A decision framework for estimating the cost of marine plastic pollution interventions

Erin L. Murphy1 | Miranda Bernard1 | Gwenllian Iacona2,3 | Stephanie B. Borrelle4,5,6 | Megan Barnes7 | Alexis McGivern8 | Jorge Emmanuel9 | Leah R. Gerber1,2

1 School of Life Sciences, Arizona State University, Tempe, Arizona, USA
2 Center for Biodiversity Outcomes, Arizona State University, Tempe, Arizona, USA
3 Resources for the Future, Washington, DC
4 David H. Smith Conservation Research Program, Society for Conservation Biology, Washington, DC
5 Department of Ecology and Evolutionary Biology, University of Toronto, Toronto, Ontario, Canada
6 College of Engineering, University of Georgia, Athens, Georgia, USA
7 Centre for Environmental Economics & Policy, School of Agriculture and Environment, University of Western Australia, Crawley, Western Australia, Australia
8 School of Geography and the Environment, University of Oxford, Oxford, UK
9 Institute of Environmental and Marine Sciences, Silliman University, Dumaguete, Philippines

Correspondence
Erin Murphy, School of Life Sciences, Arizona State University, Life Sciences Center A Wing, 427 E Tyler Mall, Room 209, Tempe, AZ 85281, USA.
Email: elmurph1@asu.edu

Abstract
Marine plastic pollution has emerged as one of the most pressing environmental challenges of our time. Although there has been a surge in global investment for implementing interventions to mitigate plastic pollution, there has been little attention given to the cost of these interventions. We developed a decision support framework to identify the economic, social, and ecological costs and benefits of plastic pollution interventions for different sectors and stakeholders. We calculated net cost as a function of six cost and benefit categories with the following equation: cost of implementing an intervention (direct, indirect, and nonmonetary costs) minus recovered costs and benefits (monetary and nonmonetary) produced by the interventions. We applied our framework to two quantitative case studies (a solid waste management plan and a trash interceptor) and four comparative case studies, evaluating the costs of beach cleanups and waste-to-energy plants in various contexts, to identify factors that influence the costs of plastic pollution interventions. The socioeconomic context of implementation, the spatial scale of implementation, and the time scale of evaluation all influence costs and the distribution of costs across stakeholders. Our framework provides an approach to estimate and compare the costs of a range of interventions across sociopolitical and economic contexts.

KEYWORDS
conservation, decision-making, equity, financial costs, plastics

Un Marco de Decisión para Estimar el Costo de Intervenciones en la Contaminación Marina por Plástico

Resumen: La contaminación marina por plásticos ha emergido como uno de los retos ambientales más prioritarios de nuestro tiempo. Mientras ha habido un aumento en la inversión global para implementar intervenciones para mitigar la contaminación por plásticos, se ha dado poca atención al costo de estas intervenciones. Desarrollamos un marco de soporte a las decisiones para identificar los costos y beneficios económicos, sociales y ecológicos de las intervenciones en la contaminación por plástico para diferentes sectores y partes interesadas. Calculamos el costo neto como una función de 6 categorías de costo y beneficio con la siguiente ecuación: costo de la implementación de una intervención (costos directos, indirectos y no monetarios) menos los costos y beneficios recuperados (monetarios y no monetarios) producidos por las intervenciones. Aplicamos nuestro marco a 2 estudios de caso cuantitativos (un plan de manejo de residuos sólidos y un interceptor de basura) y 4 casos de estudio comparativos evaluando los costos de limpieza de playas...
INTRODUCTION

Marine plastic pollution has detrimental effects on the environment, the economy, and human well-being (Beaumont et al., 2019). Recognizing the implications of this environmental problem, stakeholders—policy makers, nonprofit organizations, and businesses—have made significant investments to address plastic pollution. For instance, financial pledges at the 2017 Our Ocean Conference totaled $8.5 billion (Our Ocean, 2017) (all costs converted to 2019 U.S. dollars). However, funds for conservation efforts are limited, and these commitments have not insufficiency reduced marine plastic pollution and its ecological and social effects (Borrelle et al., 2020). To ensure these investments achieve the desired results and are economically viable, it is necessary to systematically evaluate the cost-effectiveness of interventions before implementation (Murdoch et al., 2007).

Identifying the cost-effectiveness of plastic pollution interventions requires understanding the cost of an intervention, its efficacy, and the benefits it produces (Cook et al., 2017). Current evaluations for effectiveness of plastic pollution interventions are insufficient (Löhr et al., 2017). Still, there are strategies for measuring the effectiveness of conservation policies (Sutherland et al., 2004) that could be applied to plastic pollution interventions. There is a body of costs for conservation efforts, however, is sparse, and key costs are often omitted (Iacona et al., 2018), making it difficult to inform cost analyses for plastic pollution interventions. Most evaluations of plastic pollution interventions consider only the direct costs of intervention and recovered costs (e.g., taxes) to generate revenue (e.g., Crawford, 2008). Some consider the financial or nonmonetary benefits of plastic removal (Lavee, 2010), but many costs and benefits remain overlooked. Further, the inconsistent characterization and reporting of costs make it difficult to interpret studies or use them to inform decision-making (Iacona et al., 2018).

The challenge of standardizing the cost of interventions for plastic pollution is exacerbated by the breadth of intervention types. Interventions are implemented along the entirety of the plastic life cycle, yet cost analyses are only available for a small subset of these—such as cleanups (Mouat et al., 2010), deposit refund schemes (Lavee, 2010), and plastic bag bans (Zhu, 2011)—and analyses are predominantly conducted after implementation (Oosterhuis et al., 2014). Generalizable evaluations are complicated by the fact that the costs and possible benefits of interventions are influenced by factors specific to the context in which they are implemented (Oosterhuis et al., 2014). Different interventions place the burden of costs on different stakeholders. This is especially salient for marginalized populations, who are often disproportionately affected when the full distribution of costs is ignored (Adams et al., 2010). Thus, an approach for estimating the net costs of plastic pollution interventions is critical for helping decision makers better prioritize actions to achieve their conservation goals (Wilson et al., 2009).

We developed a decision support framework to identify the costs and benefits of plastic pollution interventions accrued by a range of stakeholders. We first identified the relevant categories of costs and benefits associated with plastic pollution interventions. We then used an equation to calculate the net cost as a function of these categories. We applied the framework to two quantitative case studies informed by specific
interventions and four comparative case studies informed by the literature. Finally, to encourage more equitable decision-making, we examined how context influences the distribution of costs across stakeholders. We sought to provide an approach to estimate and compare the costs of a range of interventions across sociopolitical and economic contexts.

**METHODS**

A conventional cost–benefit analysis sums the benefits and subtracts the costs to yield the net benefits. However, our approach follows and extends on methods developed by Iacona et al. (2018), who examined the total costs of conservation interventions. We developed an equation to describe the net cost of mitigating marine plastic pollution, which we used to inform the development of our framework. Net cost is equal to the cost of implementing an intervention (direct, indirect, and nonmonetary [NM]) minus recovered costs and benefits (monetary and NM) produced by the interventions. If the sum is positive, there is a net cost. If it is negative, there is a net benefit:

\[
\text{Net cost} = (\text{direct costs} + \text{indirect costs} + \text{NM costs}) - \\
(\text{recovered costs} + \text{monetary benefits} + \text{NM benefits})
\]  

The cost and benefit categories were informed by a Web of Science search using a combination of the following terms: “cost” OR “economic” AND “marine” OR “ocean” AND “debris” OR “litter” OR “plastic.” We supplemented this with a Google Scholar search for gray literature (Appendix S1).

Direct costs represent the costs of actions required to implement the intervention (National Center for Environmental Economics, 2010). There are four categories: overhead, labor, capital assets, and consumables (Iacona et al., 2018). Indirect costs are associated with the intervention but not directly tied to the financial cost of implementing actions, such as the opportunity cost of volunteers (National Center for Environmental Economics, 2010). Recovered costs are the revenue created by the intervention to reduce net costs. They are categorized as direct costs, which are implemented to reduce the implementer’s cost, or indirect costs, which may benefit other stakeholders. Monetary benefits are the savings that would be accrued by stakeholders due to resulting reduction in marine plastic pollution. There are two categories of monetary benefits: benefits to marine sectors and healthcare savings (McIlgorm et al., 2011; Mouat et al., 2010; Newman et al., 2015). Nonmonetary costs represent the nonfinancial costs of an intervention (e.g., environmental trade-offs), and the nonmonetary benefits represent the nonfinancial benefits of implementation. Nonmonetary costs and benefits are categorized as environmental or social (McIlgorm et al., 2011; Newman et al., 2015).

Table 1 provides examples of each cost and benefit.

The framework provides a section for users to input the intervention’s description, its objectives (i.e., the primary goals of the intervention), and the spatial–temporal scale of evaluation (Table 2). Then, users record the stakeholders involved in or affected by the intervention. To identify the costs accrued by a specific stakeholder group, each stakeholder is listed in a new row. Next, the user evaluates each of the cost and benefit subcategories, as outlined below. Nonmonetary costs and benefits should be identified, even if users cannot estimate their monetary value because they often relate directly to the intervention objectives. The user can quantify them with nonmonetary units (e.g., number of animals saved). If the user wants to further enumerate nonmonetary costs and benefits, there are methods for doing so, such as ecosystem service accounting (Crossman et al., 2012). The final section provides an opportunity for users to conduct an equity evaluation, in which users identify stakeholders who would benefit or be harmed by each intervention and list net costs accrued by each stakeholder group.

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**Table 1** Cost and benefit categories and subcategories for interventions to mitigate marine plastic pollution, where costs on the left increase net cost and costs and benefits on the right decrease net cost

| Positive costs                                      | Negative costs and benefits                          |
|-----------------------------------------------------|------------------------------------------------------|
| **Direct costs:**                                    | Recovered costs:                                     |
| 1. Overhead (e.g., administration, disposal, permits) | 1. Direct (e.g., taxes, fines, fees)                  |
| 2. Labor (e.g., salaries, benefits, insurance)       | 2. Indirect (e.g., job creation, substitutes)         |
| 3. Capital assets (e.g., infrastructure, vehicles, equipment) | Monetary benefits:                                   |
| 4. Consumables (e.g., materials, gasoline)           | a. Decreased cost of marine/coastal activities       |
|                                                    | b. Shipping/yachting (e.g., entanglement, obstruction) |
|                                                    | c. Aquaculture (e.g., prop entanglement, blocked pipes) |
|                                                    | d. Agriculture (e.g., coastal agriculture pollution)  |
|                                                    | e. Increased revenue in recreation and ecotourism     |
|                                                    | f. Increased provisioning of marine resources         |
|                                                    | Monetary benefits:                                   |
| **Indirect costs:**                                  | a. Fishery (e.g., propeller entanglement, fishing plastics) |
| 1. Opportunity cost (e.g., volunteer time)          | b. Shipping/yachting (e.g., entanglement, obstruction) |
| 2. Job loss                                          | c. Aquaculture (e.g., prop entanglement, blocked pipes) |
| 3. Substitution (e.g., cost of alternative products) | d. Agriculture (e.g., coastal agriculture pollution)  |
|                                                    | e. Increased revenue in recreation and ecotourism     |
|                                                    | f. Increased provisioning of marine resources         |
|                                                    | 2. Reduced healthcare costs (e.g., injuries from plastic encounters) |
| **Nonmonetary costs:**                               | Nonmonetary benefits:                                 |
| 1. Environmental impacts of intervention (e.g., air pollution) | 1. Social benefits:                                  |
| 2. Social impacts of intervention (e.g., value of plastics lost) | a. Human welfare (e.g., sense of place, happiness)   |
|                                                    | b. Social justice (e.g., reduced inequality)          |
|                                                    | 2. Environmental health (e.g., intrinsic value, bequest value) |
TABLE 2  Decision framework to identify all costs and benefits\(^a\) associated with an intervention for marine plastic pollution and the partial costs accrued by different stakeholders

| Stakeholder | Actions and direct costs | Indirect costs | Recovered costs | Monetary benefits |
|-------------|--------------------------|----------------|-----------------|------------------|
| (e.g., NGO, government) | Steps to intervention and associated costs (e.g., enforcement, infrastructure) | Not associated with direct action (e.g., job loss, opportunity cost) | Direct or indirect revenue from implementation (e.g., fines, job creation) | Savings from plastic reduction (e.g., increased tourism) |

Nonmonetary benefits\(^b\) (e.g., environmental trade-offs, social costs)
Nonmonetary costs\(^b\) (e.g., ecosystem services, human welfare)
Equity: Payers vs. beneficiaries

\(^a\)Even if the decision maker is unable to quantify every cost, the framework allows them to better understand the costs they are and are not considering.

\(^b\)Nonmonetary costs and benefits may be included qualitatively or quantitatively based on the decision makers preference and available data.

Quantitative case studies

To demonstrate how the framework can be used to examine relative costs of alternative interventions, we applied it to two cases in which comprehensive cost evaluations were completed prior to intervention implementation. These cases allowed us to explore different interventions implemented by different actors under contrasting socioeconomic conditions.

The first case study explored implementation of a solid waste management (SWM) plan in the city of Bayawan, Negros Oriental, Philippines. The Philippines is ranked as the third largest producer of plastic pollution in the world, and plastic pollution has been found in the guts of marine species, including commercially important fish (Bucol et al., 2020). Bayawan is a 700-km\(^2\) coastal city on the island of Negros with a population of 117,900 (Philippines Statistics Authority, 2015). We explored the cost of implementing a 10-year SWM plan in Bayawan. Our examination was informed by the public document, Solid Waste Management Plan (2019–2028). The key objectives of the plan were to expand waste management services, increase recycling and composting rates, and reduce open burning to ensure the city is prepared for anticipated population growth and urbanization. Key stakeholders for implementation include the municipal government, the local community, schools, barangays (neighborhoods), and industry (marine sectors and recycling sectors). The city identified actions required to achieve these objectives: purchase more equipment, build a new special waste facility, build a water monitoring pond, implement and enforce new SWM ordinances, support the establishment of barangay-based SWM facilities, and administer school education and innovation programs (City of Bayawan, 2019).

The second case study explored the implementation of a trash interceptor at the mouth of the Jones Falls River in Baltimore over a 10-year evaluation period (Clearwater Mills, 2013). Baltimore is a large coastal city—population of 593,490—in Maryland, USA (United States Census Bureau, 2019). It is located on the Chesapeake Bay, an ecologically and socially important body of water that is negatively affected by large amounts of plastic debris and microplastic pollution (Hale et al., 2020). The Waterfront Partnership is a group of businesses that agreed to pay additional taxes into a fund for cleaning up the waterfront. We obtained cost information from the Waterfront Partnership and the CEO of Clearwater Mills, the company that built and maintains the trash wheel. Cost data were provided at the project level and focused predominantly on the cost to the Waterfront Partnership. The key objectives of the trash wheel were to improve the sanitation and water quality of Baltimore’s Inner Harbor. Key stakeholders for implementation were the Waterfront Partnership, the city of Baltimore, the public, and a local marina. Actions taken to achieve the objectives were constructing, operating, and maintaining the trash wheel and educating the public (correspondence with Clearwater Mills and Waterfront Partnership).

Comparative case studies

To better understand three key factors that influence the net costs of intervention—temporal scale of analysis, spatial scale of implementation, and socioeconomic condition—we developed four conceptual case studies. In these case studies, we compared the costs of interventions in scenarios that varied one of these factors, while holding all others constant. We explored the influence of temporal scale on costs in case studies on a time scale of one year and 20 years. For the former case, we evaluated the costs of beach cleanups in developed municipalities, and for the latter we evaluated waste-to-energy (WTE) plants in developed municipalities. We explored the influence of spatial scale of implementation by comparing the costs of beach cleanups at the municipality and national scale in a developed country over one year. Finally, we explored the influence of socioeconomic conditions by comparing the costs of a WTE plant in a municipality in a developed versus developing country.

The choice of scenarios for each comparative case study was based on the availability of peer-reviewed and gray literature evaluating interventions with the appropriate socioeconomic conditions and spatial–temporal scale. We characterized all costs and benefits identified in the literature review based...
TABLE 3 Summary of the City of Bayawan’s plan to expand solid waste management (SWM) and increase plastic waste diversion rates

Intervention: Implement mandatory waste segregation and collection throughout the city

Objective: Expand waste collection in all barangays and achieve 70% waste diversion

Scale: City of Bayawan, Negros Oriental, over 5 years

| Stakeholder | Actions and direct cost | Indirect and nonmonetary cost | Recovered cost, monetary benefit, nonmonetary benefit |
|-------------|-------------------------|--------------------------------|------------------------------------------------------|
| City        | Total capital assets:   | $247,040                       | Recovered costs: –$38,600                            |
|             | Purchase 2 garbage compacters | ($231,600)                        | OC of SWM committees                                 |
|             | Construct special waste facility | ($9,650)                                           | Tipping fees                                         |
|             | Construct water monitoring pond | ($5,790)                                           | Illegal dumping fines                                |
|             | Total administration:   | $946,086                        | Open-dumping fines                                   |
|             | Enact new SWM ordinances | ($386)                                         | Garbage stickers                                     |
|             | Enforce SWM ordinances  | ($162,120)                       | Sale of recyclables                                  |
|             | School innovation program | ($52,110)                        | Monetary benefits: Clean-up                          |
|             | Collection operations   | ($248,970)                       | Tourism                                             |
|             | Operation of BCWMEC facility | ($451,620)                       | Monetary benefits: Clean-up                          |
|             | Expansion of SWM coverage | ($30,880)                        | Monetary benefits: Clean-up                          |
| Public      | Purchase waste containers |                                 | Recovered costs: Recyclable sales                    |
|             | Composting              |                                 | Monetary benefits: Healthcare costs                 |
|             | Payment of fees/fines   | $38,600                          | Environmental costs                                 |
| Schools     | Purchase of waste containers |                                 | Nonmonetary costs: Monetary benefits               |
|             | Payment of fees/fines   |                                 | Nonmonetary benefits: Human welfare                 |
|             | Manage compost and MRF facilities |                                 | Nonmonetary benefits: Ecosystem health              |
| Barangays   | Collect/compost biodegradables |                                 | Monetary benefits: Government awards                |
|             | Enforce SWM ordinances  |                                 | −$52,110 Recyclables sales                          |
| Marine sector |                                |                                 | Monetary benefits: Interaction costs                |
|             | Recycle SWM ordinances   |                                 | Recovered costs: Sale of recyclables                |

Net costs: Government: $1,154,526. Missing costs include indirect costs (increase net) and monetary benefits (decrease net). Public: $38,600 or $0.33 per capita. Missing costs include some direct costs (increase), indirect costs (increase), recovered costs (decrease), monetary benefits (decrease), nonmonetary costs (increase) and nonmonetary benefits (increase). Schools: $52,110. Missing costs include direct costs (increase), indirect costs (increase) and more recovered costs (decrease). Barangays: Costs not available. Missing costs include direct costs (increase). Recycling sector: Costs not available. Missing costs include recovered costs (decrease). Marine Sector: Cost data not available. Missing costs include monetary benefits (increase).

Equity: Costs are negative for industry and the public, and positive for the city, barangays, and schools. This may disproportionately affect low-income communities that could be burdened by waste-segregation costs and rural communities that receive fewer services from the city and have higher burdens for at-home composting and waste management.

*Includes the city, the public, schools, barangays, and industry (recycling and marine sectors).
*All costs are in 2019 U.S. dollars. Costs included without an estimate were mentioned in the report but not considered as costs. Costs in parentheses represent a subcost of the cost listed.
*Costs identified by the authors but excluded from the city’s report.
*OC is an abbreviation for opportunity cost.

on the categories in our cost–benefit framework. We then identified how the relative costs for each of the cost and benefit categories differed based on the case study scenario (e.g., identified whether direct costs were higher or lower for beach cleanups or WTE on a 10-year time scale) (details available in Appendix S2). To standardize comparisons across case studies, we assumed effectiveness was consistent for all interventions in a scenario (i.e., a bag ban implemented in a developing country and a developed country will reduce bag use by the same proportion).

RESULTS

Implementation of a SWM plan in Bayawan

Based on available information, the net cost estimate for Bayawan over 5 years was $1,154,526 (Table 3). This was the direct costs of the program minus the costs recovered by fees, fines, and sale of recyclables. This estimate did not include indirect costs or monetary benefits, which would increase and decrease net cost, respectively.
The cost to the public was calculated as $38,600 ($0.33 per capita), which was the direct costs of fees and noncompliance fines. This estimate did not include the direct costs of purchasing waste-segregation containers, indirect costs, or nonmonetary costs, which would increase net cost. It also did not include recovered costs or benefits (monetary or NM), which would decrease net cost.

The benefit to schools was $52,110 based on the administration of government awards for the best waste management programs (net cost is negative). Importantly, these recovered costs would not be evenly distributed across schools but would benefit only schools deemed most innovative. This estimate also did not include the direct and indirect costs of implementing waste management plans in schools, which would increase costs. Also not included were additional recovered costs, such as the sale of recyclables, which would further reduce costs. Cost estimates were not available for barangays, the recycling sector, or marine sector.

The partial distributions of costs suggested the cost of this plan would fall primarily on the city. The benefits would be greatest for marine sectors, the recycling sector, and the public. The direct costs to the public appeared to disproportionately affect low-income, rural communities that historically burned or dumped waste at no cost and must either manage waste according to new ordinances or pay fines. Some low-income individuals could experience reduced income due to fewer opportunities for waste picking.

**Implementation of a trash wheel in Baltimore**

Net cost to The Waterfront Partnership over 10 years was $2,250,202 (Table 4). This was based on the direct cost of implementing the trash wheel minus costs recovered through financial support from the city, sale of trash wheel memorabilia, and tours of the trash wheel. This estimate did not include most recovered costs, monetary benefits, or nonmonetary benefits that would decrease net cost.

The cost to Baltimore was $619,900 and included the direct costs for operation and maintenance and the dumpster disposal fee. This did not include monetary and nonmonetary benefits that would decrease net costs. The primary monetary benefit to the city was reduced cleanup costs and the main nonmonetary benefits were positive perceptions and aesthetic values.

The cost to the marina was $21,600. This was the indirect cost of providing a slip for the vessel at half price. This estimate did not include the benefits gained by the marina. Finally, an estimate was not available for the cost to the public, but they accrued costs and benefits as well. The monetary benefits to the public were reduced healthcare costs. The nonmonetary costs were the environmental costs of waste collection and the nonmonetary benefits were the improvements to human welfare and environmental health. Overall, every stakeholder group felt they benefitted from implementation of the intervention.

**Comparative case studies**

The net cost of coastal cleanups in developed cities was larger when evaluated on a longer time scale (Han et al., 2010; Mouat et al., 2010; Stickel et al., 2012) (Table 5). Average annual direct costs were higher in the 10-year time scale because of anticipated increases in hourly wages and increases in plastic production and pollution that demand more hours of cleanup to achieve the same outcomes (Mouat et al., 2010; Stickel et al., 2012). Disposal costs also increased over time (Mouat et al., 2010). Generally, as landfill space decreased, disposal fees increased, and alternative disposal methods (e.g., controlled incineration) often had higher fees (Crawford, 2008). Mone-

Tary benefits decreased over the 10-year period because tourist expectations for cleanliness increase over time, which reduces the benefits of cleanups if effectiveness is held constant (Leggett et al., 2014; Mouat et al., 2010).

For WTE plants, net costs decreased as operational time increased (Crawford, 2008; Jamasb & Nepal, 2010). This was because of high direct costs. The most significant costs for WTE were capital assets, which are cheaper per annum the longer a plant operates (Lombardi et al., 2015). Some direct costs increased over time, such as operation, maintenance, and labor costs—due to increases in salaries (Crawford, 2008; Jamasb & Nepal, 2010), but capital assets dominated these other direct costs for WTE. The indirect costs of WTE also decreased with time. As technology and emission standards improved, the amount of air pollution released decreased, reducing human health costs. Decreased pollution reduced nonmonetary costs of WTE as well (Jamasb & Nepal, 2010). Energy capture also improved with advances in technology and quality of feedstock, which increased recovered costs through energy sales and increased nonmonetary benefits associated with reducing net greenhouse gas emissions (Crawford, 2008; Jamasb & Nepal, 2010).

Net costs of coastal cleanups were higher per unit cleaned when cleanups were implemented at the national level than at the municipal level (Han et al., 2010; Mouat et al., 2010; Stickel et al., 2012). Coastal cleanups implemented at the local level were most often carried out in popular tourist sites with sandy beaches (true for more than 90% of municipalities in the United Kingdom [Mouat et al., 2010]). Cleanups on these beaches had lower direct costs, including labor, transportation, and possible healthcare costs, because sandy beaches have lower plastic retention rates, are easier and safer to access, and are faster to traverse than rocky shores (Mouat et al., 2010). These beaches also provided higher monetary benefits because they received more recreational use (Han et al., 2010; Leggett et al., 2014). National-level cleanups would include a higher proportion of isolated coastlines and other shore types, such as rocky and muddy shores. Higher direct costs, including higher transport and labor costs for these regions, would raise the average cost per kilometer of coastline, whereas the monetary benefits to tourism and human health per kilometer cleaned would decrease.
### TABLE 4  Summary of case study of Baltimore, Maryland’s, trash wheel

**Intervention:** Establish a trash wheel at the mouth of the Jones Falls River

**Objective:** Clean up Baltimore harbor

**Scale:** City of Baltimore, Maryland, USA; 10 years

| Stakeholder | Action and direct cost | Indirect cost and nonmonetary cost | Recovered cost, monetary benefit, and nonmonetary benefits |
|-------------|------------------------|-----------------------------------|----------------------------------------------------------|
| Waterfront Partnership | Overhead $54,000 | | Recovered costs: |
| | Total capital assets $704,000 | | Funds from Baltimore $50,000 |
| | Floating platform ($113,400) | | Sale of memorabilia |
| | Waterwheel ($19,400) | | Trash wheel tourism |
| | Power transmission ($22,700) | | |
| | Solar panels ($58,300) | Monetary benefits: |
| | Covering structure ($147,900) | Increased tourism |
| | Controls/sensor ($13,000) | Higher property values |
| | Pump system ($20,500) | Less plastic interaction |
| | Dumpster float/dumpster ($52,900) | Nonmonetary benefits: |
| | Debris rake system ($13,000) | Positive perceptions<sup>c</sup> |
| | Log lift system ($9,700) | |
| | Miscellaneous expenses ($7,600) | |
| | Installation ($77,700) | |
| | Service vessel modification ($19,400) | |
| | Facilities, equipment ($79,900) | |
| | Total labor $1,217,100/10yrs | |
| | Insurance ($43,700/yr) | |
| | Monitoring ($19,400/yr) | |
| | Maintenance ($10,400/yr) | |
| | Dumpster transport ($37,400/yr) | |
| | Communications ($10,800/yr) | |
| | Total consumables $325,102/10yrs | |
| | Vessel operations (65,702/10yrs) | |
| | Fuel ($3,200/yr) | |
| | Registration ($162+54/yr) | |
| | Maintenance ($1,100/yr) | |
| | Slip fee ($2,200/yr) | |
| | Equipment expenses ($65,400/10yrs) | |
| | Fuel ($540/yr) | |
| | Maintenance ($1,100/yr) | |
| | Parts and materials ($4,900/yr) | |
| | Dumpster disposal ($194,000/10yrs) | |
| **Public** | Nonmonetary costs: | Monetary benefits: |
| | Environmental<sup>c</sup> | Healthcare costs<sup>c</sup> |
| | | Nonmonetary benefits: |
| | | Human welfare<sup>c</sup> |
| | | Ecosystem function<sup>c</sup> |
| **Municipality** | Operations & Maintenance $500,000/10yrs | Monetary benefits: |
| | Funds to support WFP ($50,000/yr) | Clean-up costs |
| | Disposal $119,900/10yrs | Nonmonetary benefits: |
| | Disposal fees ($11,100/yr) | Positive perceptions<sup>c</sup> |
| **Marina** | Indirect costs: | Monetary benefits: |
| | Slip donation $21,600/10yrs | Clean-up costs<sup>c</sup> |
| | | Increased recreation<sup>c</sup> |

Net costs: Waterfront partnership: 2,250,202. Missing costs include recovered costs (decrease cost), monetary benefits (decrease) and nonmonetary benefits (decrease). Public: Cost not available. Missing costs include monetary benefits (decrease), nonmonetary costs (decrease) and nonmonetary benefits (increase). Municipality: $619,900. Missing costs include monetary benefits (decrease), nonmonetary costs (decrease) and nonmonetary benefits (increase). Marina: $21,600. Missing costs include monetary benefits (decrease).

Equity: Positive for all stakeholders

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<sup>a</sup> Includes the city, the public, schools, barangays, and industry (recycling and marine sectors).

<sup>b</sup> All costs are in 2019 U.S. dollars. Costs included without an estimate were mentioned in the report but not considered as costs. Costs in parentheses represent a subcost of the cost listed.

<sup>c</sup> Costs identified by the authors but excluded from the stakeholder’s reports.
The net cost of implementing a WTE plant was higher in municipalities in developing countries than in developed countries (Lombardi et al., 2015; Yang et al., 2012). Although labor costs were lower in developing countries (Kaza et al., 2018), infrastructure costs were higher for developing countries as a function of gross domestic production, making capital costs more prohibitive (Fobil et al., 2005). Additionally, WTE plants in developing countries typically used older technology and had waste with a higher moisture content, which affected several costs and benefits. This increased maintenance costs because waste with high moisture content generates more corrosive by-products that damage boiler tubes (Zhang et al., 2015). Indirect and nonmonetary costs were also higher because both older technology and high-moisture-content waste produced more air pollution and greenhouse gasses (Lombardi et al., 2015; Yang et al., 2012). Increased rates of groundwater contamination further elevated these costs because toxic ash must be put in a landfill (Kaza et al., 2018) and landfill leakage rates were generally higher in developing countries (Zhang et al., 2015). Finally, plants in developing countries produced less energy, which decreased recovered costs (Lombardi et al., 2015).

**DISCUSSION**

Many decision makers try to maximize efficiency through wise investment when they are implementing conservation interventions (Murdoch et al., 2007). However, most assessments fail to capture the full suite of costs and benefits associated with a given intervention. As a result, investments in conservation often fail to achieve their stated objectives. Our framework provides an approach for evaluating the net cost of alternative interventions for mitigating marine plastic pollution and supports a more standardized and equitable assessment of costs and benefits. Employing our approach facilitates deliberation about the possible costs that may influence the efficiency of an intervention, allowing decision makers to compare an intervention to a business-as-usual scenario or other possible interventions before their implementation.
Decision makers can also use this framework to compare costs across locations. When costs are not fully considered or clearly presented in studies, it is difficult for decision makers to interpret these costs and understand how they may differ in their own context. Our costing framework promotes consistency in costing and reporting that will also allow researchers to better study relationships between cost and efficacy and understand how implementation context affects costs.

Use of this framework can also help increase the equity of interventions by ensuring decision makers consider the full distribution of costs to stakeholders across time. Plastic pollution disproportionately affects marginalized and low-income communities (Newman et al., 2015). Unfortunately, many conservation interventions have high social costs as well (Adams et al., 2010). For instance, WTE plants are promoted as a solution to high levels of plastic pollution interaction for marine organisms (McKinsey & Company & Ocean Conservancy, 2015). However, their historic construction in marginalized communities places higher health costs and nonmonetary costs on these individuals (UNEA, 2019). This framework enables decision makers to understand cost distributions across stakeholders, allowing them to choose more equitable interventions or implement secondary policies (e.g., benefit transfers) to reduce an intervention’s burden on vulnerable populations. To ensure this objective is achieved, it is critical that decision makers use a participatory approach, engaging with a diverse group of stakeholders in the process of identifying and analyzing costs.

**Key factors for cost**

We identified three factors decision makers should consider with the implementation of interventions for plastic pollution: temporal scale of analysis, spatial scale (i.e., international, national, municipal) of implementation, and socioeconomic conditions. The net cost of a coastal cleanup per kilometer of beach cleaned at the municipality scale increased with time scale of analysis, whereas the net cost of a WTE plant decreased. This indicates the importance of the temporal scale of cost–benefit analyses when evaluating the feasibility of individual interventions and when comparing interventions. Some interventions, such as coastal cleanups, may be cost-effective when evaluated annually because of tourism benefits (Ballance et al., 2000; Stickel et al., 2012). However, other interventions may achieve the same objective while being more cost-effective when evaluated on a longer time scale (de Araújo & Costa, 2006). Alternatively, WTE may be infeasible if considered on a short time scale, but many cities in developed countries have achieved net negative costs over the course of a few decades (Crawford, 2008). Notably, costs may shift again over time as waste streams change. There are developed countries that must now import feedstock waste to maintain their plants (Olofsson et al., 2005). Therefore, the temporal scale of analysis should be in line with the objective. If the objective is long-term sustainability, then the temporal scale of evaluation should be longer. Ultimately, it may be best for communities to implement multiple interventions that aim to achieve objectives with different time scales.

Spatial scale of implementation may significantly change the cost of an intervention; however, many interventions are advocated for across dramatically different scales of implementation. For example, plastic bag reduction policies are often implemented at the national level, but in the United States, where no federal policy has been implemented, hundreds of states and cities have implemented their own legislation (Giacovelli, 2018). Economies of scale can significantly influence the feasibility of conservation efforts (Armstrong et al., 2011). Before adopting policies that have been implemented at different scales, implementers should evaluate the cost of the intervention at their scale of implementation to ensure cost-effectiveness is not hindered.

Decision makers must also consider socioeconomic conditions when implementing interventions. Following the lead of the developed world, developing nations are investing heavily in WTE plants (UNEA, 2019). However, without external investment, low-quality technology may be implemented, which has detrimental impacts for ecosystem and human well-being (Lombardi et al., 2015; Yang et al., 2012). Additionally, indirect economic costs for local communities may be more severe in developing nations because WTE reduces the availability of high-quality waste for informal waste pickers (Kaza et al., 2018). Without consideration of the socioeconomic context, these interventions, which may be effective in certain countries, may be infeasible or detrimental in other contexts.

**Recommendations for framework use**

This framework should be used by any actor (e.g., municipality) considering the implementation of an intervention for marine plastic pollution. First, they should identify the objective of the intervention and the socioeconomic and environmental context of implementation. This information will help inform which interventions may be most effective, the time frame of consideration, and relevant stakeholders. Next, all key stakeholders must be identified and engaged early. Decision makers may be unaware of potential costs and benefits important to other stakeholders. A participatory approach will help ensure a complete assessment of costs and benefits. Finally, net costs can be quantified for each stakeholder group. Transparency throughout this process can help ensure costs are more equally shared and that social, economic, and environmental objectives will be achieved.

**Hard to quantify costs and benefits**

Many costs and benefits can be difficult to quantify—particularly indirect costs, nonmonetary costs, monetary benefits, and nonmonetary benefits. Decision makers can improve their estimates by applying other methods for quantifying costs and benefits in concert with our framework. For example, cost-effectiveness analyses—first used in public health—can be used (Bojke et al., 2018). Additionally, methods such as ecosystem service valuation can be used to estimate the value of nonmon-
etary costs and benefits of plastic pollution interventions (e.g., Beaumont et al., 2019), but the lack of standardization in these approaches may create challenges for comparing values across studies and contexts (Seppelt et al., 2012).

Addressing data gaps

It will not always be feasible to quantify every cost and benefit for an intervention. In instances where costs and benefits cannot be financially quantified, other metrics can be used (e.g., animal deaths avoided) to inform decision-making. Additionally, decision makers can rarely identify all costs and benefits to each stakeholder group but must make the decisions with the data they have (Iacona et al., 2018). Therefore, systematic identification of costs and benefits to all stakeholders can improve the decision-making process.

Considering long time horizons

Though we noted the importance of evaluating interventions on the appropriate time horizon, applying the framework over long time horizons requires additional consideration. First, quantifying costs is more difficult over long time frames. Therefore, when considering an intervention, decision makers must acknowledge the uncertainty in expected cost estimates and anticipate realized costs may be greater. Additionally, costs and benefits accrue on different time horizons (O’Mahony, 2021). Therefore, when using the framework on a long time horizon it is important to appropriately discount expected costs and benefits that are realized at different points in the future. This will allow the decision maker to make fairer comparisons across interventions in terms of their net present value.

Ultimately, use of our framework can help ensure conservation goals can be met with the limited funds available. As research on the cost of plastic pollution and the efficacy of policy measures improves, it will strengthen the quality of the cost–benefit estimates the framework provides. Future research should seek to engage decision makers in various geopolitical and socioeconomic contexts and at different scales of action to validate the efficacy of this tool and generate cost data that can be compared across contexts.

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ORCID

Erin L. Murphy https://orcid.org/0000-0003-4910-4903

Miranda Bernard https://orcid.org/0000-0002-8637-6265
Gavinllian Iaconez https://orcid.org/0000-0002-7408-3895
Stephanie B. Borrelle https://orcid.org/0000-0002-1802-7354
Megan Barney https://orcid.org/0000-0002-8300-0975
Alexis McGivery https://orcid.org/0000-0003-0806-9654
Jorge Emmanuel https://orcid.org/0000-0001-6628-4913
Leah R. Gerber https://orcid.org/0000-0002-6763-6842

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