Optimum extraction of renewable resources - Fishery

Lecture Notes for the course Natural Resource Economics (AEC-608)

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1 Introduction

Renewable resources, such as forests, fisheries, and groundwater, differ fundamentally from exhaustible resources because they can replenish themselves through natural growth or regeneration. This regenerative property means that, if managed properly, renewable resources can provide a continuous flow of benefits to society over time, rather than being depleted after a single use.

The management of renewable resources centers on balancing current use with future availability. The goal is to achieve sustainable yields-harvest levels that do not compromise the resource's ability to regenerate-while also considering economic, social, and ecological objectives. Effective management ensures that both present and future generations can benefit from the resource.

Key questions that arise in the economics and management of renewable resources include:

- **What is the optimal rate of use for a renewable resource?** This involves determining how much of the resource can be harvested without reducing its stock below a level that can sustain future use.
- **How does the biological growth process affect economic decision-making?** Since the rate at which a resource regenerates depends on its current stock, understanding the biological dynamics is crucial for setting harvest policies.
- **What are the implications of property rights and common-property regimes?** The way in which access to the resource is governed-whether through private ownership, common property, or open access-has significant effects on incentives and outcomes.
- **How do the economic optimum and the biological optimum (maximum sustainable yield) compare?** While biology may suggest a certain harvest level is sustainable, economic considerations (such as costs, prices, and discounting) may lead to a different, often more conservative, optimum.

2 Biological Growth and Resource Dynamics

The defining feature of a renewable resource is its ability to regenerate or replenish itself over time. The stock of the resource at any time, denoted $X(t)$, changes according to the interplay between its natural growth and the rate at which it is harvested or extracted by humans.

Mathematically, the evolution of the resource stock can be described by a differential equation:

$$\frac{dX}{dt} = G(X) - H(t)$$

where:

- $G(X)$ is the natural growth function, representing the net increase in resource stock due to biological processes such as reproduction, recruitment, or regrowth. The form of $G(X)$ depends on the resource but is often assumed to be logistic for simplicity.
- $H(t)$ is the harvest or extraction rate at time t, representing the amount of resource removed by human activity.

Typical growth curve:

- At low stock sizes, growth is slow because there are few individuals to reproduce or regenerate the resource (e.g., few fish to spawn).
- As the stock increases, growth accelerates due to more individuals contributing to reproduction, reaching a maximum at an intermediate stock size.
- As the stock approaches the carrying capacity K (the maximum population the environment can sustain), growth slows down and eventually stops due to limiting factors such as competition for food, space, or other resources.

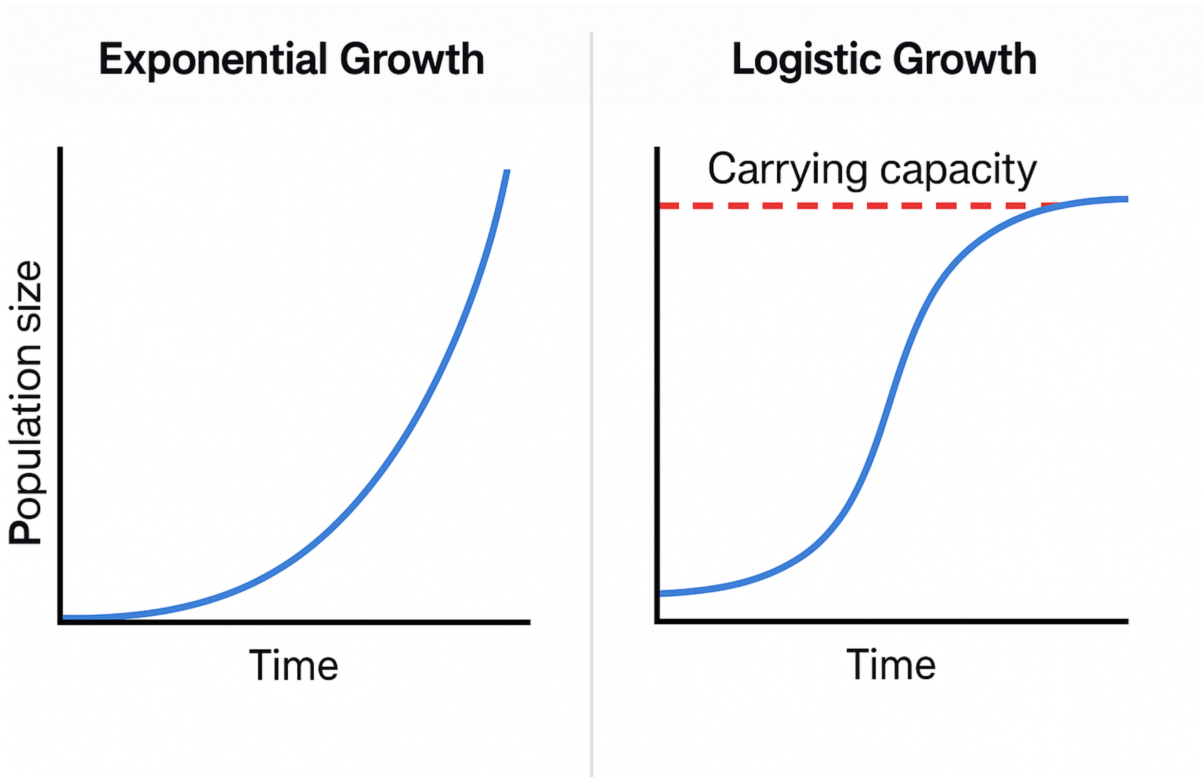

Figure 1: Biological growth law: $G(X)$ as a function of stock size X. The curve is typically hump-shaped, peaking at an intermediate stock size.

A common functional form for the growth function is the logistic growth model:

$$G(X) = rX\left(1 - \frac{X}{K}\right)$$

where:

- r is the intrinsic growth rate, representing the maximum per capita rate of increase,
- K is the carrying capacity, the maximum stock size the environment can support.

This model captures the essential features of renewable resource growth: slow growth at low and high stock sizes, and maximum growth at an intermediate stock.

3 A Model of Optimal Use

The central economic problem in renewable resource management is to determine the harvest path $H(t)$ that maximizes the present value of net benefits from the resource over time, while respecting the biological growth constraint. This is a dynamic optimization problem, as decisions made today affect the future stock and thus future harvest possibilities.

Planner's Problem

The Instantaneous growth curve is given by the expression

$$G(X) = rX\left(1 - \frac{X}{K}\right)$$

Now, first we want to find the stock (or X) at which the growth rate is maximum. If we can maintain the stock at this point then the rate of growth would be maximum, and thus we reach Maximum Sustainable Yield.

To get MSY,

Differentiate the function

$$\frac{dG(X)}{dX} = r\left(1 - \frac{X}{K}\right) + rX\left(-\frac{1}{K}\right)$$

Simplifying:

$$\frac{dG(X)}{dX} = r - \frac{rX}{K} - \frac{rX}{K} = r - \frac{2rX}{K}$$

Set the derivative equal to zero to find the critical points:

$$r - \frac{2rX}{K} = 0$$

Solving for X:

$$r = \frac{2rX}{K}$$

$$K = 2X$$

$$X = \frac{K}{2}$$

Thus, the Maximum Sustainable Yield (MSY) occurs at:

$$X = \frac{K}{2}$$

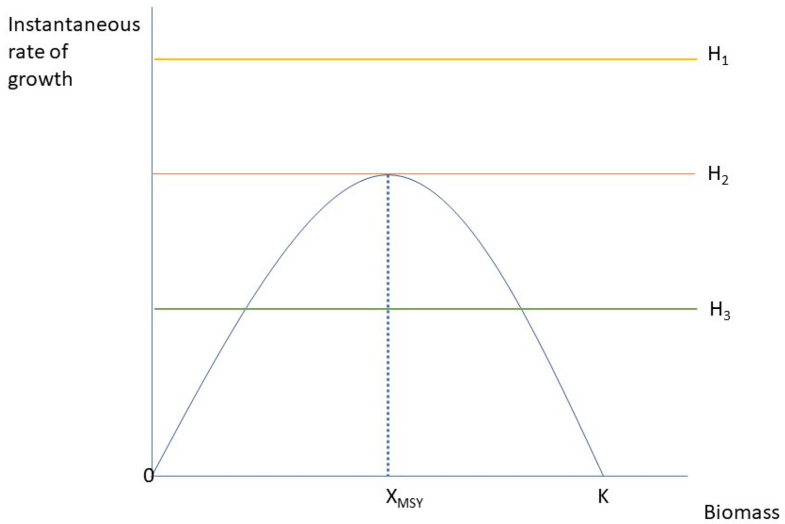

Figure 2: Harvest rates and Maximum Sustainable Yield

If you examine the figure, there are three distinct Harvest rates (harvest rate indicate harvest over a period of time).

- If the harvest rate is H_1, the rate of harvest is greater than the rate of growth. Over a period of time, there will be no stock left (Extinction of resource).
- If the harvest rate is H_2, the rate of harvest touches the growth curve corresponding to MSY- here stock will be maintained at $frack2$. Both harvest and stock will be same. This is biological optima.
- If the harvest rate is H_2, the rate of harvest intersects the growth curve at two points. Any point to the right of the MSY represent over exploitation and unsustainable.

4 Maximum Sustainable Yield (MSY) and the Biological Optimum

Maximum Sustainable Yield (MSY):

- The MSY is a key concept in renewable resource management. It represents the largest constant harvest that can be sustained indefinitely without depleting the resource.
- MSY is achieved at the stock size X_{MSY} where the natural growth function $G(X)$ reaches its maximum. At this point, the resource is growing as fast as possible, and the entire growth can be harvested each period without reducing the stock.
- For the logistic growth model, the maximum growth occurs at $X_{MSY} = K/2$, and the maximum sustainable yield is $MSY = G(K/2) = rK/4$.

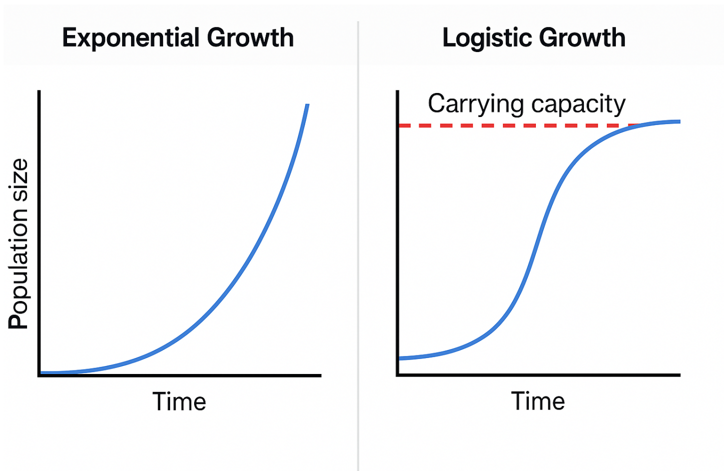

Figure 3: Growth function $G(X)$ and Maximum Sustainable Yield. The peak of the curve corresponds to MSY.

Biological vs Economic Optimum:

- The MSY is a purely biological concept. It does not consider the economic costs of harvesting, the price of the resource, or the time value of money (discounting).
- In reality, harvesting at MSY may not be economically optimal. As the stock decreases, the cost of harvesting usually increases (e.g., it takes more effort to catch fish when they are scarce).
- The economic optimum typically involves maintaining a higher stock than X_{MSY} and harvesting less than MSY. This reduces costs and can increase the present value of net benefits.

5 The Economic Optimum

MSY and Economic optima are not the same

Key points:

- The economic optimum is found by maximizing the present value of net benefits from the resource, taking into account prices, costs, and the discount rate.
- The optimal steady-state stock X^* is generally greater than X_{MSY}, because maintaining a higher stock reduces harvesting costs and provides a buffer against uncertainty or shocks.
- The optimal sustainable harvest under economic management is less than the MSY, reflecting the trade-off between current profits and future resource availability.

Harvest Function and Fishing Effort

In fisheries economics, the **harvest function** is typically modeled as:

$$H = qEX$$

where

- H is the harvest rate (catch per unit time),
- q is the catchability coefficient (efficiency of fishing effort),
- E is the fishing effort (e.g., number of boats, hours fished),
- X is the fish stock biomass.

Fishing effort (E) represents the intensity of fishing activities. It is a crucial control variable in fisheries management and can be regulated through quotas, gear restrictions, or seasonal closures.

Harvest Cost

The **cost of harvest** is typically an increasing function of effort and stock size. A simple linear cost function is:

$$C(E, X) = cE$$

where c is the cost per unit effort.

Maximum Sustainable Yield (MSY)

Maximum Sustainable Yield (MSY) is a central concept in fisheries management. It is defined as the largest constant harvest that can be sustained indefinitely without depleting the stock. For a logistic growth model:

$$G(X) = rX\left(1 - \frac{X}{K}\right)$$

the MSY is obtained at the stock size X_{MSY} that maximizes $G(X)$:

$$X_{MSY} = \frac{K}{2}$$

$$MSY = G\left(\frac{K}{2}\right) = r\frac{K}{2}\left(1 - \frac{1}{2}\right) = \frac{rK}{4}$$

At this point, the surplus production of the fishery is at its maximum, and harvesting at this rate can, in theory, be continued indefinitely.

Effort at MSY

The level of fishing effort that achieves MSY, denoted E_{MSY}, can be derived by setting the harvest function equal to MSY:

$$H = qE_{MSY}X_{MSY} = MSY$$

$$E_{MSY} = \frac{MSY}{qX_{MSY}} = \frac{rK/4}{q(K/2)} = \frac{r}{2q}$$

This is the effort level that, if maintained, would produce the maximum sustainable yield.

Economic Optima

It is the harvest that corresponds to the effort where Marginal Revenue Equals the Marginal harvest cost. Usually, for the sake of simplicity, we consider the Average cost to remain constant for all level of effort. This level corresponds to a harvest which is less than the X_MSY* and a stock level which is higher than Xt_MSY. We make the following assumptions in this analysis

- The cost function is linear with zero fixed cost (linear AC = MC)
- The total cost or harvest cost (HC) is then Effort * MC.
- The total benefit curve is a reflection of biological growth curve. At maximum effort, total benefit over long run will be zero.

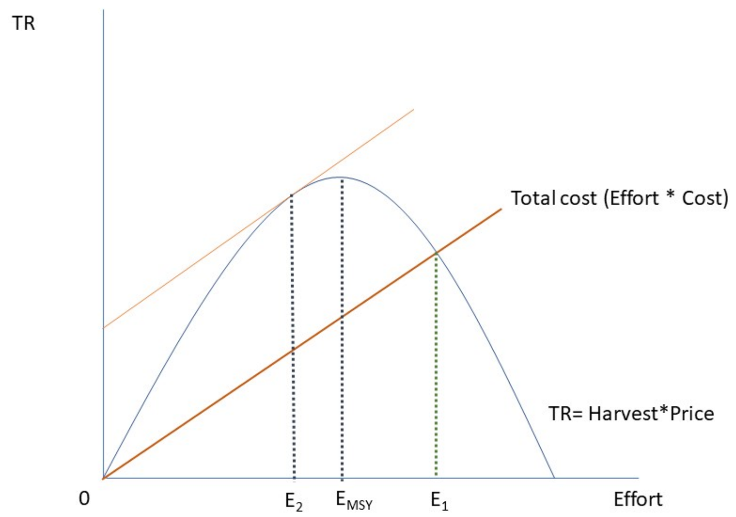

Figure 4: The Total cost curve and the fishing effort

Economic Optimum vs. MSY

While MSY maximizes the biological yield, it does not account for economic factors such as costs and prices. The **economic optimum** typically occurs at a lower level of effort and a higher stock size than MSY, because the marginal cost of harvesting rises as the stock declines. The **maximum economic yield** (MEY) is the level of catch that maximizes the net economic benefit (profit) from the fishery, and is generally less than MSY

Table 1: MSY vs. MEY

	MSY	**MEY (Economic Optimum)**
Objective	Maximize sustainable yield	Maximize profit
Effort	E_{MSY}	$E_{MEY} < E_{MSY}$
Stock size	$K/2$	$> K/2$
Harvest	$rK/4$	$< rK/4$

6 The Common-Property Problem

The inefficiency of common property management

Open Access and the Tragedy of the Commons:

- When property rights over a renewable resource are not well-defined or enforced,

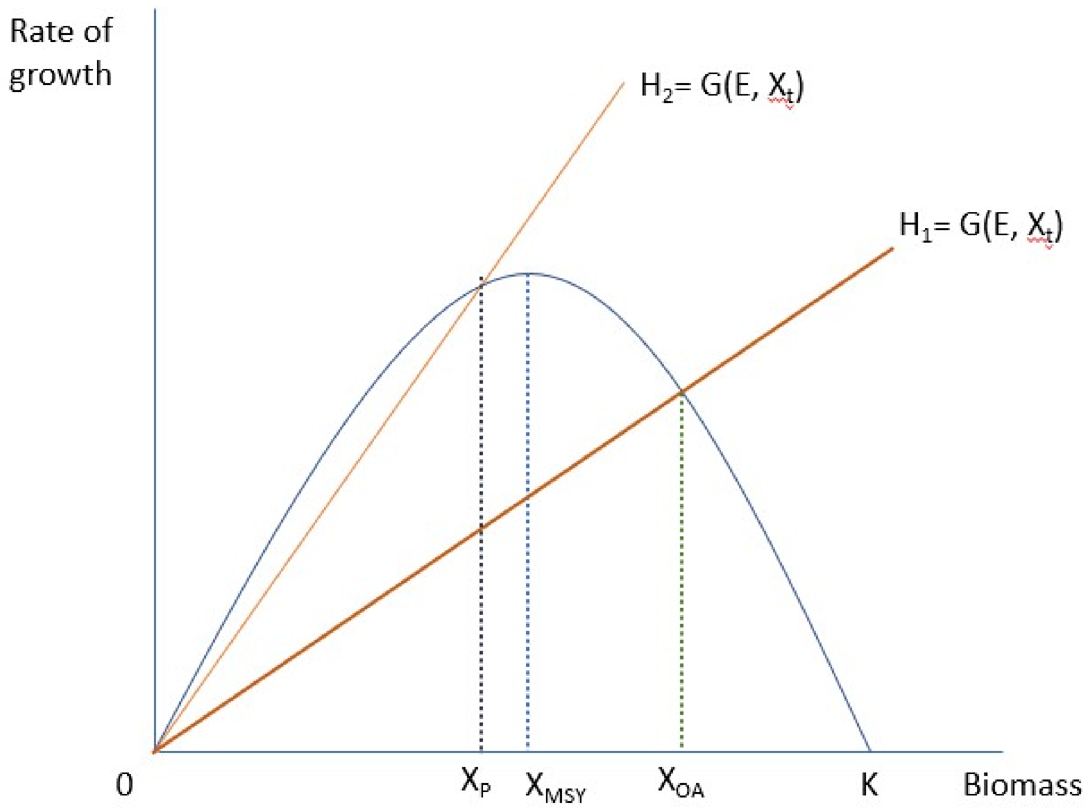

Figure 5: Harvest under private optimum is marked by X_p

the resource is subject to "open access" exploitation. This means that anyone can harvest from the resource, with little or no restriction.

- In an open access regime, each user acts independently and does not take into account the negative impact of their harvest on the resource stock and on other users. The result is a classic externality: overuse of the resource, leading to depletion and reduced benefits for all.
- This situation is known as the "tragedy of the commons," a term coined by Garrett Hardin. It describes the tendency for common-property or open-access resources to be over-exploited and degraded.

Economic Consequences:

- **Rent dissipation:** In open access, economic profits (resource rents) are driven to zero as more users enter the resource until the **average cost of harvesting equals the average revenue**. No one has an incentive to conserve the resource for the future.
- **Over-exploitation:** Resource stocks are driven below the economic optimum (harvest more than MSY), and often even below the level that can sustain MSY. This reduces both current and future yields.

- **Resource depletion or extinction:** In extreme cases, the resource may be harvested faster than it can regenerate, leading to collapse or even extinction (as has happened with some fisheries and wildlife populations).

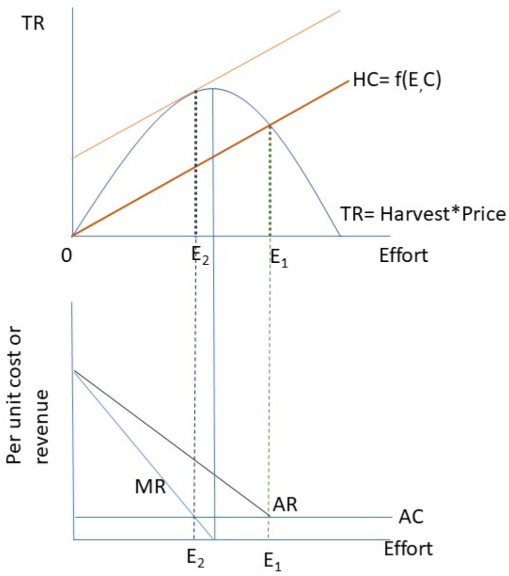

Figure 6: Equilibrium under Open Access

- In open access, AR=AC (assuming AC and MC to be linear function of effort)
- In Private Property Right, the MR is equated to MC.
- In private property regime, the effort will be less, stock maintained at level greater than MSY (Harvest less than MSY)
- In common property regime, the use of the resource is not governed by a single owner. So people continue to fish as long as they are making some profit. Price per unit (AR) equals Cost per unit (AC), is the equilibrium effort.
- Open Access equilibrium correspond to harvest which is greater than MSY in the initial periods, stock maintained at less than MSY. In the long run, the harvest rate will be same as that of private property regime, but with more effort.
- As the stock is less, effort required to catch the same amount of fish will be larger - Over exploited resource and economically inefficient.

Summary: The common-property problem illustrates the importance of institutional arrangements in resource management. Without effective governance, renewable resources are vulnerable to over-exploitation and degradation, with negative consequences for both the economy and the environment. Sustainable management requires aligning individual incentives with the collective interest in conserving the resource for the long term.

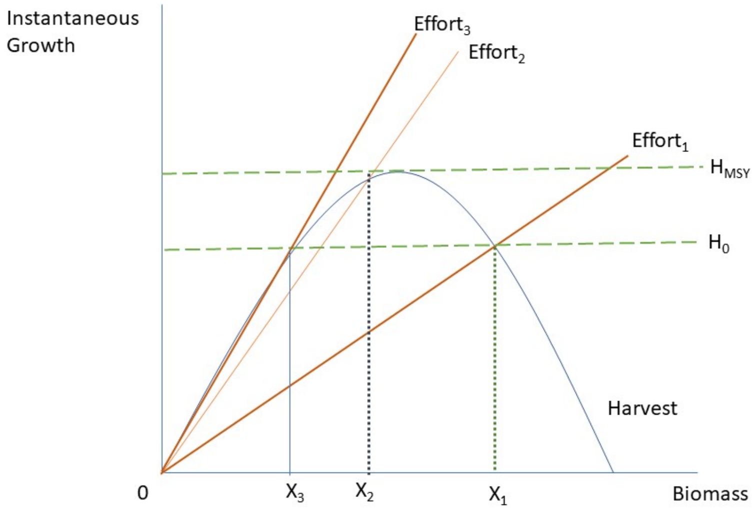

Figure 7: Under Open Access, less stock needing more effort- tragedy of commons

Policy Responses

To address the common property problem and prevent over-exploitation, various management strategies are used:

- **Establishing property rights:** Individual transferable quotas (ITQs), territorial use rights in fisheries (TURFs).
- **Regulation:** Limiting entry, effort, or catch through licenses, quotas, or seasonal closures.
- **Economic instruments:** Taxes, tradable permits, or subsidies for conservation.

Summary: Without effective management or property rights, common property fisheries are prone to over-exploitation, resulting in depleted stocks, economic inefficiency, and loss of long-term benefits for all users

7 Concluding Remarks

- Renewable resources require management strategies that balance current use with future regeneration.
- The biological optimum (MSY) is not generally the economic optimum.
- Open access leads to over-exploitation and loss of economic and ecological value.

- Effective management often requires well-defined property rights or regulatory interventions.

8 Questions

- With a biological growth model, explain MSY and Carrying capacity.
- Prove that MSY occur when the stock size is at half of the carrying capacity. Derive the equivalent effort at MSY.
- How is economic optima different from biological optima in case of fisheries?
- Explain how fishery resource managed under open access leads to over exploitation of the resource.
- Show that under open access, the optimum harvest is not efficient (more effort for a smaller harvest)
- Explain tragedy of common using fishery resource as an example and detail the policy response options.