A Seabird Population Model to Evaluate Plastic Pollution Policies

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Summary

Due to convenience and low cost, plastic is used in many settings and then is quickly disposed of. Much of this plastic makes its way into oceans, where it contributes to declines in populations of ocean creatures.

We consider predicted future seabird populations as a metric for evaluating the effect of plastic production. We model seabird population dynamics by considering births, natural deaths, and deaths due to interactions with plastic debris. Seabird population is expressed as a function of both time and mass of accumulated plastic. Our decision to use seabirds as a proxy for the health of the marine environment is backed up by scientific literature that establishes the usefulness of seabirds as a bioindicator.

We predict that if global plastic production continues at its current pace, seabirds will become endangered by 2056 and critically endangered by 2062. Since the current plastic production trend is causing rapid degradation of our marine ecosystem, we need new policies for its production and management. We describe these policies as functions of accumulated plastic. We evaluate the environmental impact of a policy by simulating the seabird population with the plastic levels set by the policy. We determine the economic cost of a policy by considering the consequent reduction in plastic consumption, together with 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 mass is less than 3,750 million metric tons. Such a policy would allow the seabird population to recover while imposing minimal economic cost to society.

We develop an equitable approach for distributing the costs of achieving the optimal policy's goals 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 their required amounts.

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Introduction

Since the large-scale production of single-use disposable plastics began in the 1950s, plastic waste has accumulated in the environment, particularly in oceans [Jambeck 2015], with 4 to 12 million metric tons of plastic waste ending up in the ocean every year [Geyer et al. 2017]. Plastic degrades at a very slow rate, so plastic added to the ocean stays there in perpetuity if no human action is taken [Gewert et al. 2015]. Marine animals can be at risk when they encounter plastic debris in their habitat.

We model trends in the growth of plastic waste and suggest changes in global policy to mitigate plastic waste and protect the environment:

- **We create a metric to assess current and projected marine environmental health** as a direct result from global plastic production.
- **We estimate plastic accumulation** since 1950 and assess current plastic production and consumption trends to predict plastic accumulation over the next several decades.
- **We reconcile conflicting economic and environmental incentives** of various plastic production policies by determining the associated environmental impacts and societal costs of each policy.
- **We recommend adjustments to global policy** to spread the responsibility of reducing plastic waste across countries without overburdening any one country.

Model

The overall goals of our model are to

- predict the point at which damage due to single-use plastic waste becomes irreparable,
- evaluate environmental impacts of policies to reduce plastic production, and
- 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 [Rajpar et al. 2018]. Thus, we use predicted future seabird population to evaluate potential policies.

We represent policies in terms of quantity of plastic. To quantify the cost of a policy, we consider the consequent reduction in plastic production, as well as how quickly the plastic production level must be changed. We also determine an optimal way to divide the global policy into a policy 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 plastic consumption.

Health of the Environment

Assumption: *Seabird population is a useful proxy for estimating global marine environmental health.*

Seabirds depend on the ocean and surrounding areas and hence are sensitive to changes in the ocean environment. They 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 [Rajpar et al. 2018].

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 [Clarke and Harris 2003]. 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 [Estes et al. 2011].

Seabird populations have been significantly impacted by plastic waste [Wilcox et al. 2015], because they may ingest plastic that they encounter, resulting in detrimental health effects and even death.

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

We model the seabird population S with the differential equation

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

where

- b is the seabird birth rate,
- d_n is the natural seabird death rate,
- d_p is the seabird death rate due to plastic per seabird per million metric tons (MT) of plastic, and
- $P(t)$ is the cumulative amount of plastic produced globally by time t.

Provided that $P(t)$ is integrable, we can solve this differential equation analytically, yielding the closed-form solution

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

Estimation of Parameters

We use the razorbill (*alca torda*) 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 interaction with oceanic plastic waste [Lavers et al. 2020]. We rely on the scientific literature to estimate model parameters (**Table 1**).

Table 1.

Parameter values for the seabird population model in **(1)**.

Parameter	Value
b	0.175
d_n	0.146
d_p	7.89×10^{-6}

- The birth rate b is obtained by multiplying the annual productivity of each pair of seabirds (0.285) by the fraction of seabirds of breeding age (approximately 8/13) [Horswill and Robinson 2015].
- The death rate d_n is the fraction of seabirds that die each year from natural causes. This is calculated as 1 minus the average of the annual survival rates of juvenile seabirds (0.630) and adult seabirds (0.895), weighted by the corresponding fractions of the population (approximately 2/13 juveniles, 11/13 adults) [Horswill and Robinson 2015].
- The parameter d_p is the annual proportion of seabird deaths due to plastic per million metric tons of cumulative plastic produced. This value is estimated by breaking down d_p as

$$d_p = \frac{\text{plastic ingestion deaths}}{\text{bird population}} \times \frac{1}{\text{cumulative plastic}}.$$

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. Around the time when the study was conducted, total cumulative plastic production was approximately 8,300 MT [Geyer et al. 2017]. Consequently, d_p is calculated as $0.321(0.204)/8300$.

We set $t = 0$ to correspond to the year 1950. To solve for the initial seabird population, we rely on a 2001 study by Chapdelaine [2001], who found that the global razorbill population was then approximately one million. Thus, we estimate that $S(51) = 10 \times 10^5$. Using this, along with the estimate of the cumulative plastic produced by 2001, we can solve for $S(0)$, the razorbill population in 1950, finding $S(0) = 3.2 \times 10^5$.

Although we use razorbills as our reference species, our model can be adapted to predict population sizes of other species by replacing b, d_n, and d_p with values appropriate for the chosen species.

Plastic Waste

Assumption: *All plastic produced ends up as waste in the environment.*

This assumption allows us to describe potential policies in terms of explicit volumes of plastic that must be cleaned up from the environment. Although some plastic may be reused or recycled, we ignore this in our calculations and set cumulative plastic waste in the environment equal to cumulative plastic produced. A consequence is that we can directly compare plastic cleanup policies. If we instead assume that only a fraction of plastic produced becomes pollution, our policies can be easily adapted by scaling by this fraction.

Plastic Production

Assumption: *In the absence of new plastic production policies, global plastic production will continue along its current trend* $P_{\mathit{trend}}(t)$.

We denote a policy response as $P_{\text{reduced}}(t)$, 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, measured in MT.

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

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

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

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

which implies

$$P_{\text{policy}}(T_a) = P_{\text{trend}}(T_a).$$

We formulate our policy model to account for the difference in behavior before and after policy activation. Until policy activation, no policy is in 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., of the seabird population), we first determine a P_{policy} that ensures seabird survival in the limiting case ($t \to \infty$). We then determine P_{reduced} as:

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

Costs of Plastic Production Policies

Assumption: *Countries will more readily accept a policy that minimizes the total quantity of plastic that they must remove from the ocean and does not require them to rapidly change their plastic production levels [Hepburn 2010].*

We formulate the 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 ($P_{\text{reduced}}(t_f)$) and the largest year-to-year reduction required ($\frac{d}{dt}P_{\text{reduced}}$). More formally, C can be written as:

$$C_{t_0,t_f}(P_{\text{reduced}}) = P_{\text{reduced}}(t_f) + \lambda \max_{[t_0,t_f]} \left\{ \frac{d}{dt} P_{\text{reduced}} \right\}, \tag{3}$$

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

We note that C is not a monetary cost but rather represents an abstract cost used to evaluate policies relative to one another.

Breakdown by Country

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

We express $P_{\text{trend}}(t)$ as a sum across cumulative plastic $P_i(t)$ for each country i at time t. We denote yearly contributions to $P_{\text{trend}}(t)$ by $\Delta P_{\text{trend}}(t)$ such that

$$P_{\text{trend}}(t+1) = P_{\text{trend}}(t) + \Delta P_{\text{trend}}(t),$$

where $\Delta P_{\text{trend}}(t)$ corresponds to the mass of plastic produced globally in year t. Likewise, yearly contributions to $P_i(t)$, the cumulative plastic produced by country i, is denoted by $\Delta P_i(t)$ such that

$$P_i(t+1) = P_i(t) + \Delta P_i(t),$$

where $\Delta P_i(t)$ corresponds to plastic produced by country i in year t.

In the absence of global policy, countries produce the amount of plastic necessary to keep their local economies running at a desirable level. Since a country's economic output is maximized at market equilibrium, the total production $\Delta P_i(t)$ of plastic in a country equals the quantity of plastic demanded by its consumers (including export). However, for many countries, $\Delta P_i(t)$ is far above the appropriate level for environmental preservation. Then $\Delta P_{\text{trend}}(t) = \sum_i \Delta P_i(t)$ contributes to a larger cumulative global plastic amount $P_{\text{trend}}(t)$ and a resulting depletion of seabird population $S(P_{\text{trend}}, t)$.

While each country caters to the best interests of its economy, all have a collective responsibility to protect the global marine environment. Countries currently ignore this responsibility. To address this problem, a global policy must be instituted as an agreement across countries to appropriately limit global plastic production and increase plastic cleanup. Later we explore how to distribute the costs of plastic reduction and cleanup equitably.

Predicting Irreversible Damage

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 mass (measured in MT) by fitting a quartic polynomial to recent plastic data (**Figure 1**).

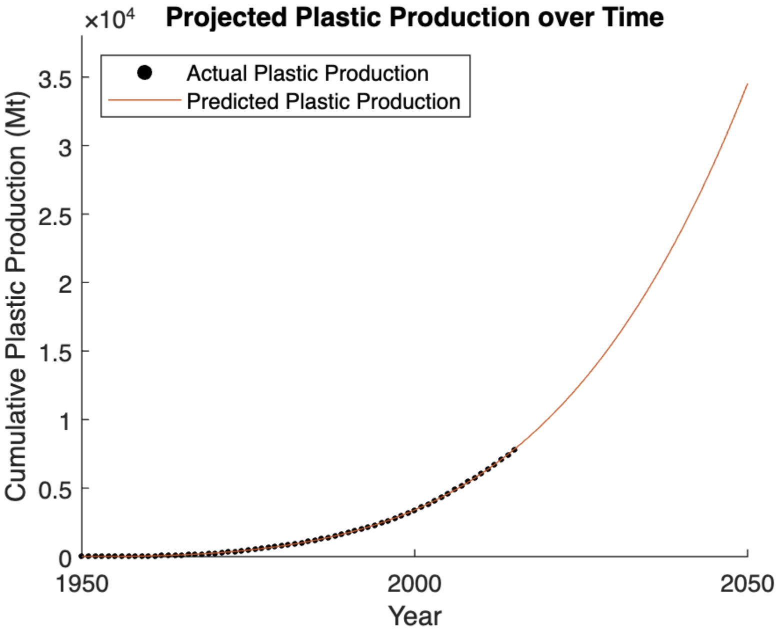

Figure 1. Plot of past and projected cumulative global plastic production. The black points are annual measures of accumulated plastic from 1950 to 2015 [Geyer et al. 2017], while the orange prediction curve is the best-fit quartic polynomial **(4)**.

The equation of the trend is

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

with an R^2 value of 0.9999. We use a quartic polynomial fit for two reasons:

- An exponential curve does not fit as well, with notable deviation between the trend line and the tails of the data.
- Using another fit, we determine that annual plastic production growth over time is cubic. Since cumulative plastic production is the integral of annual plastic production, it follows naturally that cumulative plastic production should be quartic.

Using $P_{\text{trend}}(t)$, 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 $P_{\text{trend}}(t)$ from **(4)** into **(2)**. Then the predicted seabird population is

$$S_{\text{trend}}(t) = S(0)\exp\left((b-d_n)t - d_p\int_0^t P_{\text{trend}}(t')\,dt'\right). \qquad \textbf{(5)}$$

Plotting the estimated $S_{\text{trend}}(t)$ 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 steady decline since (**Figure 2**).

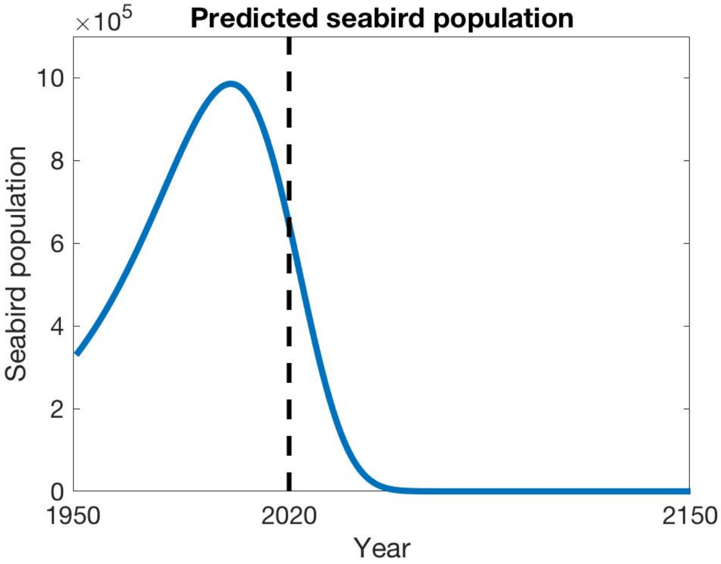

Figure 2. Projected seabird population given that global plastic production follows the current trend. The dotted line represents the current year.

The initial increase can be explained by natural population dynamics. With the birth rate 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.

A species is considered *endangered* if the population size is estimated to be fewer than 2,500 *mature* individuals and is expected to continue to decline [International Union for Conservation of Nature 2001]. Our model predicts that our reference seabird population, razorbills, will become endangered no later than **2056**. This is a slight overestimate 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, a species is considered *critically endangered* if the population size is estimated to be fewer than 250 mature individuals and is expected to continue to decline. According to our model, our reference seabird population will reach this threshold no later than **2062**.

If the current plastic production trend continues, cumulative production by 2056 will be approximately 42,000 MT, which is a 35,000 MT increase from the current cumulative level. By 2062, the cumulative amount would reach approximately 53,000 MT.

Evaluation of Global Plastic Policies

We consider three policies for mitigating plastic pollution:

1. Reduce or terminate plastic production but not engage in any additional cleanup efforts. We will show that this type of policy is insufficient if we want to save the environment from irreversible damage.
2. Require a net reduction in accumulated plastic produced until all plastic is cleaned up.
3. Require a net reduction in accumulated plastic until the amount of accumulated plastic is below a threshold level.

Both the second and third types of policy result in recovery of seabird populations, but our cost analysis shows that the third type is more realistic to implement.

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

One type of policy often proposed is to allow for continued plastic production but at a reduced level. Examples of such policies are regulations that require companies to reduce their production by some percentage every year or regulations that impose a cap on the maximum amount that can be produced.

However, this type of policy is not sufficient to save the environment.

In fact, even immediate termination of plastic production is not enough to save the seabird population, as shown in **Figure 3**.

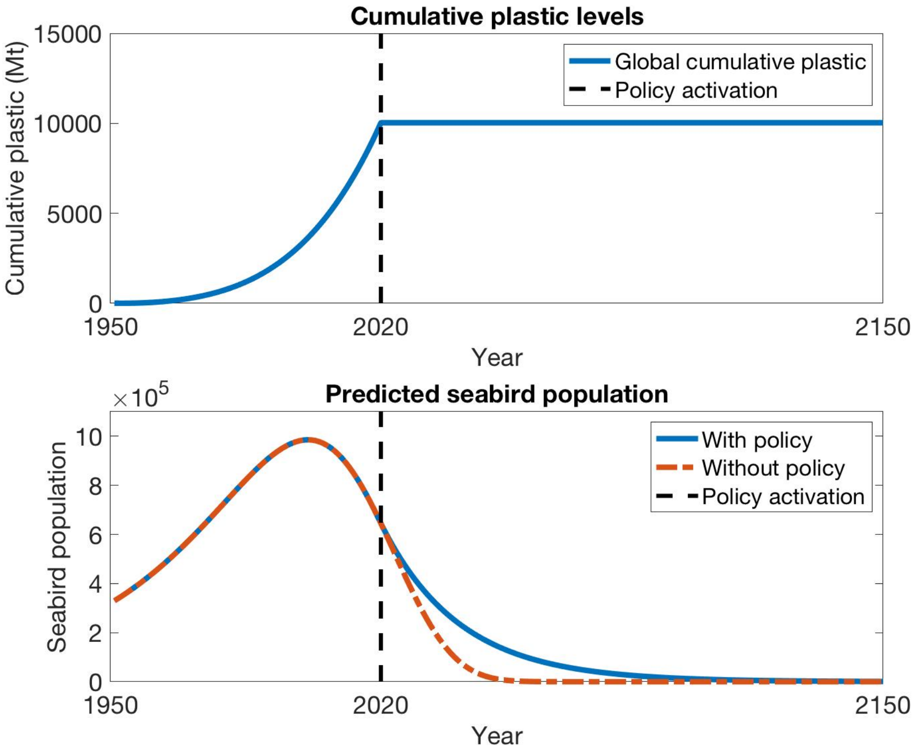

Figure 3. Top: Cumulative plastic levels given no production after 2020. Bottom: Predicted seabird population as a result of Policy Type 1 (blue upper curve) and in the absence of any policy (orange lower dashed curve). In both figures, the vertical dotted line indicates when the policy is activated.

Terminating plastic production prolongs the survival of the seabird population for several decades, but this policy still ultimately results in extinction. The reason for this bleak outcome is that the amount of plastic waste in our oceans is already so high that, in the absence of cleanup efforts, seabirds will continue to die.

Because a policy with no cleanup action is ineffective for saving the seabirds, it is not meaningful to compare its economic cost to the policies described below. Thus, we will not compute a cost for Policy Type 1.

Policy Type 2: Termination of Plastic Production with Complete Cleanup

We model the effects of a policy that both terminates plastic production *and* mandates that a constant amount of plastic waste be cleaned up each year.

Figure 4 shows the environmental impacts of stopping plastic production and engaging in cleanup efforts.

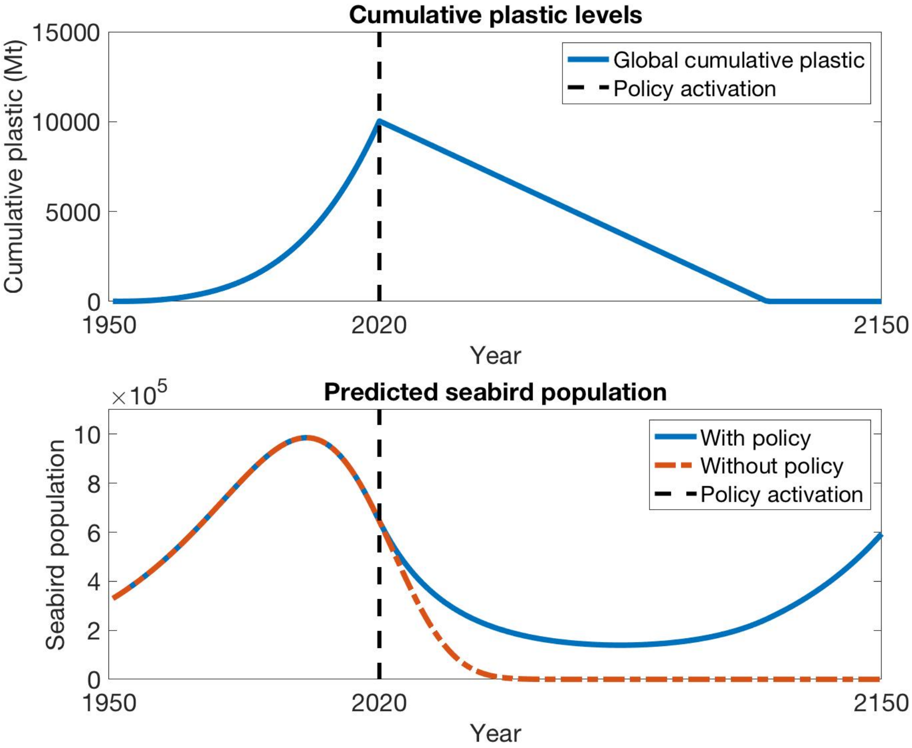

Figure 41. Top: Cumulative plastic levels given that global production is terminated in 2020 *and* an equivalent of 100 MT of previously produced plastic is cleaned up from the environment each year until all plastic pollution is completely removed. Bottom: Predicted seabird population as a result of Policy Type 2 (blue upper curve) and in the absence of any policy (orange lower dashed curve). In both figures, the vertical dashed line indicates when the policy is activated.

For convenience, we choose to remove 100 MT of previously-produced plastic each year, but the effect of a different amount can be evaluated using a similar framework. The cleanup effort is assumed to continue until all plastic waste is removed from the environment. We see that once plastic production stops and cleanup begins, the decline in seabird population begins to slow. Our model predicts that by the start of the next century, seabird populations will take off.

The tail-end behavior of the predicted bird population should be interpreted with caution. We model the interactions of declining seabirds with plastic waste but do not precisely model seabird population dynamics of large populations (e.g., the model does not account for the carrying capacity of the marine environment). Termination of plastic production plus removal lets the seabird population recover, but the extent of its increase may not be accurately reflected by our model.

Complete termination of production is not required to achieve the desired effect. 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, which we denote as $P_{\text{aggressive}}$, over an arbitrary time interval $[T_a, T_f]$ (where T_f is when all plastic is eliminated from the oceans):

$$P_{\text{aggressive}}(t) = P_{\text{trend}}(t) - P_{\text{trend}}(T_a) + \frac{P_{\text{trend}}(T_a)}{T_f - T_a}\,(t - T_a).$$

We restate the formulation of the cost metric defined in **(3)**:

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

We chose a **linear reduction policy** of 100 MT/year, since any higher polynomial or exponential reduction policy would introduce a maximum derivative of higher magnitudes, which are penalized by the cost metric defined in **(3)**. We can then compute the cost of $P_{\text{aggressive}}$:

$$C_{T_a,T_f}(P_{\text{aggressive}}) = P_{\text{trend}}(T_f) + 100\lambda.$$

Setting the interval to $[70, 200]$, corresponding to 2020 to 2150, we find $C_{70,200} = 4.60 \times 10^5 + 100\lambda$ and plastic would be eliminated from the oceans by 2120.

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

Termination of production paired with a complete cleanup results in 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 seabirds, and that they can still recover even if some plastic remains in the oceans. We calculate the maximum level of plastic that can remain not cleaned up without killing off the seabirds.

By setting dS/dt from the seabird population model to 0, we can solve for the maximum 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). We call this level $P_{\min}$ because it represents the *minimum* policy necessary to save the birds. We find

$$\frac{dS}{dt} = (b - d_n)S(t) - S(t)d_pP_{\min} = 0,$$

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

Using the values from **Table 1**, we find

$$P_{\min} = 3750\,\text{MT}.$$

If the global accumulated plastic is reduced to $P_{\min}$, the seabird population will stop declining and stabilize. 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 harm imposed on seabirds is mitigated. The seabird population reaches an equilibrium because the sum of the natural death rate and the plastic-ingestion death rate equals the birth rate.

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

$$P_{\text{feasible}}(t) = P_{\text{trend}}(t) - P_{\text{trend}}(T_a) + \left(\frac{P_{\text{trend}}(T_a) - P_{\text{target}}}{T_f - T_a}\right)(t - T_a).$$

With a reduction rate of 100 MT/year, this policy will reach $P_{\min}$ by 2082.

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:

$$\begin{aligned} C_{70,200} &= P_{\text{trend}}(200) - P_{\text{trend}}(0) - P_{\min} + 100\lambda \\ &= 4.57 \times 10^5 + 100\lambda. \end{aligned}$$

As expected, this C value is smaller than the one computed for $P_{\text{aggressive}}$ ($4.60 \times 10^5 + 100\lambda$). Since the C value of Policy Type 3 is smaller, we conclude that the optimal policy will require net reduction in accumulated

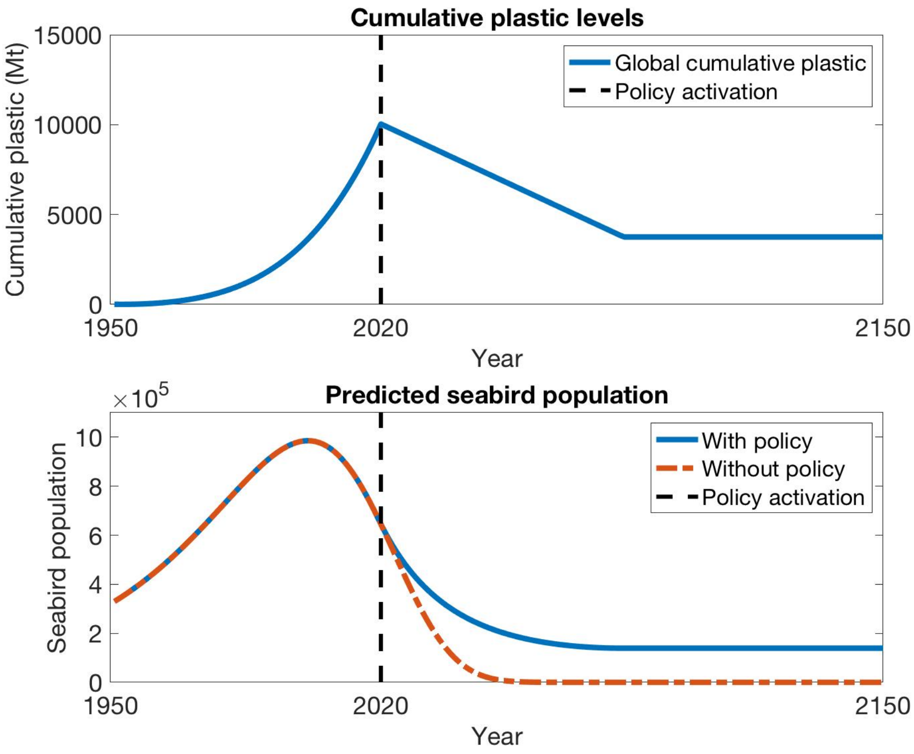

Figure 5. Top: Cumulative plastic levels with production terminated in 2020 *and* 100 MT of previously produced plastic is cleaned up each year until 2082, which is when plastic levels are reduced to 3,750 MT. Bottom: Predicted seabird population as a result of Policy Type 3 (blue upper curve) and in the absence of policies (orange lower dashed curve). In both figures, the dashed vertical line indicates when the policy is activated.

plastic until we go below the maximum mass that does not result in further seabird population decline.

Policy Division Across Countries

We 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 plastic consumption and cleaning up plastic waste, we restrict production in each country based on population and income level. We divide its plastic consumption by the 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 above 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:

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

Note that

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

by the linearity of differentiation. By examining incremental changes in cumulative policy, we can dynamically shift the 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.

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

For instance, if a policy dictates 0 plastic production ($\Delta P_{\text{policy}} = 0$), 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 ($\Delta P_{\text{policy}} = \Delta P_{\text{trend}}$). Additionally, if a country is forced to clean up more plastic than it produces ($\Delta P_{\text{policy}} < 0$), then $\alpha < 0$. Since no policies call for increased plastic production, $\Delta P_{\text{reduced}}$ 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* or the reduction of *plastic per capita*.

By multiplying the current global plastic production trend $\Delta P_{trend}(t)$ by 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 $\bar{x}_{\text{HI}}$, $\bar{x}_{\text{UMI}}$, $\bar{x}_{\text{LMI}}$, $\bar{x}_{\text{LI}}$ be the mean plastic per capita per year across the high income, upper middle income, lower middle income, and low income classes. For simplicity, let $\{\text{HI}, \text{UMI}, \text{LMI}, \text{LI}\}$ be represented by the integers $\{1, 2, 3, 4\}$, respectively. Since the four income classes share the cost burden equally, we can define the shifted mean $\tilde{x}_k$ for income class k via

$$\tilde{x}_k = \alpha\bar{x}_k.$$

Let p_k be the proportion of all 192 countries that are in income class k, so that $\sum_{k=1}^{4} p_k = 1$. Given that each income class produces $\tilde{x}_k$, global plastic production can be expressed as

$$\sum_{k=1}^{4} p_k \tilde{x}_k = \sum_{k=1}^{4} p_k \alpha \bar{x}_k = \alpha \bar{X} = \tilde{X}.$$

Thus, shifting each of the class means by α satisfies the global mean dictated by ΔP_{policy}.

To achieve $\tilde{x}_k$ for each of the four income classes, we must further consider cost-sharing across countries within each income class. For each income class k, we consider $\tilde{x}_k$ to be the ideal level of plastic per capita. 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 $\beta_{k,i}(t)$ 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:

$$\beta_{k,i}(t) = \begin{cases} \dfrac{\tilde{x}_k(t) - \sum_i \mathbb{1}\{x_i(t) \le \tilde{x}_k(t)\} x_i(t)}{\sum_i \mathbb{1}\{x_i(t) > \tilde{x}_k(t)\} x_i(t)}, & \text{if } x_i(t) > \tilde{x}_k(t); \\ 1, & \text{if } x_i(t) \le \tilde{x}_k(t), \end{cases} \tag{6}$$

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.

Policy Division Procedure

[Jambeck 2015] compiled statistics on annual plastic production and waste per country in 2010. Using these data, we assessed the maximum amount of plastic that each country should produce at time t given incremental plastic policy

$$\Delta P_{\text{policy}}(t) = \Delta P_{\text{trend}}(t) - \Delta P_{\text{reduced}}(t).$$

1. Split the 192 countries in the world into the four relative income classes: HI, UMI, LMI, LI.

2. Compute for every country the amount of plastic waste produced per person per year.
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 class.
4. Determine the deviation of each of the countries x_i from the computed means within their income classes. Rank the countries by these deviations.
5. To compute the global mean across all countries, weight each of the income class means by the proportion of total countries within that class: $\overline{X} = \sum_{k=1}^{4} p_k \bar{x}_k$, where p_k is 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 $\Delta P_{\text{policy}}(t)$.
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 $\widetilde{X} = \sum_{k=1}^{4} p_k \tilde{x}_k$. This is how we distribute the burden of plastic cleanup fairly across the four income classes.
8. For each country i and its corresponding income class k, compute the appropriate $\beta_{k,i}$.
9. For country i belonging to income class k that is producing above $\tilde{x}_k$ ($x_i > \tilde{x}_k$), cap its production at $\beta_{k,i} x_i$. 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 of countries in income class k will reduce plastic production.
10. In the edge case that $\beta_{k,i} x_i < \tilde{x}_k$ for some country i (which may happen when x_i is just above $\tilde{x}_k$), set x_i to the mean $\tilde{x}_k$ for the benefit of country i. Then $\beta_{k,i}$ is recomputed for the remaining countries within the income class k.

This data set contains data only for 2010, so derived relations between countries and their income classes are assumed to be held constant over time.

Policy Division Results

Using the above procedure to characterize each of the 192 countries, we arrive at the results in **Table 2** for each of the income classes in 2010.

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

Table 2.

Income class summary.

Income class (k)	LI	LMI	UMI	HI
Number of countries	21	44	53	74
Proportion (p_k)	.109	.229	.0156	.385
Avg. MT $\times 10^{-8}$ plastic/capita/year ($\bar{x}_k$)	2.0	6.2	4.8	10.8

Table 3.

Examples of countries with production levels above (top) and below (bottom) the mean for their income class.

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

Case Studies

We examine the cost of instituting the complete and incomplete cleanup policies described earlier for three sample countries from different income classes. Both policies require 100 MT of plastic to be cleaned up each year starting in 2020, so the initial cost burden of both policies is the same. Since no country currently has a net negative plastic production level, we have $x_i > \tilde{x}_k$ for all countries i; all countries need to participate in the reduction effort and clean up plastic regardless of their relative production per capita in their income class.

United States

The U.S. produces 12.2×10^{-8} MT of plastic per capita per year, above the HI mean of $\bar{x}_{\text{HI}} = 10.8 \times 10^{-8}$ MT. The U.S. will have to reduce yearly plastic consumption per person with $\beta_{\text{HI,US}} < 1$ since $\tilde{x}_{\text{HI}} < \bar{x}_{\text{HI}}$. Thus, $x_{\text{US}} > \tilde{x}_{\text{HI}}$ for any policy.

The cost burden of a given policy will need to be recomputed every year, depending on the previous year's net plastic accumulation.

We examine the cost burden on the U.S. in 2020, corresponding to $t = T_a = 70$, for the complete and incomplete cleanup policies detailed earlier.

The current trend in the absence of any global policy is

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

We can compute:

$$\begin{aligned}&\Delta P_{\text{trend}}(t) = \frac{d}{dt}\big(0.000262t^4 + 0.001772t^3 + 0.6967t^2 - 4.123t + 10.83\big),\\ &\Delta P_{\text{trend}}(70) \approx 479.\end{aligned}$$

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

Using these values, we compute $\alpha = -100/479 \approx -0.209$ and the new average plastic per capita for the high income class, $\tilde{x}_{\text{HI}} = \alpha\bar{x}_{\text{HI}} \approx -0.209 \times (10.8 \times 10^{-8}) \approx -2.25 \times 10^{-8}$.

All countries now must clean up more plastic than they create. To compute the U.S. contribution to this policy, we determine $\beta_{\text{HI,US}}$:

$$\beta_{\text{HI,US}} = \frac{\tilde{x}_{\text{HI}}}{\sum_i x_i} = \frac{\alpha\bar{x}_{\text{HI}}}{74\bar{x}_{\text{HI}}} = \frac{\alpha}{74} \approx -0.00282.$$

The numerator reduces to $\tilde{x}_{\text{HI}}$, since there are currently no countries for which $x_i \leq \tilde{x}_{\text{HI}}$. Similarly, since $x_i > \tilde{x}_{\text{HI}}$ 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 $\beta_{\text{HI},i} \approx -0.00282$ at $t = T_a = 70$.

Specifically for the United States,

$$(\beta_{\text{HI,US}})(x_{\text{US}}) = -(0.00282)(12.2 \times 10^{-8}) \approx -3.44 \times 10^{-10}\ \text{MT},$$

or -0.344 kg. So on average, each person in the U.S. needs to remove at least 0.344 kg of plastic waste more than they produce in 2020 to achieve the goals set by these policies.

China

China produces 4.40×10^{-8} MT of plastic per capita per year, which is below $\bar{x}_{\text{UMI}} \approx 4.79 \times 10^{-8}$ MT. We compute $\beta_{\text{UMI,CH}} = \alpha/53 \approx -0.00394$ and $(\beta_{\text{HI,CH}})(x_{\text{CH}}) \approx -1.89 \times 10^{-10}$ MT, or -0.189 kg per person in 2020.

Somalia

Somalia produces 1.96×10^{-8} MT of plastic per capita per year, which is below $\bar{x}_{\text{LI}} = 1.98 \times 10^{-8}$ MT. We compute $\beta_{\text{LI,SO}} = \alpha/21 \approx -0.00994$ and $(\beta_{\text{LI,SO}})(x_{\text{SO}}) \times -1.95 \times 10^{10}$ MT, or -0.195 kg per person in 2020.

Evaluation of Strengths and Weaknesses

Strengths

- **An interpretable metric for environmental health**. We 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 and has the advantage of easy interpretability.
- **Penalty for future damage caused by present actions**. When making decisions about plastic consumption, individuals consider environmental impact only on short-time horizons. Our seabird population model enables us to quantify future harm caused by current plastic consumption. With concrete prediction of future costs, governments and people can make better-informed decisions about their plastic consumption.
- **Prediction of outcomes if no new policies are adopted**. By fitting our models to plastic production data since 1950, we can 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 prediction highlights the urgent need for new policies for managing plastic waste if we want to prevent environmental damage from reaching an irreparable level.
- **Evaluation of societal costs of plastic production regulation**. By formulating our cost metric to depend on both total plastic reduction and the year-to-year reduction rate, we determine a policy that saves the marine environment while minimizing economic and social impacts on people. 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 that a country's people must expend on alternatives to plastic. The incorporation of a penalty for the year-to-year rate of reduction allows us to model the resistance of governments and citizens to change their behavior to reach the target plastic level. Using this cost metric, we find a policy that poses minimal economic and social burden: constant year-to-year reductions until the global plastic level is reduced to $P_{\min}$.
- **Equitably distributing responsibility for plastic production reduction**. Not all countries can contribute equally to global plastic reduction; our model assigns an individualized reduction for each country based on population size and income. By splitting countries into income classes, our model 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 per person relative to their income

class are subject to stricter plastic reduction requirements, while countries producing lower amounts per person face more lenient requirements.

Weaknesses and Further Improvements

- **Imprecise prediction when seabird populations become large**. We designed our model to predict the dynamics of seabird populations when they are at risk, so we do not focus on precisely modeling population dynamics of the seabirds once the population is no longer at risk.
- **Assumption that all plastic produced ends up as waste in the environment**. However, the policies can be scaled by the fraction of plastic produced that ends up in the environment as waste.
- **Cost metric lacks interpretable units**. While our cost metric can compare the costs of plastic reduction policies, there are no meaningful units to assign to it. Thus, it is useful only in a comparative context.
- **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 computed the optimal annual rate of reduction that minimizes cost C. While the rate of 100 MT was convenient to illustrate the implementation of a policy that reduces plastic to $P_{\min}$, we could have used a rate of smaller magnitude and still saved the seabirds (with a lesser economic burden as dictated by **(3)**). A rate of 100 MT gives the policy a lifetime of 62 years (**Figure 5**), which we believe is sufficiently long. Policies that employ a slower rate of reduction require longer timeframes to implement, which increases the risk of encountering unforeseen factors that may significantly affect the marine environment in ways unaccounted for in our model.

Conclusion

Using the seabird population as a proxy for environmental health, we find that if plastic consumption levels continue to increase at their current rate, irreversible damage will be caused to the environment by 2056. However, this damage can be avoided by new policies to manage plastic production and clean up plastic waste already in the environment. We determine that an efficient policy is to reduce accumulated plastic by a constant amount each year until the mass of plastic remaining in the environment is less than 3,750 million metric tons. This policy imposes minimal cost on society while allowing seabird populations to recover. Finally, we break this global policy into country-specific policies. We stratify countries by income class and 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 and efficient division of policy costs across countries, we present an effective solution to the marine plastic crisis.

Memo

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

The world is faced with the problem of accumulation of plastic waste in the marine environment, which has resulted in significant harm to marine animals. Since plastic does not readily break down and few plastic products are recycled, an intervention is necessary. Constructing effective policy is extremely difficult if we do not properly account for the economic incentives that created this situation. With this in mind, we assess the current state of affairs and provide a plan to cost-effectively reduce accumulated plastic waste levels from approximately 10,000 million metric tons down to 3,750 million metric tons over the next 62 years.

To quantify the environmental impacts of plastic waste accumulation, we introduce the razorbill seabird population as a proxy for assessing the health of the marine environment. Razorbills have been shown to be a valid bioindicator for the status of the marine environment. Rising plastic waste accumulation has led to deaths of marine organisms, including seabirds. Over the past several decades, seabirds have decreased in overall population due to a rising death rate caused by ingesting plastic waste. We characterize the marine environment to be in good shape when the overall seabird population is flourishing, and to be beyond saving once the seabird population dips below 2,500 (the *endangered limit*, as determined by the International Union for Conservation of Nature).

We present a plan to reduce plastic accumulation slowly over the next 62 years to guarantee the survival of the seabird population. We consider the economic cost associated with reduction of plastic production. Slow-acting policies over a long period of time incur lower economic costs and are optimal in resolving this environmental crisis.

After determining an optimal global policy, we address how to distribute the burden of responsibility. Countries have differing population and income levels, which influence their ability to contribute to plastic reduction. Our model groups countries into income classes and assesses their ability to achieve a certain plastic production per capita. This gives our model the flexibility to divide costs efficiently and equitably, ensuring that no one country faces a larger economic burden relative to their income and population.

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