

Chapter 5: Economics of Natural Resource: Optimal Harvesting of Renewable Resource

*Instructor: Aschalew Sh.
Department of Economics
PhD Candidate in Economics*

Renewable Resources

- Renewable flow resources: These are non-depletable
 - Such as solar, wave, wind and geothermal energy
- Renewable stock resources: They are **capable** of being fully exhausted.
 - living organisms: fish, cattle and forests, with a natural capacity for growth
 - inanimate systems (such as water and atmospheric systems): reproduced through time by physical or chemical processes
 - arable and grazing lands as renewable resources: reproduction by biological processes (such as the recycling of organic nutrients) and physical processes (irrigation, exposure to wind etc.).

Biological growth processes for renewable resources

- In order to investigate the economics of a renewable resource, it is first necessary to describe the pattern of biological (or other) growth of the resource.
- To fix ideas, we consider the growth function for a population of some species of fish.
- Suppose that the population stock is S and it grows at a fixed rate g .
- Then in the absence of human predation the rate of change of the population over time is given by

Cont'd

- Change of population over time:

$$\frac{ds}{dt} = \dot{s} = gs \quad \dots\dots\dots 17.1$$

- Stock level at any point in time:

$$S_t = S_0 e^{gt}$$

- in which S_0 is the initial stock level. In other words, for a positive value of g , the population grows exponentially over time at the rate g and without bounds. This is only plausible over a short span of time.

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- A simple way of representing this effect is by making the actual (as opposed to the potential) growth rate depend on the stock size. Then we have what is called density-dependent growth. Using the symbol χ to denote the actual growth rate, the growth function can then be written as

$$\dot{S} = \chi(S)S$$

- where $\chi(S)$ states that χ is a function of S , and shows the dependence of the actual growth rate on the stock size.

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- Now let us suppose that under a given set of environmental conditions there is a finite upper bound on the size to which the population can grow (its carrying capacity). We will denote this as S_{MAX} .
- A commonly used functional form for $\chi(s)$ which has the properties of compensation and a maximum stock size is the simple logistic function:

$$\chi(s) = g\left(1 - \frac{s}{S_{MAX}}\right)$$

- in which the constant parameter $g > 0$ is what we have called the intrinsic or potential growth rate of the population.

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- Where the logistic function determines the actual population growth rate, we may therefore write the biological growth function as

$$\dot{S} = \frac{dS}{dt} = g \left(1 - \frac{S}{S_{MAX}} \right) S \dots\dots\dots 17.2$$

- The changes taking place in the fish population that we have been referring to so far are 'natural' changes.

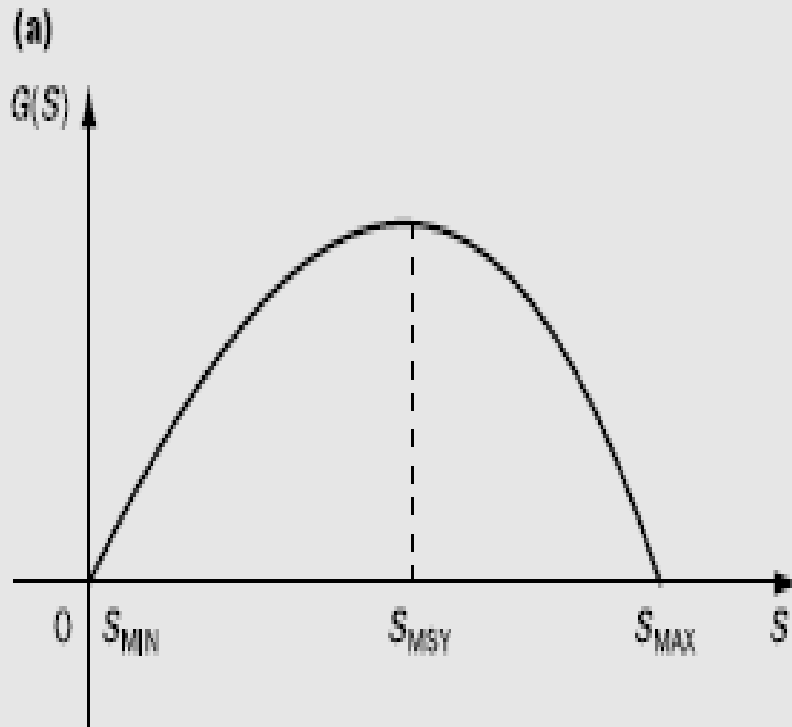
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- More completely, we shall use the notation $G(S)$ instead of $\dot{S}$ and dS/dt to make it clear that G depends on S . With this change the logistic biological growth function is

$$G(S) = g \left(1 - \frac{S}{S_{MAX}} \right) S \dots\dots\dots 17.3$$

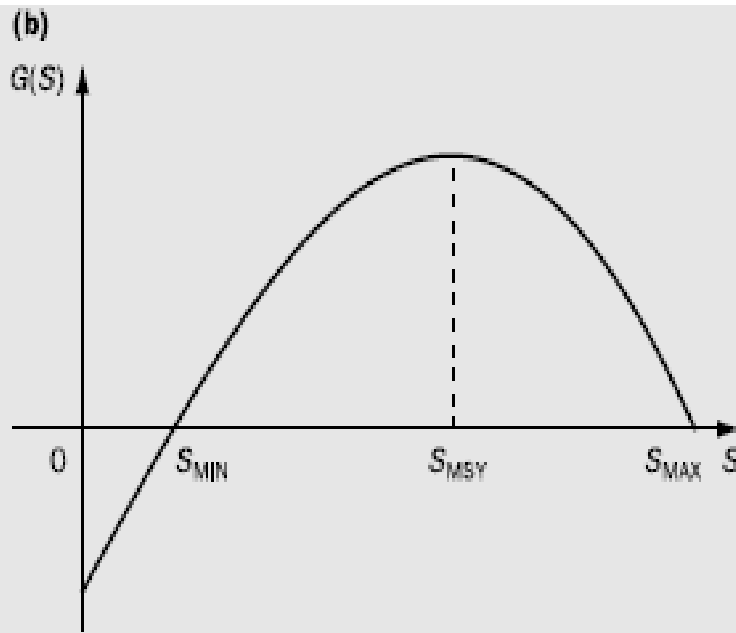
- The logistic form is a good approximation to the natural growth processes of many fish, animal and bird populations.
- Some additional information on the simple logistic growth model, and alternative forms of logistic growth, is given as follows:

Simple logistic growth is illustrated



- Three properties should be noted by inspection of this diagram.
 - a) S_{MAX} is the maximum stock size that can be supported in the environmental milieu.
 - b) the amount of growth, G , is a quadratic function of the resource stock size, S . For the simple logistic function, the maximum amount of growth (S_{MSY}) will occur when the stock size is equal to half of S_{MAX} .
 - c) The amount of biological growth G is zero only at a stock size of zero and a stock size of S_{MAX} . For all intermediate values, growth is positive.

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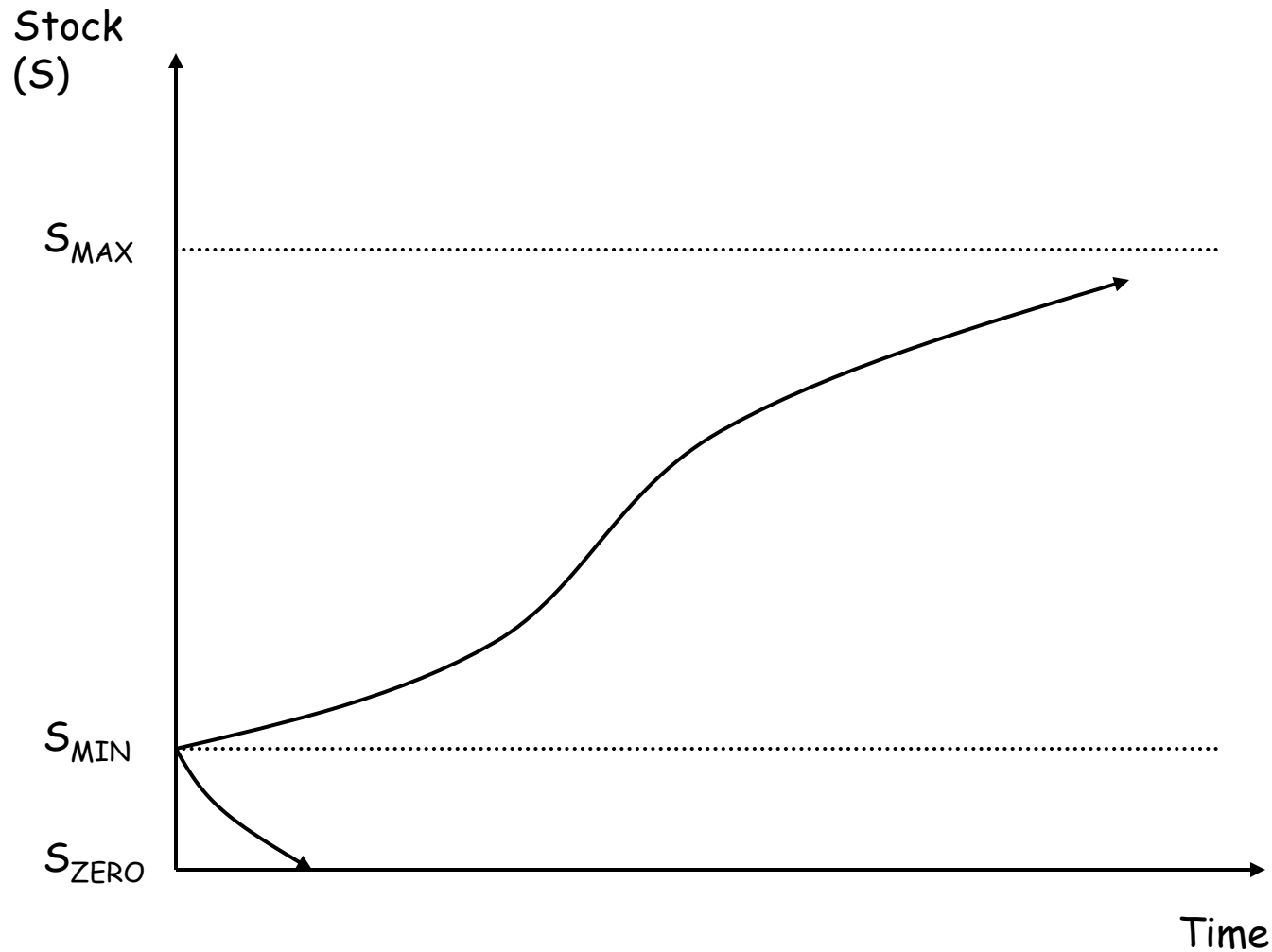


- When there is some positive population threshold level, S_{MIN} , such that the population would inevitably and permanently decline to zero if the actual population were ever to fall below that threshold. A simple generalisation of the logistic growth function that has this property is:

$$G(S) = g(S - S_{MIN}) \left(1 - \frac{S}{S_{MAX}}\right) \dots\dots 17.4$$

- Note that if $S_{MIN} = 0$, equation 17.4 collapses to the special case of equation 17.3.

Alternative logistic growth curve



Steady-state harvests

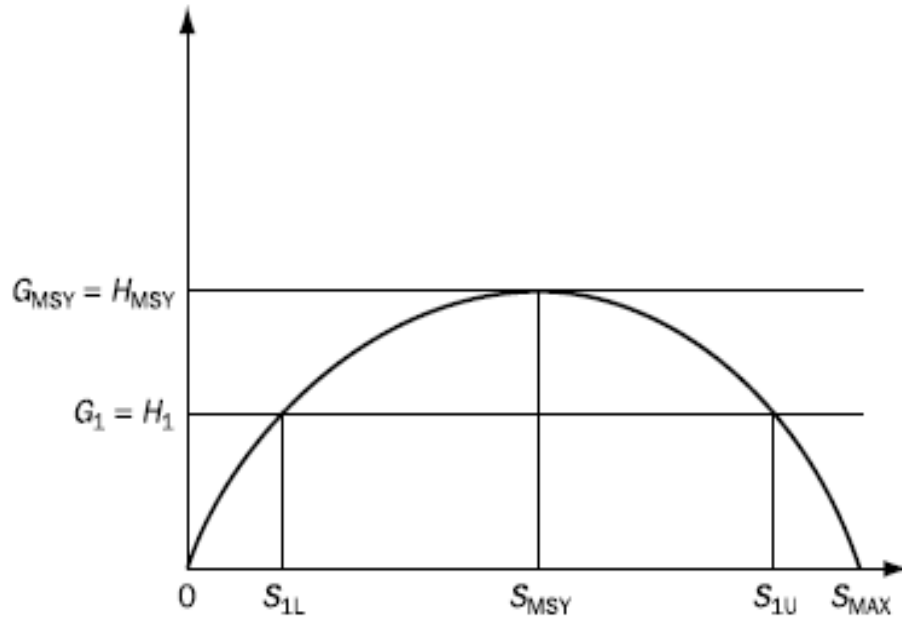


Figure 17.2 Steady-state harvests

Defining $\dot{S}$ as the actual rate of change of the renewable resource stock, with $\dot{S} = G - H$, it follows that in steady-state harvesting $\dot{S} = 0$ and so the resource stock remains constant over time.

H_1 is a feasible steady-state harvest if the stock size is maintained at either S_{1L} or S_{1U} .

The biological growth can be expressed in terms of rate of change $\rightarrow$ slope

Compare the rate of change in the stock to the size of the stock

Maximum sustained yield (MSY) occurs when the rate of growth of the resource reaches a maximum. MSY can be harvested from the stock and if allowed to regenerate itself, MSY can be harvested next time around and so on.

An open-access fishery

- The open-access fishery model shares two of the characteristics of the standard perfect competition model.
 - First, if the fishery is commercially exploited, it is assumed that this is done by a large number of independent fishing ‘firms’. Therefore, each firm takes the market price of landed fish as given.
 - Second, there are no impediments to entry into and exit from the fishery. But the free entry assumption has an additional implication in the open-access fishery, one which is not present in the standard perfect competition model.

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- The open-access model has two components:
 1. a biological sub-model, describing the natural growth process of the fishery;
 2. an economic sub-model, describing the economic behaviour of the fishing boat owners.

The model described

1) Biological sub-model

- In the absence of harvesting and other human interference, the rate of change of the stock depends on the prevailing stock size

$$\frac{ds}{dt} = \dot{s} = gs \quad \text{.....17.5}$$

Cont'd

2) Economic sub-model

2.1) *The harvest function (or fishery production function)*

$$H = H(E, S) \dots\dots\dots 17.6$$

- Where H= harvest, E= effort exerted, S=the stock size
- This relationship can take a variety of particular forms.

$$H = eES \dots\dots\dots 17.7$$

- Where e is a constant number, often called the catch coefficient. Dividing each side by E , we have

$$\frac{H}{E} = eS$$

- which says that the quantity harvested per unit effort is equal to some multiple (e) of the stock size.

Cont'd

- We have already defined the fish-stock growth function with human predation as the biological growth function less the quantity harvested. That is,

$$\dot{S} = G(S) - H \dots\dots\dots 17.8$$

- ***The costs, benefits and profits of fishing***

- The total cost of harvesting, C , depends on the amount of effort being expended

$$C = wE \dots\dots\dots 17.10$$

- where w is the cost per unit of harvesting effort, taken to be a constant.

Cont'd

- Let B denote the gross benefit from harvesting some quantity of fish. The gross benefit will depend on the quantity harvested, so we have

$$B = B(H)$$

- In a commercial fishery, the appropriate measure of gross benefits is the total revenue that accrues to firms.
- Assuming that fish are sold in a competitive market, each firm takes the market price P as given and so the revenue obtained from a harvest H is given by

$$B = PH \dots\dots\dots 17.11$$

- Fishing profit is given by

$$NB = B - C \dots\dots\dots 17.12$$

Bioeconomic equilibrium

- Biological equilibrium occurs where the resource stock is constant through time (that is, it is in a steady state). This requires that the amount being harvested equals the amount of net natural growth:

$$G = H \dots\dots\dots 17.14$$

- Economic equilibrium requires that the amount of fishing effort be constant through time.
- Such an equilibrium is only possible in open-access fisheries when rents have been driven to zero, so that there is no longer an incentive for entry into or exit from the industry, nor for the fishing effort on the part of existing fishermen to change.

Cont'd

- We express this by the equation

$$NB = B - C = 0 \dots\dots\dots 17.15$$

- which implies (under our assumptions) that $PH = wE$.

Notice that when this condition is satisfied, $dE/dt = 0$ and so effort is constant at its equilibrium (or steady-state) level $E = E^*$.

Open-access steady-state equilibrium

- We use fishery's yield-effort relationship.
- Recall a biological equilibrium $H = G$.
- Then, by substituting the assumed functions for H and G , we obtain:

$$gS \left(1 - \frac{S}{S_{MAX}} \right) = eES \dots\dots\dots 17.16$$

which can be rearranged to give

$$S = S_{MAX} \left(1 - \frac{e}{g} E \right) \dots\dots\dots 17.17$$

- It implies a unique equilibrium stock at each level of effort.

Cont'd

- Next substitute equation into equation ($H = eES$), giving

$$H = eES_{MAX} \left(1 - \frac{e}{g} E \right) \dots \dots \dots 17.18$$

- In an open-access economic equilibrium, profit is zero, so

$$PH = wE \dots \dots \dots 17.19$$

$$\pi(S) = R(S) - C(S) = 0$$

- The steady-state stock solution can then be obtained as follows:

Cont'd

- Given that we are assuming that the industry is competitive and so each firm is a price taker), $R(S) = PH(S)$. Steady state biological equilibrium requires that $H(S) = G(S)$.
- A bioeconomic equilibrium requires simultaneous satisfaction of these two equilibrium conditions. Substituting the second into the first gives: $PG(S) = C(S)$

Cont'd

- For our assumed functions

$$C = C(E) = wE$$

$$H = eES \Rightarrow E = \frac{H}{eS} \text{ and so}$$

$$C = \frac{wH}{eS} \dots\dots\dots (i)$$

- Since in steady state $H = G$ and with $G(S)$ given by Equation 17.3 we have:

$$C(S) = \frac{w}{eS} gS \left(1 - \frac{s}{S_{MAX}}\right) = \frac{wg}{e} \left(1 - \frac{s}{S_{MAX}}\right) \dots\dots\dots (ii)$$

giving the total cost as a function of stock.

Cont'd

- Now we obtain an expression for revenue. As

$$G(S) = gS \left(1 - \frac{s}{S_{MAX}}\right)$$

hence total revenue is

$$R(S) = PG(S) = PgS \left(1 - \frac{s}{S_{MAX}}\right) \dots\dots\dots (iii)$$

which shows total revenue as a function of stock.

- Hence,

$$\frac{wg}{e} \left(1 - \frac{s}{S_{MAX}}\right) = PgS \left(1 - \frac{s}{S_{MAX}}\right)$$

$$\frac{wg}{e} = PgS$$

Cont'd

$$S^* = \frac{w}{Pe} \dots \dots \dots (iv)$$

$$H=G=eES$$

$$gS \left(1 - \frac{s}{S_{MAX}} \right) = eES$$

- Substitute for S then rearrange

$$g \frac{w}{Pe} \left(1 - \frac{w}{PeS_{MAX}} \right) = eE \frac{w}{Pe}$$

$$g \frac{w}{Pe} \left(1 - \frac{w}{PeS_{MAX}} \right) = \frac{wE}{P}$$

$$E^* = \frac{g}{e} \left(1 - \frac{w}{PeS_{MAX}} \right) \dots \dots \dots (v)$$

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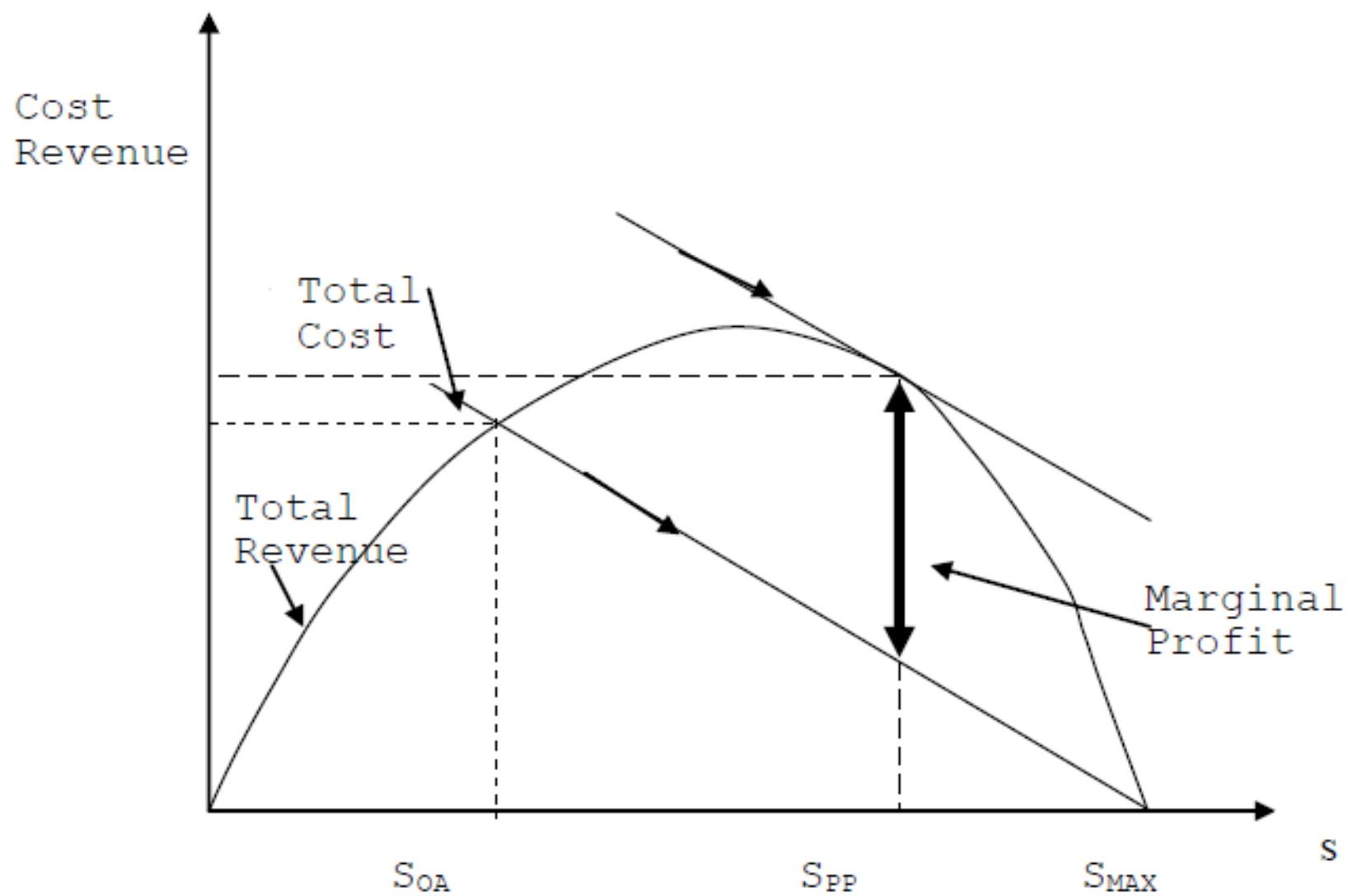
- Substituting S^* and E^* into $H = eES$ then yields

$$H^* = e \frac{g}{e} \left(1 - \frac{w}{PeS_{MAX}} \right) \frac{w}{Pe}$$

$$H^* = \frac{gw}{Pe} \left(1 - \frac{w}{PeS_{MAX}} \right) \dots \dots \dots (vi)$$

- The outcome can be illustrated diagrammatically, as in Figure 1 below. The total cost and total revenue curves shown in the diagram are Equations (ii) & (iii) respectively. The open access equilibrium is at SOA.

Figure 1 The static private fishery and open access fishery equilibria compared.



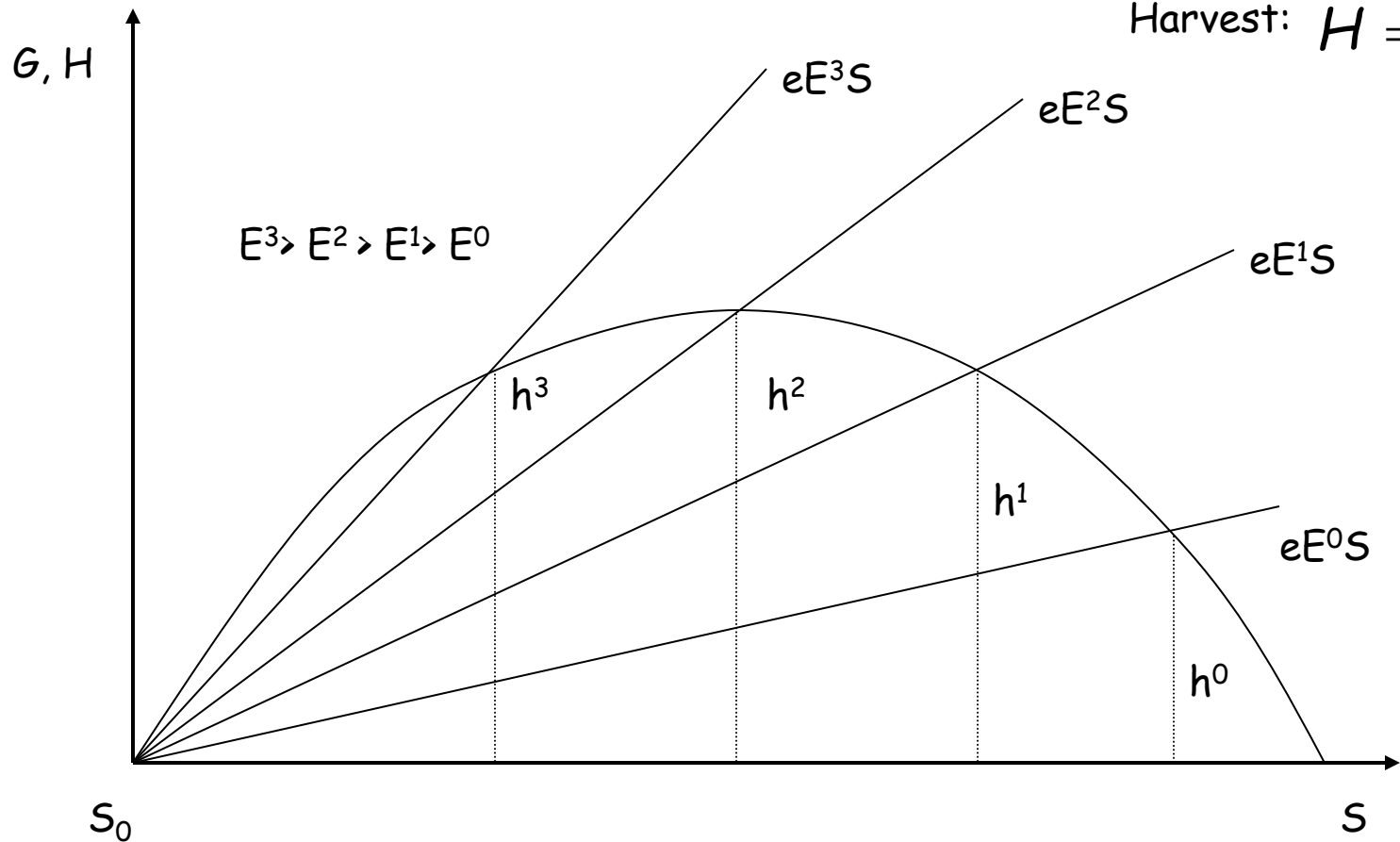
Steady-state equilibrium fish harvests and stocks at various effort levels

- Figure below shows equilibrium relationships in stock-harvest space. The inverted U-shape curve is the logistic growth function for the resource.
- Three rays emanating from the origin portray the harvest-stock relationships (from the function $H = eES$) for three different levels of effort.
- If effort were at the constant level E_1 , then the unique intersection of the harvest-stock relationship and biological growth function determines a steady-state harvest level H_1 at stock S_1 .

Figure 17.3 Steady-state equilibrium
fish harvests and
stocks at various effort levels

Effort: $E = \frac{H}{eS}$

Harvest: $H = eES$



Cont'd

- The lower effort level $E2$ determines a second steady-state equilibrium (the pair $\{H2, S2\}$).
- The particular point on this yield-effort curve that corresponds to an open-access equilibrium will be the one that generates zero economic profit. How do we find this?

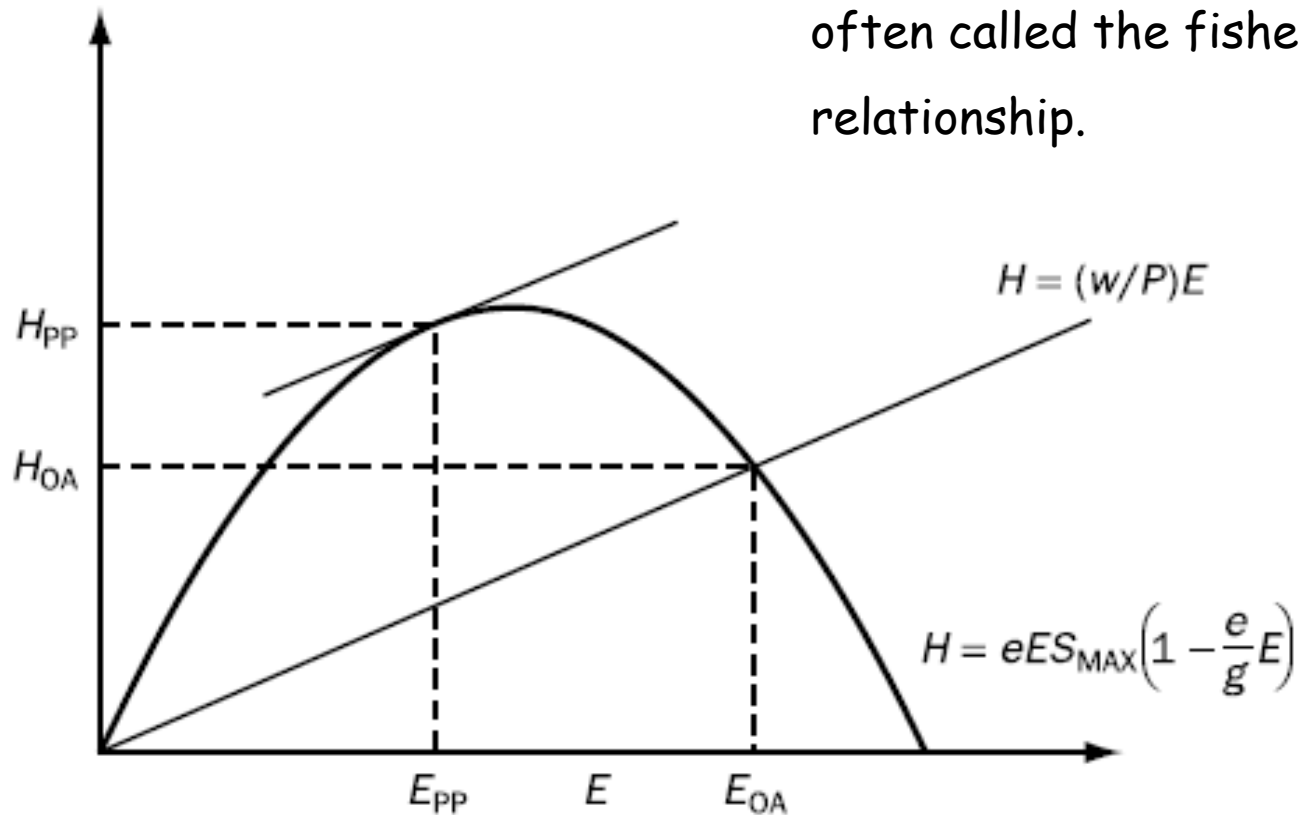
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- The zero economic profit equilibrium condition $PH = wE$ can be written as $H = (w/P)E$. For given values of P and w , this plots as a ray from the origin with slope w/P in Figure 17.4. The intersection of this ray with the yield-effort curve locates the unique open-access equilibrium outcome.

Cont'd

- Alternatively, multiplying both functions in Figure 17.4 by the market price of fish, P , we find that the intersection point corresponds to $PH = wE$.
- This is, of course, the zero profit condition, and confirms that $\{EOA, HOA\}$ is the open-access effort-yield equilibrium.

Figure 17.4 Steady-state equilibrium yield-effort relationship



- The inverted U-shape curve here portrays the steady state harvests that correspond to each possible effort level. It describes what is often called the fishery's yield-effort relationship.

Cont'd

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A Simple Harvesting Model

Stock growth function $\dot{S} = G(S) - H$

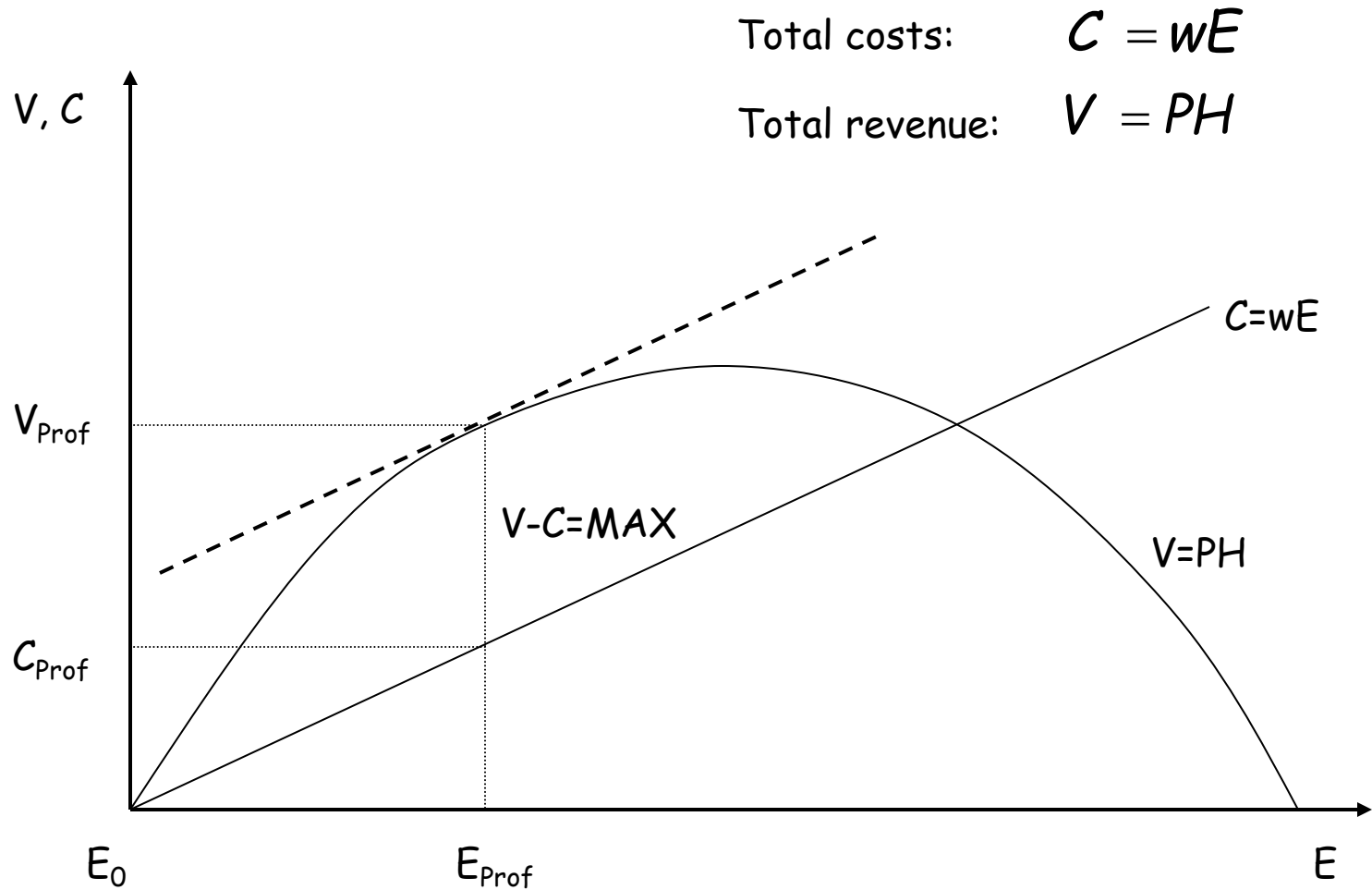
Harvest $H = H(E, S) = eES \Rightarrow \frac{H}{E} = eS$

Costs $C = wE$

Revenue $V = PH$

Price $P = P(H), \frac{\partial P}{\partial H} < 0$

Profit Maximisation



Open Access, Steady State

Net growth of stock in steady state:

$$\dot{S} = G(S) - H = 0 \Rightarrow H = G(S)$$

Harvest: $H = H(E, S) = eES \Rightarrow \frac{H}{E} = eS$

- where e is a constant number, often called the catch coefficient. Dividing each side by E , we have

Cost: $C = wE = w \frac{H}{eS}$

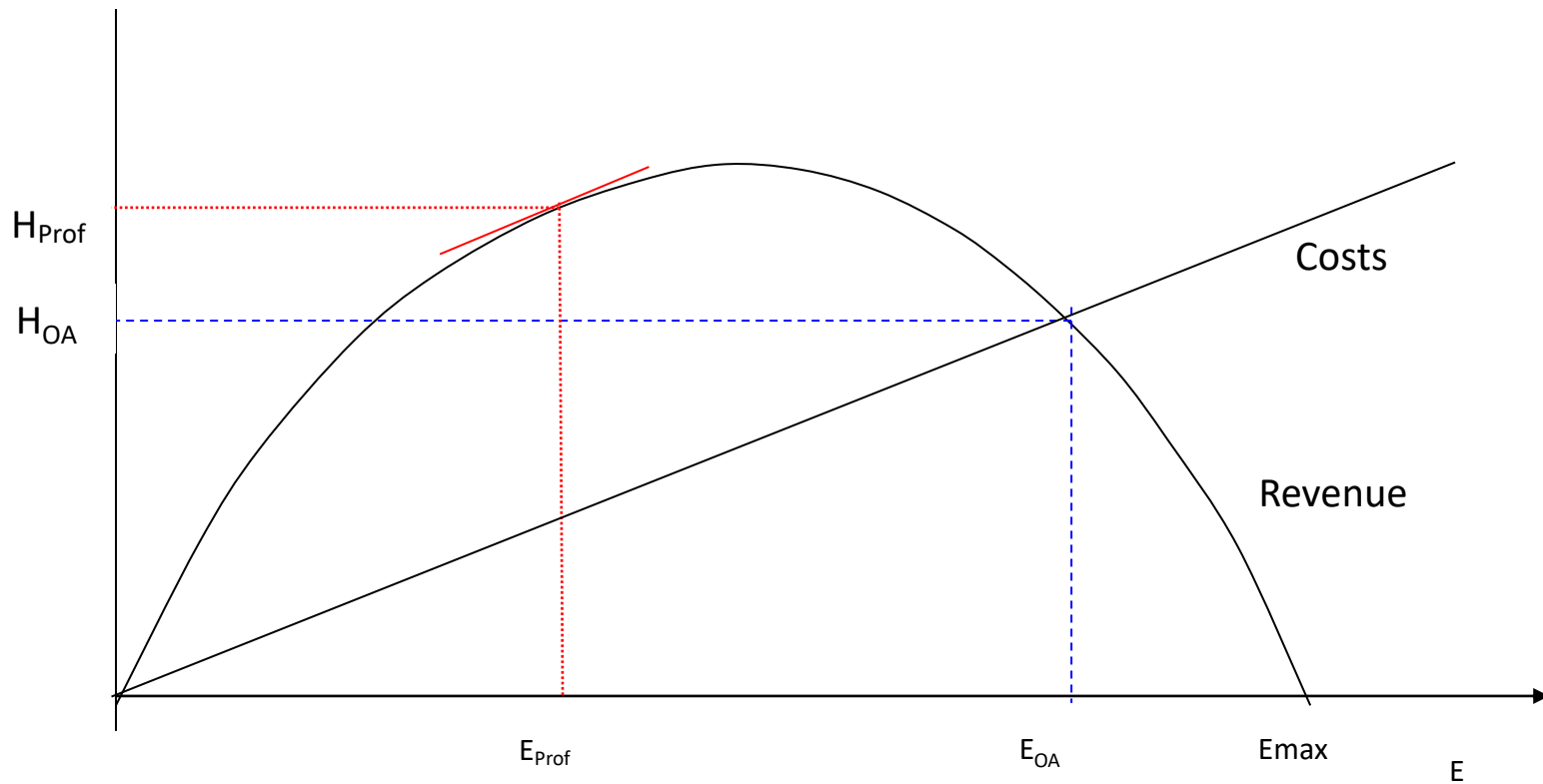
Revenue: $V = PH$

For open access: $C = wE = V = PH$

$$\Leftrightarrow C = \frac{w}{eS} H = V = PH \Rightarrow \frac{w}{eS} = P$$

Equilibria: $V = C$ and $G(S) = H$

Profit maximisation and open access equilibrium



Open access vs Restricted access fisheries

- Consequences of open access: entry continues until all rents are dissipated (profit per boat = zero).
- Stock sizes will tend to be lower, and harvest rates will tend to be higher (but may not always be) compared with a restricted access fishery.
- Extinction is more likely, but will not necessarily happen.

Introducing time

Objective function: $\max_{H_t} NPV = \int_{t=0}^{\infty} (V_t(H_t) - C(H_t, S_t)) e^{-it} dt$

Equations of motion: $\dot{S} = G(S_t) - H_t$

Hamiltonian: $L = V_t(H_t) - C(H_t, S_t) + p_t (G(S_t) - H_t)$

Necessary conditions:

$$\frac{\partial L}{\partial H_t} = 0 = \frac{\partial V_t}{\partial H_t} - \frac{\partial C_t}{\partial H_t} - p_t \quad V_t = P_t H_t \Rightarrow p_t = P_t - \frac{\partial C_t}{\partial H_t}$$

$$\dot{p}_t = ip_t - \frac{\partial L}{\partial S_t} = ip_t + \frac{\partial C}{\partial S_t} - p_t \frac{\partial G}{\partial S_t}$$

Social optimum is market outcome iff: $\rho = i$

Interpretation

$$ip_t = \dot{p}_t - \frac{\partial \mathcal{C}}{\partial S_t} + p_t \frac{\partial G}{\partial S_t}$$

ip_t = the value of postponing revenue ($p = P - c$)

$\dot{p}_t$ = the change in value

$\frac{\partial \mathcal{C}}{\partial S}$ = the change in harvesting costs

$\frac{\partial G}{\partial S} p$ = the change in growth times the shadow value of the stock

Interpretation (2)

$$i = \frac{\dot{p}_t}{p_t} - \frac{\partial C}{\partial S_t} \bigg/ p_t + \frac{\partial G}{\partial S_t}$$

Hotelling: the discount rate equals
the proportionate growth in net price plus
the proportionate reduction in harvesting costs plus
the marginal natural growth rate

Profit maximisation and stock effect (1)

In steady state: $\dot{p}_t = 0$ and $G(S) = 0$

$$ip_t = p_t \frac{\partial G}{\partial S_t} - \frac{\partial C}{\partial S_t}$$

Fundamental equation:
$$i = \frac{\partial G}{\partial S_t} - \frac{1}{p_t} \frac{\partial C}{\partial S_t}$$

Stock effects if:

Add units to the stock if:
$$ip < \frac{\partial G}{\partial S_t} p - \frac{\partial C}{\partial S_t}$$

Harvest additional units if:
$$ip > \frac{\partial G}{\partial S_t} p - \frac{\partial C}{\partial S_t}$$

Profit maximisation and stock effect (2)

- If harvesting costs do not depend on stock size:

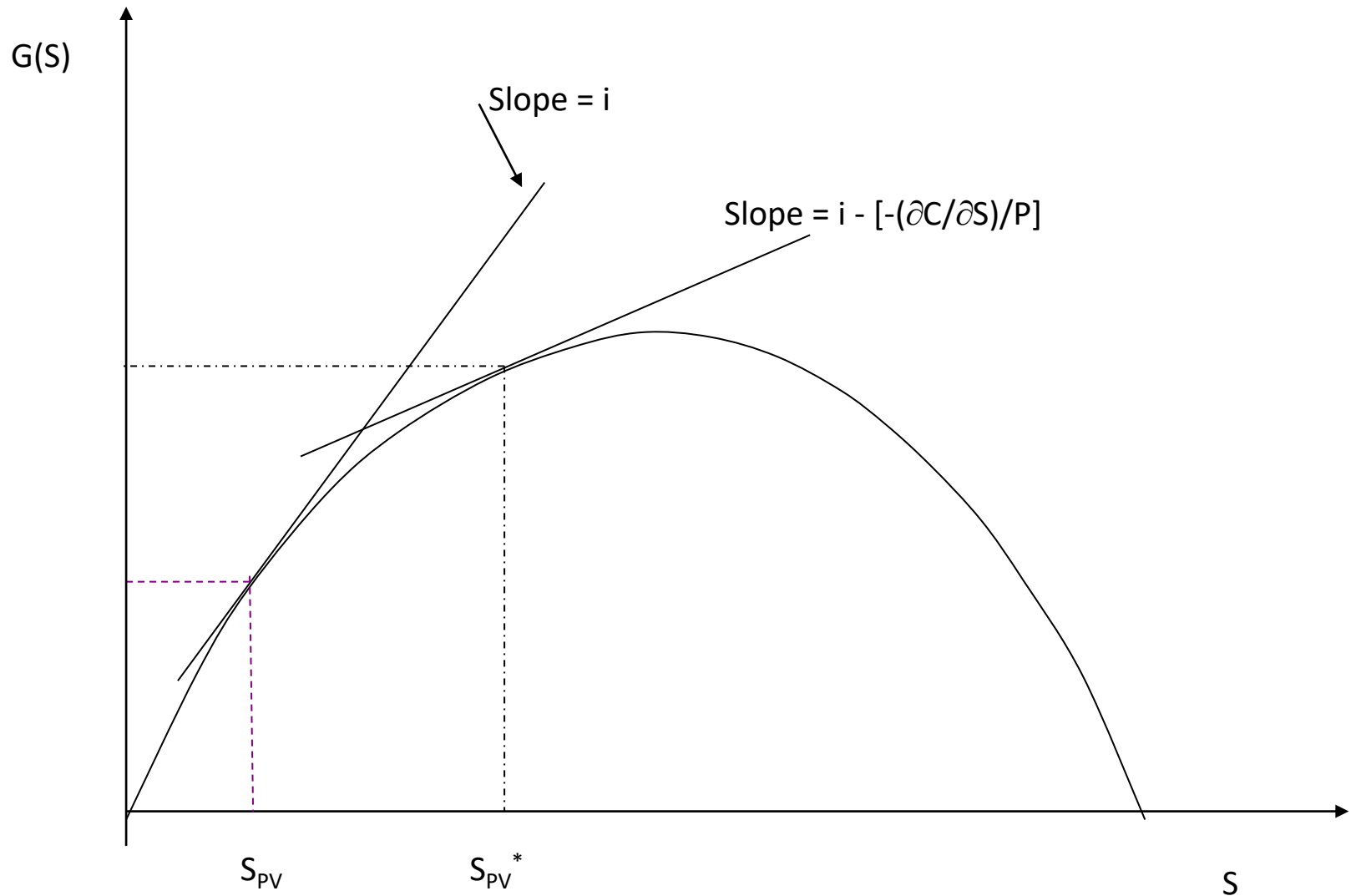
$$\frac{\partial \mathcal{C}}{\partial S_t} = 0 \Rightarrow i = \frac{\partial \mathcal{G}}{\partial S_t}$$

- If harvesting costs depend on stock size:

$$i = \frac{\partial \mathcal{G}}{\partial S_t} - \frac{1}{p_t} \frac{\partial \mathcal{C}}{\partial S_t}$$

- For a given i :
 - Stock size is higher
 - dG/dS is lower since $(dC/dS)/p$ is negative
 - $i > dG/dS$

Harvest Costs and Stock Effect



Sum up

- Equilibrium conditions:

- Dynamic

$$ip_t = \dot{p}_t - \frac{\partial \mathcal{C}}{\partial S_t} + p_t \frac{\partial G}{\partial S_t}$$

- Static

$$ip = -\frac{\partial \mathcal{C}}{\partial S} + p \frac{\partial G}{\partial S}$$

- Static profit maximisation equilibrium only if $i=0$

$$\frac{\partial \mathcal{C}}{\partial S} = p \frac{\partial G}{\partial S}$$

- Open access equilibrium is independent of discount rate

Fisheries

- If $H > G$, fish stocks fall, perhaps to (local) extinction
- Reasons
 - Open access, little incentive to preserve
 - It may be profitable ...
 - Ignorance and uncertainty
 - Variability, shocks, disturbances
- Contributing factors
 - High market price, high elasticity
 - Low harvesting costs
 - Low stock growth
 - High discount rate

Renewable Resource Policy

- End open access
- Information
- Create forward or future markets
- Taxes
- Tradeable permits
- Technical restrictions
- Time restrictions