the results of terminating plastic production and undertaking an incomplete cleanup of plastic waste. The cleanup efforts reduce plastic pollution to a level at which the lethal harm imposed on seabirds is extant, but minimal. In this scenario, the seabird population reaches an equilibrium because sum of the natural death rate and the death rate due to lethal plastic ingestion is equal to the birthrate.

Now we will compute the cost of this less aggressive policy. We fix target global plastic level $P_{target} \leq P_{min}$ to be achieved by time t_f. As mentioned before, if $P_{target} = P_{min}$, the seabird population will stabilize (but not grow). If $P_{target} < P_{min}$, the seabird population will stabilize and grow. Now we can formulate policy $P_{feasible}$ that stops all production and linearly reduces global plastic levels to P_{target} by time T_f:

$$P_{feasible} = P_g(t) - P_g(T_a) - \left(\frac{P_g(T_a) - P_{target}}{T_f - T_a}\right) t$$

We compute the the cost over the same time interval as before ($C_{2020,2150}$) for the sake of comparison:

$$C_{2020,2150} = P_g(2150) + \lambda \left(\frac{P_g(2020) - P_{target}}{2150 - 2020}\right) = 8.9972e4 + \lambda \left(77.1882 - \frac{P_{target}}{130}\right)$$

Since we know λ is positive and that $0 < P_{target} \leq P_{min}$, we know this C value is smaller than the one computed for $P_{aggressive}$, as expected. Since the C value of policy type 3 is the smallest, we conclude that the optimal policy will be of this form (i.e., the optimal policy will require a constant net reduction in accumulated plastic until we go below the maximum volume that does not result in further seabird population decline).

5 Policy Division Across Countries

We want to divide the cost burden of implemented policies proportionally across countries by assessing the appropriate amount of plastic for each country to produce. Since each country has different capabilities of reducing their plastic consumption and cleaning up plastic waste, we restrict plastic production in each country based on their population and income level. To simplify the interpretation of a country's aggregate plastic use in a year, we divide its plastic consumption by the country's population to arrive at average plastic used per capita per year. Furthermore, we classify each of the countries into four relative income classes: High Income, Upper Middle Income, Lower Middle Income, Low Income. As such, we can assess how much plastic each country should produce per person relative to their income class.

Given that the cost burden of implemented policies P_{policy} comes in the form of accumulated cost $C(P_r)$, countries will prefer to examine the breakdown of their own costs as time progresses. For this reason, we define the following:

$$\Delta p_{policy} = \frac{d}{dt}(P_{policy}), \Delta p_{trend} = \frac{d}{dt}(P_{trend}), \Delta p_r = \frac{d}{dt}(P_r)$$

Note that $\Delta p_{policy}(t) = \Delta p_{trend}(t) - \Delta p_r(t)$ by the linearity of the differentiability operator. By examining incremental changes in cumulative policy, we can dynamically shift cost burden across different countries over time.

To further quantify the overall shift of global plastic production, we define α to be the ratio of :

$$\alpha(t) = \frac{\Delta p_{policy}(t)}{\Delta p_{trend}(t)} = \frac{\Delta p_{trend}(t) - \Delta p_r(t)}{\Delta p_{trend}(t)} = 1 - \frac{\Delta p_r(t)}{\Delta p_{trend}(t)}$$

Note that since it is a dimensionless ratio, the defined proportion for α can be used interchangeably across units for defining the reduction of *plastic* given a policy and reduction of *plastic per capita* given a policy. We can also see that $\alpha(t) < 1$ for all time t since $\Delta p_r(t) < \Delta p_{trend}(t)$.

By multiplying the current global plastic production trend $\Delta p_{trend}(t)$ by a factor of α, we arrive at the reduced global plastic production $\Delta p_{policy}(t)$ dictated by the policy. Each of the four income classes will share the burden of decreasing their average plastic consumption per capita by α. We define $\overline{X}$ to be the average plastic consumption per capita across all countries prior to any policy introduction. Additionally to meet the objectives set by the policy, we define $\widetilde{X} = \alpha\overline{X}$ to be the average plastic consumption per capita across all countries after policy introduction.

Let $\bar{x}_{HI}$, $\bar{x}_{UMI}$, $\bar{x}_{LMI}$, $\bar{x}_{LI}$ be the mean plastic per capita per year across the high income, upper middle income, lower middle income, and low income classes. Since the four income classes share the cost burden equally, we can define the shifted means $\tilde{x}_{HI}$, $\tilde{x}_{UMI}$, $\tilde{x}_{LMI}$, $\tilde{x}_{LI}$:

$$\tilde{x}_{HI} = \alpha\bar{x}_{HI}, \quad \tilde{x}_{UMI} = \alpha\bar{x}_{UMI}, \quad \tilde{x}_{LMI} = \alpha\bar{x}_{LMI}, \quad \tilde{x}_{LI} = \alpha\bar{x}_{LI}$$

Note that shifting each of the class means by α maintains the global production mean dictated by $\Delta p_{policy}(t)$ since

$$\overline{X} = p_{HI}\bar{x}_{HI} + p_{UMI}\bar{x}_{UMI} + p_{LMI}\bar{x}_{LMI} + p_{LI}\bar{x}_{LI}$$

Additionally, we can multiply both sides by α to achieve

$$\widetilde{X} = p_{HI}\tilde{x}_{HI} + p_{UMI}\tilde{x}_{UMI} + p_{LMI}\tilde{x}_{LMI} + p_{LI}\tilde{x}_{LI}$$

where p_{HI}, p_{UMI}, p_{LMI}, p_{LI} are the proportions of the total 192 countries in each income class and $p_{HI} + p_{UMI} + p_{LMI} + p_{LI} = 1$.

To achieve $\tilde{x}_k$ for each of the four income classes ($k \in \{1, 2, 3, 4\}$), we must further consider cost sharing across countries within each income class. We consider $\tilde{x}_k$ to be the ideal level of plastic per capita for each of the income classes k. However, there certainly will be countries producing above $\tilde{x}_k$ and countries producing below $\tilde{x}_k$. If a country intends to produce plastic per capita at a level below $\tilde{x}_k$, then this country should be left untouched by the global policy. On the contrary, if a country intends to produce plastic per capita at a level above $\tilde{x}_k$, then appropriate restrictions will need to be imposed.

Country-specific restrictions come in the form of a multiplicative factor $\beta_{k,i}(t)$ where $\beta_{k,i}$ is computed for each country i to achieve $\tilde{x}_k$ within each income class k at time t. Since countries with per capita plastic production $x_i < \tilde{x}_k$ are left untouched, $\beta_{k,i} = 1$ for these countries. However for countries with per capita plastic production $x_i > \tilde{x}_k$, $\beta_{k,i}$ will need to be computed for each income class k to achieve $\tilde{x}_k$. More specifically, $\beta_{k,i}$ can be defined for each income class as follows:

$$\beta_{k,i}(t) = \begin{cases} \frac{\tilde{x}_k(t) - \sum_i \mathbb{1}\{x_i(t) \leq \tilde{x}_k(t)\} x_i(t)}{\sum_i \mathbb{1}\{x_i(t) > \tilde{x}_k(t)\} x_i(t)} & \text{if } x_i(t) > \tilde{x}_k(t) \\ 1 & \text{if } x_i(t) \leq \tilde{x}_k(t) \end{cases}$$

where each sum is taken across all countries i in income class k. Since $x_i(t)$ and $\tilde{x}_k(t) = \alpha(t)\bar{x}_k(t)$ are functions of time, $\beta_{k,i}(t)$ must also fluctuate with time and allow for dynamic cost sharing between countries across time t.

5.1 Policy Division Procedure

Using the dataset obtained from Jambeck et al.[1], we conducted the following procedure to assess the maximum amount of plastic each country should produce given some incremental plastic policy $\Delta p_{policy}(t) = \Delta p_{trend}(t) - \Delta p_r(t)$ at time t:

1. Split each of the 192 countries in the world into four relative income classes: High Income, Upper Middle Income, Lower Middle Income, Low Income.
2. Compute the amount of plastic waste produced per person per year for every country.
3. For each of the four income classes, compute the average amount of plastic waste produced per person per year across all countries in that income classes. Let these mean values be represented as $\bar{x}_1, \bar{x}_2, \bar{x}_3, \bar{x}_4$.
4. Determine the deviation of each of the countries x_i from the computed means within their income classes. Rank these countries by these deviations.
5. Weight each of the income class means by the proportion of total countries within that class to compute the global mean across all countries. $\overline{X} = p_1\bar{x}_1 + p_2\bar{x}_2 + p_3\bar{x}_3 + p_4\bar{x}_4$ where p_k represents the proportion of total countries in income class k.
6. Multiply the global mean $\overline{X}$ by some constant α to achieve to the incremental plastic policy constraint $\Delta p_{policy}(t)$.
7. Multiply the means of each of the four income classes by α in order to diminish the global mean by α. Define $\tilde{x}_k = \alpha\bar{x}_k$ for each income class k where $\widetilde{X} = p_1\tilde{x}_1 + p_2\tilde{x}_2 + p_3\tilde{x}_3 + p_4\tilde{x}_4$.
8. For each income class k, compute the appropriate β_i for each country i.
9. Cap the countries i producing above $\tilde{x}_k$ ($x_i > \tilde{x}_k$) at $\beta_{k,i}x_i$ for each income class k. Note that since we don't want to penalize countries at or below the mean, countries above the mean for their income class must handle the burden of plastic reduction for countries below the mean. Therefore, only some subset countries in class k will be reduced by constant amount $\beta_{k,i}$ rather than the entire income class.

10. In the edge case that $\beta_{k,i}x_i < \tilde{x}_k$ for some country i where x_i is just above $\tilde{x}_k$, x_i is set to the mean $\tilde{x}_k$ for the benefit of country i. $\beta_{k,i}$ is recomputed for the remaining countries within the income class k.

Remark: Note that this dataset only contains data for 2010, so derived relations between countries and their income classes are assumed to be held constant over time.

5.2 Policy Division Results

Using the above procedure to characterize each of the 192 countries, we arrive at the following results for each of the income classes in 2010:

Income Class Labels (k)	LI	LMI	UMI	HI
Income Class Counts (out of 192)	21	44	53	74
Income Class Proportions (p_k)	0.109	0.229	0.0156	0.385
Plastic per Capita per Year in Mt ($\bar{x}_k$)	1.98e-8	6.17e-8	4.79e-8	1.08e-7

We give additional results specific to each income class below:

- Low income countries with a yearly plastic per capita *above* $\bar{x}_{LI}$ include:
  Comoros, Haiti, Liberia, Myanmar, and Cambodia
- Low income countries with a yearly plastic per capita *below* $\bar{x}_{LI}$ include:
  Mozambique, Madagascar, Tanzania, Kenya, and Guinea
- Low middle income countries with a yearly plastic per capita *above* $\bar{x}_{LMI}$ include:
  Guyana, Sri Lanka, Maldives, Vanuatu, and Guatemala
- Low middle income countries with a yearly plastic per capita *below* $\bar{x}_{LMI}$ include:
  India, Ghana, Cameroon, Indonesia, and Angola
- Upper middle income countries with a yearly plastic per capita *above* $\bar{x}_{UMI}$ include:
  Saint Kitts and Nevis, Saint Lucia, Seychelles, Grenada, and Costa Rica
- Upper middle income countries with a yearly plastic per capita *below* $\bar{x}_{UMI}$ include:
  Jamaica, Romania, Gabon, Mexico, and Cuba
- High income countries with a yearly plastic per capita *above* $\bar{x}_{HI}$ include:
  Trinidad and Tobago, Kuwait, Antigua Barbuda, Barbados, and Germany
- High income countries with a yearly plastic per capita *below* $\bar{x}_{HI}$ include:
  Brunei, Denmark, Sweden, Belgium, and Oman

6 Case Studies

Here we examine the application of instituting the above global plastic policies on three sample countries from different income classes.

6.1 United States

The United States is one of 74 countries within the high income class (HI). It produces 1.2195e-7 Mt of plastic per capita per year, which is above $\bar{x}_{HI} = 1.08$e-7. We know solely from this information that the United States will have to reduce yearly plastic consumption per person with $\beta_{HI,US} < 1$ since $\tilde{x}_{HI} < \bar{x}_{HI}$. Thus, $x_{US} > \tilde{x}_{HI}$ for any policy.

Given the complete and incomplete cleanup policies detailed in Sections 5.1.2 and 5.1.3, we can examine the cost burden on the US at $t = T_a = 70$ using the framework detailed above.

The current trend $P_{trend}(t) = 0.000262t^4 + 0.001772t^3 + 0.6967t^2 - 4.123t + 10.83$ in the absence of any global policy. We can compute:

$$\Delta p_{trend}(t) = \frac{d}{dt}(0.000262t^4 + 0.001772t^3 + 0.6967t^2 - 4.123t + 10.83)$$
$$\Delta p_{trend}(70) = 0.001048(70)^3 + 0.005316(70)^2 + 1.3934(70) - 4.123 = 478.927$$

The required global cleanup policy is $P_{policy}(t) = -100t + 10,034$. We can compute $\Delta p_{policy}(t) = \frac{d}{dt}(-100t + 10,034) = -100$.

Using these values, we can compute $\alpha = \frac{-100}{478.927} = -0.2088$ and compute the new average plastic per capita for the high income class $\tilde{x}_{HI} = \alpha\bar{x}_{HI} = -0.2088(1.08\text{e-}7) = 2.256\text{e-}8$.

Note that since no country is cleaning up trash prior to the implementation of this policy, all 192 countries will have now have to change their policies to clean up more trash than they create. To compute the US contribution to this policy, we must determine $\beta_{HI,US}$.

$$\beta_{HI,US} = \frac{\tilde{x}_{HI}}{\sum_i x_i} = \frac{\alpha\bar{x}_{HI}}{74\bar{x}_{HI}} = \frac{\alpha}{74} \approx -0.002822$$

We can see that the numerator reduces to $\tilde{x}_{HI}$ since there are currently no $x_i \leq \tilde{x}_{HI}$. Similarly since all $x_i > \tilde{x}_{HI}$, the denominator reduces to the sum across all countries. For this reason, every country in the high income class will have the same $\beta_{HI,i} \approx -0.002822$ at $t = T_a = 70$.

Specifically for the United States, $(\beta_{HI,US})(x_{US}) = (0.002822)(1.2195\text{e} - 7) = -(3.441\text{e} - 10)$. Since $-(3.441\text{e} - 10)$ million metric tons is equivalent to -0.3441 kg, each person in the United States needs to pick up at least 0.3441 kg of plastic waste more than they produce by the end of 2020 to achieve the yearly goals set by this policy.

6.2 China

China is one of 53 countries within the upper middle income class (UMI). It produces 4.396e-8 Mt of plastic per capita per year, which is below $\bar{x}_{UMI} = 4.79$e-8. Since plastic production per capita is below the mean, it is currently unclear whether $\beta_{UMI,Ch} < 1$ since this depends on the value for $\tilde{x}_{UMI}$. This value can be determined below by computing α given some policy.

Using the same complete and incomplete cleanup policies at $t = T_a = 70$, we can compute $\beta_{HI,Ch} = \alpha/53 = -0.00394$ and $(\beta_{HI,Ch})(x_{Ch}) = -(1.887\text{e-}10)$. Since $-(1.887\text{e-}10)$ million metric tons is equivalent to -0.1887 kg, each person in China needs to pick up at least 0.1887 kg of plastic waste more than they produce by the end of 2020 to achieve the yearly goals set by this policy.

6.3 Somalia

Somalia is one of 21 countries within the lower income class (LI). It produces $1.96\text{e-}8$ Mt of plastic per capita per year, which is below $\bar{x}_{LI} = 1.98\text{e-}8$. Since plastic production per capita is below the mean, it is currently unclear whether $\beta_{LI,Som} < 1$ since this depends on the value for $\tilde{x}_{LI}$. This value can be determined below by computing α given some policy.

Using the same complete and incomplete cleanup policies at $t = T_a = 70$, we can compute $\beta_{LI,Som} = \alpha/21 = -0.009943$ and $(\beta_{LI,Som})(x_{Som}) = -(1.949\text{e-}10)$. Since $-(1.949\text{e-}10)$ million metric tons is equivalent to -0.1949 kg, each person in Somalia needs to pick up at least 0.1949 kg of plastic waste more than they produce by the end of 2020 to achieve the yearly goals set by this policy.

7 Evaluation of Strengths and Weaknesses

7.1 Strengths

Our model offers the following strengths:

1. **An interpretable metric for environmental health**. The natural environmental is incredibly complex, as it is comprised of an uncountable number of animals, plants, and other natural phenomena. We managed to distill the complexity of evaluating the health of the environment into a single metric: seabird population. Our use of seabird population as a bioindicator is validated by scientific literature. Using seabird population metric has the advantage of interpretability, because it straightforward to understand what is meant by the projected future bird population at some point in time.

2. **Penalty for future damage caused by present actions**. One reason that so much harm has been done to the environment is that, when people make decisions, they only consider the immediate benefit and/or costs of their decision. When a person uses a single-use water battle, they do not consider the environmental damage that will result from their action. However, through our seabird population model, we are able to quantify the future harm that will be caused by current plastic consumption. By providing a concrete prediction of future costs, governments and people can make better informed decisions about their plastic consumption

3. **Prediction of outcomes if no new policies are adopted**. By fitting our models to data on plastic production since 1950, we were able to predict the environmental effects

of allowing plastic production to continue along its current trend. If no new plastic regulations are introduced, our model shows that the seabird population will quickly die out. This highlights the urgent need of the adoption of new policies for managing plastic waste if we want to prevent environmental damage from reaching an irreparable level.

4. **Evaluation of societal costs of plastic production regulation**. By formulating our cost metric to depend on both the total plastic reduced and year-to-year reduction rate of any given policy, we were able to able to determine what policies countries are more likely to adopt. The dependency on total cost allows us to model the overall feasibility of the target plastic level set by the policy. This takes into account the total economic burden of plastic on the country - the loss of profit to the plastic industry and the additional amount of money country citizens must expend on plastic alternatives.The dependency on the year-to-year rate allows us to model how willing a country is to expend resources to reach the target plastic level, and how resistant the country is to change corporate and consumer behavior as well. Thus, we were able to determine the minimum policy that poses minimal economic and social burden on a country - a the target plastic level to P_{min} with a constant year-to-year reduction of global plastic levels to reach that target.

5. **Equitably distributing responsibility for plastic production reduction**. Not all countries are able to contribute equally to global plastic reduction. For this reason, our model assigns individualized plastic reduction caps for each country based on population size and income. By splitting countries into income classes, our model effectively assesses how much each country is capable of reducing relative to other countries of the same income class. Countries that produce higher amounts of plastic per person relative to their income class are subject to strict plastic reduction requirements, while countries producing lower amounts of plastic per person face much more lenient requirements.

7.2 Weaknesses and Further Improvements

Our model has the following limitations:

1. *Imprecise prediction when seabird populations become large*. Because our model was created with the intention of predicting dynamics of seabird populations when they are at risk, we chose not to focus on precisely modeling population dynamics of the seabirds once the population gets large and they are no longer at risk. Therefore, we chose not to introduce added complexity by including a carrying capacity in the seabird population model, since it was not relevant to the goal of our model. However, a consequence of this decision is that in situations when the seabird population is able to recover, our model overestimates the long run growth of the population since we do not account for the effect of inter-species competition.

2. *Assumption that the proportion of plastic produced that ends up in the ocean stays constant*. We assume that for every metric ton of plastic produced, a fraction will become marine pollution and will increase the risk of seabird plastic ingestion. Further,

we assume that this fraction remains constant over time. Our policy recommendations could be further improved by analyzing the effects of policies that change this fraction (e.g., by imposing stringent regulations on how companies dispose of plastic waste).

3. *Cost metric lacks interpretable units*. While our cost metric is able to compare the 'adoptability' of one potential plastic reduction policy over another, there are no meaningful units to assign to the actual function. Thus, it is only useful in comparative context.

4. *We can*. While our policy cost metric determines that a constant year-to-year reduction is the most adoptable policy, we have not fully defined every concrete detail about that policy given an arbitrary P_{target}. It is possible, given an arbitrary P_{target}, to determine a timeline that minimizes the cost as much as possible - using our seabird model, we can define a longest possible time interval that still stabilizing the seabird population. However, we ran out of time to compute this metric and decided to use the $[2020, 2150]$ interval that was able to restablize the seabird population with $P_{target} = P_{min}$ instead.

5. *Physical country size may serve as a confounding factor in assessing limits by country*. While stratifying countries by income aided in computing the appropriate plastic level per capita, we believe this analysis alone may not have been sufficient for holistically evaluating the economic capabilities of each country. Physical country size was noted to be a confounding factor since smaller-sized countries tend to have larger plastic per capita relative to larger countries in the same income class. More specifically, smaller countries are much more likely to have lower populations, which raises yearly plastic per capita.

8 Conclusion

Using seabird population as a proxy for environmental health, we determined that if plastic consumption levels increase at their current rate, irreversible damage will be caused to the environment by the year 2056. However, this can be avoided by adopting new policies to manage plastic production and clean up plastic waste that currently exists in the environment. We determined that an efficient policy is to reduce accumulated plastic by a constant amount each year until the volume of plastic that remains in the environment is less than 3,750 million metric tons. This policy imposes the minimal cost on society while still allowing seabird populations to recover. Finally, we break this global policy into country-specific policies. Since evenly splitting economic costs across all countries may result in heavier burdens for certain countries, we stratify each country by income class and manually evaluate each country's ability to pay given their plastic production per capita. Through the estimation of the seabird population, environmental evaluation of global policies, and efficient division of cost across countries, we present this report as an effective solution to the marine environmental crisis.

9 Appendix

9.1 Memo

To the International Council of Plastic Waste Management (ICM):

The world is faced with the difficult task of addressing the accumulation of plastic waste around the world as the marine environment continues to deteriorate. The introduction of plastic waste into the marine environment has had serious repercussions over the past 70 years, resulting in significant harm to marine animals. Since plastic does not readily break down naturally and few plastic plastic products are properly recycled, human intervention into this escalating environmental crisis is past due. We realize that constructing effective policy is extremely difficult if we do not properly account for the complex economic incentives that created this situation to begin with. With this in mind, we present our report as a means of properly assessing the current state of affairs and providing a plan to cost-effectively reduce plastic waste levels from approximately 10,000 million metric tons down to 3,750 million metric tons over the next 130 years in order to preserve the marine environment.

To properly quantify the environmental impacts of plastic waste accumulation at any given time, we introduce the razorbill population as a proxy for estimating the health of the marine environment. Razorbills are one of many seabird species that are shown to be valid bioindicators for the status of the marine environment. Rising plastic waste accumulation has led to the unfortunate encounters and subsequent deaths of marine organisms, including seabirds. Over the past several decades, seabirds have suffered a significant decrease in their overall population due to their rising death rate caused by increased plastic consumption. We characterize the marine environment to be in good shape when the overall seabird population is flourishing. Likewise, we characterize the marine environment to be beyond saving once the seabird population dips below 2500, which is determined by the IUCN to be the *endangered limit*.

In our report, we present a plan to slowly reduce plastic accumulation over the next 130 years and guarantee the survival of the seabird population. While diminishing the amount of accumulated plastic benefits the overall seabird population, it counters the economic incentives of profit-maximizing countries. From the perspective of the individual countries, there is an economic cost resulting from adopting plastic reduction policies. This cost tends to take the form of the amount of plastic that would have been produced in the absence of the policy minus the plastic that would be produced if the policy was in place. This is synonymous to the opportunity cost of adopting a global policy. As a result, slow-acting policies over a long period of time incur lower economic costs and are optimal in resolving this environmental crisis.

Even in enacting an optimal global policy, the complex issue of how to best distribute the burden of responsibility comes into question. Certain countries have differing population and income levels, which may influence these countries' abilities to contribute to plastic reduction with respect to other countries. As such, our model accounts for division of cost across countries by grouping them into income classes and assessing their ability to achieve a certain plastic production per capita. This gives our model the flexibility to divide cost efficiently and to ensure that no one country faces a larger economic burden relative to their income and population than other countries.

The projected timeline can be accelerated if new technology is developed that allows us to clean up plastic waste more rapidly. The timeline for restoring environmental health may be hindered if external sources of environmental degradation are introduced. For example, if global warming accelerates, downward pressure on seabird populations and other marine species will increase. Therefore, it will take a longer time period and greater cleanup efforts to restore seabird population to a level where it can sustain itself.

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