Problem Chosen	2020 MCM/ICM Summary Sheet	Team Control Number
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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 determine that an appropriate global policy is 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 finding a good 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 of 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 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 its detrimental effects. It is estimated that 4 to 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 there in perpetuity if no human action is taken [3]. The lives of marine animals are put at risk when they encounter plastic debris in their habitat. In some cases, these encounters result in death. As such, it is important to be able to balance the convenience of using single-use plastic with the resulting damage to the marine environment.

In this report, we present a model to assess current trends in the growth of plastic waste 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 current and projected marine environmental health** as a direct result from global plastic production
- **Estimate plastic accumulation** since 1950 and assess current plastic production and consumption trends to predict plastic accumulation over the next several 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 the responsibility of reducing plastic waste across countries 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 [4]. 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 cost of a policy, we consider the total magnitude of reduction in plastic consumption necessary to achieve the policy, as well as how quickly plastic consumption levels must be changed to adhere to the policy. We also determine an optimal way to divide the global policy into policies for each individual country. Since some countries will incur higher economic costs when reducing plastic production, we use relative income, population, and current plastic production per capita 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 their marine surroundings, 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 [4].

In addition to being a good reflection of the general health of the marine environment, seabirds are worthy of protection in their own right. As a top predator, seabirds play an important role in regulating population dynamics of marine species and are critical for the normal functioning of the marine ecosystem [5]. 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 [6].

Studies have shown that seabird populations have been significantly impacted by plastic waste [7]. Seabirds are at risk of accidentally ingesting plastic that they encounter in marine waters, which can have detrimental health effects and may even lead to death. As plastic production has increased, escalating amounts of plastic have ended up in the ocean, which ultimately increases the risk to seabirds.

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

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

$$\frac{dS}{dt} = (b - d_n)S - d_p S P(t), \tag{1}$$

where b is the seabird birth rate, d_n is the natural seabird death rate, d_p is the number of seabird deaths due to plastic per seabird per million metric ton of plastic, and $P(t)$ is the cumulative amount of plastic that has been produced globally by time t. The first term represents changes in the seabird population due to natural factors. The second term represents deaths caused by plastic pollution. Intuitively, when seabird population and/or plastic pollution increases, the risk of lethal interactions between seabirds and plastic increases.

Assuming that $P(t)$ is an integrable and differentiable function, we can analytically solve this differential equation, yielding a closed-form solution:

$$S(t) = S(0)\exp\left((b - d_n)t - d_p \int_0^t P(t')dt'\right) \tag{2}$$

2.1.1 Estimation of Parameters

To use our model of seabird population as a concrete metric of environmental health, we rely on 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 its breeding and survival rates and feeding behaviors are representative of the average seabird. Razorbills have a conservation status of "near threatened," and are at risk of interactions with oceanic plastic waste since they use the ocean as their feeding grounds [8]. Thus, monitoring their population is important.

Parameter	Value
b	0.326
d_n	0.146
d_p	8.395e-06

Table 1: Parameter values for the seabird population model described in Equation (1)

Table 1 shows the parameter values that we use in our seabird population equation. The birth rate b is obtained by multiplying the productivity of each pair of seabirds (0.895) by the fraction of seabirds that are at breeding age (approximately $8/13$), as determined through observational studies [9]. d_n represents the fraction of seabirds that die each year from natural causes. 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) [9]. d_p is the number of seabird deaths due to plastic per seabird per million metric tons of cumulative plastic produced. This value is estimated by breaking down d_p as

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

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 [10]. Around the time the study was conducted, total cumulative plastic production was approximately 8300 Mt [2]. Consequently, d_p is computed as $0.321(0.204)/8300$.

For convenience, we choose $t = 0$ to correspond to the year 1950. To solve for the initial seabird population, we rely on a 2001 study by Chapdelaine *et al.*, who found that the global razorbill population was approximately one million at the time of the study. Thus, we estimate that in 2001 ($t = 51$), there were one million razorbills, i.e., $S(51) = 10\text{e}6$ [11].

Using this, along with an estimate of the cumulative plastic produced by 2001 obtained from Geyer *et al.* [2], we can solve for $S(0)$, the razorbill population in 1950.

It is useful to note that although razorbills were chosen as 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, global plastic production will continue along its current trend $P_{trend}(t)$.

2.2.1 Modeling Plastic Production Policies

We denote a policy response as $P_{reduced}(t)$, which includes both the total amount of plastic cut from production in year t and the total amount of plastic cleaned up from the environment in year t. $P_{reduced}(t)$ is measured in Mt.

We can then compute $P_{policy}(t)$, which is the total amount of plastic in the ocean at time t given $P_{reduced}(t)$:

$$P_{policy}(t) = P_{trend}(t) - P_{reduced}(t) \tag{3}$$

Assumption: Prior to the time of policy activation (T_a), countries do not have any plastic clean up efforts in place and are not reducing the global level of accumulated plastic, i.e.:

$$P_{reduced}(t) = 0, \forall t \in [0, T_a]$$

which implies

$$P_{policy}(T_a) = P_{trend}(T_a)$$

Remark: We formulated our policy model to account for the difference in behavior before and after policy activation. At time of activation T_a, no policy has been put into effect, so the global plastic level should just be the value of P_{trend}.

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

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

2.2.2 Costs of Plastic Production Policies

Assumption: Countries will more readily accept a policy that (1) minimizes the total quantity of plastic they must remove from the ocean and (2) does not require them to rapidly change their plastic production levels.

Countries are shown to adopt and enact plastic reduction policies that are easy to achieve and do not change much over time [12]. We formulate a cost C of a particular plastic reduction policy over the time interval $[t_0, t_f]$ as the sum of the total plastic saved from the ocean ($P_{reduced}(t_f)$) and the largest year-to-year reduction required ($\frac{d}{dt}P_{reduced}$). More formally, C can be written as:

$$C_{t_0,t_f}(P_{reduced}) = P_{reduced}(t_f) + \lambda \max_{[t_0,t_f]} \left\{ \frac{d}{dt} P_{reduced} \right\} \tag{4}$$

where $\lambda > 0$ is a constant that represents a country's reluctance to extreme change in plastic production levels from year to year.

Remark: It is important to note that C is not a monetary cost but rather represents an abstract cost used to evaluate policies relative to each other.

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 look into plastic production by individual countries. We can break down cumulative global plastic in the absence of policies, $P_{trend}(t)$, 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 $P_i(t+1) = P_i(t) + \Delta P_i(t)$. $\Delta P_i(t)$ 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 total supply of plastic in 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 economy, they have a collective responsibility to protect the global marine environment. The problem is that countries currently ignore this responsibility. In 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, we explore how to equitably distribute the costs of plastic reduction and cleanup by requiring countries with larger $\Delta P_i(t)$ (with respect to population size) 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 environmental damage reach an irreversible level?*

We estimate future cumulative plastic volumes (measured in Mt) by fitting a quartic polynomial to recent plastic data (Figure 1). The equation of the trend line is

$$P_{trend}(t) = 0.000262t^4 + 0.001772t^3 + 0.6967t^2 - 4.123t + 10.83 \tag{5}$$

with an R^2 value of 0.9999. We use a quartic polynomial fit for two reasons. First, an exponential curve does not fit as well ($R^2 = 0.9936$), with notable deviation between the trend line and the tails of the data. Second, we determined that annual plastic production over time is cubic using another fit. Since cumulative plastic production is the integral of annual plastic production, it follows naturally that cumulative plastic production should be quartic.

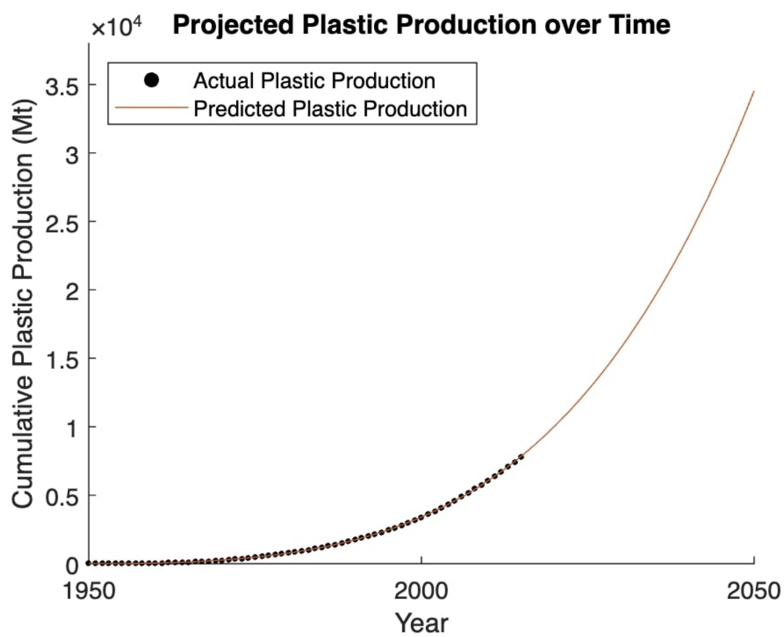

Figure 1: Plot of past and projected cumulative global plastic production. The black points represent annual measures of accumulated plastic from 1950 to 2015 obtained from Geyer *et al.* [2], while the orange line is the best-fit quartic polynomial given by Equation (5).

Using $P_{trend}(t)$, we can predict the future cumulative plastic production if we follow the current trend determined by existing plastic production policies. Assuming that plastic production continues at its current pace, we can project the future seabird population by substituting $P_{trend}(t)$ from Equation (5) into Equation (2). Thus, the predicted seabird population given that we follow current plastic production trends can be written as

$$S_{trend}(t) = S(0)\exp\left((b - d_n)t - d_p\int_0^t P_{trend}(t')dt'\right) \tag{6}$$

Plotting the estimated $S_{trend}(t)$ 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 peaked around the year 2000 and has been in a steady decline since (Figure 2). The initial increase can be explained by natural population dynamics. Since the birth rate is greater than the death rate ($b > d_n$), seabird population has a tendency to increase exponentially in the absence of external factors. However, the dangers of plastic waste impose a downward pressure on seabird 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.

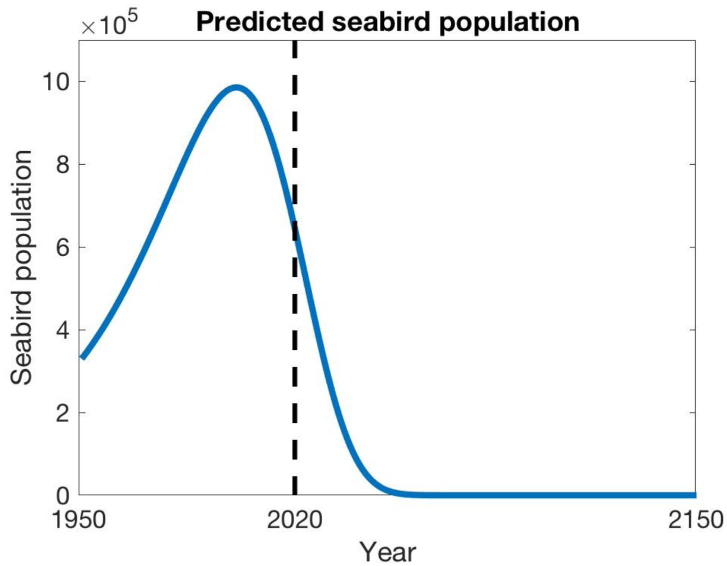

Figure 2: Projected seabird population given that global plastic production follows the current trend. The dotted line represents the current year.

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 [13]. 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 most likely 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 [13]. 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 mitigating plastic pollution. 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 the 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 our cost analysis shows that 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 policy is not sufficient to save the environment.

In fact, even the immediate termination of plastic production is not enough to save the sea bird population, 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 the population without policy line (orange line) for several decades, but this policy still ultimately results in extinction. 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 of 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, it is not meaningful to compare their economics costs to the policies described below, which actually have an impact on the environment. Thus, we will not compute the cost C for Policy Type 1.

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; 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

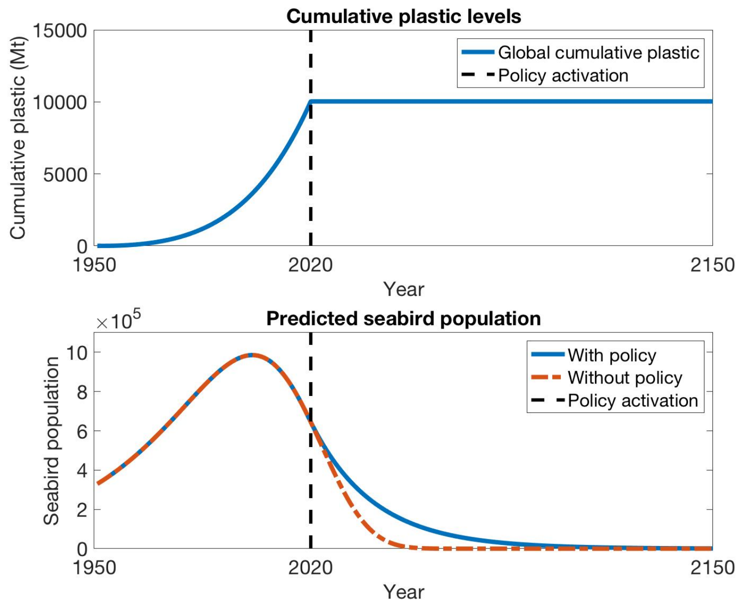

Figure 3: (Top) Cumulative plastic levels given that global plastic production is immediately terminated. (Bottom) Predicted seabird population as a result of Policy Type 1 (blue) and in the absence of policies (orange). In both figures, the dotted black line indicates the time at which the policy is put into effect.

a constant amount of plastic waste to be cleaned up each year (e.g., each year, 5 Mt of plastic must be cleaned up from the ocean).

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). 100Mt was chosen for convenience, but the effect of different volumes of annual cleanup can be evaluated using a similar framework. 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 the purpose of our seabird model is 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 that termination of plastic production causes the seabird population to recover, but the extent of this increase may not be accurately reflected by our model.

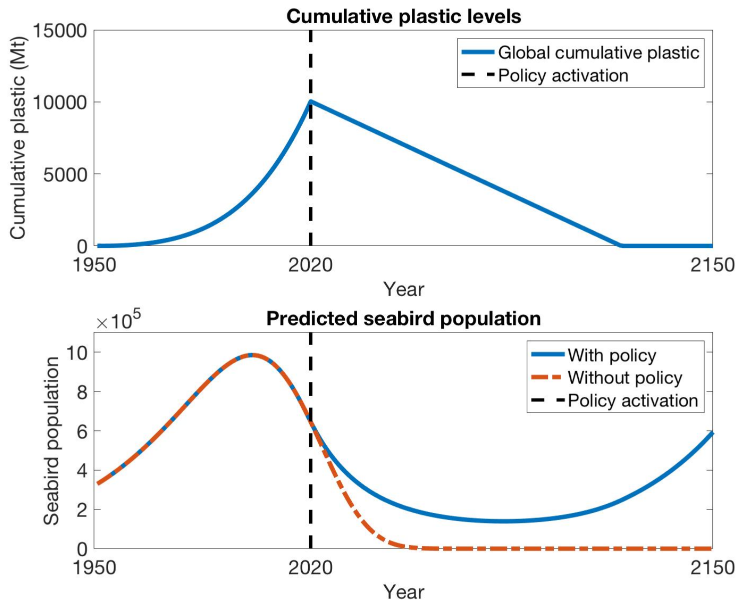

Figure 4: (Top) Cumulative plastic levels given that global plastic production is immediately terminated *and* an equivalent of 100 Mt of previously produced plastic is cleaned up from the environment each year until plastic pollution is completely removed. (Bottom) Predicted seabird population as a result of Policy Type 2 (blue) and in the absence of policies (orange). In both figures, the dotted black line indicates the time at which the policy is put into effect.

Additionally, a complete termination of plastic production is not necessarily required to achieve 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 comparison with more realistic plans.

We first determine a general formulation of the total-cleanup policy, denoted as $P_{aggressive}$ on an arbitrary time interval $[T_a, T_f]$ (where T_f is the time when all plastic is eliminated):

$$P_{aggressive}(t) = P_{trend}(t) - P_{trend}(T_a) - \frac{P_{trend}(T_a)}{T_f - T_a}t \tag{7}$$

As a reminder, we restate the formulation of the cost metric defined in Equation (4):

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

We chose a linear reduction policy, since any higher polynomial or exponential reduction policies would introduce maximum derivatives of higher magnitudes, which is penalized by the cost metric defined in Equation (4). We can then compute the cost of $P_{aggressive}$:

$$C_{T_a,T_f}(P_{aggressive}) = P_{trend}(T_f) + \lambda \left(\frac{P_{trend}(T_a)}{T_f - T_a} \right) \tag{8}$$

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 the seabird population. However, complete plastic cleanup is likely unrealistic due to limitations in pollution cleanup technology. 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. 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 a threat to the seabirds (e.g. the seabird population will no longer be in decline):

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

$$P_{min} = \frac{b - d_n}{d_p} \tag{9}$$

If the global accumulated plastic is reduced to a level that is equal to P_{min}, seabird populations will stop declining and stabilize. We call this plastic level P_{min} because it represents the *minimum* policy necessary to save the environment. If the quantity of global plastic is reduced below P_{min}, the seabird population will 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 the sum of the natural death rate and the plastic-ingestion death rate is equal to the birth rate.

Now, we 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. Note that P_{target} and P_{min} are fixed numbers and are not functions of time. 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 $P_{feasible}(t)$ that stops all production and linearly reduces global plastic levels to P_{target} by time T_f:

$$P_{feasible}(t) = P_{trend}(t) - P_{trend}(T_a) - \left(\frac{P_{trend}(T_a) - P_{target}}{T_f - T_a} \right) t \tag{10}$$

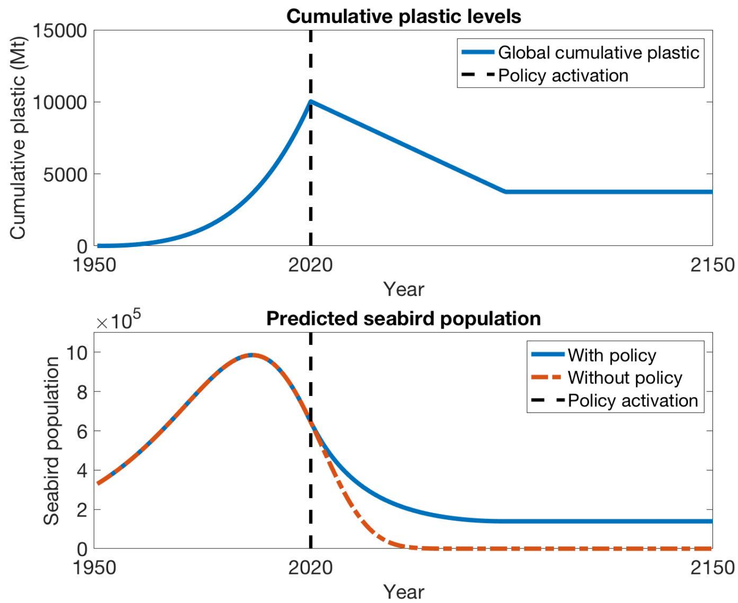

Figure 5: (Top) Cumulative plastic levels given that global plastic production is immediately terminated *and* an equivalent of 100 Mt of previously produced plastic is cleaned up from the environment each year until plastic levels are reduced to 3,753.7 Mt. (Bottom) Predicted seabird population as a result of Policy Type 3 (blue) and in the absence of policies (orange). In both figures, the dotted black line indicates the time at which the policy is put into effect.

We compute the cost of Policy Type 3 over the same time interval used for Policy Type 2 ($C_{2020,2150}$) for the sake of comparison:

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

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 $P_{aggressive}$ (1.6902e5 + λ77.188), as expected. Since the C value of Policy Type 3 is the smallest, we conclude that the optimal policy is 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 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 account for a country's population size, we divide its plastic consumption by the country's population to arrive at average plastic used per capita per year. Furthermore, we classify each country into one of four income classes: High Income, Upper Middle Income, Lower Middle Income, and Low Income. By doing so, we can assess how much plastic each country should produce per person relative to their income class.

The policies outlined in Sections 4.2 and 4.3 prescribe the total amount of plastic reduction required over time. However, when evaluating the feasibility of a policy, countries will likely want to know how much plastic reduction is required *each year*. For this reason, we define the annual plastic reduction to be the derivative of the cumulative plastic reduction:

$$\Delta P_{policy} = \frac{d}{dt}(P_{policy}), \quad \Delta P_{trend} = \frac{d}{dt}(P_{trend}), \quad \Delta P_{reduced} = \frac{d}{dt}(P_{reduced}) \tag{11}$$

Note that $\Delta P_{policy}(t) = \Delta P_{trend}(t) - \Delta P_{reduced}(t)$ 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 proportion of the amount of plastic consumed in the presence of policy to the amount of plastic consumed in the absence of policy.

$$\alpha(t) = \frac{\Delta P_{policy}(t)}{\Delta P_{trend}(t)} = \frac{\Delta P_{trend}(t) - \Delta P_{reduced}(t)}{\Delta P_{trend}(t)} = 1 - \frac{\Delta P_{reduced}(t)}{\Delta P_{trend}(t)} \tag{12}$$

For instance, if a policy dictates 0 plastic production ($\Delta P_{policy} = 0$), then $\alpha = 0$. On the other hand, if a policy provides no restriction on plastic consumption, then $\alpha = 1$ since the amount of plastic produced in the presence of policy would match the amount produced in the absence of policy ($\Delta P_{policy} = \Delta P_{trend}$). Additionally, if countries are forced to clean up more plastic than they consume ($\Delta P_{policy} < 0$), then $\alpha < 0$. Since no policies call for increased plastic production, $\Delta P_{reduced}$ is nonnegative, so we must have $\alpha \leq 1$. Note that since α is a dimensionless ratio, we can use it to measure the reduction of *plastic* given a policy or the reduction of *plastic per capita* given a policy.

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 192 total countries that are 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 ($k \in \{HI, UMI, LMI, LI\}$), 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:

$$\beta_{k,i}(t) = \begin{cases} \frac{\tilde{x}_k(t) - \sum_i \mathbb{1}\{x_i(t) \le \tilde{x}_k(t)\} x_i(t)}{\sum_i \mathbb{1}\{x_i(t) > \tilde{x}_k(t)\} x_i(t)} & \text{if } x_i(t) > \tilde{x}_k(t) \\ 1 & \text{if } x_i(t) \le \tilde{x}_k(t) \end{cases} \tag{13}$$

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

Jambeck *et al.* compiled statistics on annual plastic production and waste per country in 2010 [1]. Using this data, we used the following procedure to assess the maximum amount of plastic each country should produce given incremental plastic policy $\Delta P_{policy}(t) = \Delta P_{trend}(t) - \Delta P_{reduced}(t)$ 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. For simplicity, let $\{HI, UMI, LMI, LI\}$ be represented by the integers $\{1, 2, 3, 4\}$ respectively. As such, we can let the corresponding 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 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 reduce the global mean by α. Define $\tilde{x}_k = \alpha\bar{x}_k$ for each income class k where $\widetilde{X} = p_1\tilde{x}_1 + p_2\tilde{x}_2 + p_3\tilde{x}_3 + p_4\tilde{x}_4$. This is how we distribute the burden of plastic cleanup fairly across the four income classes.

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 do not 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 data set 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
Number of countries	21	44	53	74
Proportion (p_k)	0.109	0.229	0.0156	0.385
Avg. Mt. of plastic per capita per year ($\bar{x}_k$)	1.98e-8	6.17e-8	4.79e-8	1.08e-7

Table 2: Income Class Summary

Table 3 gives examples of countries that are producing above and below the mean for their income class.

Relative plastic level	LI	LMI	UMI	HI
Above $\bar{x}_k$	Cambodia	Egypt	Argentina	Germany
	Comoros	Guatemala	Costa Rica	Ireland
	Haiti	Nicaragua	Malaysia	Netherlands
	Liberia	Sri Lanka	Turkey	New Zealand
	Myanmar	Syria	South Africa	United States
Below $\bar{x}_k$	Bangladesh	India	China	Australia
	Kenya	Nigeria	Cuba	Canada
	Madagascar	Philippines	Iran	Denmark
	Somalia	Ukraine	Libya	Puerto Rico
	Tanzania	Yemen	Mexico	Sweden

Table 3: Examples of low income, low middle income, upper middle income, and high income countries with plastic production levels above (top) and below (bottom) the mean for their income class.

6 Case Studies

Here we examine the cost of instituting the global plastic reduction policies described in Sections 4.2 and 4.3 in the year 2020 using three sample countries from different income classes. Both policies require 100 Mt of plastic to be cleaned up starting in 2020, so the cost burden of both policies in 2020 is the same. Since these policies require a net cleanup of plastic, and no countries currently have a net negative plastic production level, $x_i > \tilde{x}_k$ for all countries, so all countries have to participate in the reduction effort and clean up plastic regardless of their relative plastic production per capita in their income class.

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 4.2 and 4.3, we can examine the cost burden on the US in the year 2020, which corresponds to $t = T_a = 70$, using the framework detailed above.

The current trend in the absence of any global policy is $P_{trend}(t) = 0.000262t^4 + 0.001772t^3 + 0.6967t^2 - 4.123t + 10.83$. 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 $\tilde{x}_{HI} = \alpha\bar{x}_{HI} = -0.2088(1.08\text{e-}7) = -2.256\text{e-}8$.

Since we assume 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 countries for which $x_i \leq \tilde{x}_{HI}$. Similarly, since $x_i > \tilde{x}_{HI}$ for all i, 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, $(\beta_{HI,US})(x_{US}) = -(0.002822)(1.2195\text{e-}7) = -(3.441\text{e-}10)$. $-(3.441\text{e-}10)$ million metric tons is equivalent to -0.3441 kg, so 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 these policies.

6.2 China

China is one of 53 countries within the upper middle income class (UMI). It produces $4.396\text{e-}8$ Mt of plastic per capita per year, which is below $\bar{x}_{UMI} = 4.79\text{e-}8$. Since China's plastic production per capita is below the mean for their income class, it is not immediately clear whether $\beta_{UMI,Ch} < 1$ (i.e., if a reduction is required) since this depends on the value of $\tilde{x}_{UMI}$. This value can be determined below by computing α given some policy.

Considering the complete and incomplete cleanup policies at $t = T_a = 70$, we can compute $\beta_{HI,Ch} = \alpha/53 = -0.00394$ and $(\beta_{HI,Ch})(x_{Ch}) = -(1.887\text{e-}10)$. $-(1.887\text{e-}10)$ million metric tons is equivalent to -0.1887 kg, so 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 these policies.

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 not immediately clear whether $\beta_{LI,Som} < 1$ since this depends on the value for $\tilde{x}_{LI}$. This value can be determined by computing α given some policy.

Considering the complete and incomplete cleanup policies at $t = T_a = 70$, we can compute $\beta_{LI,Som} = \alpha/21 = -0.009943$ and $(\beta_{LI,Som})(x_{Som}) = -(1.949\text{e-}10)$. $-(1.949\text{e-}10)$ million metric tons is equivalent to -0.1949 kg, so 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 these policies.

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 manage to distill the complexity of evaluating the health of the environment into a single metric: the size of the seabird population. Our use of the seabird population as a bioindicator is validated by scientific literature. Using the seabird population as our metric has the advantage of interpretability, because it is 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**. When making decisions about plastic consumption, individuals only consider environmental impact on short local time horizons. Our seabird population model enables us 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 plastic production data since 1950, we are 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 for 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 reduction and year-to-year reduction rate of any given policy, we are able to able to determine a policy that saves the marine environment while minimizing economic and social impacts on the global population. Total plastic reduction serves as a proxy for the total economic burden of plastic reduction on each country, i.e., the loss of profit to the plastic industry and the additional amount of money the country's citizens must expend on plastic alternatives. The incorporation of a penalty for the year-to-year rate of reduction allows us to model the resistance of governments and citizens to quickly change their behavior to reach the target plastic level. Using this cost metric, we are able to determine the policy that poses minimal

economic and social burden: constant year-to-year reductions until the global plastic level is reduced to P_{min}.

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 plastic production relative to other countries in the same income class. Countries that produce higher amounts of plastic per person relative to their income class are subject to stricter plastic reduction requirements, while countries producing lower amounts of plastic per person face 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 is not relevant to the goal of our model. However, a consequence of this decision is that in situations where 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 intra- and 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. Furthermore, 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 feasability of potential plastic reduction policies, there are no meaningful units to assign to the metric. Thus, it is only useful in a comparative context.

4. *We have not determined the specific optimal policy that should be adopted to reach a given target global plastic level*. 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 the minimum 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 stabilizes the seabird population, thus minimizing the maximum derivative in Equation 4. However, given the timeframe that typical environmental protection agreements last, we decided an interval of 130 years for enacting our policy is sufficiently long and should not be extended further.

8 Conclusion

Using the seabird population as a proxy for environmental health, we determine that if plastic consumption levels continue to 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 determine 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 contribute to the reduction effort given their plastic production per capita. Through estimation of the seabird population over time, evaluation of the environmental impacts of global policies, and efficient division of policy costs across countries, we present this paper as an effective solution to understanding the marine environmental crisis.

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