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Fishing for Litter: Creating an Economic Market for Marine Plastics in a Sustainable Fisheries Model

Linh Nguyen[1,2] *and Roy Brouwer*[3,1*]

[1] Department of Environmental Economics, Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, Netherlands, [2] Tinbergen Institute, Amsterdam, Netherlands, [3] Department of Economics and the Water Institute, University of Waterloo, Waterloo, ON, Canada

This paper studies an economy specialized in fisheries facing a rising marine litter problem. We present a dynamic optimization model to explain the mechanism through which marine litter causes inefficiencies in the fishery sector. We do so by investigating the properties of the model when the marine litter externality is internalized through the price of fish. We find that if the marine litter externality is neglected, fish harvest increases, and ocean quality deteriorates. We subsequently explore the possibility of introducing an incentive scheme where marine litter can be traded in a hypothetical market. The introduction of a so-called fishing-for-litter market removes the inefficiencies caused by fishermen neglecting marine litter and provides a direct incentive for them to maximize overall welfare through resource recovery, i.e. by converting plastic waste into a new valuable resource.

Keywords: marine litter, fishing for litter, plastics pollution, sustainable fishery, resource recovery

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****Correspondence:***
Roy Brouwer
rbrouwer@uwaterloo.ca

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INTRODUCTION

Oceans are essential to global well-being and economic development (Bennett et al., 2019). They provide the necessary resources for sea fisheries in coastal communities. Especially in areas where other economic opportunities are scarce, sea fisheries provide a vital source of employment and income (Pascoe et al., 2019). However, our oceans are unfortunately heavily overfished and contaminated with marine litter (Campbell et al., 2016; Nash et al., 2017). Marine litter is present in every ocean (Cheshire et al., 2009; Eriksen et al., 2014; Pham et al., 2014) and 61-87% of it is made up of plastics (Barnes et al., 2009; Worm et al., 2017; Barboza et al., 2019). Plastics are extremely resistant to biodegradation and difficult to remove. Over time, large plastic items do not dissolve, but rather break down into tiny particles that can travel vast distances and spread throughout the marine environment (Law, 2017). Lighter pieces float at the sea surface, accumulate in ocean gyres or get washed ashore, while heavier pieces sink to the ocean floor where they gradually decompose (Maes et al., 2018; Kane et al., 2020). Plastics enter the marine food web through ingestion by marine organisms, and there is growing concern also for the potential consequences for human food safety and public health (Vethaak and Leslie, 2016; Leslie and Depledge, 2020). Marine litter originates from numerous economic sectors and activities. Two key contributing sectors are fisheries (e.g., accidental loss or deliberate dumping of buoys, nets, ropes, and other waste from fishing crew) and retail (e.g., plastic bags, bottles, packaging, cosmetics and personal care products) (Watkins et al., 2015; Löhr et al., 2017). Although marine litter has attracted increasing attention in recent years, relatively few studies have investigated their social costs (Brouwer et al., 2017).

The objective of this study is to examine how marine litter affects the fishing industry, one of the key industries that rely on the marine environment. Marine litter causes negative impacts on the fishery sector in a variety of ways, all of which result in either reduced revenues or increased costs (European Parliament, 2019). In order to mitigate the impacts of marine litter on the fishery sector, the environmental organization KIMO initiated the "Fishing for Litter" program in 2000 in co-operation with the Dutch Fisheries Association with the aim to clear the North Sea of litter. The program has since its initiation also been implemented in Belgium, Germany, the U.K., Ireland, Sweden, Norway, Denmark, Italy, Croatia and Spain. During their fishing activities, fishermen usually catch litter as a by-product in their nets. By providing them with hardwearing bags, the initiative encourages fishermen to collect and deposit litter onshore at designated waste disposal sites. The program has been shown to reduce the volume of litter accumulating in the oceans (OSPAR, 2007), thereby allowing fishermen to spend more time on their regular fish catching activities by reducing the amount of time they have to spend untangling litter from nets. The fishery sector is believed to be able to play a significant role in removing marine litter from oceans and seas (Ronchi et al., 2019).

This paper aims to incorporate the impacts of marine litter on marine fisheries in a dynamic economic optimization model to explain how marine litter leads to inefficiencies, and how these inefficiencies can be alleviated through the introduction of different incentive schemes. The main research question is twofold: what challenges does the fishery sector face when the externalities of marine litter are not accounted for, and how can these negative externalities be mitigated to benefit the fishery sector? To this end, we first compare the fishermen's utility when marine litter externalities are internalized through the price of fish to a situation where the externalities are not accounted for in the fishermen's decision-making. Here, we assume that increasing societal demand for cleaner oceans is reflected in the price for fish and we use a utility instead of a profit function to account for the fishery sector's sense of stewardship for marine resources, which is typically omitted from conventional profit functions. Secondly, we explore the implications of creating a new economic market based on the existing "Fishing for Litter" scheme, where we add a novel element, namely that the litter caught by participating fishermen can be sold as part of national and international resource recovery programs.

The paper is organized as follows. The next section reviews the literature on the economic costs of marine litter. The third section summarizes the fishery economics literature and is followed in the fourth and fifth sections by a description of an optimal control model related to the economics of fishery with and without the litter externality. This model is extended in the one but last section, focusing on the creation of an economic market for fishing for litter. Finally, the last section concludes.

THE ECONOMIC COST OF MARINE LITTER

The fishery sector faces various direct and indirect economic costs from marine litter. The direct costs typically consist of the labor and material costs spent on repairing and replacing damaged or lost gear including entangled propellers, fouled anchors and rudders, or blocked intake pipes and valves (European Parliament, 2019). Wallace (1990) reports that in the Eastern US, over 45% of the fishing vessels had their propellers disabled, over 30% had their gear fouled, and almost 40% had their engine cooling system clogged by plastic debris at some point during the time they are out to catch fish. In Irian Jaya, Indonesia, Nash (1992) finds that more than half of the gill net fish expeditions of a small fishery community had debris fouling their nets and as a result the community changed its fishing activities. Mcllgorm et al. (2011) report that floating debris becomes entangled in the propellers and affects the engine cooling system which may pose navigational hazards or immobility of vessels. In a survey among Scottish fishermen carried out by Mouat et al. (2010), 95% of the vessels reported to damage their nets on debris on the ocean floor, among others due to old wires on the seabed. On average, marine litter costs the Scottish fishing industry an estimated 12 to 13 million euros per year. This is equivalent to approximately 5% of the total annual revenues from fisheries (Mouat et al., 2010).

In addition, the sector also experiences indirect losses of earnings, for example due to reductions in the quality of fish. Micro-plastics can be taken up by small organisms such as zooplankton and shellfish at the bottom of the trophic chain from where they can move to the next level in the food web (Wright et al., 2013). Ingestion may block the digestive tract, alter the metabolism system and fat storage, which in turn can cause reduced feeding capacity and malnutrition. A stomach filled with plastic can create a false sense of satiation and ultimately lead to starvation. Toxic chemicals absorbed from plastics can furthermore lead to hormone disorders and reduce a fish's reproductive capacity (Gregory, 2009; Lozano and Mouat, 2009). There is a growing body of evidence that shows that marine plastics pose human health risks through the food chain (Galloway, 2015; Lusher, 2015; Rochman, 2015; Barboza et al., 2019). Although it is difficult to establish and quantify the full extent of potential human health problems, plastics can carry toxic compounds which include persistent organic pollutants such as PCBs, DDT and bisphenol-A. These chemicals may disrupt the human endocrine system and give rise to various diseases if ingested in significant amounts (Thompson et al., 2009; Gallo et al., 2018). Once consumers become aware of these health impacts, the fishery sector may suffer significant losses if this leads to a drastic fall in demand for fish (Brouwer et al., 2015). For example, Van der Meulen et al. (2014) show that the release of information that mussels and oysters become smaller in size and absorb poisonous chemical substances in micro-plastics caused a loss of up to 0.7% of annual income in the UK aquaculture sector.

Another factor contributing to the indirect costs for fisheries is a phenomenon called "ghost fishing". According to the United States' National Oceanic and Atmospheric Administration (NOAA), ghost fishing occurs when derelict fishing gear, i.e. any fishing gear such as trawl nets, gill nets, traps, cages and pots discarded, lost or abandoned in the marine environment, continues to fish. The durable nature of materials used in fishing equipment means that they can continue to indeterminately trap and kill marine wildlife for decades. Ghost fishing has been identified as a key damage factor in commercial fisheries (Macfadyen et al., 2009), undermining the conservation efforts of vulnerable fish stocks (Sheavly and Register, 2007).

Finally, fisheries incur losses in revenue due to a reduction in their potential harvestable catch and the sustainability of their catch in general (Butler et al., 2013; Arthur et al., 2014; Bilkovic et al., 2014).

METHODOLOGICAL APPROACH AND NOVELTY

Traditional economic fishery models, often called bio-economic models, can be used to study the effects of modifications in environmental quality on the commercial harvesting of fish stocks (Seijo et al., 1998; Prellezo et al., 2012). In this section, we specify how our model resembles and where it deviates from the standard bio-economic fishery model. Bio-economic models usually rely on some key assumptions, which we also utilize in our modelling framework here. We base our model on the common assumption that fishermen have the maximization of the discounted net present value of resource rents as their main objective (Arnason, 2009). They seek a long-term sustainable fish stock when deciding on their catch level (Clark et al., 2005).

Our theoretical framework is an extension of the Schaefer-Gordon model (Gordon, 1954; Schaefer, 1991) by using a dynamic specification. The dynamic approach allows us to analyze the adjustment process in which an optimal harvest level is attained, taking account of a discount rate. Compared to other dynamic modelling studies, we include the environmental quality component as an argument in the utility function rather than as an exogenous factor. This is in line with Freeman (1993), who extends the basic dynamic bio-economic model by including an additional explanatory variable to represent an environmental influence.

Contrary to previous modelling frameworks where environmental quality is not included as a control variable, changes in environmental quality occur endogenously in the model presented in this study, affecting both the objective function and the imposed constraint. Another important deviation from the standard fishery model is that the Schaefer-Gordon model specifies a profit function, while we express the optimization problem using a utility function. In this way, we are able to account for the fishery sector's strong sense of stewardship for marine resources, as for example expressed by fishermen's participation in voluntary initiatives such as Fishing for Litter, which is typically omitted from a conventional profit function.

The mathematical structure of our model is an application of optimal control theory to the management of fisheries. We adapt the standard optimal control model to analyze in a stylized fashion the externalities associated with marine litter and add in a "Fishing for Litter" market as an innovative solution. In the model extension, the paper is heading towards a solution for an environmentally sustainable fishery sector, which we define as the sustainable harvest of fish that can be realized based on fishermen's efforts of litter recovery. Hence, an environmentally sustainable optimum is the maximum fish harvest, which maximizes utility of fishermen that can be sustained in the steady state subject to a constraint on ocean quality with litter catch effort. Given the objective of our study, we put special emphasis on sustaining a certain level of ocean quality while studying the economics of the fishery sector. To this end, we specify a logistic litter growth function instead of a logistic fish stock growth function usually described in the standard Schaefer-Gordon model. This constraint describes how (fast) litter in the ocean reaches its maximum capacity.

MODEL BUILDING BLOCKS

Public Preferences for Ocean Quality

We consider an economy that supplies fish to the market which presumably has full information and no transaction costs. Market clearing conditions dictate that the equilibrium price reflects the marginal cost and utility attached to the last unit of fish traded on the market. We denote O_t as a general index for the current stock of ocean quality, which includes a wide range of factors including the quality of water and marine habitats, fish stocks, and the sustainability of ocean health; and H_t as the aggregate harvest of marine resources (fish). We assume that at any time t, the preferences of fish consumers are positively influenced by O_t. Public preferences are presented by their willingness to pay (WTP) for fish as:

$$p_H = p(O_t) = O_t^{\phi} \tag{1}$$

where $\phi \in [0,1)$ is a measure of public preferences for ocean clean-up, and $\frac{\partial p_H}{\partial O} > 0, \frac{\partial^2 p_H}{\partial O^2} < 0$.

Equation (1) can be interpreted as the inverse demand function for fish. Let us suppose for a moment that we have a price for ocean quality p_o. Then, at the optimal level of demand for fish we have:

$$p_H = p_O|MRS| \tag{2}$$

where MRS is the marginal rate of substitution between ocean quality and fish harvest. If we assume that the price of ocean quality is 1 then equation (2) tells us that at the optimal level of demand for fish harvest, the price of fish equals marginal WTP, which measures how much a consumer is willing to sacrifice of ocean quality for a marginal amount of extra fish harvest. The trade-off between fish harvest and ocean quality plays out in our model as follows: when the level of fish harvest is small (and ocean quality is high), a consumer is willing to give up more of ocean quality to gain a little bit more of fish ($\frac{\partial p_H}{\partial O} > 0$). Conversely, when the level of fish harvest is large (and ocean quality is low), a consumer is willing to give up less of ocean quality for a marginal gain in fish. In short, marginal WTP reflects the general public's diminishing marginal utility ($\frac{\partial^2 p_H}{\partial O^2} < 0$).

Fisherman's Utility

For simplicity, we assume that the revenues of a representative fisherman are a function of fish harvest and the price of fish, without any significant capital or labor costs. As a result, the total revenue is equal to the profit that the fishery owner obtains:

$$TR = H_t p(O_t) \tag{3}$$

Equation (3) represents a production function of the fishery sector where H_t and O_t enter as input factors.

At the same time, the fisherman's utility at time t is determined by his consumption level C_t and ocean quality O_t. The lifetime utility of the representative fisherman is given by an infinitely discounted sum of (logarithmic) instantaneous utility:

$$U_t = \int_t^\infty u(C_t, O_t)e^{-\rho t}dt = \int_t^\infty (ln\, C_t + \beta\, ln\, O_t)e^{-\rho t}dt \tag{4}$$

where $\rho \in (0,1)$ is the discount rate. The concavity of the logarithmic utility function indicates diminishing marginal utility as a result of an increase in consumption level aggregated across all fishermen. The explicit functional form of the utility function is needed to obtain a close-formed solution.

The Evolution of Ocean Quality

We follow the common approach in the economic growth and environment literature, which describes environmental quality as an accumulated stock of renewable resources (Bovenberg and Smulders, 1995; Smulders and Gradus, 1996). In our case, the ocean quality is a stock variable of renewable marine resources. We adhere to another convention in the literature (Becker, 1982; Cerina, 2007), that is, we define the stock of ocean quality as the difference between the maximum tolerable level of litter $\bar{P}$ and the current litter amount P_t where $0 < P_t < \bar{P}$:

$$O_t = \bar{P} - P_t \tag{5}$$

Differentiating both sides with respect to time we obtain the law of evolution of ocean quality:

$$\dot{O}_t = -\dot{P}_t \tag{6}$$

The fishery sector accumulates litter *via* the accidental or deliberate act of dumping fishing gear into the seas. Hence the more fishing activities take place, the more litter there is. We assume that litter increases proportionally with harvest level at a rate α. Several studies in the environmental-economics growth modelling literature adopt the assumption that the stock of pollution is absorbed and processed at a natural rate because nature has a regenerative capacity to compensate for the adverse pollution effects. We slightly deviate from this notion in our study and assume that litter is removed by existing man-made efforts at an exogenous rate $0 < m_0 < 1$ due to the non-decomposable nature of most marine litter (Kershaw, 2015). Combining the two assumptions, we arrive at the change in litter in time:

$$\dot{P}_t = \alpha H_t - m_0(\bar{P} - O_t) \qquad \alpha > 0 \tag{7}$$

Combining (6) and (7) we obtain the motion equation of ocean quality:

$$\dot{O}_t = m_0(\bar{P} - O_t) - \alpha H_t \tag{8}$$

OPTIMAL SOLUTION WHEN INTERNALIZING MARINE LITTER IMPACTS

In this section, the fishery owner is informed about public preferences for ocean quality when solving his utility maximization problem. In this case, we assume that the fisherman is aware that the unit price of fish p_H is influenced by ocean quality O_t, as described in equation (1). Consumers' WTP for fish will fall if they become, for example, concerned about the health consequences of having micro-plastics in the food chain, including fish products. Conversely, consumers' WTP for fish will rise if they are assured about the clean ocean environment. The fisherman solves in this case the following optimization problem:

$$\max_{\{H_t\}} \int_0^\infty \left\{ (H_t O_t^\phi) + \beta\, ln\,(O_t) \right\} e^{-\rho t}dt \tag{9}$$

$$\text{s.t. } \dot{O}_t = m_0(\bar{P} - O_t) - \alpha H_t \tag{10}$$

The externality of marine litter is internalized by substituting the explicit form of the fish price in equation (1). This is an optimal control problem with one state variable O_t and one control variable H_t. The first order condition and Euler equation are:

$$\mu_t = \frac{1}{\alpha H_t} \tag{11}$$

$$\frac{\dot{\mu}_t}{\mu_t} = \rho + m_0 - \frac{\phi + \beta}{O_t \mu_t} \tag{12}$$

where μ_t is a period-t utility value of having one more unit of ocean quality in period t.

The resulting optimal dynamic system is described as:

$$\frac{\dot{H}_t}{H_t} = \frac{(\phi + \beta)\alpha H_t}{O_t} - (m_0 + \rho) \tag{13}$$

$$\dot{O}_t = m_0(\bar{P} - O_t) - \alpha H_t \tag{14}$$

The complete mathematical characterization of the system can be found in the **Appendix** to this paper.

Steady State

In equilibrium, there is no change in ocean quality, i.e., $\dot{O} = 0$. From (13) and (14), we can see that $\dot{O} = 0$ implies $\dot{H} = 0$.

$$\dot{H} = 0 \Rightarrow H_1^{so}(O) = \frac{(m_0 + \rho)}{(\phi + \beta)\alpha} O_t \tag{15}$$

$$\dot{O} = 0 \Rightarrow H_2^{so}(O) = \frac{m_0}{\alpha}(\bar{P} - O_t) \tag{16}$$

The existence of a unique steady state can be proven geometrically. The two loci are two straight lines with $H_1(O)$ having a positive slope and $H_2(O)$ having a negative slope and a positive vertical intercept. Therefore, the two loci intersect in the positive orthant (O,H) plane. The unique steady state is given by:

$$O_{so} = \frac{\phi + \beta}{m_0 + \rho + m_0(\phi + \beta)} m_0 \bar{P} \tag{17}$$

$$H_{so} = \frac{m_o + \rho}{m_0 + \rho + m_0(\phi + \beta)} \frac{m_0 \bar{P}}{\alpha} \tag{18}$$

The system exhibits instability. The equilibrium (O_{so},H_{so}) is a local saddle point for the system (13) and (14) (**s**ee the **Appendix** for the complete proof). All the steady state values of the relevant variables (the control variable H and the state variable O) are now expressed as functions of the parameters of the model.

Comparative Analysis

The steady state level of ocean quality increases with the general public's care for ocean quality ($\frac{\partial O_{so}}{\partial \phi} > 0$), with the fishermen's care for ocean quality ($\frac{\partial O_{so}}{\partial \beta} > 0$), when litter is removed at a faster pace ($\frac{\partial O_{so}}{\partial m_0} > 0$), and with the maximum level of litter in the oceans ($\frac{\partial O_{SO}}{\partial \bar{P}} > 0$). However, it decreases when fishermen care less about future utility ($\frac{\partial O_{so}}{\partial \rho} > 0$).

Similarly, the steady state level of fish harvest decreases with the general public's care for ocean quality ($\frac{\partial H_{so}}{\partial \phi} < 0$) and fishermen's care for ocean quality ($\frac{\partial H_{so}}{\partial \beta} < 0$). It increases when litter is removed at a faster pace ($\frac{\partial H_{so}}{\partial m_o} > 0$), ocean quality is more capable to carry a higher maximum level of litter ($\frac{\partial H_{so}}{\partial p} > 0$) and when fishermen care less about future utility ($\frac{\partial H_{so}}{\partial \bar{P}} > 0$).

It is interesting to analyze how the fisherman's revenues react with regards to his preference for ocean quality β. As β grows, its total effect on revenue is ambiguous: an increasing β leads to a higher steady-state value of ocean quality O, which increases the WTP and hence the revenue. Yet an increasing β causes a lower steady-state value of fish harvest H which reduces revenue. At a low β, an increase in the fisherman's care for ocean quality eventually leads to an increase in his revenue. This is because a low level of β means a low level of O. When O is low, the general public attaches a high marginal value to even a slight improvement in ocean quality. Therefore, their WTP grows significantly when O increases, enough to override the lower fish harvest and result in a higher revenue. By the same token, at a high enough β, the marginal value and WTP that the general public attaches to an improvement in ocean quality is no longer high enough to compensate for the reduction in fish harvest due to too much care for ocean quality from fishermen, so that the revenue inevitably decreases in this case. These findings might be particularly interesting for policymakers. When fishermen become aware of the general public's concerns for marine litter, policies that raise fishermen's awareness and stimulate them to participate in litter recovery initiatives might help to mitigate the issue and enhance the fishery sector's economic development.

SOLUTION WITHOUT LITTER EXTERNALITY

Unlike in the optimal case, often fishermen are not fully informed about public preferences for ocean quality. They may not realize that the marine litter externality can affect their revenues through consumers' WTP. Hence, it is appropriate here to assume that the fisherman takes the price of fish as given. He solves the following optimal control problem with one state variable O_t and one control variable H_t:

$$\max_{\{H_t\}} \int_0^{\infty} \{ln\,(H_t p_H) + \beta\, ln\,(O_t)\} e^{-\rho t} dt \tag{19}$$

$$\text{s . t. } \dot{O}_t = m_0(\bar{P} - O_t) - \alpha H_t \tag{20}$$

The externality of marine litter is neglected in the fisherman's revenue function by keeping the price of fish constant, rather than substituting its explicit form as in equation (1). The first order condition and Euler equation are:

$$\mu_t = \frac{1}{\alpha H_t} \tag{21}$$

$$\frac{\dot{\mu}_t}{\mu_t} = \rho + m_0 - \frac{\beta}{O_t \mu_t} \tag{22}$$

where μ_t is a period-t utility value of having one more unit of ocean quality in period t. The resulting optimal dynamic system is characterized as follows:

$$\frac{\dot{H}_t}{H_t} = \frac{\beta \alpha H_t}{O_t} - (m_0 + \rho) \tag{23}$$

$$\dot{O}_t = m_0(\bar{P} - O_t) - \alpha H_t \tag{24}$$

The mathematical characterization of the system can be found in the **Appendix** to this paper.

Steady State

We are interested in a sustainable equilibrium in which there is no change in ocean quality ($\dot{O} = 0$). From (23) and (24), we can see that $\dot{O} = 0$ implies $\dot{H} = 0$.

$$\dot{H} = 0 \Rightarrow H_1^e(O) = \frac{m_0 + \rho}{\beta \alpha} O_t \tag{25}$$

$$\dot{O} = 0 \Rightarrow H_2^e(O) = \frac{m_0}{\alpha}(\bar{P} - O_t) \tag{26}$$

The existence of a unique steady state can be proven geometrically as before. The unique steady state is given by:

$$O_e = \frac{\beta}{m_0 + \rho + m_0\beta} m_0 \bar{P} \tag{27}$$

$$H_e = \frac{m_0 + \rho}{m_0 + \rho + m_0\beta} \frac{m_0 \bar{P}}{\alpha} \tag{28}$$

This system exhibits instability. The equilibrium (O_e,H_e) is a local saddle point for the system (23) and (24) (**s**ee the **Appendix** for the complete proof). The steady state values differ from (O_{so},H_{so}) in that the term ϕ is no longer present because the fisherman takes public preferences as given.

Compared with the optimal case in the previous section, we will always have $H_{so} > H_e$ and $O_{so} > O_e$. When the litter externality is not accounted for in the price of fish, fishermen focus only on harvesting more fish and do not care for ocean quality. The reason lies in the absence of the elasticity of public WTP with respect to ocean quality ϕ. Without understanding the public's care and concerns for marine litter, fishermen are not incentivized to care either.

In this case, the steady state value for O is not a function of public preferences for ocean quality (ϕ). Consequently, when β = 0 (fishermen do not care for ocean quality), ocean quality drops to 0. This is of course at the extreme, but it still shows how imperative it can be for fishermen to know that marine litter concerns can affect consumers' WTP and in turn affect their revenues.

CREATING A MARKET FOR MARINE PLASTICS RECOVERY

Public Preferences for Marine Plastics Recovery

The initiative "Fishing for Litter" aims to mitigate the impacts of plastics pollution in oceans and seas by giving fishermen bags to separate litter from their fish catch. We go one step further by imagining there is societal demand and hence a WTP for this litter (e.g. for resource recovery purposes), such that the litter caught and brought ashore can be traded on a hypothetical market. In this way, fishermen are provided a direct financial incentive to start fishing for litter besides, or instead of, fishing for fish. This could be made possible through introducing a new resource recovery sector that demands the litter caught from the fishery sector (Dijkstra et al., 2021).

Fisherman's Utility

A fisherman dedicates part of his time to catching litter which he could have spent on catching fish. This implies that the current revenue is reduced to:

$$TR = H_t p_H - l H_t p_H \tag{29}$$

where l represents the fraction of a fisherman's revenue devoted to catch litter or the fisherman's effort in catching litter. However, since the fisherman can trade the litter recovered in the market at a price, he can gain back some, all, or more than what he has invested (γ). The total revenue that the fisherman obtains is therefore:

$$TR = H_t p_H - l H_t p_H + \gamma l H_t p_H \tag{30}$$

The lifetime utility of a representative fisherman is given by the infinitely discounted sum of instantaneous utilities as specified in the equation below:

$$U_t = \int_t^\infty (H_t p_H - l H_t p_H + \gamma l H_t p_H) + \beta \ln\ (O_t)] e^{-\rho t} dt \tag{31}$$

where ρ ∈ (0,1) is the discount rate.

The Effect of Fishing for Litter

The effort that fishermen put into catching litter is introduced such that the rate of litter removal is increased as the amount of effort in catching litter increases. Let $m(m_0,l)$ be the function of litter recovery where m_0 is the exogenous removal rate (due to external factors) and l is the fishing-for-litter effort. We further assume that $m(m_0,l)$ has the following characteristics:

$$m(m_0, l)|_{l=0} = m_0 \tag{32}$$

$$m(m_0, l)|_{l=1} = 1 \tag{33}$$

$$\frac{\partial\, m(m_0, l)}{\partial\, l} > 0 \quad \forall \cdot l > 0 \tag{34}$$

The first assumption (eq. 32) means that when fishermen exert no effort to catch litter, litter is removed at exogenous rate m_0. The second assumption (eq. 33) tells us that if fishermen exert all effort into catching litter, the whole stock of current litter is removed. The third assumption (eq. 34) tells us that the recovery function is increasing in effort l.

We assign the following explicit form to $m(m_0,l)$ that satisfies these three assumptions:

$$m(m_0, l) = m_0 + (1 - m_0) l \tag{35}$$

The motion equation of ocean quality now becomes:

$$\dot{O}_t = (m_0 + (1 - m_0) l)(\bar{P} - O_t) - \alpha H_t \tag{36}$$

FISHING FOR LITTER

We showed in the previous section that a deviation from the optimal solution occurs when the externality of marine litter is not captured in the production function. What we will see in this section is that an appropriate policy design such as a market for trading marine litter creates incentives which induce fishermen to replicate the optimal solution. The fisherman's optimization problem now becomes:

$$\max_{\{H_t\}} \int_0^\infty \{\ln\ (1 - l + \gamma l) H_t p_H + \beta\ \ln\ (O_t)\} e^{-\rho t} dt \tag{37}$$

$$\text{s.t.}\ \dot{O}_t = [m_0 + (1 - m_0) l](\bar{P} - O_t) - \alpha H_t \tag{38}$$

Similar to problem (19), a fisherman maximizes his lifetime utility taking public preferences as given. This is again an optimal control problem with one state variable O_t and one control variable H_t.

The first order condition and Euler equation are:

$$\mu_t = \frac{1}{\alpha H_t} \tag{39}$$

$$\frac{\dot{\mu}_t}{\mu_t} = \rho + m_0 + (1 - m_0)l - \frac{\beta}{O_t \mu_t} \tag{40}$$

The resulting optimal dynamic system is:

$$\frac{\dot{H}_t}{H_t} = \frac{\beta \alpha H_t}{O_t} - [m_0 + (1 - m_0)l + \rho] \tag{41}$$

$$\dot{O}_t = [m_0 + (1 - m_0)l](\bar{P} - O_t) - \alpha H_t \tag{42}$$

Steady State

We are interested in an equilibrium which implies sustainability for ocean quality, i.e. $\dot{O} = 0$. This implies that $\dot{H} = 0$:

$$\dot{H} = 0 \Rightarrow H_1^{fl}(O) = \frac{m_0 + (1 - m_0)l + \rho}{\beta \alpha} O_t \tag{43}$$

$$\dot{O} = 0 \Rightarrow H_2^{fl}(O) = \frac{m_0 + (1 - m_0)l}{\alpha} (\bar{P} - O_t) \tag{44}$$

The existence of a unique steady state can be proven geometrically as before. The steady state is given by:

$$O_{fl} = \frac{\beta[m_0 + (1 - m_0)l]}{\rho + [m_0 + (1 - m_0)l](1 + \beta)} \bar{P} \tag{45}$$

$$H_{fl} = \frac{\rho + m_0 + (1 - m_0)l}{\rho + [m_0 + (1 - m_0)l](1 + \beta)} [m_0 + (1 - m_0)l] \frac{\bar{P}}{\alpha} \tag{46}$$

The equilibrium (O_{fl},H_{fl}) is a local saddle point for the system described in equations (41) and (42) (see the **Appendix** for the proof). Similar to the steady state values in (27) and (28), (O_{fl},H_{fl}) do not contain the term ϕ because the fisherman takes public preferences as given. Nevertheless, (O_{fl},H_{fl}) contains the term l which measures fishermen's efforts for litter recovery. This was not the case in (27) and (28).

Comparative Analysis

Comparing the fish harvest to the second model, we have:

$$H_{fl} = H_e \text{ when } l = 0$$
$$H_{fl} > O_e \quad \forall \ l > 0$$

This shows that an effort in fishing-for-litter by fishermen always increases the fish harvest compared to the case when marine litter is not accounted for. Additionally, the more they invest in fishing for litter, the more fish harvest fishermen have $\frac{\partial H}{\partial l} > 0$.

The same results applied to ocean quality. We have:

$$O_{fl} = O_e \text{ when } l = 0$$
$$O_{fl} > O_e \quad \forall \ l > 0$$

This indicates that as long as fishermen put effort into catching litter, ocean quality will always be better compared to the case where litter is not accounted for. Additionally, the more effort fishermen put into catching litter, the better ocean quality will get ($\frac{\partial O}{\partial l} > 0$). An increase in fishermen's fishing-for-litter efforts gives rise to an increase in fish harvest. Similarly, when O is low, the marginal economic value that fishermen assign to a slightly improved ocean quality is high, so they are expected to invest more effort in catching litter. As a consequence, an increase in ocean quality allows fishermen to catch more fish.

Clearly with a market for plastics recovery, fishermen are better off in terms of both fish harvest and ocean quality compared to a situation where plastic litter is not accounted for. The difference lies in the effort fishermen put into fishing for litter. Although fishermen are not informed about public preferences for ocean quality, the marine litter externality is directly accounted for in fishermen's behavior. In essence, a market for litter recovery has transferred public preferences for less marine litter to fishermen and created an active response action within the sector. More specifically, public WTP for plastic litter recovery provides fishermen with a direct incentive to catch more litter. This policy has proven to tackle plastic litter issues as well as enhance the development of the fishery sector, even if fishermen do not have full information about public preferences.

CONCLUSIONS

At the heart of the global plastics problem is a linear economy. Most of the time, producers provide, and consumers buy single-use items that are disposable or have planned obsolescence. This externality of global consumption patterns has brought about tremendous costs to the oceans and seas from which we derive many benefits. Our results chart a way forwards towards a circular economy in which marine plastics are recovered and repurposed for alternative use or recycled into a new product (Dijkstra et al., 2020). The shift towards a sustainable plastics economy, i.e. an economy with plastics that have a more durable or even sustainable life cycle, can bring about better ocean quality and ultimately more marine resources for the fishery sector.

This paper analyses a solution to the marine plastics problem by presenting a dynamic economic optimization model in which the fishery sector maximizes its life-time utility as a steward of our oceans and seas. We analyze the dynamic properties of the model in two distinct versions. We find that when the plastic litter externality is not internalized through the price of fish, the fish harvest is higher and ocean quality deteriorates compared to a situation where marine litter is internalized through the price of fish. We then analyze a possible solution, namely an incentive scheme based on the existing "Fishing for Litter" initiative, where the public's WTP for plastic litter recovery encourages fishermen to catch and remove the plastics from our oceans and seas. We conclude that a market for marine plastics recovery provides fishermen with a direct incentive to catch litter. As a result, the policy effectively tackles the global marine litter problem and contributes at the same time to the development of a more efficient and sustainable fishery sector.

We acknowledge that a possible limitation of our model is that the results might depend on the specific choice of the functional form of the utility function. This particular representation is chosen because it enables us to develop a tractable model of dynamic optimization that provides insights into the fishing for litter decision-making process over time. A more generic form would not have teased out this distinction. However, a more general constant elasticity of substitution (CES) function might allow for a simpler and perhaps different solution, which is worth exploring in the future. Another extension of the model would be the inclusion of the capital, labor and material costs in the profit function, including the damage costs of marine litter to catch rates.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

LN: conceptualization, methodology, formal analysis, and writing–original draft. RB: conceptualization, methodology, writing–review and editing, and supervision. All authors contributed to the article and approved the submitted version.

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APPENDIX

Mathematical Characterization of the Optimal Solution Model

The Pontryagin maximum principle states that we can solve the optimization problem using a standard Hamiltonian function. We use the Hamiltonian to directly arrive at the time evolution of the system so that we can predict what state the system will evolve into after an infinitesimal interval of time elapses. In the optimal solution model, the fisherman's problem is:

$$\max_{\{H_t\}} \int_0^{\infty} \left\{ (H_t O_t^{\phi}) + \beta \, ln\,(O_t) \right\} e^{-\rho t} dt$$

$$\text{s.t. } \dot{O}_t = m_0(\bar{P} - O_t) - \alpha H_t$$

Using the present-value multiplier λ_t, we define the present-value Hamiltonian:

$$H(\lambda_t, O_t, H_t, t) = [\ln H_t + \phi \ln O_t + \beta \ln O_t] e^{-\rho t} + \lambda_t [m_0(\bar{P} - O_t) - \alpha H_t]$$

First order conditions:

$$\frac{\partial L}{\partial H_t} = 0 \Rightarrow \frac{\partial H}{\partial H_t} = 0$$

$$\frac{\partial L}{\partial O_t} = 0 \Rightarrow \frac{\partial H}{\partial O_t} = -\dot{\lambda}_t$$

Note that H explicitly depends on time. Using the current-value multiplier μ_t, we define the current-value Hamiltonian, which does not explicitly depend on time as follows:

$$H^A = He^{-\rho t} = \ln H_t + \phi \ln O_t + \beta \ln O_t + \mu_t [m_0(\bar{P} - O_t) - \alpha H_t]$$

where $\mu_t = e^{\rho t} \gamma_t$ which implies that $\dot{\mu}_t = \rho \mu_t + \dot{\lambda}_t e^{\rho t}$.

The new first order conditions become:

$$\frac{\partial H}{\partial H_t} = 0 \quad \Rightarrow \frac{\partial H^A}{\partial H_t} = 0$$

$$\frac{\partial H}{\partial O_t} = -\dot{\lambda}_t \Rightarrow \frac{\partial H^A}{\partial O_t} = -\dot{\mu}_t + \rho \mu_t$$

From the new first order conditions, we obtain the first order condition and Euler equation:

$$\mu_t = \frac{1}{\alpha H_t}$$

$$\frac{\dot{\mu}_t}{\mu_t} = \rho + m_0 - \frac{\beta}{O_t \mu_t}$$

Differentiating the first order conditions and equating it to the Euler equation, we obtain the optimal dynamic system:

$$\frac{\dot{H}_t}{H_t} = \frac{(\phi + \beta)\alpha H_t}{O_t} - (m_0 + \rho)$$

$$\dot{O}_t = m_0(\bar{P} - O_t) - \alpha H_t$$

Proof That the Steady State (O_{so}, H_{so}) Is a Local Saddle Point:

Rewrite system (13) and (14) as:

$$\dot{H}_t = \frac{(\phi + \beta)\alpha H_t^2}{O_t} - (m_0 + \rho)H_t$$

$$\dot{O}_t = m_0(\bar{P} - O_t) - \alpha H_t$$

Linearizing the system around the steady state (O_{so},H_{so}) we have:

$$\begin{bmatrix} \dot{H} \\ \dot{O} \end{bmatrix} = J \begin{bmatrix} H - H_{so} \\ O - O_{so} \end{bmatrix}$$

where

$$J = \begin{bmatrix} \frac{\partial H}{\partial H} | H = H_{so}, O = O_{so} & \frac{\partial H}{\partial O} | H = H_{so}, O = O_{so} \\ \frac{\partial O}{\partial H} | H = H_{so}, O = O_{so} & \frac{\partial O}{\partial O} | H = H_{so}, O = O_{so} \end{bmatrix}$$

$$= \begin{bmatrix} m_0 + \rho & -\frac{(m_0+\rho)^2}{\alpha(\phi+\beta)} \\ -\alpha & -m_0 \end{bmatrix}$$

So that $detJ = -(m_0 + \rho)m_0 - \frac{(m_0+\rho)^2}{\phi+\beta} < 0$

So the unique steady state is a local saddle point. ▪

Proof That the Steady State (O_e, H_e) Is a Local Saddle Point:

Rewrite system (23) and (24) as:

$$\dot{H}_t = \frac{\beta \alpha H_t^2}{O_t} - (m_0 + \rho)H_t$$

$$\dot{O}_t = m_0(\bar{P} - O_t) - \alpha H_t$$

Linearizing the system around the steady state (O_e,H_e) we have:

$$\begin{bmatrix} \dot{H} \\ \dot{O} \end{bmatrix} = J \begin{bmatrix} H - H_e \\ O - O_e \end{bmatrix}$$

where

$$J = \begin{bmatrix} \frac{\partial H}{\partial H} | H = H_e, O = O_e & \frac{\partial H}{\partial O} | H = H_e, O = O_e \\ \frac{\partial O}{\partial H} | H = H_e, O = O_e & \frac{\partial O}{\partial O} | H = H_e, O = O_e \end{bmatrix}$$

$$= \begin{bmatrix} m_0 + \rho & -\frac{(m_0+\rho)^2}{\alpha(\alpha\beta)} \\ -\alpha & -m_0 \end{bmatrix}$$

So that $detJ = -(m_0 + \rho)m_0 - \frac{(m_0+\rho)^2}{\beta} < 0$

So the unique steady state is a local saddle point. ▪

Proof That the Steady State O_{fl}, H_{fl} Is a Local Saddle Point:

Rewrite system (41) and (42) as:

$$\dot{H}_t = \frac{\beta\alpha H_t^2}{O_t} - [m_0 + (1 - m_0)l + \rho]H_t$$

$$\dot{O}_t = [m_0 + (1 - m_0)l](\bar{P} - O_t) - \alpha H_t$$

Linearizing the system (41) and (42) around the steady state (O_{fl},H_{fl}), we have:

$$\begin{bmatrix} \dot{H} \\ \dot{O} \end{bmatrix} = J \begin{bmatrix} H - H_{fl} \\ O - O_{fl} \end{bmatrix}$$

where

$$J = \begin{bmatrix} \rho + m_0 + (1 - m_0)l & -\frac{[\rho+m_0+(1-m_0)l]^2}{\alpha\beta} \\ -\alpha & -m_0 - (1 - m_0)l \end{bmatrix}$$

So that

$$\det J = -[\rho + m_0 + (1 - m_0)l][m_0 + (1 - m_0)l] - \frac{[\rho + m_0 + (1 - m_0)l]^2}{\beta} < 0$$

So the unique steady state is a local saddle point. ■