

Stocks vs. Flows: Second-Best Incentives for Stock-Generated Externalities

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Abstract

Conventional wisdom states that incentives targeting stocks and flows can lead to equivalent externalities correction. However, this may not hold when externalities are directly produced from stocks of capital (“stock-generated externalities”) rather than flows of production. Examples of these stocks include trees with respect to CO₂ absorption, shellfish and water cleaning, and livestock and methane emissions. I present an infinite horizon, continuous time model of incentives aimed at improving environmental quality through targeting stocks versus flows. The setting focuses on an extractive firm which privately owns a renewable stock that jointly produces a private good and social benefits. I compare the performance of stock and flow policies in steady state to the social optimum and a no-policy benchmark. The model is then calibrated to industry and scientific parameters of Eastern oyster (*C. virginica*) production in the Chesapeake Bay, where shellfish cultivation yields water filtration benefits, to explore short run dynamics. Overall, stock-targeted incentives can achieve socially-optimal levels of the resource and environmental quality in steady state. While flow-targeting may yield short run benefits, the allocations are no different than no-policy in the long run. Lack of long run efficacy from flow-targeting is likely driven by revenue constraints that disallow the firm to increase stock abundance across time. This paper presents a theory of incentive design aimed at minimizing environmental damages through management of privately-owned renewable natural resources.

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1 Introduction

Conventional wisdom states that externalities scale with flows of production. Previous models of environmental policy performance have therefore focused on controlling external damages stemming from firm activity (Gordon, 1954; Baumol, 1972; Nordhaus, 1992; Farzin and Tahvonen, 1996; Schmutzler and Goulder, 1997; Golosov et al., 2014; Folini et al., 2024). Damages from atmospheric CO₂ emissions, overfishing, and Superfund sites are classic examples of this type of “flow-generated externality,” and policies targeting both stocks of inputs and flows of output can yield equivalent levels of environmental quality in this setting (Holtermann, 1976). However, more theoretical attention must be paid to a number of atypical externality production functions of major policy importance. One such externality is produced directly from stocks of inputs, which I call “stock-generated externalities.”¹ Firm-level price incentives targeting either stocks or flows may not yield equivalent environmental outcomes along the intensive margin when this type of externality is present. I attempt to highlight the issue of incentive design for stock-generated externalities in this paper.

Stocks of renewable natural resources, also called natural capital, are common sources of stock-generated externalities. Trees, shellfish, and ungulates, among others, can produce external environmental effects such as atmospheric CO₂ absorption, surface water filtration, erosion mitigation, and greenhouse gas emissions in absence of human intervention.² Instrumentalizing living natural resources to combat environmental damages, otherwise known as “nature-based solutions,” has been promoted by researchers (Dasgupta, 2021; Barrett et al., 2022; Zeng and Hausmann, 2022; Taylor et al., 2023), advocates (IUCN, 2026), and the popular press (Depro et al., 2008; DePillis et al., 2024; Hotakainen, 2024). Policies aimed at industries that own these stocks are being pursued by NGOs, firms, and governments at various levels (UN Framework Convention on Climate Change, 2016; U.S. Department of Agriculture, 2021; Sandi, 2025; Sengupta and Fuente, 2024; Aronoff and Rafey, 2025).

¹As a thought exercise, compare atmospheric greenhouse gasses (GHGs) generated from factory production versus cows. While many cows are destined for beef or dairy production, various species of cattle have existed independent of human intervention (Felius et al., 2014). All cattle regardless of ownership and species produce methane (CH₄), a potent GHG, via enteric fermentation (Johnson and Johnson, 1995; Quinton, 2019). Therefore, external damages are “stock-generated,” as they scale directly from the stock of cows and indirectly from firm activity.

By contrast, GHG emissions from factory production would not occur without, well, factories. If factories stopped operating one day but the stock of machinery remained, assuming the machines were not running extraneously, GHG emissions would cease. Therefore, external damages are “flow-generated,” as they are directly derived from the flow of production and indirectly from the stock of machinery.

Note that the model presented in this paper abstracts away from active “investments” in the stock through e.g. plantings, as in Chichilnisky et al. (1995). Investments in the natural resource stock may affect second-best policy performance and is the subject of future work.

²These types of externalities are often called “ecosystem services” when the effects are positive.

While an optimal policy would target a direct measure of the benefits or damages produced by the resource stock, policies are necessarily second-best in reality (Lipsey and Lancaster, 1956). The first-best requires a level of monitoring and administration that is infeasible for most agencies and programs. To put things into perspective, imagine a stand of trees owned by a lumber firm. A first-best incentive targeting CO₂ filtration would pay the firm based on the exact amount of carbon taken out of the atmosphere by every living tree at every instant, specific to the species. Given that precise measurement is prohibitively expensive, proxy policy targets must be used (Jack et al., 2008).³

Whether stocks *and* flows are close enough approximations to the direct external effect remains an open question, especially given current policy design. The most common proxy implemented in price incentive programs that target externalities from privately-owned natural capital, such as the USDA’s Conservation Reserve Program, those implemented as a part of REDD+, and Denmark’s recently passed Livestock Tax to curb methane emissions, are approximations of the total resource stock (Jayachandran, 2013; U.S. Department of Agriculture, 2020a; Kampmann, 2024; Izquierdo-Tort et al., 2025). Other policies, such as Maryland’s Nutrient Credit Trading Program, use observed output as their main policy target (Sandi, 2025) and researchers have considered equivalents to the latter to minimize methane emissions from livestock (Funke et al., 2022).⁴⁵ Empirical counterfactuals for performance of different incentive targets are difficult to come by given heterogeneity of target species and the recency of the policies, among other factors.

Can firm-level incentives targeting either stocks or flows yield equivalent levels of environmental quality when attempting to internalize a stock-generated externality? I find that the answer is no; flow-targeted incentives significantly underperform relative to stock-targeting. To answer this question at length, I present a stylized dynamic optimization model of renew-

³In addition, incentive design must account for other potential sources of market failure, such as weak property rights and imperfect information among producers. Work by Jack, Jayachandran, Sims and others, in addition to broader news coverage, highlights the need for careful design of incentives for ecosystem services to address these additional issues (Engel et al., 2008; Jack et al., 2008; Prager et al., 2016; Jack and Jayachandran, 2019; Teytelboym, 2019).

⁴The process of livestock rearing may induce other environmental externalities through deforestation, especially in countries with inconsistent enforcement (Assunção et al., 2023; Dominguez-Iino, 2025). Cattle ranching-driven deforestation has been associated with more remote farms with higher output, total acreage, and total forest cover within farm based on a property-level analysis in the country (Skidmore et al., 2021) and can driven by increases in herd size or shifts in grazing location due to pasture degradation. The theoretical setting in this paper assumes not only strong institutions, but that the firm has utilized all of its productive land, i.e. it has already cleared all viable parts of the plot for production. Both preclude exploration of external effects on other resource stocks through both illicit and legal activity.

⁵While some claim that wood products and forest regrowth post-harvest maintain carbon neutrality or notable carbon sequestration benefits, tree harvest may result in an additional 3.5-4.2 Gt of CO₂ annually (U.S. Forest Service, 2020; Peng et al., 2023; Taylor et al., 2023).

able resource extraction where a stock of privately-owned capital jointly produces a social benefit.⁶ The model draws heavily from the seminal work of Dasgupta and Heal (1974) and Chichilnisky et al. (1995).⁷ I explore a collection of centralized and decentralized equilibria meant to represent what happens in the theoretical optimum and more realistic policy settings: 1) the Social Planner’s problem, 2) the no policy benchmark, 3) a stock-targeted incentive, and 4) a flow-targeted incentive. The latter two scenarios are theoretical analogues to real-world, second-best policies that have been implemented or recently passed in forestry, fisheries, and livestock management. Given its simplicity, the model can be applied to other problems where privately-owned renewable resource stocks have a direct, external value to society through shoreline defense, biodiversity, and groundwater conservation, among others.

As a brief overview of the model, let there be a representative firm and a representative consumer. Time is continuous and infinite. The consumer gains utility from both consumption of a private good and from the size of the natural resource stock. One can think of the latter preference as societal benefits from ecosystem services provided by the stock, existence, or another non-market stock-generated benefit. The firm owns the natural resource stock and engages in resource extraction within a fixed production area to produce the private good, which it does using frontier technology. Extraction is costless and the resource grows exogenously, which implies that the stock can exist in perpetuity. In absence of a policy, the firm can only maximize profits by selling the private good. It does not internalize the social benefits provided by the renewable natural capital stock it owns without a policy in place. Whether incentives that scale with the stock *or* flows of production yield equivalent short- and long-run social benefits is then explored.

The theoretical results show a striking divergence in incentive performance in steady state. A stock-targeted incentive can yield the Social Planner’s allocations, while flow incentives are no better than no-policy. All incentives that marginally increase in the stock, i.e. stock subsidies, allow the firm to internalize the social value of the stock. A subset of stock subsidies that converge to the Social Planner’s steady state values lead to the socially optimal level of the resource stock in the long run. However, policies targeting flows incentivize stock management only in the most indirect sense – the marginal unit extracted or conserved,

⁶Private ownership/leasing and extraction are common features in industries such as lumber, livestock and shellfish aquaculture (Butler and Wear, 2013; U.S. Department of the Interior, 2025; Washington State Department of Natural Resources, 2025). The issue of resource conservation under weak property rights, such as those that induce the common resource stock externality, in the presence of social benefits from the resource stock is the subject of future work.

⁷An earlier version of Chichilnisky et al. (1995) elaborates on the rationale behind the “Green Golden Rule” and dynamic paths for sustainable consumption in the presence of a renewable natural resource (Beltratti et al., 1993).

rather than the entirety of the stock itself. Further, any impact that a flow policy has on social benefits provision in this setting are inherently dynamic. When the system settles into its steady state, firms revert to the same profit maximization behavior as if no policy existed.

The result is likely driven by revenue constraints for the firm. Under no-policy, the firm has one source of revenue, namely extraction/private good production, over which to profit maximize. In steady state, the firm will maintain a level of the stock that maximizes profits over this singular dimension. But what if the private good was not its only revenue source? Under stock-targeting, the firm now offers two goods – the private good and the resource stock, which the firm is paid to manage. Extraction is inherently marginal with respect to the stock, so payments received for the stock itself allow the firm to accumulate higher levels than under no-policy. By contrast, flow-targeting only changes the price of the private good, implying that the firm’s sole source of revenue is the same as under no-policy. Lack of revenue sources that more closely scale with the stock acts as a constraint which prevents the firm from increasing the resource stock beyond the no-policy benchmark in steady state.

The model is then expanded to include pollution dynamics and environmental benefits provision to explore how the policies perform along their time paths. It is calibrated to scientific and industry parameters from the Chesapeake Bay, USA, where commercial Eastern oyster (*C. virginica*) cultivation is being used as a means to reduce fertilizer damages in the namesake watershed (Sandi, 2025). The calibration is used not only to explore the dynamic paths of natural resource accumulation and pollution, but other general constraints a policymaker may experience. For example, the size of the incentive and the frequency of policy adjustments could vary based on pre-set fiscal spending periods or regime change (Battaglini and Coate, 2008).

The dynamic results support the theoretical narrative – policy target matters above all else. The time paths of flow incentives, regardless of sign, track closely with the no-policy path. This supports the inference that firms have little incentive to deviate from the profit maximizing level of extraction in the presence of a flow-targeted policy. Flow incentives, as have been implemented in current policy, lead to excess short run extraction even when set at the “Pigouvian” values (up to a 0.05% decrease in biomass). Flow disincentives can have minor increases in resource accumulation prior to steady state. However, the effects are generally minor, with up to a 0.2% increase in biomass under the harshest disincentive scenario, while the producer welfare losses from such a policy are substantial. The environmental benefits from a disincentive on flows do not outweigh the losses in producer welfare in this setting.

Meanwhile, sign and scale of a marginal incentive can matter substantially for natural resource accumulation under stock-targeting. Positive marginal incentives on stocks lead to increases in resource accumulation along the entire time path. Stock-targeted incentives can achieve the social optimum when the value of the marginal incentive is structured to converge to the Social Planner’s solution in steady state. Frequency of policy updates, i.e. whether the policies adjust every five, ten, etc. years, matters little for policy performance regardless of target. The results together emphasize the importance of incentive targets when attempting to maximize environmental quality through the intensive margin.

The primary contribution of this paper is a dynamic, decentralized theoretical model to evaluate the performance of both first- and second-best instruments when externalities are generated from stocks rather than flows. Core literature modeling externality-correcting policies has typically focused on optimal (Nordhaus, 1992; Farzin and Tahvonen, 1996; Acemoglu et al., 2012; Golosov et al., 2014; Shapiro, 2016) or second-best policies for flow-generated externalities, such as greenhouse gas and criteria emissions.⁸ The second-best can stem from distortionary taxation (Bovenberg and Goulder, 2002; Fullerton and Wolverton, 2005; Barrage, 2020), uncertainty/opaqueness of externality measurement (Shortle and Dunn, 1986; Schmutzler and Goulder, 1997; Cremer and Gahvari, 2002; Jacobsen et al., 2020), and heterogeneous externality production (Claassen and Horan, 2001; Xabadia et al., 2008; Knittel and Sandler, 2018). Incorporating exogenously growing capital further complicates modeling (Heal, 1998; Arrow et al., 2000), as does direct consumer valuation of the stock or, equivalently, the externality produced by the stock (Fenichel and Abbott, 2014). Theoretical work in this area has understandably utilized simplifying assumptions for tractability. Some authors present policy dynamics in a centralized market (Tahvonen and Kuuluvainen, 1991; Chichilnisky et al., 1995), while others strictly model the producer side and/or assume a static social value of the externality in a dynamic setting (DePiper et al., 2017; Tahvonen and Rautiainen, 2017; Assmuth et al., 2021).

This paper presents a simple model that marries the key components of these different strands of literature by decoupling the consumer and producer’s problems and incorporating a dynamically-adjusting social value of the renewable stock. Combining these elements allows for the model to more fully capture policy performance across time. Included policies align with the imperfect measurement literature, where the policy targets are more or less imperfect proxies for externalities production. I provide ordinal theoretical performance results for incentives targeting second-best proxies to internalize stock-generated externalities.

⁸Dasgupta et al. (1980) also explore the dynamic implications of different tax policies within a centralized market based on their seminal work on non-renewable resource extraction (Dasgupta and Heal, 1974).

Further, I numerically evaluate the performance of other policy deviations from the first-best, such as infrequent incentive updates and comparison of different sign and scale of policies, in order to mimic some of the real-world administrative constraints faced by policymakers.

I also contribute to empirical and policy work on incentives to internalize stock-generated externalities by providing a flexible theoretical framework underlying policy performance. In particular, there is a growing set of randomized agricultural programs aimed at internalizing the ecosystem benefits provided by natural resources either within or buffering privately-owned agricultural plots, otherwise known as Payments for Ecosystem Services (PES) (Jack et al., 2008; Alix-Garcia et al., 2015; Jayachandran et al., 2017). There are also a growing number of government- and privately-implemented programs incentivizing land conservation and water purification in lieu of (or in conjunction with) farm or aquaculture production to reduce ecosystem degradation (Teytelboym, 2019; U.S. Department of Agriculture, 2020a; Frey et al., 2021; Sandi, 2025; Taylor et al., 2023; Aronoff and Rafey, 2025). For example, recent legislation passed by Denmark will tax producers of cows and pigs starting in the year 2030 in order to curb methane emissions. The tax will be levied based on total stock held by producers, proxying the total amount of methane generated from the animals' physiological processes (Khalil, 2024; Sengupta and Fuente, 2024). These policies and programs are generally characterized as unrelated to other natural resource-based policies. My point of view is that at their core, these programs attempt to address the same underlying problem highlighted in this paper. My hope is that the framework presented here can help researchers and policymakers with policy design to internalize stock-generated externalities going forward.

2 Model

I begin with a stylized model of renewable natural resource extraction. The firm engages in costless harvest. Time is continuous and infinite. A representative consumer has preferences over both consumption of a private good C_t and the stock of natural capital S_t , where subscript t represents that the variables change over, but are not explicit functions of, time.

$$U(C_t, S_t) \tag{1}$$

Utility is assumed to be well-behaved and increasing in S_t ($U_C, U_S > 0$, $U_{CC}, U_{SS} \leq 0$). Preferences are assumed to be separable in C_t and S_t .⁹¹⁰ Preferences over S_t is general

⁹Separability is a common functional form assumption in environment and natural resources contexts (Tahvonen and Kuuluvainen, 1991; Bovenberg and Smulders, 1995; Heal, 1998).

¹⁰The version of the model with preferences over the stock of pollution is assumed to decrease in pollution stock and therefore implicitly increase in the stock of the natural resource. See Section 3.1.

enough to capture direct benefits generated from accumulation (e.g. from ecosystem services, existence, etc.) and benefits from the change in the stock at every instant t .

Production consists of harvesting H_t amount of the natural resource at every instant. The production function is denoted

$$F(H_t) \tag{2}$$

where $F_H > 0$ and $F_{HH} \leq 0$. The generality of these functional forms allows for modeling flexibility over different preferences and technology assumptions, such as under markets for commodities with decreasing returns to scale.¹¹

Meanwhile, the natural resource changes exogenously through function

$$G(S_t) \tag{3}$$

which is logistic in time. This function, drawn from the population dynamics literature, is often parabolic in S_t such that $G(S_t) > 0$ for all $S_t \in [0, \bar{S}]$. The upper bound $\bar{S}$ represents the population carrying capacity, i.e. the maximum level of resource stock that a given geographic area can naturally support. For all $S_t > \bar{S}$, $G(S_t) < 0$.¹²

While a parabolic functional form is the primary one used in this paper, it is not the only population growth function that can be applied. A parabolic form emphasizes that too much resource stock, say too many individuals within a population, can be detrimental for a natural population to thrive because increased competition for resources to survive. Too few individuals can also threaten the survival of a population, also called an Allee effect (Dennis, 1989). For some threshold $\underline{S} > 0$, Allee effects are represented by initial convexity of the population growth function from $S_t \in [0, \underline{S}]$, followed by concavity from $S_t \in [\underline{S}, \bar{S}]$. (see Appendix Figure A.1 for illustrations of common single-species population growth functions).¹³ The model results do not fundamentally change in the presence of Allee effects, so I assume a parabolic function in S_t for ease of exposition.

The stock of the natural resource evolves by the equation

$$\dot{S} = G(S_t) - H_t \tag{4}$$

¹¹Note that increasing returns to scale technologies are not always found in extractive natural resources-based industries (Stier, 1980; Scuderì and Chen, 2019).

¹²I do not consider time-varying carrying capacities in this paper, but time variance may play a role in determining the optimal harvest under the different policy scenarios (Carson et al., 2009).

¹³The parabolic form is called a pure compensation growth function, while a growth function that is both convex and concave but positive up to $\bar{S}$, i.e. a function with weak Allee effects such that $\underline{S} = 0$, is referred to as a depensation growth function. The functional form with strong Allee effects ($\underline{S} > 0$) is called a critical depensation growth function.

where $\dot{S}$ denotes the change in the natural resource stock with respect to time. Note that Equation 4 is nearly identical to classic wild capture fisheries models in bioeconomics (Gordon, 1954; Clark and Munro, 1975; Schaefer, 1991). Here I explicitly focus on a situation where the firm solely owns the stock of the natural resource within a fixed production area to capture the decisions by agents in industries where property rights are more secure, such as the lumber or aquaculture industries. Further, I do not focus on extensive margin effects due to the complexity of environmental characteristics of neighboring geographic areas, such as the presence of wild natural capital stock, water flow, and sediment porosity and permeability, among others. Depending on these characteristics and the production technology of the firm, expansion and contraction of production areas can lead to unclear changes in levels of the natural resource stock (both cultivated and wild).

2.1 The Planning Problem

The Social Planner's objective is to maximize the discounted present value of social welfare given choices in consumption C_t and the state of the natural capital stock S_t at every instant. ρ represents the social discount rate and private goods production $F(H_t)$ is equal to consumption for all t .

$$U_0 = \max_{\{C_t, S_t\}_{t=0}^{\infty}} \int_0^{\infty} e^{-\rho t} U(C_t, S_t) dt \quad (5)$$

$$\dot{S} = G(S_t) - H_t$$

$$C_t = F(H_t)$$

$$S_0 > 0$$

The first order necessary conditions (FONCs) yield the following Euler equation, which is also the condition that equates marginal benefits and marginal costs of natural resource stock accumulation for each t .

$$G_S + \frac{U_S}{U_C} \frac{1}{F_H} = \rho - \frac{\dot{U}_C}{U_C} - \frac{\dot{F}_H}{F_H} \quad (6)$$

Y_X denotes the derivative of a function Y with respect to X_t , where t is suppressed for clarity. On the left hand side, the marginal benefits of stock accumulation include both private returns in the form of the marginal growth of the stock, as well as public returns, which is represented by the marginal rate of substitution between stock and consumption, scaled by the marginal product of harvest. On the right hand side is the marginal cost of

stock accumulation, which includes both intertemporal consumption and production choices.

A steady state is defined as a set of allocations $\{C^*, H^*, S^*\}$ such that $\dot{S} = 0$ and $\dot{U}_C = \dot{F}_H = 0$. This gives us the following steady state condition.

$$G_{S^*} + \frac{U_{S^*}}{U_{C^*}} \frac{1}{F_{H^*}} = \rho \quad (7)$$

The social discount rate ρ plays a major role in determining the optimal level of the natural resource stock in a steady state equilibrium. A myopic Social Planner implies $\rho \rightarrow \infty$ and a natural resource stock in steady state that is lower than the population is at its maximum growth (i.e. its maximum sustainable yield (MSY)). In other words, the Social Planner makes choices that deplete the stock in steady state in the presence of myopia. By contrast, a Social Planner that values the future the same as the present is represented by $\rho = 0$. In this scenario, S^* is higher than its maximum sustainable yield—the optimal result under the Green Golden Rule (Beltratti et al., 1993; Chichilnisky et al., 1995). The choice of discount rates in the presence of environmental externalities is a topic of active debate (see Heal (2017) and Polasky and Dampha (2021) for comprehensive reviews). Given the problem modeled here, where the representative consumer maintains positive utility in entire stock of the natural resource, a discount rate closer to zero is more appropriate (Clark, 1973). For the remainder of the Section 2, I assume a social discount rate $\rho \rightarrow 0$.

Note that the Planning Problem is strongly reminiscent of Chichilnisky et al. (1995) and Heal (1998). I further break this model apart to explore a collection of incentive-based policy states of the world to understand how natural capital accumulation differs by policy.

2.2 The Decentralized Equilibrium Under No Policy

Let there be a world with a representative consumer and a representative firm, where the firm does not internalize the social benefits generated from a stock of natural capital that it owns, i.e. no incentive-based policy exists. I refer to this world as “no-policy.”

The firm’s objective is to maximize the discounted present value of profits from private goods production subject to resource stock growth. θ_t is the internal rate of return at time t .¹⁴

$$\Pi_0 = \max_{\{H_t, S_t\}_{t=0}^{\infty}} \int_{t=0}^{\infty} e^{-\int_0^t \theta(\tau) d\tau} F(H_t) dt \quad (8)$$

¹⁴The choice of a time-varying internal rate of return assumes no arbitrage along the equilibrium path and is a feature commonly observed in firms. See Gormsen and Huber (2023) for a recent overview of time-varying corporate discount rates.

$$\begin{aligned}\dot{S} &= G(S_t) - H_t \\ S_0 &> 0\end{aligned}$$

Market prices are normalized to 1. The FONCs for the representative firm yield

$$G_S = \theta_t - \frac{\dot{F}_H}{F_H} \quad (9)$$

where the left hand side represents the marginal benefits with respect to stock accumulation and only consists of the firm's private benefits. The right hand side represents its marginal costs, which includes its internal rate of return and the growth rate of marginal production.

On the other side of the market, the consumer must now take into account the evolution of assets they hold to make choices over consumption. The consumer owns claims A_t on firm profits π_t , where instantaneous consumption choices help determine the evolution of the value of future claims $q_t \dot{A}$, reminiscent of (Lucas, 1978).¹⁵

$$q_t \dot{A} = A_t \pi_t - C_t \quad (10)$$

The consumer maximizes their present discounted value of utility

$$U_0 = \max_{\{C_t, A_t\}_{t=0}^{\infty}} \int_0^{\infty} e^{-\rho t} U(C_t, S_t) dt \quad (11)$$

subject to Equation 10, where claims on assets in the initial period is positive ($A_0 > 0$). Notice that even though the consumer has preferences over the stock of the natural resource, it does not play a role in the consumer's problem directly and, therefore, is taken as given. In this setting, consumers have no say over how the firm manages their stock of the natural resource. Rather, they influence firm behavior strictly through the consumption of the private good.¹⁶ The FONCs yield the following Euler equation

$$\frac{\dot{q}}{q_t} + \frac{\pi_t}{q_t} = \rho - \frac{\dot{U}_C}{U_C} \quad (12)$$

where the left hand side represents the marginal benefits of accumulating assets, consisting of the growth rate of future claims price and firm profits normalized by future claims price.

¹⁵This is conceptually similar to a Lucas tree model under homogeneous agents without uncertainty and, potentially, with actual trees.

¹⁶The setting implies that while we may be in a world where "green goods" are for sale, the consumer cannot induce the firm to provide a higher level of the "green" characteristic specifically (Kotchen, 2006).

An equilibrium transition path exists if there are allocations $\{C_t, H_t, A_t, S_t\}_{t=0}^{\infty}$ and profits $\{\pi_t\}_{t=0}^{\infty}$ such that

1. The consumer and producer maximize their objectives subject to the evolution of claims on profits and the natural resource stock, respectively, and
2. Private good and asset markets clear, i.e.
 - (a) $C_t = F(H_t) = \pi_t$
 - (b) $A_t = 1$

for all t . To ensure 2(b), the following no arbitrage condition must hold where the consumer's marginal benefit of asset accumulation is equal to the firm's internal rate of return.

$$\theta_t = \frac{\dot{q}}{q_t} + \frac{\pi_t}{q_t} \quad (13)$$

Along an equilibrium path Equation 9 can therefore be rewritten as

$$G_S = \rho - \frac{\dot{U}_C}{U_C} - \frac{\dot{F}_H}{F_H} \quad (14)$$

which resembles the Social Planner's Euler Equation (Equation 6). The main difference is that the marginal benefits from stock accumulation only consist of its private returns in the form of marginal stock growth because the firm does not internalize the social benefits generated from the natural capital stock.

A steady state market equilibrium is defined as a set of allocations $\{C^*, H^*, S^*\}$ and profits $\{\pi^*\}$ such that $\dot{S} = \dot{A} = 0$. This implies the following steady state equilibrium condition.

$$G_{S^*} = \rho \quad (15)$$

Given $G(S^*) = H^*$ and a consumer that is as patient as the Social Planner, Equation 15 suggests that the firm will aim to harvest at a level that effectively maximizes the growth of the natural resource stock to maximize profits, i.e. harvests near its maximum sustainable yield (MSY) denoted H_{MSY} . Profit maximizing behavior at MSY echoes the classic steady state result in sole-owner bioeconomic models (Gordon, 1954; Clark and Munro, 1975).

Now that we have allocations under both the Social Planner and BAU as theoretical benchmarks, we can explore how social benefits under various policy targets differ from each.

2.3 Stock Incentives

Suppose the firm is provided an incentive at time $t = 0$ dependent on the total stock of the resource that it owns. The stock must be living in order for the firm to receive a payment.

There are no administrative costs to policy implementation. The firm's objective function is now to maximize the present discounted value of profits, which now consists of both the private good and any revenues (or costs) based on the total stock.

$$F(H_t) + \sigma(S_t) \quad (16)$$

$\sigma(S_t)$ is an exogenously-determined policy function differentiable in S_t and autonomous with respect to t .¹⁷ The consumer's budget constraint includes lump sum "payments" γ_t .¹⁸

$$q_t \dot{A} = A_t \pi_t - C_t - \gamma_t \quad (17)$$

An equilibrium transition path exists if there are allocations $\{C_t, H_t, A_t, S_t\}_{t=0}^{\infty}$, profits and taxes $\{\pi_t, \gamma_t\}_{t=0}^{\infty}$ such that

1. The consumer and producer maximize their own objectives subject to the evolution of claims on profits and the natural resource stock, respectively
2. Private good and asset markets clear, i.e.
 - (a) $C_t = F(H_t) = \pi_t$
 - (b) $A_t = 1$, and
3. The balanced budget condition $\gamma_t = \sigma(S_t)$ holds.

The FONCs give us the following condition for the equilibrium transition path.

$$G_S + \frac{\sigma_S}{F_H} = \rho - \frac{\dot{U}_C}{U_C} - \frac{\dot{F}_H}{F_H} \quad (18)$$

Compared to Equation 6, a stock incentive $\sigma(S_t)$ that will yield the Social Planner's allocations for all t exists if the marginal incentive σ_S is equal to the marginal rate of substitution between the natural resource stock and private good consumption. However, we may not be able to define a policy function that yields the Social Planner's path.

In order for σ_S to equal to the marginal rate of substitution between the natural resource

¹⁷In other words, $\sigma(\cdot)$ is not an explicit function of time.

¹⁸I am agnostic to the direction of $\sigma(S_t)$ (and therefore γ_t). Rather, the theoretical results will yield a policy direction. See Proposition 1 broader implications.

stock and private good consumption, C_t must be expressed as a function of S_t , which is not possible for all t . For clarity, combining Equation 4 and the equivalence between production and consumption would lead to the following equation

$$C_t = F(G(S_t) - \dot{S}) \quad (19)$$

which defines the relationship between consumption and the resource stock for all t . Given that $\dot{S}$ is endogenously determined by C_t , the right hand side of the equation is only known to the policymaker retrospectively. This implies knowledge of S_t may not be sufficient to determine contemporaneous C_t and a policy function $\sigma(S_t)$ that yields the Planner's allocations across all instants is not knowable in this setting. However, we can derive policies that yield the Planner's steady state allocations.

Suppose we are in steady state as defined in Section 2.2. Equation 18 reduces to

$$G_{S^*} + \frac{\sigma_{S^*}}{F_{H^*}} = \rho \quad (20)$$

Given $\dot{S} = 0$, we can now express C^* strictly as a function of S^* .

$$C^* = F(G(S^*)) \quad (21)$$

Equation 21 implies that a policy that takes the following functional form

$$\sigma_{S^*} = \frac{U_{S^*}}{U_{C^*}} = \frac{U_{S^*}}{U_{F(G(S^*))}} \quad (22)$$

can lead to the socially optimal levels of the natural resource stock in steady state, as well as the following proposition.

Proposition 1 *Suppose an incentive $\sigma(S_t)$ on the producer that is differentiable in S_t . If in steady state, the marginal incentive takes the following functional form*

$$\sigma_{S^*} = \frac{U_{S^*}}{U_{C^*}}$$

where $C^* = F(G(S^*))$, then the level of the resource stock will converge to the social optimum.

Proposition 1 provides some clarity on policy design. First, the marginal incentive must eventually converge to the marginal rate of substitution between social benefits and consumption under the Social Planner. Trivially, a policymaker may set a constant marginal

policy such that Equation 22 holds for all t to obtain levels of the natural resource stock that eventually converge to the social optimum. However, there may be time-varying policies that achieve the same steady state level of the stock.

For illustration, suppose that we have the following consumer preferences

$$U(C_t, S_t) = \ln C_t + \ln S_t \quad (23)$$

with a linear production function $F(H_t) = H_t$, and a Pearl-Verhulst equation with an intrinsic population growth rate $g = 1$ and a population carrying capacity $\bar{S}$.

$$G(S_t) = S_t \left(1 - \frac{S_t}{\bar{S}}\right) \quad (24)$$

Taken together, a steady state marginal policy that satisfies Proposition 1 will take the form

$$\sigma_{S^*} = \frac{U_{S^*}}{U_{C^*}} = \left(1 - \frac{S^*}{\bar{S}}\right) \quad (25)$$

When expressed in aggregate terms, this implies that the following functional form of $\sigma(S_t)$ will yield the socially optimal levels of the natural resource stock in steady state.

$$\sigma(S_t) = S_t \left(1 - \frac{S_t}{2\bar{S}}\right) \quad (26)$$

Assuming $S_t \leq \bar{S}$ for all t , Equation 26 suggests that a time-varying incentive that converges to the socially optimum closely maps to the growth of the natural resource.

This is encouraging for policymakers, as many natural resource management strategies already rely on biological stock assessments and estimations of the growth of the stock, updated at regular intervals (U.S. Department of Agriculture, 2022; National Oceanic and Atmospheric Administration, 2023). Note that a marginal policy function σ_S that yields the socially optimal level of the stock in steady state may not have an elementary antiderivative with respect to S_t (i.e. obtaining $\sigma(S_t)$ is not straightforward). However, policies that are defined on a marginal basis are often implemented in practice, so it may be sufficient from a policymaker's perspective to strictly obtain the functional form of the marginal incentive.

A broader implication of stock-targeting is that given $U_C, U_S > 0$ and by Equations 6 and 20, any positive marginal incentive $\sigma_S > 0$ will yield a natural capital stock that is higher than BAU across time. This further implies that as long as the stock-targeted policy is a

subsidy, a policymaker stands to obtain some extra social benefit relative to doing nothing.¹⁹

The higher accumulation of resource stock in steady state relative to BAU is likely driven by differences in firm incentives. Under a policy that subsidizes accumulation of the stock, the firm now has two sources of revenue – private goods production and its inventory of the natural resource. This allows the an additional degree of freedom for the firm to forgo revenue from private production in favor of stock accumulation, analogous to the behavior of a multi-product firm. Increases in stock can now yield increased returns with respect to either source of revenue in the future. This begs the question of whether an incentivize on harvest may be able to achieve similar results. For that, we turn to our last policy.

2.4 Flow Incentives

Now consider a world where the firm is incentivized at $t = 0$ based on some transformation of the flow of production – in this case the total harvest of the natural resource. The firm’s objective is to now maximize the present discounted value of

$$F(H_t) + \tau(H_t) \tag{27}$$

where $\tau(H_t)$ is a twice differentiable function of H_t and is autonomous with respect to t . $\tau(H_t)$ may be either an increasing or decreasing function of H_t . As in Section 2.3, the consumer “pays” for the policy in a lump sum manner and the equilibrium path is defined as before, which yields the following condition along the equilibrium path.

$$G_S = \rho - \frac{\dot{U}_C}{U_C} - \frac{\dot{F}_H + \dot{\tau}_H}{F_H + \tau_H} \tag{28}$$

Equation 28 differs substantially from the Social Planner’s transition path (Equation 6) in a couple of key ways. For one thing, S_t does not appear in any term other than the marginal growth of the stock, similar to BAU. Further, $\dot{\tau}_H$ implies that the incentive must be time-varying in order for the policy to have an effect on stock accumulation, whereas U_S/U_C could be constant across time.²⁰ This is likely because an incentive on harvest alters the price faced by producers for private good production, similar to the effect of a tax or subsidy on intertemporal consumption choices.

For a flow policy to produce socially optimal levels of the natural resource stock across time,

¹⁹At least in this stylized world with no policy administration costs. Costs of administration can be accounted for in this model with an explicit policymaker’s objective.

²⁰Note that $\tau_H \neq -F_H$ otherwise the path becomes undefined.

it is sufficient to show that an incentive yields the Social Planner's allocations in steady state. Suppose that we are in a steady state as defined in previous sections. The Euler equation is

$$G_{S^*} = \rho + \frac{\dot{\tau}_{H^*}}{F_{H^*} + \tau_{H^*}} \quad (29)$$

where $\dot{\tau}_{H^*} \neq 0$. Given that the policy is a function of harvest H_t and not explicitly of t , harvest itself must also be time-varying. Note that the change in the marginal incentive with respect to time can also be expressed as

$$\dot{\tau}_H = \tau_{HH} \dot{H} \quad (30)$$

H^* in steady state implies $\dot{H} = 0$, which contradicts $\dot{\tau}_{H^*} \neq 0$. Equation 29 reduces to

$$G_{S^*} = \rho \quad (31)$$

which is the steady state Euler equation under BAU or no policy.²¹ This brings us to the following proposition.

Proposition 2 *There does not exist an autonomous flow incentive $\tau(H_t)$ on the producer that can achieve the socially optimal allocations for all t . Further, the stock of the natural resource under such a policy will eventually converge to that under no policy.*

The mechanism underlying this result is likely revenue constraints on the firm. There is only one pathway for the policymaker to alter the choices of the firm in this state of the world – revenue from the private good. Recall that under a zero discount rate, the firm will obtain a level of harvest and natural capital stock that maximizes its sustainable yield, and profits, under no-policy in steady state. Given that a flow policy is intended to alter the direct returns to private goods production, the channel by which the firm is allowed to adjust behavior is the same as under no-policy. Lack of other revenue sources disallows the firm to accumulate stock beyond the no-policy scenario across all periods. In other words, the firm has no incentive to deviate from no-policy level of extraction, at least in steady state. Unlike what we see under stock policies, this implies that a flow policy cannot fully internalize a stock-generated externality in this setting in the long run.

Proposition 2 does not rule out that for some t , flow-targeting can yield improvements in stock accumulation over no policy. Any bite from a flow-targeted policy is inherently dynamic, so there may be some instants where a flow incentive yields larger social benefits

²¹The result trivially reduces to BAU in steady state if the policy $\tau(H_t)$ is not twice differentiable.

than no-policy. Comparing Equations 14 and 28, it must be the case that

$$\frac{\dot{F}_H + \dot{\tau}_H}{F_H + \tau_H} > \frac{\dot{F}_H}{F_H} \quad (32)$$

for the firm to accumulate a higher amount of the resource stock relative to no policy for some t . This is driven by two components – the marginal incentive τ_H and its change over time $\dot{\tau}_H$. Suppose for illustration that $\dot{F}_H > 0$ along the path. On the one hand, if $\dot{\tau}_H > 0$, then the firm may be incentivized to reduce harvest today if it anticipates that it can obtain higher returns from harvest in the future. However, an increase in the marginal incentive can simultaneously have a dampening effect on stock accumulation through progressively increasing current returns to harvest, so changes in stock accumulation relative to BAU may be minimal. On the other hand, if the policy is a marginal *disincentive* on harvest, $\tau_H < 0$ for all t , then the firm may reduce harvest at each instant.²²

To gain clarity about the length of time potential improvements are obtained and to dynamically explore other possible incentive structures, I apply more specific functional forms and pollution dynamics to the model. The choices are informed by the inorganic nitrogen emissions problem in the Chesapeake Bay, where cultivation of oysters for food consumption may provide water purification benefits.

3 Nutrient Pollution and Oyster Aquaculture in the Chesapeake Bay

Nutrient pollution is a problem faced by coastal regions around the world (Selman et al., 2009). Nutrient emissions are measured in loads, or the total amount of a substance released within a water body at a given point in time (e.g. tons per year discharged into a river) (Cahn and Hartz, 2013). Excess nutrient loads come from a variety of point and non-point sources, such as stormwater treatment plants and agricultural fertilizer runoff (Rose et al., 2015; Yang et al., 2022). Fertilizers enable plant growth, so high nutrient levels can lead to hypoxia (low dissolved oxygen) through decay of excess particulate organic matter (POM), as well as increased prevalence of toxic algae (Anderson et al., 2008; Rabalais et al., 2009; Rabotyagov et al., 2014; Taylor and Heal, 2023). Both channels increase mortality in species that are commercially valuable and necessary for a functioning ecosystem (National Oceanic

²²Further, there may exist a non-autonomous flow policy, i.e. a policy that is an explicit function of t , that can satisfy Equation 29 for all t . However, time-dependence that does not otherwise violate other assumptions can also lead to a degenerate policy trajectory $\tau_H \rightarrow \infty$.

and Atmospheric Administration, 2024b; Chesapeake Bay Program, 2025).

Requirements for nutrient load standards in ground and surface water were established through the Clean Water Act (CWA) of 1972, but enforcement at the state level has remained a challenge (U.S. Environmental Protection Agency, 2007). Several reasons include difficulty in identifying non-point pollution sources, exceptions made for agricultural producer dredge and fill emissions, and state flexibility to set water quality criteria (U.S. Environmental Protection Agency, 2025a; Horan et al., 2025; U.S. Environmental Protection Agency, 2025b). Efforts to control nutrient emissions from non-point sources, primarily from agricultural fertilizer use, have been generally ineffective (Tomczyk et al., 2023).

One approach to reduce damages from excess nutrients is bivalve shellfish aquaculture. Shellfish habitat are typically estuaries and bays, which are common pathways for coastal nutrient runoff (Dumbauld et al., 2009). Bivalve cultivation jointly produces not only private goods (harvested shellfish) but also environmental benefits through surface water cleaning (Kellogg et al., 2013, 2014; Bricker et al., 2018, 2020; Ray and Fulweiler, 2021). Bivalve shellfish consume excess POM, the product of nutrient emissions, through filter-feeding and re-release as more inert biodeposits. Shellfish have also been found to absorb nutrients directly into shell and tissue (Dalrymple and Carmichael, 2015; Darrow et al., 2017; Rullens et al., 2019; van der Schatte et al., 2020).

There have been small-scale studies and reviews of nutrient removal benefits from oyster cultivation (see Ray and Fulweiler (2021) for a recent meta-analysis). The value of these services range from \$5,500 to \$99,000 on an annual per hectare basis, with up to \$470 million per year in some regions of the U.S. (Grabowski et al., 2012; Bricker et al., 2018).²³ For example, a study of Chesapeake Bay Eastern oyster (*C. virginica*) aquaculture estimated that a farm deploying a floating rack system with 286 oysters/m² per raft may be able to remove 331 kg/hectare of nitrogen and 47 kg/hectare of phosphorus per 12 to 24-month period (Higgins et al., 2011).²⁴ Per-unit costs of nitrogen removal through shellfish cultivation tend to be far lower than comparable mechanical methods (Rose et al., 2015).

²³There is broad consensus that properly-managed farms provide net ecosystem benefits, though improper management can have detrimental impacts on the surrounding ecosystem (Porter et al., 2004; Forrest et al., 2009; Dumbauld et al., 2009; Oo and Oo, 2016; Gentry et al., 2020; Barrett et al., 2022).

²⁴Common growing methods are rack and bag systems, where the oysters are flipped or turned using manual labor or, primarily, tidal energy (University of Maryland, 2024). These methods prevent Eastern oysters from “cementing” to each other to form reefs. Oyster reefs, while ecologically valuable, can lead to oyster mortality via sedimentation and misshapen oyster meat, which farmers are generally unable to sell (Jordan-Cooley et al., 2011; Bruce et al., 2021). Other commercially-valuable oyster species like Pacific oysters (*C. gigas*) also form reef structures and are subject to the same cultivation modes, though not all species use other individuals as substrate (Escapa et al., 2004; Brumbaugh and Coen, 2009).

There are few government programs incentivizing nutrient removal services from oysters. Some have incorporated oyster buybacks from farmers or payments for oyster reef restoration activities (Rutgers University Office of Communications, 2021; Native Oyster Restoration Alliance, 2025). One ongoing industry-focused policy is the Chesapeake Bay Nutrient Credit Trading Program.²⁵²⁶ Eutrophication is a major issue for the region. Nearly 132 million kg of nitrogen enters the watershed per year according to a 2021 report by the U.S. Geological Survey. The watershed supports a variety of sectors, including agricultural and commercial seafood production, as well as aquatic recreation. In Maryland and Virginia, commercial seafood production alone contributed 34,000 jobs and \$890 million in local income in 2009. Recreational fishing generated revenues of \$1.6 billion in 2011. Concerns have been raised that excess nutrient emissions will further harm these coastal industries (Clune et al., 2021).

Total maximum daily loads (TMDLs) for nitrogen, phosphorus and sediment were initially set in 2010 for the Chesapeake Bay Watershed in an attempt to minimize damages from poor water quality. Specifically, goals were set at 185.9 million pounds of nitrogen, 12.5 million pounds of phosphorus, and 6.45 billion pounds of sediment per year, which represented a “25 percent reduction in nitrogen, 24 percent reduction in phosphorus and 20 percent reduction in sediment” (U.S. Environmental Protection Agency, 2014). States in the region discussed establishing nutrient credit trading programs as a way of meeting this goal, with a subset spearheading this effort (U.S. Environmental Protection Agency, 2025c). The Maryland Department of Environment and Agriculture implemented their nutrient credit trading program in 2018. In 2019, oyster aquaculture firms were included as voluntary participants under the Maryland program. Credits from oyster farming can be generated from harvest of up to four different size classes and ploidies (diploid and triploid). Larger oysters and higher ploidy generate a larger number of credits (Sandi, 2025).

There are a number of factors affecting the impact of the current policy. A majority of the oysters cultivated in the region are intended for the fresh half-shell market. Based on industry accounts, the vast majority of half-shell consumers prefer oysters that are in the small or extra small size grades (approximately 2 to 3 inches in length). Incentives to harvest at larger size classes, which are associated with higher filtration benefits, may be weak given the oyster consumer preferences for smaller oysters.²⁷ More importantly, denitrification has

²⁵The jurisdictions for the watershed include Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia and the District of Columbia. Not all states participate in nutrient credit trading (U.S. Environmental Protection Agency, 2025c).

²⁶For a recent review of water quality trading, see Horan et al. (2025).

²⁷Though more credits are generated from larger oysters, the per unit difference in credit generation is small, so the returns to growing larger oysters that may not be large enough to change the resource stock, i.e. biomass, held by the farms (Maryland Department of the Environment, 2023).

been more strongly associated with unharvested oyster reefs rather than harvested oyster aquaculture (Kellogg et al., 2014; Bruce et al., 2021; Ray et al., 2021).²⁸ Taken together, the evidence suggests that policies to reduce nutrient pollution through oyster aquaculture may perform better by incentivizing oyster biomass accumulation rather than harvest—the latter of which is currently implemented in the Maryland Nutrient Credit Trading Program.²⁹

3.1 Model with Nutrient Pollution

The model presented in Section 2 is quite general. I add specificity to the model from Section 2 to include the functional forms and parameters from economic and scientific literature, as well as pollution dynamics informed by the regional and regulatory context of the Chesapeake.

This specific industry and region fit the model in a few ways. First, oysters are filter feeders, which means oyster farmers do not incur feed costs, similar to lumber and unlike the livestock and fin fish aquaculture industries (National Oceanic and Atmospheric Administration, 2025). Further, according to both industry and government sources, farms have shifted towards production methods that utilize tidal energy, which minimizes labor and capital needed to generate “cupped” oysters for the half-shell market (Briggs and Gear, 2025). Given that the model abstracts away input costs, the lack of feed and minimization of other input costs by technologies at the frontier allow for the industry parameters to more closely fit the model. Further, leases to expand cultivation area are notoriously hard to obtain in the region (Metcalf, 2023). Therefore, limiting the model and calibration to intensive margin effects matches the industry’s regulatory constraints. Finally, though the Nutrient Credit Trading Program is active, oyster farm participation has been low in terms of total credits generated, which allows for a relatively clean interpretation of the calibration results (Maryland Department of the Environment, 2023).

To understand how the policies evaluated in steady state perform across time, functional forms and parameters for the numerical calibration must be made, as well as dynamic ad-

²⁸Note that a 2021 meta-analysis found no significant difference between oyster aquaculture and reef culture with respect to aquatic NH_4^+ , NO_x , and PO_4^{3-} removal (Ray and Fulweiler, 2021). However, the same authors concluded in a separate study that there are fundamental difficulties in study comparisons due to “methodological differences between studies, incomplete data reporting, and inconsistent measurements of environmental variables that may be used to predict denitrification” (Ray et al., 2021).

²⁹Note that extraction when oysters are at their largest may help remove more nitrogen relative to allowing deceased individuals to decay in the watershed (Bricker et al., 2020). The model in this paper assumes live biomass contributes to ecosystem benefits production in the broadest sense but does not explicitly address timing of harvest. There is recent work in forestry economics that incorporates timing of harvest in the presence of carbon storage incentives (see Tahvonen and Rautiainen (2017)), though more can be done to model the phenomenon in natural resource-based industries.

ditions to fit the nutrient pollution setting from which I draw. First, let the consumer have preferences over consumption C_t and the stock of pollution D_t , where pollution is taken as given. I assume a CRRA utility function for the consumer that is separable in consumption and pollution stock. The utility function for the representative consumer is

$$U(C_t, D_t) = \log(C_t) - \frac{D_t^{1-\eta} - 1}{1-\eta} \quad (33)$$

where $\eta < 1$. For simplicity, the representative consumer is assumed to have risk-neutral preferences over consumption.

Private goods production is a decreasing returns to scale Cobb-Douglas production function

$$F(H_t) = H_t^\alpha \quad (34)$$

such that $\alpha \in (0, 1)$. This reflects the presence of decreasing returns to scale in extractive renewable resources industries, such as the oyster industry, based on the production function estimation literature (Stier, 1980; Nautiyal and Singh, 1985; Scuderi and Chen, 2019).³⁰ The firm is assumed to operate at its frontier.

The growth function of the natural resource is a Pearl-Verhulst logistic growth function

$$G(S_t) = gS_t \left(1 - \frac{S_t}{\bar{S}}\right) \quad (35)$$

where $g = r - m$ is the intrinsic population growth rate, equal to the recruitment rate r (total spat divided by total adult oysters) less the mortality rate m , and $\bar{S}$ is the environmental carrying capacity within the cultivation area (Schaefer, 1991). While the Pearl-Verhulst growth function abstracts away from other exogenous factors that affect the population, it contains enough of the key features of single species population growth to serve as an initial benchmark for modeling and is thus considered the workhorse of mathematical ecology (Berryman, 2003; Shorrocks, 2024).³¹ Based on Equation 35, the level of the stock that attains maximum sustainable yield is $S_{MSY} = \bar{S}/2$ and the steady state level of harvest that attains maximum growth, or MSY, is $H_{MSY} = G(S_{MSY})$.

³⁰This can be due to many factors. For example, a lumber company that fells a tree may not observe ex ante that the lumber is low quality due to parasite infestation, adverse weather events, etc. They may therefore need to discard timber that would otherwise have been sold with better quality wood.

³¹Other functions can be substituted in that account for other population growth characteristics, such as Allee effects, as mentioned in Section 2 (Liermann and Hilborn, 2001).

The primary addition to the model is the evolution of pollution stock $\dot{D}$ in the watershed.

$$\dot{D} = e - B(S_t) \quad (36)$$

e represents emissions net of decay. $B(S_t)$ is the total amount of pollution removed by the stock of the resource at every instant, and implies that D_t is a function of S_t . The model in Section 2 is therefore a generalization of the one presented here. Net emissions are

$$e = e_{enter} - e_{exit} \quad (37)$$

where e_{enter} represents the total amount of exogenous emissions of inorganic nitrogen (N) that flow into the Chesapeake Bay watershed, measured in kilograms (kg) per year, and e_{exit} is the amount of inorganic N exiting the watershed through surface water transport. Given that the watershed system is complex and unstable, the equation below is used as a stylized back-of-the-envelope calculation for e_{exit} based on information reported in Lindsey et al. (2003), Lee et al. (2014) and Clune et al. (2021).

$$e_{exit} = SW \cdot RE \cdot e_{enter} \quad (38)$$

SW is the proportion of water per year entering the surface water network from either the groundwater system or from soil runoff. RE is the proportion of water that exits the Bay. e therefore represents the amount of inorganic N remaining in the watershed per year.

Finally, nitrogen removal benefits are based on Jordan-Cooley et al. (2011), which presents a model of oyster reef population growth with filtration and sedimentation. Due to the prevailing aquaculture techniques of rack and bag culture, which prevent oysters from using other individuals as substrate (Ray et al., 2021), I simplify the filtration function so that sedimentation is no longer a factor obstructing water filtration. F_{max} is the maximum filtration rate.³²

$$B(S_t) = F_{max} S_t \quad (39)$$

³²Filtration with sedimentation in Jordan-Cooley et al. (2011) is a function of oyster biomass

$$F(S_t) = \frac{F_{max}}{[Cg]_{max}} [Cg(S_t)] e^{\frac{[Cg]_{max} - Cg(S_t)}{[Cg]_{max}}}$$

where C is the maximum possible deposition rate, $g(S_t)$ represents sedimentation on deposition ($g(S_t) < 0 \forall t$), and $[Cg]_{max}$ is the maximum possible deposition given sedimentation for a given t . Without sedimentation (setting $g(S_t) = g_{max}$) yields

$$F(S_t) = F_{max}$$

The filtration function notation used above was reported in Lipcius et al. (2019).

There are a couple of important ecological and biological points to note. First, the Pearl-Verlhust population growth model, by construction, obscures away from age structure. This aggregation can have implications for predicting environmental benefits from the stock, as is elaborated on in the Discussion.

Second, studies have shown that nitrogen can be re-released into the ecosystem through oyster mortality and decomposition if oysters are not harvested at the end of the lifecycle. While nitrogen contained in tissue is immediately released upon decomposition, total nitrogen that remains in the watershed depends on location of the cultivation area and shell burial (Kellogg et al., 2013; Malmquist, 2013).³³

Given the lack of age structure in the Pearl-Verlhust model and the complexity of nutrient re-release, Equation 39 is interpreted as an upper bound approximation of the benefits provided by the natural resource stock. Note that the paths of pollution accumulation in this model are partially attenuated by the lower bound estimate of carrying capacity $\bar{S}$ (see description of parameters in Table 1) which greatly determines natural resource stock accumulation and, therefore, the change in nutrient pollution in the watershed.

The complete Social Planner's problem with nutrient pollution dynamics is presented below.

$$\begin{aligned}
U_0 &= \max_{\{C_t, S_t\}_{t=0}^{\infty}} \int_0^{\infty} e^{-\rho t} \left(\log(C_t) - \frac{D_t^{1-\eta} - 1}{1-\eta} \right) dt & (40) \\
\dot{S} &= gS_t \left(1 - \frac{S_t}{\bar{S}} \right) - H_t \\
\dot{D} &= e - F_{max}S_t \\
C_t &= H_t^{\alpha} \\
S_0 &> 0, D_0 > 0
\end{aligned}$$

The Euler Equation under the Social Planner is thus

$$g \left(1 - \frac{2S_t}{\bar{S}} \right) - \phi_t F_{max} \frac{C_t}{\alpha H_t^{\alpha-1}} = \rho - \left(\frac{\dot{C}}{C_t} \right)^{-1} - \frac{[\dot{H}_t^{\alpha-1}]}{H_t^{\alpha-1}} \quad (41)$$

$\phi_t < 0$ represents the shadow cost of nitrogen pollution stock accumulation. ϕ_0 is calibrated to \$10/kg N at $t = 0$ based on the upper bound of the social cost of nitrogen reported in Keeler et al. (2016). $-\phi_t F_{max} = U_S$ is therefore the marginal value to society of an additional

³³Shells contain approximately half of the total nitrogen sequestered in an oyster (Kellogg et al., 2013; Dalrymple and Carmichael, 2015).

kg of oysters accumulated with respect to the nitrogen filtration benefit it provides at time t . Note that the trajectory of the stock of pollution may not reach a steady state. This is due to fact that, first, the level of pollution is taken as given by the consumer where the only method of control in this setting is natural resource stock accumulation, and second, there are biological constraints in the system that can prevent a steady state level of pollution to be reached, even under the Social Planner. The rest of the results follow as in Section 2.³⁴

Equation 41 also suggests use of the following time-varying marginal stock subsidy.

$$\sigma_S = -\phi_t F_{max} \left(g S_t \left(1 - \frac{S_t}{\bar{S}} \right) \right)^\alpha \quad (42)$$

The functional form for $\sigma(S_t)$ cannot be pinned down because Equation 42 does not yield an elementary antiderivative with respect to the stock. However, given that the marginal policy function is a monotonic transformation of the growth function, which is commonly modeled by stock assessment biologists, the marginal incentive is implementable if S_t is known.

The parameters used for numerical calibration are presented in Table 1, along with the sources for each parameter where applicable. Reports of individual oysters of commercial harvest size (76 mm or approximately 3 inches shell length) are converted to kg of wet weight biomass using Mann et al. (2009).³⁵ Carrying capacity is approximated as the maximum commercial harvest of Eastern oysters between 1993 and 2022 and serves as a lower bound of the environmental carrying capacity. Filtration rate F_{max} was converted from the effect size reported in Cornwell et al. (2023) for the Chesapeake Bay Program Partnership to annual N per acre per year removed by 300 grams of oyster dry weight per square meter.

The harvest technology employed in this model does not provide a one-to-one comparison with the production inputs reported in previous production function estimation studies of the oyster industry (Scuderi and Chen, 2019; Beckensteiner et al., 2021), so I choose $\alpha = 0.8$ as an informed starting point based on discussions with industry professionals.³⁶ The pollution curvature parameter and initial values are chosen for ease of graphical display.

³⁴Other additions to this model can include costs to natural resource accumulation or harvest. The addition of these costs do not fundamentally alter the conclusions of this paper.

³⁵All dry weight measures are converted to wet weight by multiplying dry weight in g by 100. One standard bushel of oysters weighs approximately 45 to 60 lbs and contains between 100 to 150 oysters. Conservatively, the smallest average market size oyster (76 mm shell length) weighs 4.8 oz unshucked. Given that an oyster shell weighs 1 to 2.5 oz, 1 g of oyster dry weight is equivalent to 3.5274 oz wet weight, which is the approximate wet weight of shucked oyster of market size (Grizzle et al., 2017).

³⁶ α can also vary with environmental and regulatory conditions, which I do not explore in this paper.

3.2 Numerical Analysis

All numerical results are generated in Matlab 2025a using `ode45`. I use the equilibrium conditions and functional forms stated above as inputs. The system is optimized over 100 years ($T = 100$) for ease of display and the paths are continue along its steady state trajectories as $t \rightarrow \infty$. Initial guesses for the transition path of harvest are made under each policy scenario.³⁷ Paths are chosen based on maximization of total surplus in present values over the following functional forms: linear, exponential, and sigmoidal. The specific functional forms and total surplus results are presented in Appendix Section B.

No-policy and the flow incentive yield a closed form solution for the stock in steady state under a 2% discount rate at $S_T^{np} = 9,596,296.406$ kg, where the superscript np indicates steady state allocations under no policy and the flow incentive. Extraction at the end of the graphical time period is then $H_T^{np} = 1,702,760.055$ kg. The time paths under the Social Planner do not have closed form solutions in steady state. However, the theoretical results suggest that S_T^* under the Social Planner is greater than under no policy or the flow incentive, so I set $H_T^* = H_T^{np} \cdot 0.8$ for illustrative purposes. The transition paths are adjusted from their initial guesses over 25 iterations with a step size of 0.000001.

3.2.1 Theoretical Benchmarks

To understand how policy deviations may help or hinder environmental benefits provision across time, we must first address how the natural resource and pollution evolve under the theoretical benchmarks. Figure 1a shows the evolution of the natural resource stock across time. The blue line represents the trajectory under the social optimum and the green line is the equilibrium path under no policy. The natural resource stock under the social optimum diverges away from the no policy benchmark immediately and converges to the steady state level of the stock at approximately 14.7 million kg of biomass within 40 years. The pollution stock (Figure 1b) similarly diverges between the two benchmarks, where the stock of pollution under the social optimum is lower than no policy for all instants except $t = 0$, though the trajectories more noticeably diverge at $t = 8$. This is driven by differences in extraction or harvest—the level of harvest under no policy exceeds the social optimum across time. The trajectories align with the theoretical results of Sections 2.1 and 2.2, where lower levels of harvest under the social optimum result in a natural resource stock that is higher than the firm’s maximum sustainable yield $S^* > S_{MSY}$ in steady state.

³⁷The trajectories can adjust based on initial values for H_0 , S_0 , D_0 and end value H_T^* . Paths under different initial value guesses and H_T^* in particular do not fundamentally change the results.

The following subsections explore how proxy policies, incentives targeting stocks or flows, with other policy design choices, can affect dynamic environmental benefits provision. Given the straightforward correspondence between the resource stock, pollution, and extraction, I mainly focus on the trajectories of the resource stock for the remainder of the section.

3.2.2 Constant Marginal Incentives

Based on Equation 18, a stock-targeted incentive must be a subsidy for a firm to conserve more resource stock than under no policy across time. By contrast, the results in Section 2.4 suggest that either a flow-targeted tax or a flow subsidy that increases over time may incentivize a firm to accumulate more resource stock. Here, I focus on flow-targeted taxes and stock-targeted subsidies with constant marginal values across time. Performance of time-varying flow subsidies is discussed in the next section.

Figure 2 presents the time paths of the natural resource stock under constant marginal subsidies relative to the no policy (green line) and socially optimal (blue) benchmarks. The policies vary by size of the subsidy to illustrate how scale can affect stock accumulation for illustrative purposes. “Small” (yellow) is the trajectory calibrated under an incentive set at 1000 USD per kg of the resource stock across time. “Medium” (orange) is under a subsidy of 10,000 USD per kg. “Large” (red) is under a subsidy of 445,000 USD per kg. In Figure 2a, “Very Large” (purple) is under a subsidy of 8,092,113.71 USD per kg, i.e. the socially optimal monetary value of resource stock accumulation at $t = 0$ multiplied by two. In Figure 2b, “Very Large” (purple) corresponds to a subsidy of 20,230,284.25 USD per kg, i.e. the socially optimal value of resource stock accumulation at $t = 0$ multiplied by five.

There is a striking difference in the performance of stock subsidies versus flow taxes across time. Increasing the value of a stock subsidy increases the stock of biomass, consistent with the results in Section 2.3 (Figure 2a). As the value increases, the firm accumulates more resource stock across the time path, though order of magnitude increases subsidy value yield lower relative increases in biomass accumulation. Taxes on flows, i.e. harvest, do little to induce the firm to increase the resource stock beyond no policy (Figure 2b). While flow taxes can push the firm to accumulate the natural resource in the short run, gains in the stock and, therefore, environmental quality, are minimal. The largest penalties on flows induce, at most, a 0.2% increase in the resource stock at its peak (Figure 3). Unsurprisingly, such a policy may not be worthwhile cost-benefit-wise. Firms experience large negative profits across time without substantial gains in total consumer utility, especially under scenarios that would yield even minor notable increases in the resource stock (Figure A.2).

3.2.3 Time-Varying Policies

There are a plethora of incentives one can model with values that vary across time, whether one targets stocks or flows. Here, I focus on those of with the most policy-relevance—stock subsidies predicted to obtain the social optimum, and a flow subsidy that a well-intentioned policymaker sets at the “socially optimal” values across time ($\tau_H = U_S/U_C$ for all t). The latter is the analogue to credit design under the Maryland Nutrient Credit Trading Program.

First, Proposition 1 suggests that for a stock policy, any marginal incentive that equals the marginal rate of substitution between the stock and consumption in steady state can yield allocations that converge to the social optimum. Figure 4 shows how these trajectories deviate from the Social Optimum under two policies – one that instantaneously updates (“Time-Varying”, orange) based on Equation 42, and one that is set at the steady state value of stock accumulation for all t (“Steady State”, yellow). The time paths for both policies coincide closely with the Social Optimum across time. The slightly higher initial levels of biomass under a time-varying stock subsidy is primarily from an initial approximation error, where the policy does not fully account for the effects of harvest on the growth of the resource, though deviations from the social optimum prior are small (within 0.015%).

By contrast, a well-intentioned flow subsidy set at the “socially optimal” values across time results in lower stock accumulation relative to no policy (within 0.05%) in the short run (black line in Figure 4b). The results support the hypothesis in Section 2.4 that small instantaneous increases in the subsidy may induce a firm to extract more today if it does not foresee large returns to conserving biomass for future production.

This is further supported by the results in Figure 5, which implement the time-varying policies described above but with five, ten, 25, and 50 year lags in updates to mimic administrative constraints by policymakers. In general, the paths do not deviate much from their respective benchmarks (Social Optimum for stock subsidies, No Policy for flow subsidies) across the paths. Interestingly, for flow subsidies, the five and 10 year policy updates result in lower levels of biomass accumulation relative to larger increases under the 25 and 50 year lags in policy adjustments. The results support the interpretation of Equation 32 where the firm reduces harvest today if it anticipates higher returns from harvest in the future, which occurs in policy lag calibration (Figure A.4). The results together suggest that time variation in either stock- or flow-targeted policies may not play a strong role in changing firm accumulation of natural resources and, therefore, environmental benefits provision.

4 Discussion

The theoretical and calibration results point to a relatively straightforward story—to maximize the environmental benefits provided by a natural resource, incentives targeting a more direct proxy for those benefits, accumulation of the resource stock, outperform extraction or harvest incentives in both the short and long run. While this does not preclude the success of other incentive structures that include harvest as a component (for example, a flow incentive that adjusts conditional on the stock), the relationships highlighted in this paper must be addressed first for incentives to meet the intended goal of improving environmental quality.

There are several limitations to interpretation of this work, as well as potential avenues for model extension. First, the results are purely ordinal. While the model is calibrated to parameters that reflect the realities of the region and industry of focus, there are important economic and ecological realities I abstracted away from to provide clarity over policy performance rankings. For example, a significant contributor of water quality benefits are non-harvested oyster reefs, which often exist adjacent to aquaculture operations. A primary rationale for reef restoration is to improve local surface water quality (National Oceanic and Atmospheric Administration, 2024a). The model does not account for adjacent stocks that independently affect environmental quality and their interactions with firm operations or provision of ecosystem services via commercial production. Therefore, interpretations of dollar values and levels of benefits from the calibration should be interpreted with caution.

Second, the model does not account for the costs of policy administration, which can influence the relative attractiveness of some policies versus others. While flows are far easier to measure, the numerical exercise suggests that in the presence of program implementation costs, the benefits of a flow incentive may not be enough to warrant the policy. Further, the costs of the stock subsidy can outweigh its benefits if a policymaker wants to obtain levels of the resource, and thereby environmental quality, that are higher than the social optimum.

Third, the model is agnostic to harvest timing and species age composition. Studies suggest there may be an age class at which environmental benefits are maximized for an individual oyster. After this age is reached individuals can, on net, re-release the offending pollutant (Dalrymple and Carmichael, 2015). Due to the aggregate nature of the growth function, I am unable to distinguish how age composition affects the different policy scenarios. The presence of a socially optimal harvest age can have implications for policy performance. Age-differentiated policy performance is an intended line of future work.

Fourth, the results capture strictly intensive margin effects. Though the industry fits the

model in this paper, changes to the extensive margin occur in similar industries (U.S. Department of Agriculture, 2020b; U.S. Department of the Interior, 2025; Scott et al., 2025). Flow incentives can affect environmental quality along the extensive margin in ambiguous ways, especially if there are naturally-occurring stocks of target species in the production perimeter. Increases in environmental quality can happen in areas where the stock is sparse *ex ante*. Decreases can arise in areas with high species densities due to production methods that “spread out” the stock. The latter occurs in the oyster industry, where aquaculture displaces densely-populated reefs if barriers to obtain additional leases are sufficiently low.

Finally, the analysis abstracts away from other industry phenomena such as firm heterogeneity and technical change and does not explore policies that are explicit functions of time. Aside from the reasons stated in Section 2.4, a subsidy that is an increasing function of time in real terms would be fiscally impractical given government budget constraints. This is therefore not a class of incentives featured in this paper. Future lines of research can include firm heterogeneity, technical change, non-convex environmental benefits functions, and other goods that are substitutes/complements to either the private good or social benefit (Starrett, 1972; Sudit and Whitcomb, 1976; Xabadia et al., 2008; Jordan-Cooley et al., 2011).

5 Conclusion

Economists have generally assumed that internalizing environmental externalities can be done by targeting flows of production. However, this may not be the case when externalities are generated from stocks of natural capital. I employ a dynamic optimization model of renewable natural resource extraction using an infinite horizon, continuous time framework to evaluate how policy targets effect the efficacy of incentive programs instrumentalizing privately-owned natural capital to improve environmental quality. I find that even under an idealized setting with no firm entry, costless extraction, stable institutions, etc., policies targeting flows of production provide no additional environmental benefit in steady state. Subsidies that target accumulation of the resource stock, a closer proxy of environmental benefits production, yield higher social gains relative to no policy in steady state. A subset of stock-targeted policies can yield socially optimal allocations if appropriately designed.

I then explore dynamic paths that lead to the theoretical steady state results by calibrating counterfactual policies to address inorganic nitrogen pollution in surface and groundwater. The model is calibrated to hydrological parameters from the Chesapeake Bay as well as biology and industry parameters for Eastern oyster production and its associated water cleaning benefits. In addition to the core stock versus flow policy comparison, I vary the policies by

sign, scale, and lags in policy updates to mimic real world administrative constraints.

The dynamic results support those derived in the theory, where the time path of all calibrated flow policies closely track the paths under no policy. While taxes on flows incentivize firms to minimally improve environmental quality in the short run, due to substantial negative returns across time relative to gains in consumer surplus, the overall welfare benefits of a flow tax appear to be minimal. Further, the scale and sign of the policies matter for how closely stock-targeting leads to the socially optimal level of environmental quality. Delays in updating the monetary value of incentives matter little regardless of target.

The results can be explained by revenue constraints for the firm under different policy targets. First, under stock-targeting, the producer operates as a multi-product firm, where it produces both the private good and an environmental service proxied by the natural capital stock held in inventory. This allows for the firm to forego production of the private good in favor of maximizing revenues generated from the resource stock. Allowing for revenue generation from its resource stock intuitively leads to increases in resource conservation/accumulation.

Second, under flow-targeting, the firm obtains revenues solely from private goods production, i.e. extraction. This revenue source is the same as the no-policy scenario and in this state of the world, the firm obtains a stock level that maximizes profits across time but is lower than what is socially optimal. Without other revenue sources that more directly scale with the social or environmental benefit, namely the stock itself, the firm does not have the incentive to substantially increase their stock beyond the no-policy scenario. Based on both the theoretical and numerical results, policymakers instrumentalizing privately-owned living natural resources should implement policies that directly target the accumulation of those stocks, as in many PES programs, rather than those that target harvest.

The model presented in this paper emphasizes the importance of living natural resources as sources of external benefits or damages in and of themselves, as well as the need to account for the special dynamics of these resources when designing policies. The results align with a recent review highlighting potential failures in nature-based credit markets when proxy targets of incentives are too far removed from the biological and ecological characteristics that provide environmental benefits (zu Ermgassen et al., 2026). While the current paper focuses on privately-owned natural resources as instruments to improve environmental quality, the general setting can be extended to other natural resource settings such as species conservation, shoreline protection, and groundwater management. The broader hope is that the model presented here serves as useful tool for policymakers and researchers as we continue to explore market-based and regulatory tools to minimize damages to the environment.

6 Tables and Figures

Table 1: Parameters and Sources

Parameters		Estimate	Source
Recruitment rate	r	0.4349	Maryland Department of Natural Resources (2020)
Mortality rate	m	0.1	Doering et al. (2021)
Carrying capacity	$\bar{S}$	20,411,640 kg	Tarnowski (2023)
Nitrogen loadings	e_{enter}	131,541,680 kg/yr	Clune et al. (2021)
Surface water	SW	0.5	Clune et al. (2021)
River export	RE	0.72	Lee et al. (2014)
Filtration rate	F_{max}	5.29 kg/kg/yr	Cornwell et al. (2023)
Social discount rate	ρ	2%	Council of Economic Advisers (2024)
Output elasticity	α	0.8	Industry Sources
Pollution curvature	η	0.75	
Initial harvest	H_0	$H_{MSY} \cdot 0.75$	
Initial stock	S_0	$S_{MSY} \cdot 0.45$	
Initial pollution	D_0	10,000,000 kg	

Figure 1: Resource and Pollution stock Trajectories Under Theoretical Benchmarks

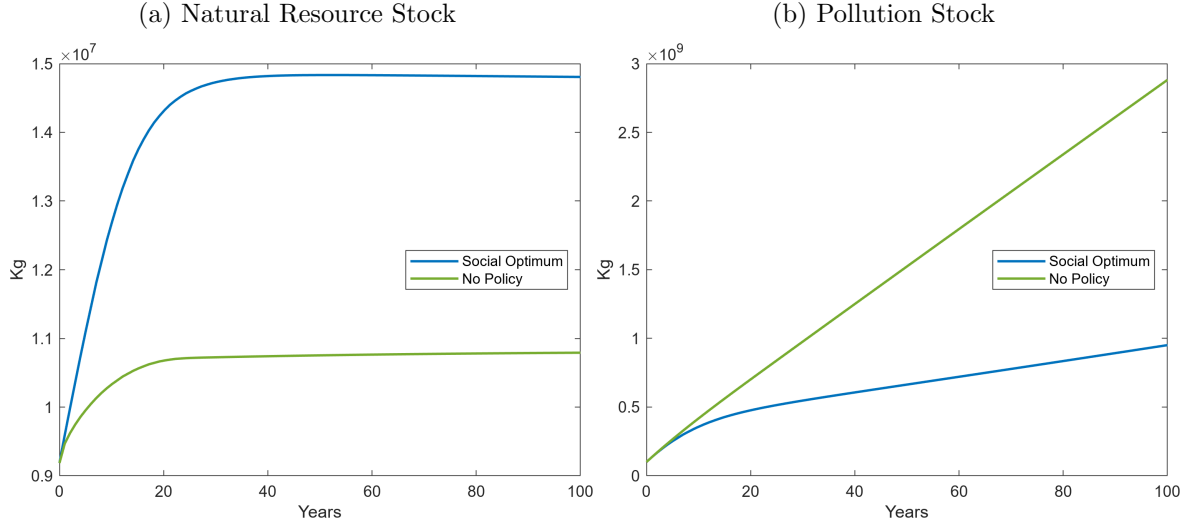


Figure 1a displays the levels of the natural resource stock, measured in kilograms (kg), over time under the socially optimal and no-policy theoretical scenarios. Figure 1b displays the levels of the inorganic nitrogen stock, measured in kilograms (kg), over time under the same theoretical scenarios. Lines in blue are trajectories under the Social Optimum. Lines in green are trajectories under No Policy.

Figure 2: Resource Stock Trajectories Under Constant Marginal Incentives

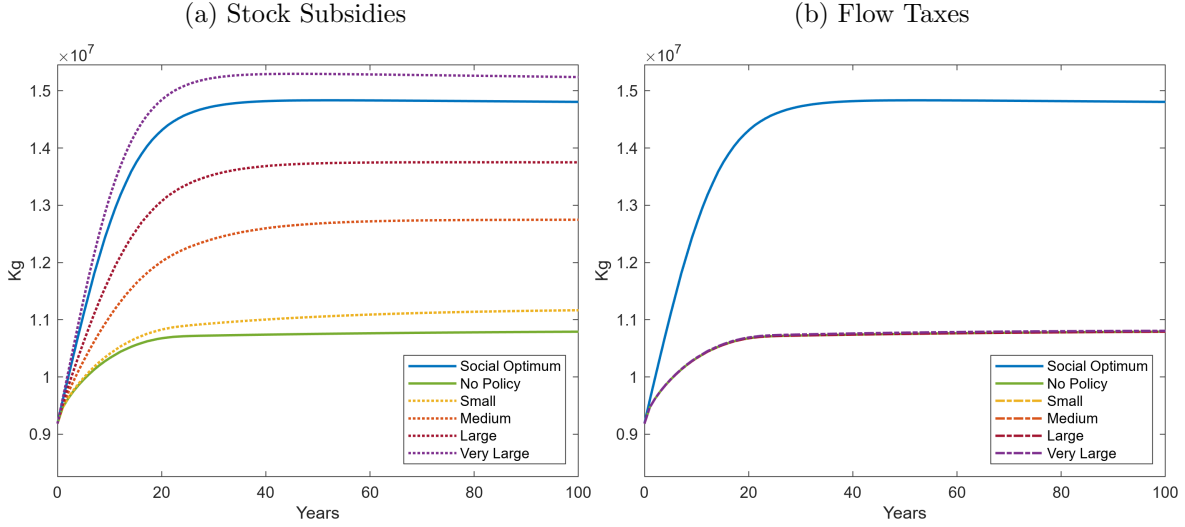


Figure 2a shows the levels of the natural resource stock, measured in kilograms (kg), over time under marginal stock-targeted incentives set at a single value for all t (dotted lines). “Small” (yellow) is the trajectory calibrated under an incentive set at 1000 USD per kg of the resource stock. “Medium” (orange) is under a subsidy of 10,000 USD per kg. “Large” (red) is under a subsidy of 445,000 USD per kg. “Very Large” (purple) is under a subsidy of 8,092,113.71 USD per kg, i.e. the socially optimal monetary value of resource stock accumulation at $t = 0$ multiplied by two. Figure 2b displays the levels of the natural resource stock, measured in kilograms (kg), over time under progressively increasing constant marginal flow-targeted disincentives (dot-dash lines). The dollar values are the negatives of those featured in Figure 2a except the “Very Large” disincentive (purple), which is the trajectory under a tax of 20,230,284.25 USD per kg, i.e. the socially optimal value of resource stock accumulation at $t = 0$ multiplied by five. Socially optimal (solid blue) and No Policy (solid green) trajectories are included for comparison.

Figure 3: Resource Stock Deviations from No-Policy Under Constant Marginal Flow Taxes

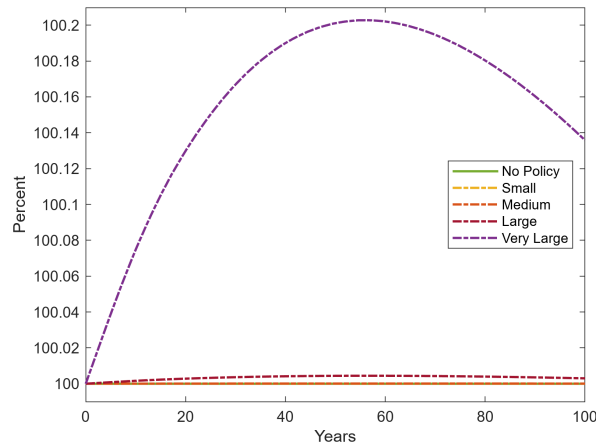
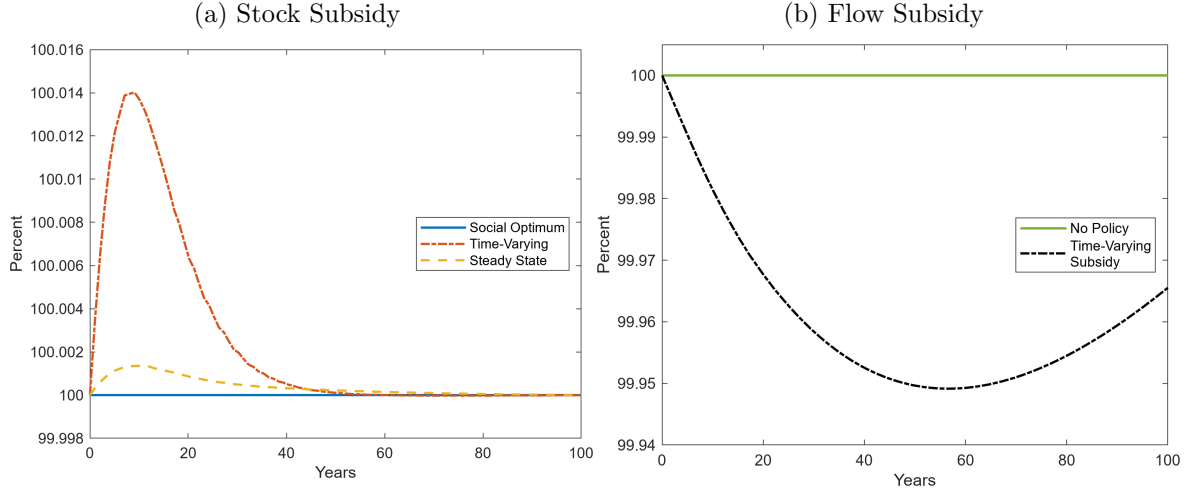


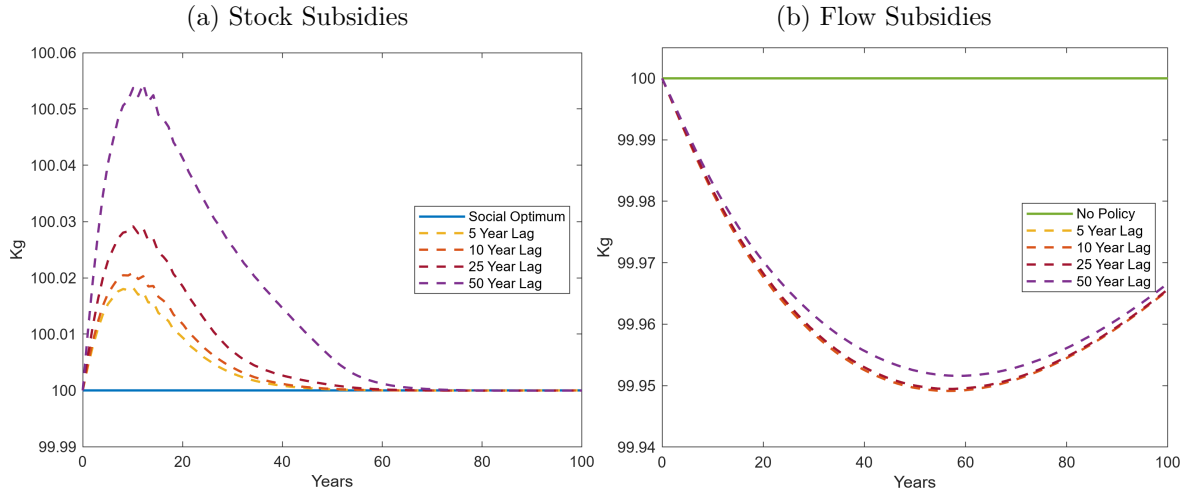
Figure 3 shows the deviations of the natural resource stock from the no policy benchmark under marginal flow-targeted disincentives set at a single value for all t (dot-dash lines). “No Policy” (solid green) is indexed at 100 for all instants. “Small” (yellow) is the trajectory calibrated under a tax set at 1000 USD per kg of the resource stock. “Medium” (orange) is under a tax of 10,000 USD per kg. “Large” (red) is under a tax of 445,000 USD per kg. “Very Large” (purple) is under a tax of 20,230,284.25 USD per kg, i.e. the socially optimal value of resource stock accumulation at $t = 0$ multiplied by five.

Figure 4: Resource Stock Deviations from Benchmarks Under Time-Varying Subsidies



Figures 4a-4b show the deviations of the resource stock from the theoretical benchmarks under subsidies that, primarily, vary over time. In Figure 4a, “Social Optimum” (solid blue) is indexed at 100 for all instants. The orange dot-dashed line (“Time-Varying”) is the trajectory deviation under a time-varying subsidy set that converges to the steady state value of stock accumulation under the Social Planner. The yellow dashed line (“Steady State”) is the trajectory deviation under a subsidy set at the steady state value of stock accumulation under the Social Planner for all t . In Figure 4b, “No Policy” (solid green) is indexed at 100 for all instants. The black dot-dashed line (“Time-Varying”) is the trajectory deviation under a time-varying subsidy set at the value of stock accumulation as if under the Social Planner.

Figure 5: Resource Stock Deviations from Benchmarks Under Subsidies with Update Lags



Figures 5a-5b show the deviations of the resource stock from the theoretical benchmarks under “socially optimal” incentives that vary over time but exhibit lags in updates (dashed lines). In Figure 5a, “Social Optimum” (solid blue) is indexed at 100 for all instants. In Figure 5b, “No Policy” (solid green) is indexed at 100 for all instants. The trajectories are calibrated to incentives that update every 5 years (yellow), 10 years (orange), 25 years (red), and 50 years (purple).

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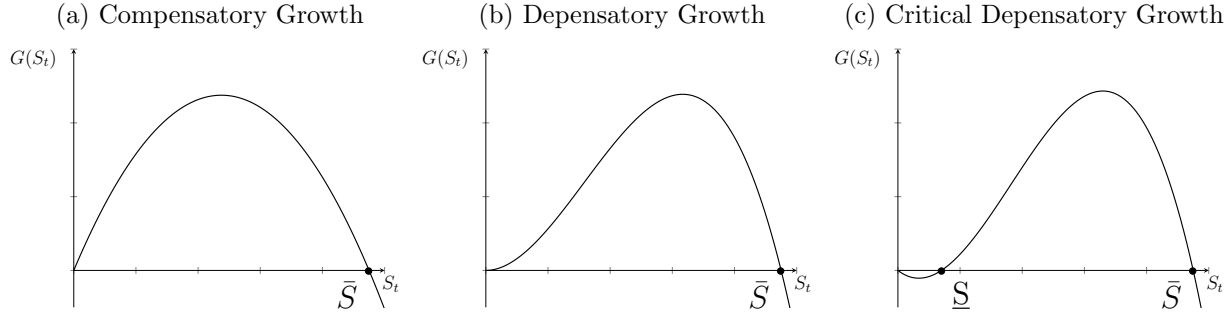
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Appendix for “Stocks vs. Flows”

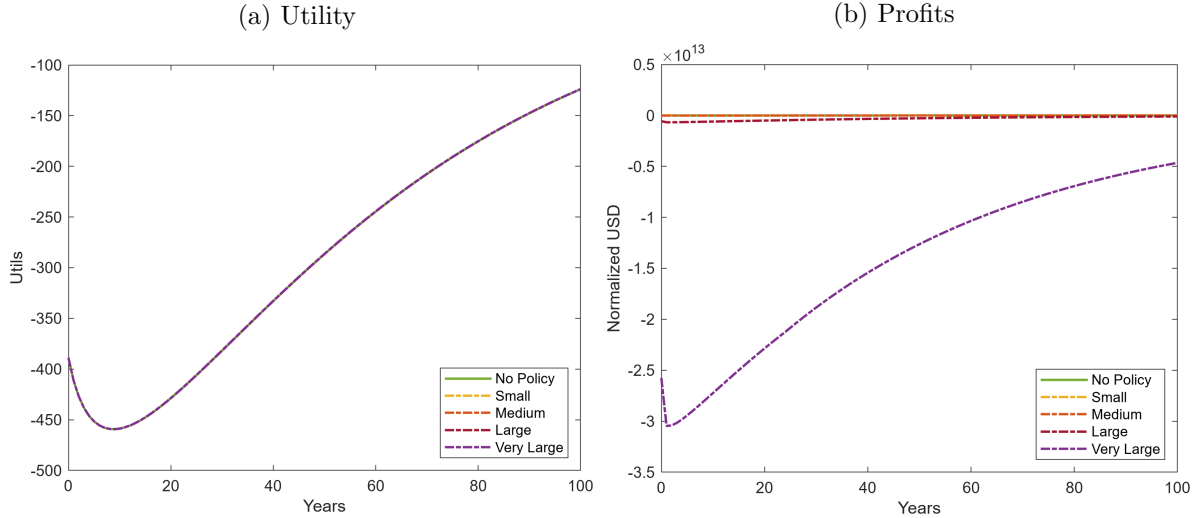
A Figures

Figure A.1: Population Growth Functions



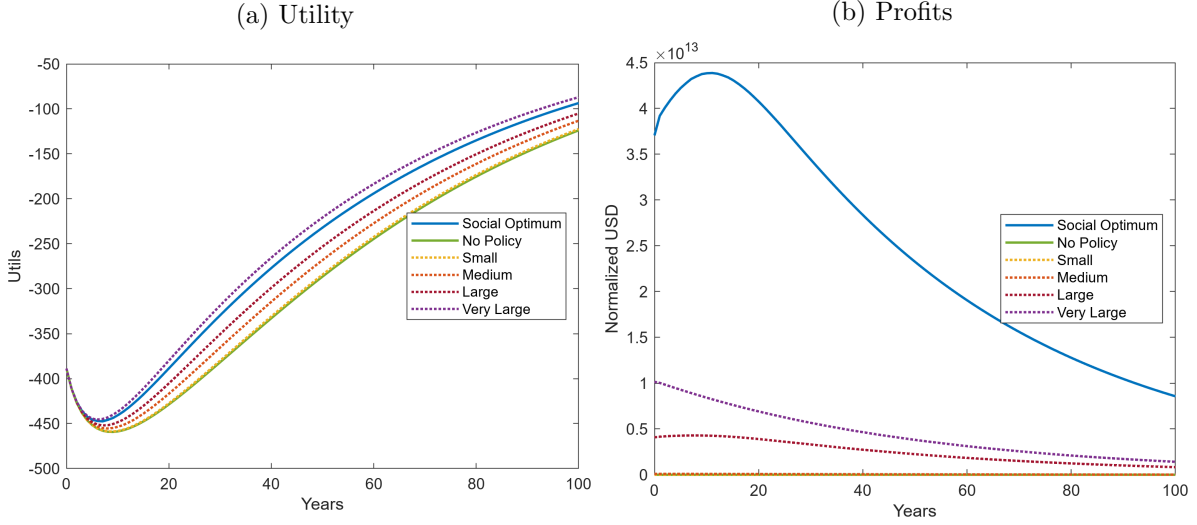
The figures represent different population growth functions for a single species within a fixed geographic area, i.e. habitat. Panel (a) represents pure compensatory growth, which is concave with respect to the total stock of biomass S_t across all levels of biomass, and where population growth converges to zero as the stock reaches the environmental carrying capacity $\bar{S}$, which is time-invariant under the current model. Panel (b) represents depensatory growth, which is concave up to a given level of biomass and then concave, converging to $\bar{S}$. Panel (c) represents critical depensatory growth, where growth is negative up to a critical threshold $\underline{S} > 0$, also referred to as the “Allee threshold.” This indicates that the population may collapse at or below some positive stock level $\underline{S}$.

Figure A.2: Utility and Profit Trajectories Under Constant Marginal Flow Taxes



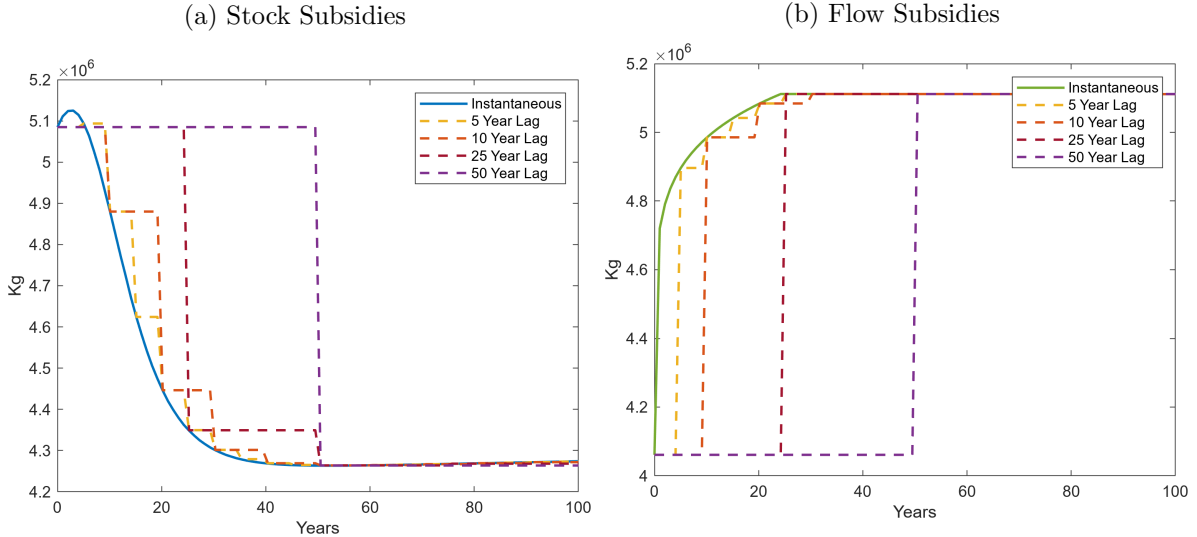
Figures A.3a-A.2b show the trajectories of utility and profits, respectively, in present values under marginal flow-targeted disincentives set at a single value for all t (dot-dash lines). “Small” (yellow) is the trajectory calibrated under a tax set at 1000 USD per kg of the resource stock. “Medium” (orange) is under a tax of 10,000 USD per kg. “Large” (red) is under a tax of 445,000 USD per kg. “Very Large” (purple) is under a tax of 20,230,284.25 USD per kg, i.e. the socially optimal monetary value of resource stock accumulation at $t = 0$ multiplied by five. No Policy (solid green) is included for comparison.

Figure A.3: Utility and Profit Trajectories Under Constant Marginal Stock Subsidies



Figures A.3a-A.3b shows the trajectories of utility and profits, respectively, in present values under marginal stock-targeted incentives set at a single value for all t (dotted lines). “Small” (yellow) is the trajectory calibrated under an incentive set at 1000 USD per kg of the resource stock. “Medium” (orange) is under a subsidy of 10,000 USD per kg. “Large” (red) is under a subsidy of 445,000 USD per kg. “Very Large” (purple) is under a subsidy of 8,092,113.71 USD per kg, i.e. the socially optimal value of resource stock accumulation at $t = 0$ multiplied by two. Socially optimal (solid blue) and No Policy (solid green) trajectories are included for comparison.

Figure A.4: Incentive Trajectories Under Policy Lags



Figures A.4a-A.4b show the values of stock- and flow-targeted incentives that exhibit lags in updates (dashed lines). In Figure A.4a, the time-varying stock incentive that converges to the Social Optimum is in solid blue. In Figure A.4b, the “socially optimal” flow subsidy ($\tau_H = U_S/U_C$ for all t) are in solid green. The trajectories are calibrated to incentives that update every 5 years (yellow), 10 years (orange), 25 years (red), and 50 years (purple).

B Harvest Trajectories and Total Surplus

An initial guess of the trajectory for harvest must be provided in order to calibrate the model. The system adjusts over subsequent iterations based on the evolution of the state variables (the stocks of the natural resource and pollution) and the costate equations (the Euler equation). However, the model does not provide direct insight into the shape of the time path for the control variable of the system. Therefore, I provide the following guesses of the trajectory: linear, exponential, and sigmoidal. The functional forms of each guess are below.

$$H_t = \begin{cases} H_0 + \left(\frac{|H_t - H_0|}{T}\right) t & \text{if } H_0 < H_t \\ H_0 - \left(\frac{|H_t - H_0|}{T}\right) t & \text{otherwise} \end{cases} \quad (43)$$

$$H_t = \begin{cases} H_0 + \left(\frac{|H_t - H_0|}{(0.25T)^\chi}\right) t^\chi & \text{if } t \leq 0.25T \text{ \& } H_0 < H_t \\ H_0 - \left(\frac{|H_t - H_0|}{(0.25T)^\chi}\right) t^\chi & \text{if } t \leq 0.25T \text{ \& } H_0 > H_t \\ H_t & \text{if } t > 0.25T \end{cases} \quad (44)$$

$$H_t = \begin{cases} H_0 + |H_t - H_0| \left(\frac{1}{1+\psi e^{\omega t}}\right) & \text{if } H_0 < H_t \\ H_0 - |H_t - H_0| \left(\frac{1}{1+\psi e^{\omega t}}\right) & \text{otherwise} \end{cases} \quad (45)$$

The exponential time path is piecewise based on $t \leq 0.25T$ in order to allow flexibility in the time to convergence, which in the current model is set at 25 years after policy implementation. The curvature parameter $\chi = 0.15$ reflects quick convergence to the steady state and is chosen based on conversations with industry professionals. Similarly, $\psi = 50$ and $\omega = -0.4$ determine the speed and timing of convergence under a sigmoidal trajectory.

Each time path is given the same H_0 , while the ending values H_t depend on theoretical predictions. BAU and flow incentives are given $H_t = H_{MSY}$, while the system under the Social Planner and stock incentive are given $H_t = 0.8H_{MSY}$. The system is then calibrated to each initial guess, and the present discounted values of consumer and producer surplus are calculated to find the trajectory that maximizes total surplus. Using parameters and initial values in Table 1, the following surpluses were calculated for the main policy calibrations.

The exponential trajectory for harvest maximizes total surplus under all scenarios. The calibrations under time varying policy updates and policies under different signs and scales similarly choose exponential paths as the surplus maximizing initial guess. Therefore, I use exponential paths as the primary initial guess for the system in the results presented in

Section 3.2.

Table B.1: Harvest Trajectories and Surpluses

Policy	Initial Guess	Producer Surplus	Consumer Surplus	Total Surplus
Social Planner	Linear	3,373,956.37	-24,490.76	3,349,465.61
	Exponential	3,477,056.73	-25,210.19	3,451,846.53
	Sigmoid	3,453,650.69	-24,946.73	3,428,703.96
BAU	Linear	3,626,551.43	-25,493.32	3,601,058.11
	Exponential	4,128,596.12	-29,344.84	4,099,251.28
	Sigmoid	4,014,456.99	-27,801.29	3,986,655.69
Stock	Linear	3,373,860.87	-24,489.49	3,349,371.38
	Exponential	3,476,926.41	-25,208.71	3,451,717.69
	Sigmoid	3,453,532.18	-24,945.39	3,428,586.79
Flow	Linear	3,628,154.99	-25,504.93	3,602,650.05
	Exponential	4,128,750.16	-29,346.82	4,099,403.33
	Sigmoid	4,014,971.70	-27,805.87	3,987,165.83