Block 3: Renewable Resources

1. Definition
2. Logistic Growth Model
3. Open Access Fishery

      - algebraic

      - graphic

      - comparative static

Source: Perman et al. (2003): Natural Resource and Environmental Economics

What are Renewable Resources?

- Renewable flow resources
  - Such as solar, wind, wave, geothermal energy.
  - These energy flow resources are non-depletable

- Renewable stock resources
  - 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.)
  - **Are capable of being fully exhausted**

Renewable Resources

- Key points of interest
  - Private property rights do not exist for many forms of renewable resources
  - The resource stocks are often subject to open access; tend to be overexploited

- Biological growth process
  - $G_t = S_{t+1} - S_t$
  - Where S = stock size and G is amount of growth
  - This is called density dependent growth
  - Continuous time notation: G = G(S)

Renewable Resources

- Biological growth process
    - An example: simple logistic growth

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

    - Where g is the intrinsic growth rate (birth rate minus mortality rate) of the population
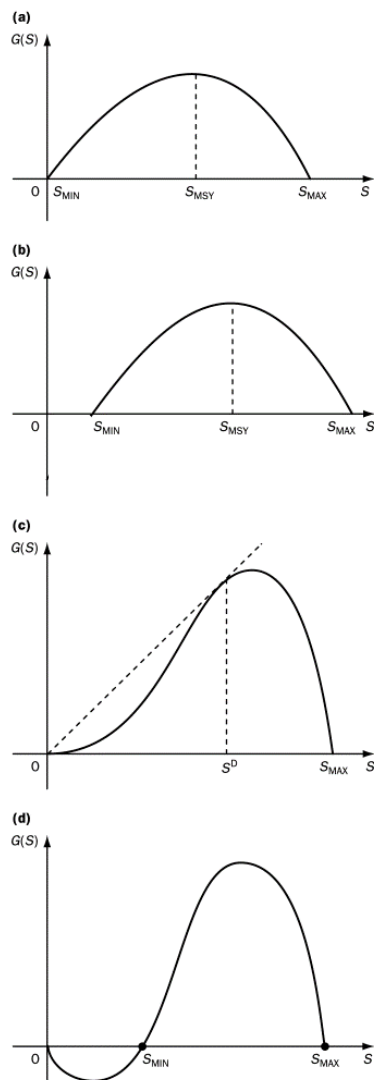
Logistic Growth Model

Figure 17.1 (a) Simple logistic growth;
(b) Logistic growth with a minimum population
threshold; (c) Logistic growth with depensation;
(d) Logistic growth with critical depensation

Simple logistic growth (Figure 17.1a):

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

or equivalently

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

Logistic growth with a positive population minimum threshold, S_{MIN} (Figure 17.1b):

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

Modified logistic model (with $\alpha > 1$) exhibiting depensation (Figure 17.1c).

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

Generalised logistic function with critical depensation: (Figure 17.1d).

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

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Logistic Growth Model

- Depensation
  - A decrease in the breeding population (mature individuals) leads to reduced production and survival of eggs or offspring
  - Causes: predation levels rising per offspring (giving the same level of overall predator pressure), allee effect (particularly the reduced likelihood of finding a mate)

- Critical depensation
  - When the level of depensation is high enough that the population is no longer able to sustain itself
  - Population size has a tendency to decline when population drops below a certain level
  - Leads to population collapse / extinction

Logistig Growth Model

- Steady-state harvest: Figure 17.2

$G_{MSY} = H_{MSY}$

$G_1 = H_1$

0

S_{1L}

S_{MSY}

S_{1U}

S_{MAX}

Logistig Growth Model
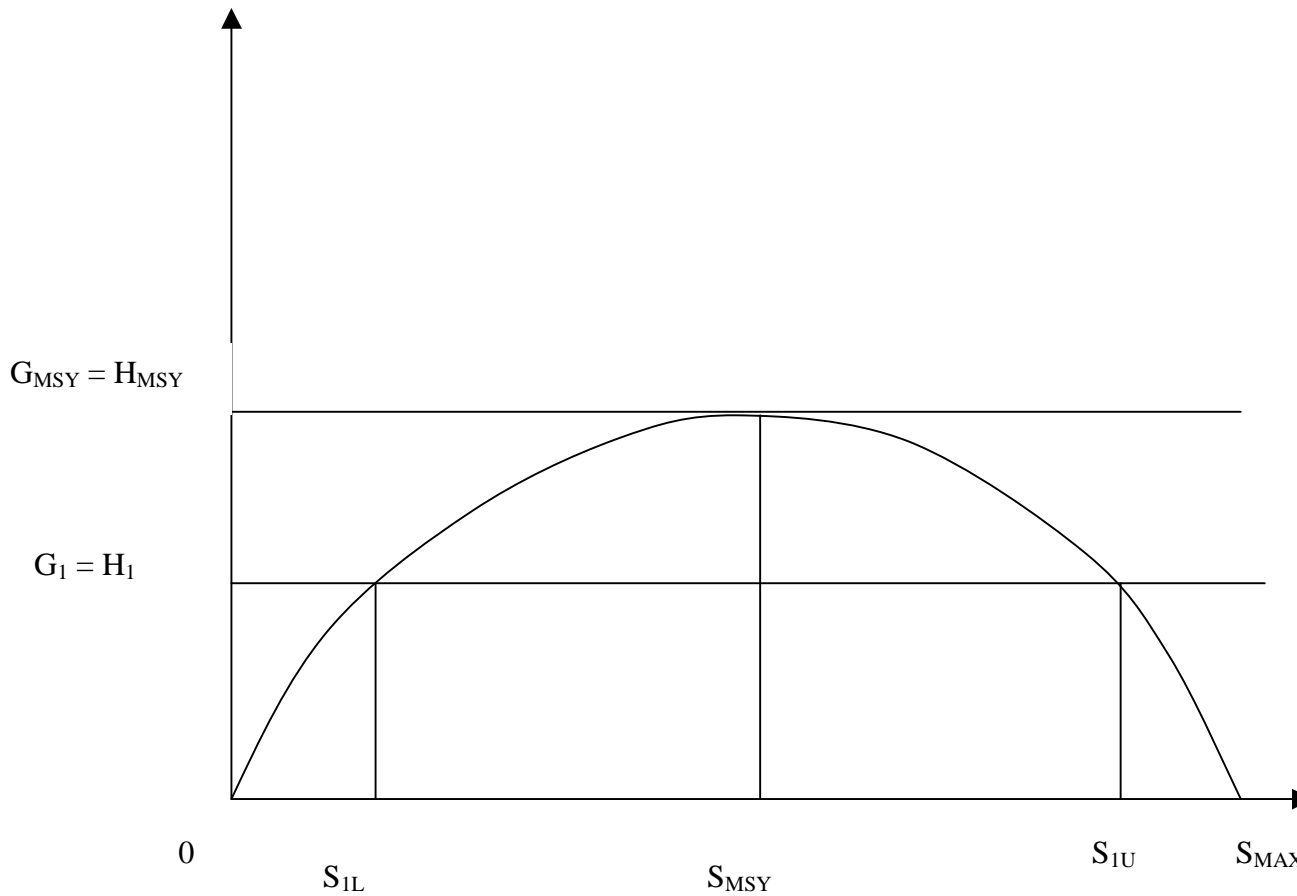
- Steady-state harvests
  - Consider a period of time in which the amount of the stock being harvested (H) is equal to the amount of net natural growth of the resource (G)
  - Suppose also that these magnitudes remain constant over a sequence of conescutive periods
  - We call this steady-state harvesting, and refer to the (constant) amount being harvested each period as a sustainable yield

- With steady-state harvesting the resource stock remains constant over time
  - Feasibility: Figure 17.2 stock size (SMSY) at which the quantity of net natural growth is at a maximum (GMSY)
  - If at a stock of SMSY harvest is set at the constant rate HMSY, we obtain a maximum sustainable yield (MSY) steady state
  - A resource management program could be devised which takes this MSY in perpetuity

Logistic Growth Model

- It is sometimes thought to be self-evident that a fishery, forest or other renewable resource should be managed so as to produce its maximum sustainable yield

- Economic theory does not, in general, support this proposition

- HMSY is not the only possible steady-state harvest. Indeed, Figure 17.2 shows that any harvest level represented by a point on the growth curve is a feasible steady-state harvest, and that any stock between zero and SMAX can support steady-state harvesting
    - H1 is a feasible steady state harvest if the stock size is maintained at either S1L or S1U
    - Which of these two stock sizes would be more appropriate for attaining a harvest level of H1 is also a matter we investigate further

Economic Models of a Fishery

- Open access fishery
    - Enter if profit per boat is positive
    - Leave if profit per boat is negative
    - In steady-state, R = C (revenue = costs)

- Closed access (private property) fishery
    - Static (single period) model: select E (effort) to max profit = R − C
    - Dynamic (intertemporal) model

Open Access Fishery

- 2 components (table 17.1 next slide)
    - Biological sub-model, describing the natural growth process of the fishery
    - Economic sub-model, descibing econ. behavior of the fishing boat owners

- 2 kinds of solutions
    - Equilibrium (steady-state) solution; consists of a set of circumstances in which the resource stock size is unchanging over time (a biological equilibrium) and the fishing fleet is constant with no net inflow or outflow of vessels (an economic equilibrium). Because the steady-state equilibrium is a joint biological-economic equilibrium, it is referred to as *bioeconomic equilibrium*
    - Dynamic solution; we look at the adjustment path towards the equilibrium, or from one equilibrium to another as conditions change. Important implications for whether a fish population may be driven to exhaustion, and indeed whether the resource itself could become extinct

Open Access Fishery

Table 17.1 The open-access fishery model

		General specification	Specific forms assumed
BIOLOGICAL SUB-MODEL:			
Biological growth	(17.5, 17.3)	$dS/dt = G(S)$	$G(S) = g\left(1 - \dfrac{S}{S_{MAX}}\right)S$
ECONOMIC SUB-MODEL:			
Fishery production function	(17.6, 17.7)	$H = H(E, S)$	$H = eES$
Net growth of fish stock	(17.8)	$dS/dt = G(S) - H$	$dS/dt = g\left(1 - \dfrac{S}{S_{MAX}}\right)S - H$
Fishery costs	(17.9, 17.10)	$C = C(E)$	$C = wE$
Fishery revenue	(17.11)	$B = PH$, P constant	$B = PH$, P constant
Fishery profit	(17.12)	$NB = B - C$	$NB = B - C = PeES - wE$
Fishing effort dynamics: open-access entry rule	(17.13)	$dE/dt = \delta \cdot NB$	$dE/dt = \delta(PeES - wE)$
BIOECONOMIC EQUILIBRIUM CONDITIONS:			
Biological equilibrium	(17.14)	$G = H$	$G = H$
Economic equilibrium	(17.15)	$E = E^*$ at which $NB = 0$	$E = E^*$ at which $NB = 0$

Note: Numbers in parentheses refer to the appropriate equation number in the text.

Open Access Fishery

- Price determination
  - Exogenous price: market price = P
  - This is not the only possible way of proceeding; could have market price determined via demand curve, and so varying with the harvest rate

Open Access Fishery

- Entry and Exit
  - How is fishing effort determined under conditions of open access?
  - Level of economic profit prevailing in the fishery?
  - Economic profit: difference between total revenue from the sale of harvested fish and total cost incurred in resource harvesting
  - Given that there is no method of excluding incomers into the industry, nor is there any way in which existing firms can be prevented from changing their level of harvesting effort, effort applied will continue to increase as long as it is possible to earn positive economic profit
  - Conversely, individuals or firms will leave the fishery if revenues are insufficient to cover the cost of fishing
  - A simple way of representing this algebraicly: $dE/dt = \delta \cdot NB$ where δ is a positive parameter indicating the responsiveness of industry size to industry profitability. When economic profit (NB) is positive, firms will enter the industry; when it is negative they will leave. The magnitude of that response, for any given level of profit or loss, will be determined by δ

Open Access Fishery

- Bioeconomic Equilibrium
    - We close our model with two equilibrium conditions that must be satisfied jointly
    - 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: $G = H$
    - Economic 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. We express this by the equation $NB = B - C = 0$ which implies (under our assumptions) that $PH = wE$
    - Notice that when this condition is satisfied, $dE/dt = 0$ and so effort is constant at ist equilibrium (or steady-state) level $E = E*$

Open Access Fishery

Analytical expressions for the open-access steady-state

equilibrium

The analytical expressions for E^*, S^* and H^* (where an asterisk denotes the equilibrium value of the variable in question) as functions of the model parameters alone are:

$$E^* = \frac{g}{e}\left(1 - \frac{w}{PeS_{MAX}}\right) \qquad\qquad (17.20)$$

$$S^* = \frac{w}{Pe} \qquad\qquad (17.21)$$

$$H^* = \frac{gw}{Pe}\left(1 - \frac{w}{PeS_{MAX}}\right) \qquad\qquad (17.22)$$

Open Access Fishery (baseline parameters)

Table 17.2 Parameter value assumptions for the illustrative numerical example

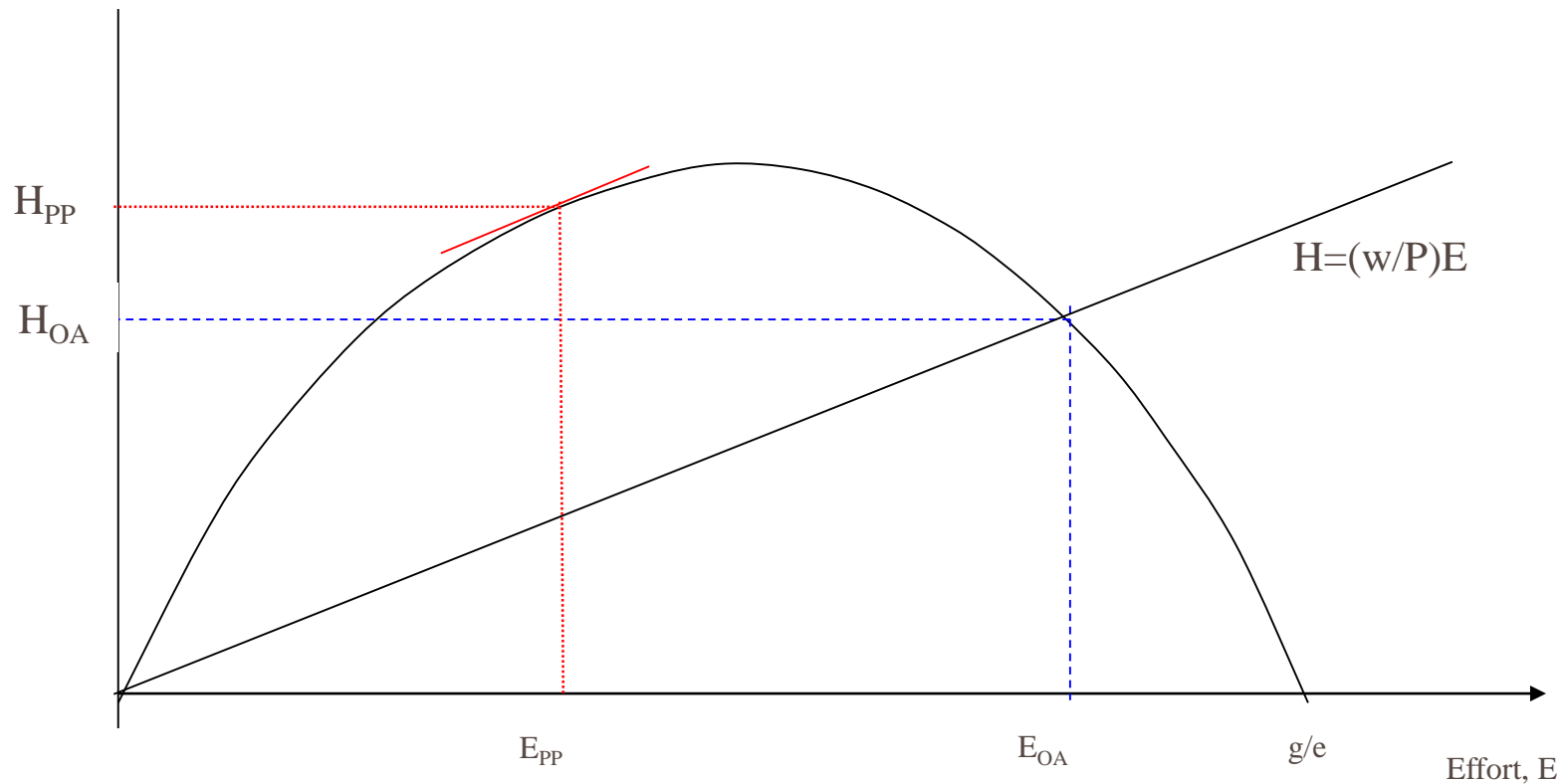| Parameter	Assumed numerical value
g	0.15
S_{MAX}	1
e	0.015
δ	0.4
P	200
w	0.6

Open Access Fishery

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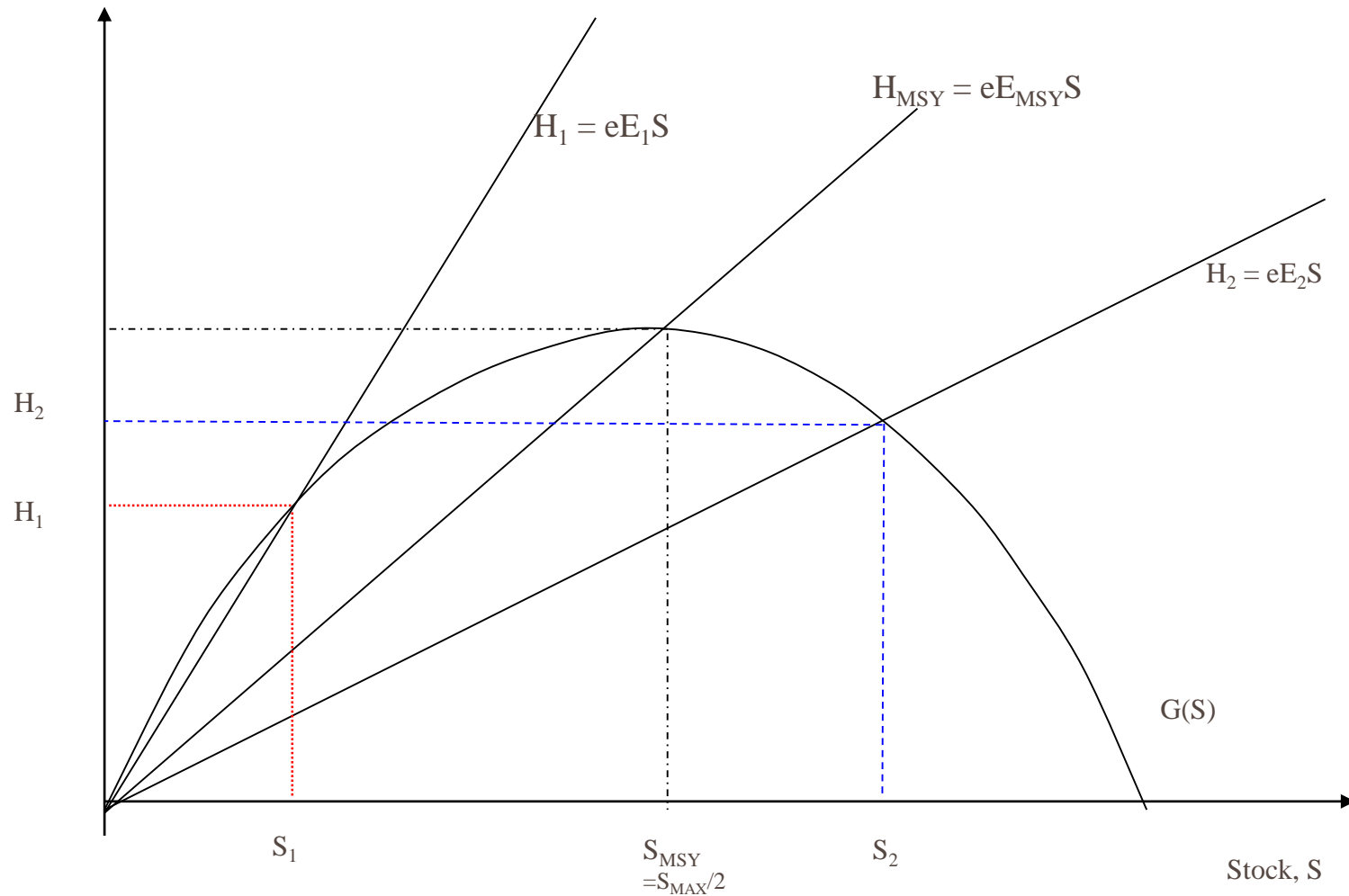
Open Access Fishery

Figure 17.4 Steady-state equilibrium "fishery's yield-effort relationship"

Open Access Fishery (graphic solution)

- Unique open access equilibrium outcome

  - We will have that effort level where ZERO ECONOMIC PROFIT occurs (open access assumptions)
  - 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

Open Access Fishery (comparative statics)

- It is helpful to inspect how the steady state equilibrium magnitudes of effort, stock and harvest in an open access fishery regime change in response to changes in the parameters or exogenous variables of that model.

- Table 17.2 showed that for a particular illustrative (or baseline) set of parameter values, the steady state equilibrium magnitudes of stock, effort and harvest were $S^* = 0.2$, $E^* = 8.0$ and $H^* = 0.024$ respectively. But we would also like to know how the steady state equilibrium values would change in response to changes in the model parameters. This can be established using comparative static analysis.

- Comparative static analysis is undertaken by obtaining the first-order partial derivatives of each of these three equations with respect to a parameter or exogenous variable of interest and inspecting the resulting partial derivative.

Open Access Fishery (comparative statics)

Table 17.3 Comparative static results: open access steady-state equilibrium

	P	w	e	g	δ
S^*	–	+	–	0	0
E^*	+	–	?	+	0
H^*	?	?	?	+	0

The Dynamics of Renewable Resource Harvesting

- Discussion so far has been exclusively about steady states; equilibrium outcomes which, if achieved, would remain unchanged provided that relevant economic or biological conditions remain constant

- Dynamic resource harvesting important (see slide 11)!
  - This would consider questions such as how a system would get to a steady state if it were not already in one, or whether getting to a steady state is even possible
  - In other words, dynamics is about transition or adjustment paths
  - Dynamic analysis might also give us information about how a fishery would respond, through time, to various kinds of shocks and disturbances

- The dynamics of the open access fishery model are driven by two differential equations, determining the instantaneous rates of change of S and E
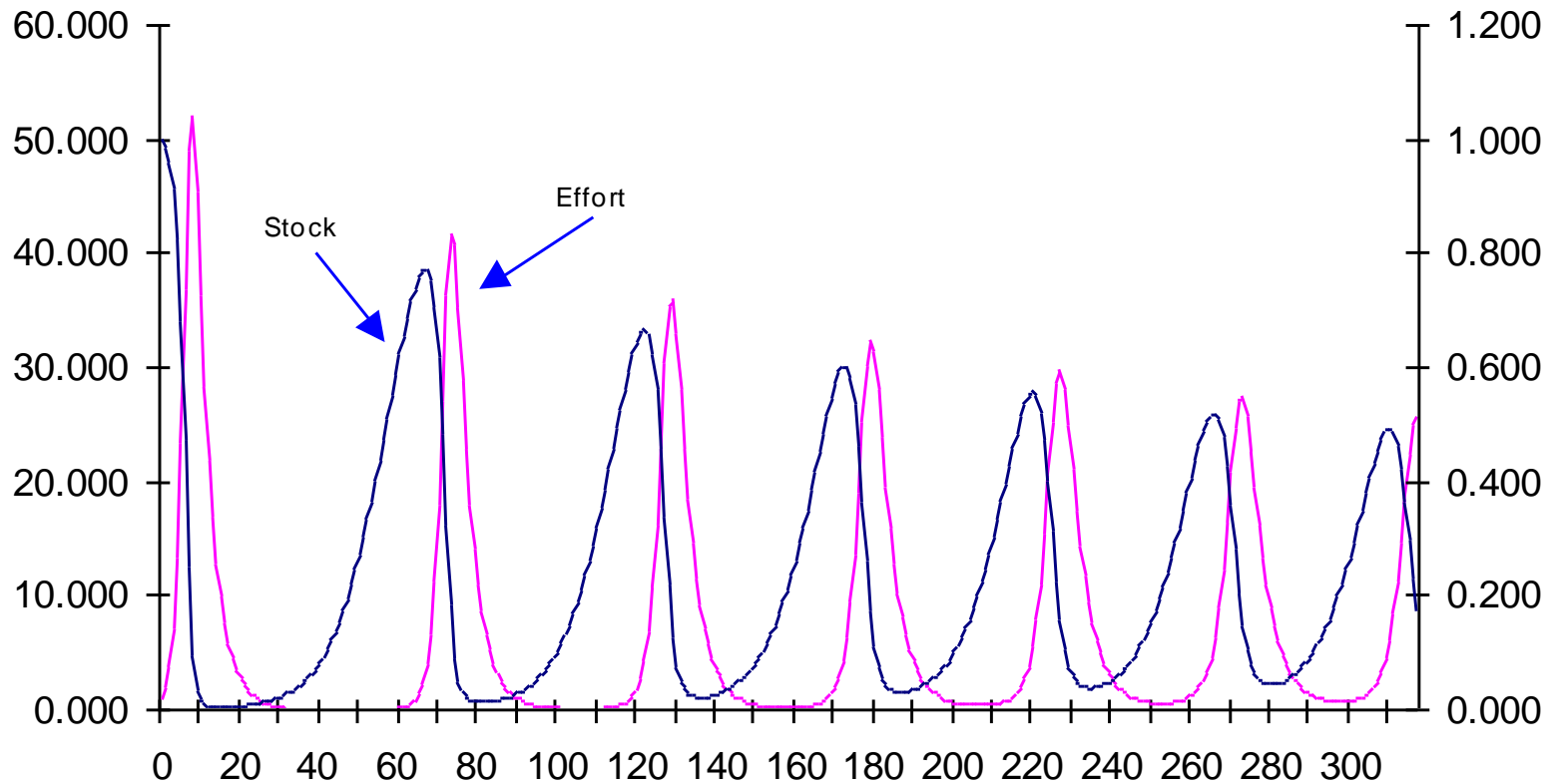
The Dynamics of Renewable Resource Harvesting
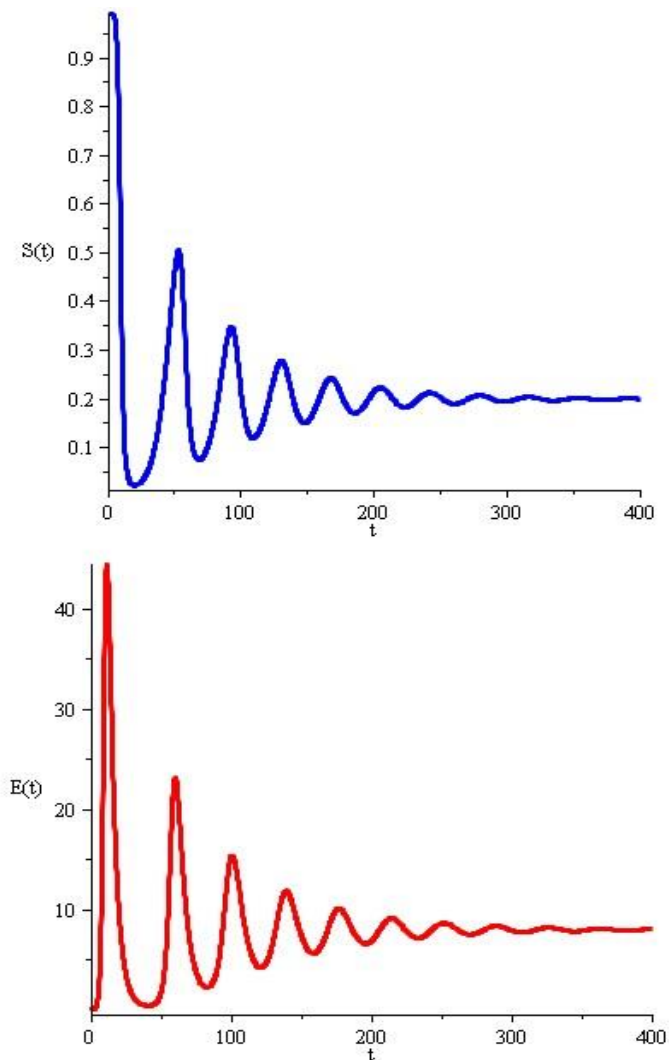
Stock (blue) and effort (red) dynamic paths for the open access model:

- New stock, not previously been commercially exploited
- Now becomes available for unregulated open-access commercial exploitation; market price high and fishing cost (per unit of effort) low due to big stock
- Many boats enter market (big economic profit), capacity is built up
- Effort is rising over time as new boats are attracted in, and stock is falling (because new recruitment to stock is low)
- Process of increasing E and decreasing S will persist for some time, but not indefinitely; as stock becomes lower, fish become harder to catch, therefore cost per fish caught rises
- Eventually this results in the case that many boats make losses rather than profit, therefore this described process reverses (stock rising, effort falling)
- E and S repeatedly over- and undershooting equilibrium outcomes characterizes open-access resource harvesting

Continuous time only; in discrete time, particular parameter combinations lead to extinction (even when parameters describe the existence of a steady state with positive stock and effort)
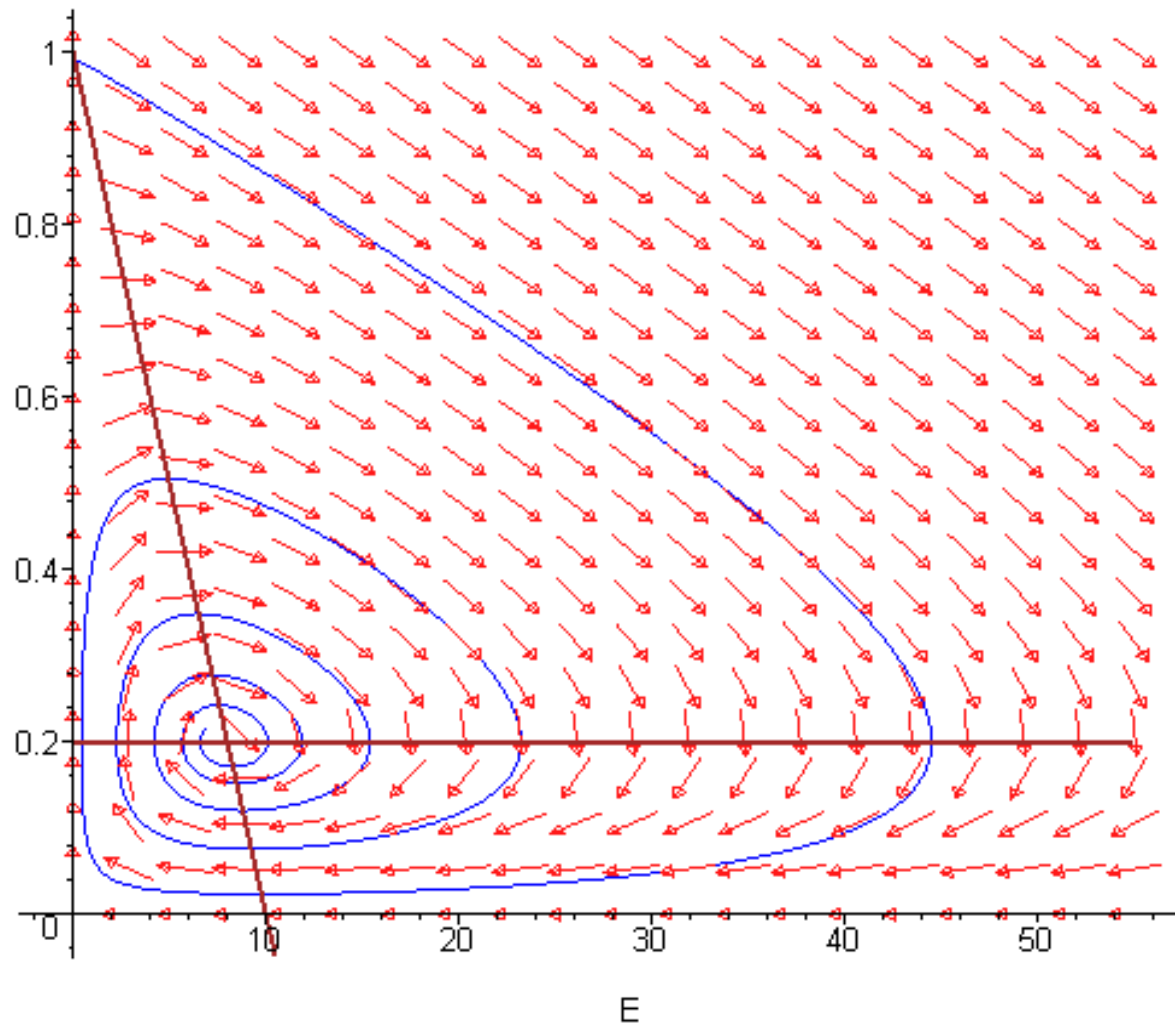
The Dynamics of Renewable Resource Harvesting
Overlying paths to illustrate their relative phasings

Which of these should one use?

- Often choice is made on the basis of analytical or computational convenience.

- If these two approaches yielded results that were exactly (or very closely) equivalent, then convenience would be an appropriate choice criterion.

- However, they do not. In some circumstances discrete time modelling generates results very similar to those obtained from a continuous time model.

- But this is not generally true. Indeed, the two approaches may differ not only quantitatively but also qualitatively. That is, discrete time and continuous time models of the same phenomenon will often yield results with very different properties.

Which of these should one use?

- This suggests that the choice should be made in terms of which approach best represents the phenomena being modelled.

- Let us first think about the biological component of a renewable resource model. Gurney and Nisbet (1998, page 61) take a rather particular view on this matter and argue that

- "The starting point for selecting the appropriate formalism must be therefore the recognition that real ecological processes operate in continuous time. Discrete-time models make some approximation to the outcome of these processes over a finite time interval, and should thus be interpreted with care. This caution is particularly important as difference equations are intuitively appealing and computationally simple. However, this simplicity is an illusion … . …. incautious empirical modelling with difference equations can have surprising (adverse) consequences."

- It is undoubtedly the case that much ecological modelling is done in continuous time.

- But the Gurney and Nisbet implication that all ecological processes are properly modelled in continuous time would not be accepted by most ecologists.

- Flora and fauna where generations are discrete are always modelled in discrete time. Some ecologists, and others, would argue that discrete time is appropriate in other situations as well.

Which of these should one use?

- When it comes to the economic parts of bioeconomic models of renewable resources, it is also far from clear a priori whether continuous or discrete time modelling is more appropriate.

- Economists often have a predilection for continuous time modelling, but that may often have a lot to do with physics emulation and mathematical convenience.

- Discrete time modelling is appropriate for quite a range of economic problems; and when we get to the data, except for financial data, it's a discrete time world.

- All that can really be said on this matter is that we should select between continuous and discrete time modelling according to the purposes of our analysis and the characteristics of the processes being modelled.

- For example, where one judges that a process being modelled involves discrete, step-like changes, and that capturing those changes is of importance to our research objectives then the use of discrete-time difference equations would be appropriate.

Which of these should one use?

Excel Übung:

http://www.pearsoned.co.uk/highereducation/ resources/permannaturalresourceandenvironm entaleconomics4e/

Dynamic Harvesting with Minimum Population Size

- One extension to the simple open access model is to deal with biological growth processes in which there is a positive minimum viable population size.

- Box 17.1 introduced several alternative forms of logistic growth. Of particular interest are those shown in panels (b) and (d) of Figure 17.1, in which there is a threshold stock (or population) size SMIN such that if the stock were to fall below that level the stock would necessarily fall towards zero thereafter. There would be complete population collapse.

- In these circumstances, steady-state equilibria are hard to defend, as the fishery collapse prevents one from being obtained. Even though parameter values may suggest the presence of a steady-state equilibrium at positive stock, harvest and effort levels, if the stock were ever to fall below SMIN during its dynamic adjustment process, the stock would irreversibly collapse to zero.

1. Where a renewable resource has some positive threshold population size the likelihood of the stock of that resource collapsing to zero is higher than it is in the case of simple logistic growth, other things being equal

2. Moreover, the likelihood of stock collapse becomes greater the larger is SMIN. These results are to a degree self-evident. A positive minimum viable population size implies that low populations that would otherwise recover through natural growth may collapse irretrievably to zero.

Dynamic Harvesting with Minimum Population Size

- But matters are actually more subtle than this.

- In particular, where the renewable resource growth function exhibits critical depensation, the dynamics no longer exhibit the stable convergent properties shown in Figures 17.4 and 17.5.

- Indeed, over a large domain of the possible parameter configurations, the dynamics become unstable and divergent.

- In other words, the adjustment dynamics no longer take one to a steady-state equilibrium, but instead lead to population collapse. The stock can only be sustained over time by managing effort and harvest rates; but the management required for sustainability is, by definition, not possible in an open access fishery.

- This illustrates two general points about renewable resources:
1. under conditions of open access, the specific properties of the biological growth function for that resource have fundamental implications for its sustainability.
2. open access conditions are likely to be incompatible with resource sustainability where biological growth is characterised by critical depensation.

Volatility and Randomness

- In practice the environment in which the resource is situated may change in an unpredictable way.

- When open access to a resource is accompanied by volatile environmental conditions, and where that volatility is fast-acting, unpredictable and with large variance, outcomes in terms of stock and/or harvesting can be catastrophic.

- Simple intuition suggests why this is the case.

- Suppose that environmental stochasticity leads to there being a random component in the biological growth process. That is, the intrinsic growth rate contains a fixed component, g, plus a random component u, where the random component may be either positive or negative at some instant in time. Then the achieved growth in any period may be smaller or larger than its underlying mean value as determined by the growth equation 17.3. When the stochastic component happens to be negative, and is of sufficient magnitude to dominate the positive fixed component, actual growth is negative. If the population were at a low level already, then a random change inducing lower than normal, or negative, net growth could push the resource stock below the point from which biological recovery is possible. This will, of course, be more likely the further above zero is SMIN.

- Example: EU-fishing quotas depend on scientist's estimates

Private-Property Fishery

- In an open-access fishery, firms exploit available stocks as long as positive profit is available. While this condition persists, each fishing vessel has an incentive to maximize its catch.

- But there is a dilemma here, both for the individual fishermen and for society as a whole.
  - From the perspective of the fishermen, the fishery is perceived as being overfished. Despite each boat owner pursuing maximum profit, the collective efforts of all drive profits down to zero.
  - From a social perspective, the fishery will be economically 'overfished' (this is a result that is established in Section 17.11). Moreover, the stock level may be driven down to levels that are considered to be dangerous on biological or sustainability grounds.

- What is the underlying cause of this state of affairs? Although reducing the total catch today may be in the collective interest of all (by allowing fish stocks to recover and grow), it is not rational for any fisherman to individually restrict fishing effort.
  - There can be no guarantee that he or she will receive any of the rewards that this may generate in terms of higher catches later. Indeed, there may not be any stock available in the future. In such circumstances, each firm will exploit the fishery today to its maximum potential, subject only to the constraint that its revenues must at least cover its costs.

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Private-Property Fishery: Specifications

- A private-property fishery has the following three characteristics:

1. There is a large number of fishing firms, each behaving as a price-taker and so regarding price as being equal to marginal revenue. It is for this reason that the industry is often described as being competitive.
2. Each firm is wealth maximizing.
3. There is a particular structure of well-defined and enforceable property rights to the fishery, such that owners can control access to the fishery and appropriate any rents that it is capable of delivering.

- What exactly is this particular structure of private property rights? Within the literature there are several (sometimes implicit) answers to this question. We shall outline two of them.
    1. A private property fishery refers to the harvesting of a single species from lots of different biological fisheries, fishing grounds. Each fishing ground is owned by a fishing firm. That fishing firm has private property rights to the fish which are on that fishing ground currently and at all points in time in the future.[9] All harvested fish, however, sell in one aggregate market at a single market price.
    2. The fishery as being managed by a single entity which controls access to the fishery and coordinates the activity of individual operators to maximize total fishery profits (or wealth). Nevertheless, harvesting and pricing behavior are competitive rather than monopolistic.

Two versions of the static profit-maximising private-property fishery model

- Our analysis of the private-property fishery proceeds in two steps.

  – The first develops a simple static model of a private-property fishery in which the passage of time is not explicitly dealt with.

  – The second develops a multi-period intertemporal present-value maximising fishery model

- The first case turns out to be a special case of the second in which owners use a zero discount rate.

Simple Static Profit-Maximizing PP Fishery Model

- In the simple static model of a private-property fishery, the passage of time (and so time-value of money) is not explicitly dealt with.

- In effect, the analysis supposes that biological and economic conditions remain constant over some span of time.

- It then investigates what aggregate level of effort, stock and harvest would result if each individual owner (with enforceable property rights) managed affairs so as to maximize profits over any arbitrarily chosen interval of time.

- This way of dealing with time – in effect, abstracting from it, and looking at decisions in only one time period but which are replicated over multiple periods – leads to its description as a static fishery model.

Simple Static Profit-Maximizing PP Fishery Model

- The biological and economic equations of the static private-property fishery model are identical to those of the open-access fishery in all respects but one.

- The difference lies in that the open-access entry rule , $dE/dt = \delta \cdot NB$, which implies a zero-profit economic equilibrium, no longer applies.

- Instead, owners choose effort to maximize economic profit from the fishery. This can be visualized by looking back to Figure 17.4.

$H=(w/P)E$

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

H_{PP}

H_{OA}

E_{PP} E_{OA} g/e
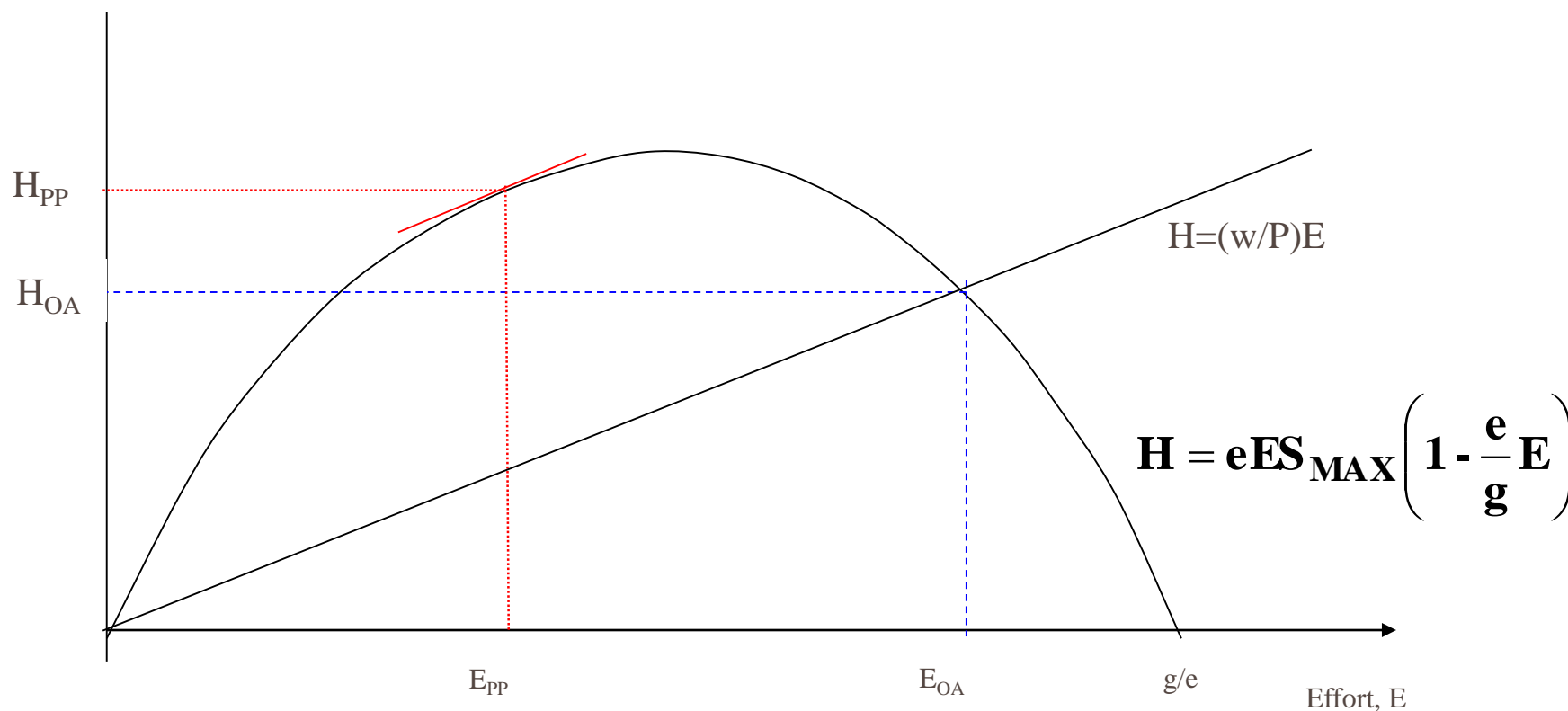
Effort, E

Static Private Property: owners choose effort to maximize economic profit from the fishery. Multiply both functions by the market price of fish. The inverted U-shape yield–effort equation then becomes a revenue–effort equation. And the ray emerging from the origin now becomes $PH = wE$, with the right-hand side thereby denoting fishing costs. Profit is maximized at the effort level which maximizes the surplus of revenue over costs. Diagrammatically, this occurs where the slopes of the total cost and total revenue curves are equal. This in indicated in by the tangent to the yield–effort function at EPP being parallel to the slope of the $H = (w/P)E$ line.

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Steady-State OA and PP Comparison

Table 17.4 Steady-state open-access and static private-property equilibria compared: parametric solution equations and numerical values of steady state solutions under baseline parameter value assumptions

	Open access		Static private property	
	Open access parametric solution equation	Baseline numerical value	Static private property parametric solution equation	Baseline numerical value
Stock	$S^* = \dfrac{w}{Pe}$	0.200	$S^*_{PP} = \dfrac{1}{2}\dfrac{PeS_{MAX} + w}{Pe}$	0.600
Effort	$E^* = \dfrac{g}{e}\left(1 - \dfrac{w}{PeS_{MAX}}\right)$	8.000	$E^*_{PP} = \dfrac{1}{2}\dfrac{g}{e}\left(1 - \dfrac{w}{PeS_{MAX}}\right)$	4.000
Harvest	$H^* = \dfrac{gw}{Pe}\left(1 - \dfrac{w}{PeS_{MAX}}\right)$	0.024	$H^*_{PP} = \dfrac{1}{4}g\left(S_{MAX} - \dfrac{w^2}{P^2e^2S_{MAX}}\right)$	0.036

Comparative Statics Comparison

Table 17.5 Comparative static results: open access compared with static private property

	P	w	E	g	δ
Open access					
S^*	−	+	−	0	0
E^*	+	−	?	+	0
H^*	?	?	?	+	0
Static private property					
S^*_{PP}	−	+	−	0	0
E^*_{PP}	+	−	?	+	0
H^*_{PP}	+	−	+	+	0

The Present-Value-Maximizing Fishery Model

- The present-value-maximizing fishery model generalizes the model of the static private-property fishery, and in doing so provides us with a sounder theoretical basis and a richer set of results.

- The essence of this model is that a rational private-property fishery will organize its harvesting activity so as to maximize the discounted present value (PV) of the fishery.

- This section specifies the present-value-maximizing fishery model and describes and interprets its main results. Full derivations have been placed in Appendix 17.3.

- The individual components of our model are very similar to those of the static private fishery model. However, we now bring time explicitly into the analysis by using an intertemporal optimization framework.

- Initially we shall develop results using general functional forms. Later in this section, solutions are obtained for the specific functions and baseline parameter values assumed earlier.

Model specification

- It is assumed that the market price of fish is a constant, exogenously given, number, and that the market for landed fish is competitive.

- We regard harvest levels as the instrument (control) variable.

- To facilitate this, we specify fishing costs as a function of the quantity harvested and the size of the fish stock.

$$C_t = C(H_t, S_t) \qquad C_H > 0, \; C_S < 0$$

- The initial population of fish is S_0, the natural growth of which is determined by the function $G(S)$.

- The fishery owners select a harvest rate for each period over the relevant time horizon (here taken to be infinity) to maximise the present value (or wealth) of the fishery, given an interest rate i.

$$\text{Max} \int_0^\infty \{PH_t - C(H_t, S_t)\} e^{-it} dt$$

subject to

$$\frac{dS}{dt} = G(S_t) - H_t$$

and initial stock level $S(0) = S_0$.

The Present-Value-Maximizing Fishery Model

- The necessary conditions for maximum wealth include

$$p_t = P - \frac{\partial C(H,S)}{\partial H_t} \qquad (17.29)$$

$$\frac{dp_t}{dt} = ip_t - p_t \frac{dG(S)}{dS_t} + \frac{\partial C(H,S)}{\partial S_t} \qquad (17.30)$$

- It is very important to distinguish between upper-case P and lower-case p in equation 17.29, and in many of the equations that follow.

- P is the market, or landed, or gross price of fish; it is, therefore, an observable quantity. As the market price is being treated here as an exogenously given fixed number, no time subscript is required on P.

- In contrast, lower-case pt is a shadow price, which measures the contribution to wealth made by an additional unit of fish stock at the wealth-maximizing optimum. It is also known as the net price of fish, and also as unit rent.

The Present-Value-Maximizing Fishery Model

Three properties of the net price deserve mention:

1. Unobservable quantity
2. Like all shadow prices, it will vary over time, unless the fishery is in steady-state equilibrium. In general, therefore, it is necessary to attach a time label to net price
3. Equivalence between the net price equations for renewable / non-renewable

- Equation 17.29 defines the net price of the resource (pt) as the difference between the market price and marginal cost of an additional unit of harvested fish.

- Differential equation 17.30 governs the behavior over time of the net price, and implicitly determines the harvest rate in each period.

- Note that if growth is set to zero (as would be the case for a non-renewable resource) and the stock term in the cost function is not present (so that the size of the resource stock has no impact on harvest costs) then the net price equation for renewable resources (equation 17.30 above) collapses to a special case that is identical to its counterpart for a non-renewable resource

The Present-Value-Maximizing Fishery Model

Steady-state equilibrium in the present-value-maximising fishery

In a steady state all variables are unchanging with respect to time, which implies that $dp/dt = 0$ and also that $G(S) = H$. Hence the optimising conditions 17.29 and 17.30 collapse to the simpler forms

$$p = P - \frac{\partial C(H,S)}{\partial H} \tag{17.31}$$

$$ip = p\frac{dG(S)}{dS} - \frac{\partial C(H,S)}{\partial S} \tag{17.32}$$

The Present-Value-Maximizing Fishery Model

Interpretation of equation 17.32

- A decision about whether to defer some harvesting until the next period is made by comparing the marginal costs and benefits of adding additional units to the resource stock. By not harvesting an additional unit this period, the fisher takes an opportunity cost that consists of the foregone return by holding a stock of unharvested fish. The marginal cost of the investment is *ip*, as sale of one unit of the harvested fish would have led to a revenue net of harvesting costs (given by the net price of the resource, *p*) that could have earned the prevailing rate of return on capital, *i*. Since we are considering a decision to defer this revenue by one period, the present value of this sacrificed return is *ip*.

- The owner compares this marginal cost with the marginal benefit obtained by not harvesting the additional unit this period. There are two categories of marginal benefit:

1. As an additional unit of stock is being added, total harvesting costs will be reduced by the quantity $C(S) = \partial C/\partial S$ (note that $\partial C/\partial S < 0$)

2. The additional unit of stock will grow by the amount dG/dS. The value of this additional growth is the amount of growth valued at the net price of the resource

The Present-Value-Maximizing Fishery Model, Intuition

A present-value-maximising owner will add units of resource to the stock provided the marginal cost of doing so is less than the marginal benefit. That is:

$$ip < \frac{\mathrm{d}G}{\mathrm{d}S}\, p - \frac{\partial C}{\partial S}$$

This states that a unit will be added to stock provided its 'holding cost' (ip) is less than the sum of its harvesting cost reduction and value-of-growth benefits. Conversely, a present-value-maximising owner will harvest additional units of the stock if marginal costs exceed marginal benefits:

$$ip > \frac{\mathrm{d}G}{\mathrm{d}S}\, p - \frac{\partial C}{\partial S}$$

These imply the asset equilibrium condition, equation 17.32.

When 17.32 is satisfied, the rate of return the resource owner obtains from the fishery is equal to i, the rate of return that could be obtained by investment elsewhere in the economy. This is one of the intertemporal efficiency conditions identified in Chapter 11. To confirm that this equality exists, divide both sides of equation 17.32 by the net price p to give

$$i = \frac{dG}{dS} - \frac{\left(\frac{\partial C}{\partial S}\right)}{p} \tag{17.33}$$

Equation 17.33 is a version of what is sometimes called the 'fundamental equation' of renewable resources. The left-hand side is the rate of return that can be obtained by investing in assets elsewhere in the economy. The right-hand side is the rate of return that is obtained from the renewable resource. This is made up of two elements:

- the natural rate of growth in the stock from a marginal change in the stock size;
- the value of the reduction in harvesting costs that arises from a marginal increase in the resource stock.

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Table 17.6 Steady-state equilibrium outcomes from the illustrative spreadsheet model for baseline parameter values in (a) a static private-property fishery, (b) a PV-maximising fishery with various interest rates and (c) an open-access fishery

i	Static private fishery*			PV-maximising fishery			Open-access fishery*		
	S	E	H	S	E	H	S	E	H
0.0	0.6	4.0	0.036	0.6000	4.0000	0.0360	0.20	8.0	0.024
0.1	0.6	4.0	0.036	0.4239	5.7607	0.0366	0.20	8.0	0.024
0.2	0.6	4.0	0.036	0.3333	6.6667	0.0333	0.20	8.0	0.024
0.3	0.6	4.0	0.036	0.2899	7.1010	0.0309	0.20	8.0	0.024
0.4	0.6	4.0	0.036	0.2677	7.3333	0.0293	0.20	8.0	0.024
0.5	0.6	4.0	0.036	0.2527	7.4734	0.0283	0.20	8.0	0.024
0.6	0.6	4.0	0.036	0.2434	7.5660	0.0276	0.20	8.0	0.024
0.7	0.6	4.0	0.036	0.2369	7.6314	0.0271	0.20	8.0	0.024
0.8	0.6	4.0	0.036	0.2320	7.6798	0.0267	0.20	8.0	0.024
0.9	0.6	4.0	0.036	0.2283	7.7171	0.0264	0.20	8.0	0.024
1.0	0.6	4.0	0.036	0.2253	7.7467	0.0260	0.20	8.0	0.024
10.0	0.6	4.0	0.036	0.2024	7.9759	0.0242	0.20	8.0	0.024
100.0	0.6	4.0	0.036	0.2002	7.9976	0.0240	0.20	8.0	0.024

* Static private fishery and open-access fishery steady-state equilibrium values do not vary with the interest rate. These equilibrium values have been copied into every row for purposes of comparison.

Source of data: The Excel file *Comparative statics.xls*, to be found in the Additional Materials for Chapter 17

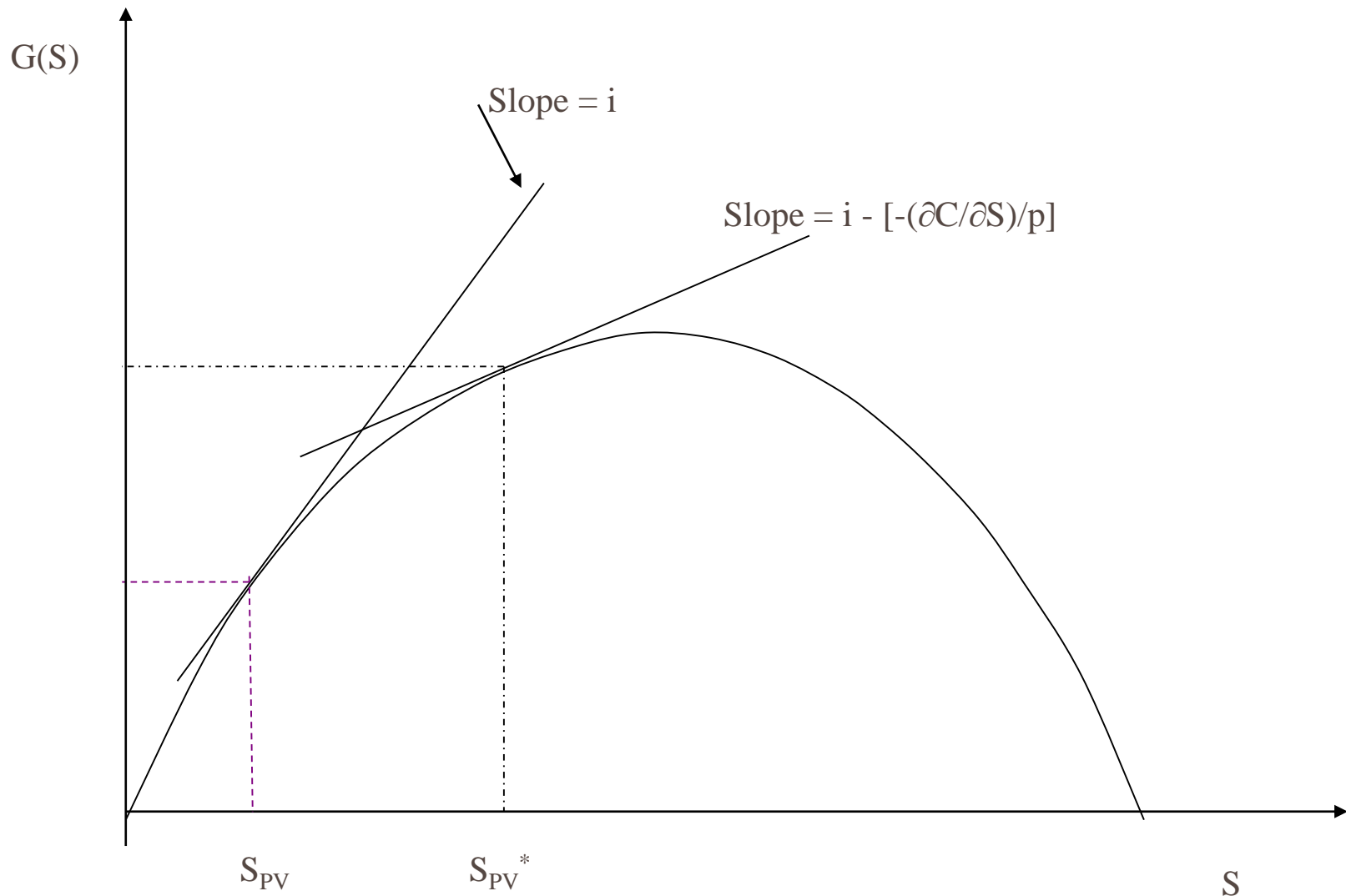Three important results are evident from an inspection of the data in Table 17.6:

1. In the special case where the **interest rate is zero, the steady-state equilibria of a static private-property fishery and a PV-maximising fishery are identical**. For all other rates they differ.
2. For non-zero interest rates, the steady-state fish stock (fishing effort) in the PV profit-maximising fishery is lower (higher) than that in the static private fishery, and becomes increasingly lower (higher) the higher is the interest rate.
3. **As the interest rate becomes arbitrarily large, the PV-maximising outcome converges to that of an open-access fishery**.

The Consequence of a Dependence of Harvest Costs on the Stock Size

- The specific functions used in this chapter for harvest quantity and harvest costs are $H = eES$ and $C = wE$ respectively. Substituting the former into the latter and rearranging yields $C = wE/eS$.

- It is evident from this that, under our assumptions, harvest costs depend on both effort and stock. However, suppose that the harvest equation were of the simpler form $H = eE$. In that case we obtain $C = wE/e$ and so costs are independent of stock.

- In such (rather unlikely) cases, when harvesting costs do not depend on the stock size, $\partial C/\partial S = 0$ and so the steady-state PV-maximizing condition (17.32) simplifies to $i = dG/dS$.

- This interesting result tells us that a private PV-maximizing steady-state equilibrium, where access can be controlled and costs do not depend upon the stock size, will be one in which the resource stock is maintained at a level where the rate of biological growth (dG/dS) equals the market rate of return on investment (i) – exactly what standard capital theory suggests should happen.

- This is illustrated in Figure 17.7.

Figure 17.7 Present value maximizing fish stocks with and without dependence of costs on stock size, and for zero and positive interest rates

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- If i = 0 and ∂C/∂S = 0 (that is decision makers use a zero discount rate and harvesting costs do not depend on the stock size) then the stock rate of growth (dG/dS) should be zero, and so the present-value-maximising steady-state stock level would be the one generating the maximum sustainable yield, SMSY.

In Figure 17.7, the straight line labelled 'Slope = i' would be horizontal and so tangent to the growth function at SMSY. Intuitively, it makes sense to pick the stock level that gives the highest yield in perpetuity if costs are unaffected by stock size and the discount rate is zero. However, this result is of little practical relevance in commercial fishing, however, as it is not conceivable that owners would select a zero discount rate.

- If i > 0 and ∂C/∂S = 0 (that is decision makers use a positive discount rate and harvesting costs do not depend on the stock size) then SPV is less than the maximum sustainable yield stock, SMSY.

- When total costs of harvesting, C, depend negatively on the stock size, the present-value-maximizing stock is higher than it would be otherwise.

- In the general case where a positive discount rate is used and $\partial C/\partial S$ is negative, the steady-state present-value-maximising stock level may be less than, equal to, or greater than the maximum sustainable yield stock.

Which one applies depends on the relative magnitudes of i and $(\partial C/\partial S)p$. Inspection of Figure 17.7 shows the following:

$$i = -(\partial C/\partial S)p \ \square \ S*PV = SMSY$$

$$i > -(\partial C/\partial S)p \ \square \ S*PV < SMSY$$

$$i < -(\partial C/\partial S)p \ \square \ S*PV > SMSY$$

This confirms an observation made earlier in this chapter: a maximum sustainable yield (or a stock level SMSY) is not in general economically efficient, and will only be so in special circumstances. For our illustrative numerical example, using baseline parameter values, it turns out that this special case is that in which $i = 0.05$; only at that interest rate does the PV-maximising model yield the MSY outcome.14

Open-Access, Static Private-Property and PV-Maximising Fishery Models in a Single Framework

- All three fishery models investigated here can be related to one another and so what might appear to be three fundamentally different sets of models and results can all be reconciled with one another and encompassed within a single framework.

- Consider first the two private-property fishery models. The static private-property fishery is a special case of the PV fishery – the case in which the interest rate is zero. Put another way, the steady-state PV-maximizing fishery results collapse to those of the simple private fishery model when the interest (discount) rate is zero.

- The open-access fishery model can also be brought into this encompassing framework. We can do so by observing that an open-access fishery can be thought of as one in which the absence of enforceable property rights means that fishing boat owners have an infinitely high discount rate. The interest rate of boat owners in an open-access fishery is, in effect, infinity, irrespective of what level the prevailing interest rate in the rest of the economy happens to be. We have already demonstrated that as increasingly large values of i are plugged into the PV-maximizing solution expression, outcomes converge to those derived from the open-access model.

Socially Efficient Resource Harvesting

- If we go through the process (as in section 17.11) of identifying the necessary conditions for socially optimal resource allocation decisions, we find that privately maximising decisions (as with the NPV maximising private property fishery model) will be socially efficient provided that a number of conditions are satisfied.

These conditions include:

1. The market in which fish are sold is a competitive market.

2. The (gross) market price, P, correctly reflects all social benefits (i.e. there are no externalities on the demand side).

3. There are no fishing externalities on the cost side.

4. The private and social consumption discount rates are identical, $i = r$.

- If these conditions are satisfied, the first-order conditions for social efficiency are identical to those for the PV-maximising fishery. Hence the PV-maximising fishery would be socially efficient.

- But, of course, it also follows that if one or more of those conditions is *not* satisfied, private fishing will not be socially efficient.
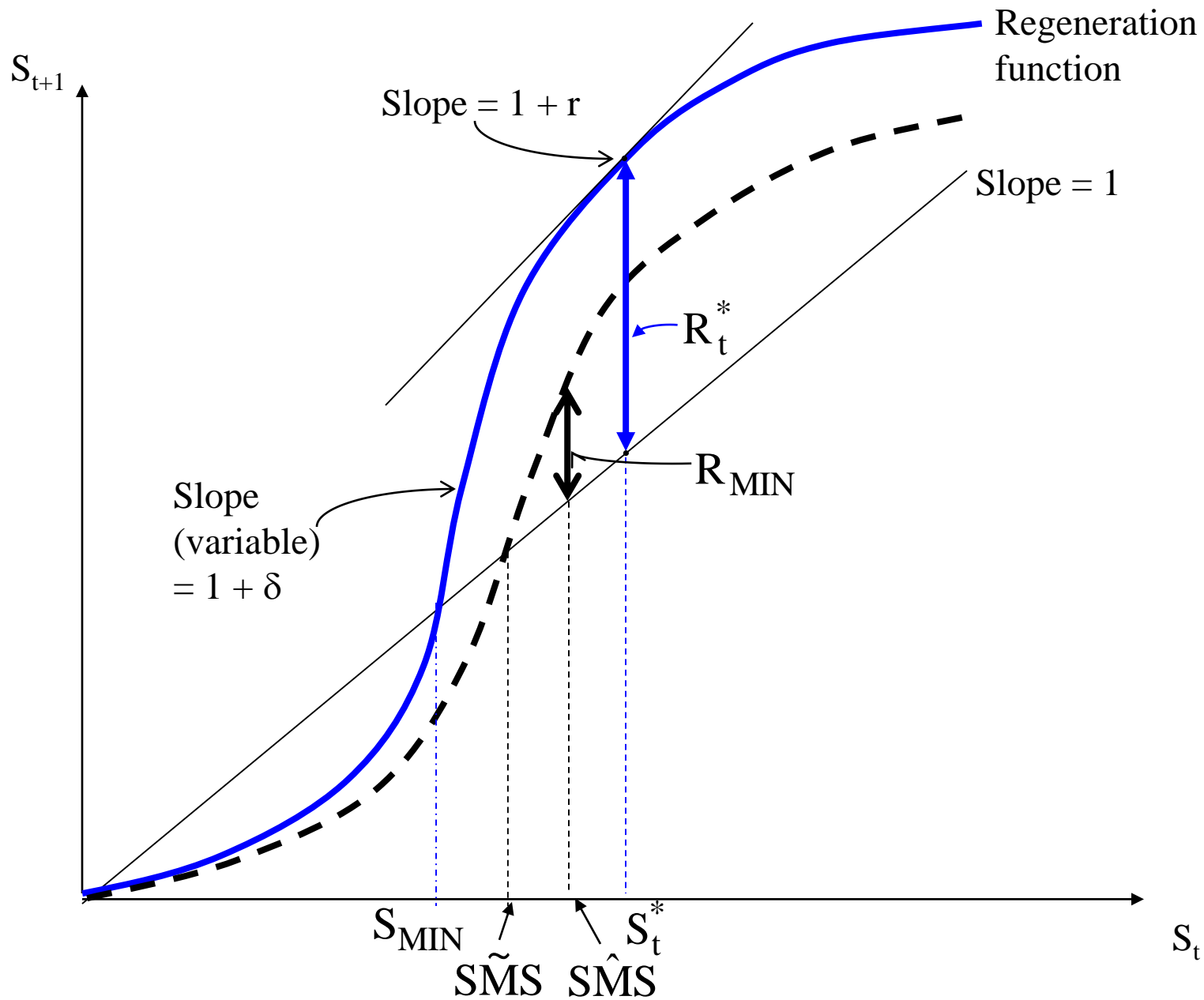
Figure 17.8 A safe minimum standard of conservation

Excess Harvesting and Species Extinction

There are many reasons why human behaviour may cause population levels to fall dramatically or, in extreme cases, cause species extinction. These include:

• Even under restricted private ownership, it may be 'optimal' to the owner to harvest a resource to extinction. Clark (1990) demonstrates, however, that this is highly improbable.

•Ignorance of or uncertainty about current and/or future conditions results in unintended collapse or extinction of the population.

•Shocks or disturbances to the system push populations below minimum threshold population survival levels.

The Present-Value-Maximizing Fishery Model

- the higher is the market (gross) resource price of the resource

- the lower is the cost of harvesting a given quantity of the resource

- the more that market price rises as the catch costs rise or as harvest quantities fall

- the lower the natural growth rate of the stock, and the lower the extent to which marginal extraction costs rise as the stock size diminishes

- the higher is the discount rate

- the larger is the critical minimum threshold population size relative to the maximum population size.

Forestry

- As far as forests as sources of timber are concerned, much of the previous analysis applies.

- But what is also important here is the multiple service functions of much forestry.

Renewable Resources Policy

Command-and-control:

- Quantity restrictions on catches (EU Total Allowable Catches)

- Fishing season regulations

- Technical restrictions on the equipment used - for example, restrictions on fishing gear, mesh or net size, or boat size.

Incentive-based policies:

- Restrictions on open access/property rights

- Fiscal incentives

- Establishment of forward or futures markets

- Marketable permits ('individual transferable quotas', ITQ)