Renewable Resources

Renewable resources resources that can reproduce, grow, and die.

Economically important renewable resources include:

- Forests
- Fisheries
- Grasslands (used for grazing)
- Groundwater fed by rainfall and surface water percolation

Issues for analysis:

- Growth functions and equations of motion for renewable resource systems.
- Steady-state behavior of renewable resource systems.
- Open access, inefficient market outcomes, and policy corrections.
- Dynamic behavior of renewable resource systems.

A **steady-state** is a permanent level of stock that is maintained throughout time.

An **Equation of Motion** is a formula that defines what happens to the stock over time.

For example, when S_t denotes the resource inventory at period t:

- If $S_{t+1} - S_t > 0$, then the resource stock is growing over time
- If $S_{t+1} - S_t < 0$, then the resource stock is shrinking over time
- If $S_{t+1} - S_t = 0$, then the resource stock is in a steady state ($S_t = S_{t+1} = S_{t+2} \ldots$)

A Biological Model of A Fishery

Growth Functions

Let St represent the stock of a renewable resource at time t. For example, let St represent the biomass of a fish population at time t.

Let g(At, St) represent the **growth function** of the stock during time period t, where growth is a function of the level of the stock at the beginning of period t, St, and an exogenous parameter At, which represents factors other than stock which might affect growth in period t.

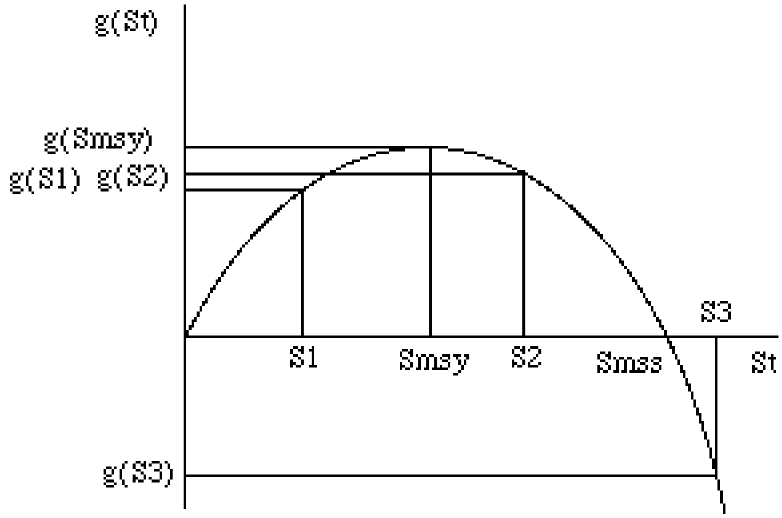
Carrying Capacity and MSS

The carrying capacity of an environment is the maximum level of stock that the environment can sustain indefinitely. **Carrying capacity is also called the maximum sustainable stock**. At the maximum sustainable level, Births = Deaths, and the growth rate of the stock is zero.

Steady-States

At the carrying capacity, the growth of the fish population is zero and the stock is in a **steady-state**. A steady-state is a situation in which the level of the stock is constant over time. There can be more than one steady-state. For example, a stock level of zero is also a steady-state, because at zero the stock level cannot rise (i.e., there are no fish to reproduce) and the stock level cannot fall below zero stock.

Fisheries growth function g(S_t)



St = stock of renewable resource at time t
g(St) = biological growth of renewable resource at time t

There are two steady-states: the origin and S_{mss}.

To the right of the origin, the growth of the stock at first increases with the level of the stock (point S1), but then food scarcity, disease, etc. cause growth to decline with further stock increases (point S2).

Eventually, carrying capacity S_{mss} is reached and growth falls to zero.

To the right of Smss (point S3), the stock is at an unsustainably high level, and growth is negative (g(S3)). To the right of S_{mss}, stock will fall until carrying capacity is reached.

Equation of Motion

We can express the relationships between stock level, growth and harvest in an **equation of motion** for the renewable resource:

$$S_{t+1} = S_t + g(S_t) - X_t$$

"stock next period equals stock this period plus growth this period minus harvest this period."

We can rearrange the equation of motion as follows:

$$S_{t+1} - S_t = g(S_t) - X_t$$

says that "the *change* in the stock equals growth minus harvest."

If we are in steady-state, then we know that the change in the stock is zero:

$$S_{t+1} - S_t = 0 = g(S_t) - X_t \qquad \Rightarrow \qquad g(S_t) = X_t$$

in steady-state, growth equals harvest

Sustainable Yields and MSY

- A **sustainable yield** of fish refers to the level of harvest which will result in a steady-state fish population. *Every point on the growth curve above represents a sustainable yield*.
- Every sustainable yield is associated with a steady-state stock of fish.
- The highest possible sustainable yield is called the **maximum sustainable yield**, denoted X_{msy}. The level of the *stock* associated with X_{msy} is called the stock level that supports maximum sustainable yield.

Optimal Fish Harvest in Steady-State (Zero Interest Rate)

In steady-state, harvest must equal growth: $g(A_t,S_t) = X_t$

$B(X_t)$: benefits derived from fish harvest

$C(X_t, S_t)$: total cost of fish harvest (depends on harvest and stock)

- $C_x > 0$ (the more you fish, the more it costs; i.e., positive MC)
- $C_s < 0$ (cost of fishing declines as the level of stock increases)

$$\max_{X_t,S_t} B(X_t) - C(X_t, S_t) \quad \text{subject to: } g(A_t, S_t) = X_t$$

we only need to examine one of the time periods if we are in steady-state.

$$\max_{X,S} B(X) - C(X, S) \quad \text{subject to: } g(A, S) = X$$

The Lagrangian expression for this problem is:

$$L = B(X) - C(X, S) + \lambda\,[g(A, S) - X]$$

FOC's:

(1) $$\frac{dL}{dX} = \frac{dB(X)}{dX} - \frac{dC(X,S)}{dX} - \lambda = 0$$

(2) $$\frac{dL}{dS} = -\frac{dC(X,S)}{dS} + \lambda\frac{dg(A,S)}{dS} = 0$$

(3) $$\frac{dL}{d\lambda} = g(A,S) - X = 0$$

Optimal Harvest in Steady-State (cont.)

FOC (1) says that price (MB) = the MC of changing the harvest level plus the user cost of changing the harvest level.

FOC (2) says that the VMP of the stock (λg_S) = the MC of changing the stock level. The marginal cost associated with changing the stock level is the change in the cost of finding the fish in the ocean as the stock level declines.

How does the steady-state stock level, S_{ss}, compare with maximum sustainable yield stock level, S_{msy}?

From FOC (1), λ = price - MC with respect to X. Hence, FOC (2) can be rewritten as:

$$(P - C_x)g_S = C_S$$

Now, **because C(X, S) falls as S increases**, (**$C_S < 0$**), we know that **$(P - C_x)g_S$ must be negative** for FOC (2) to hold.

· **Given $P - C_x \geq 0$** in steady-state (which must hold for $\pi \geq 0$), then it follows that **$g_S < 0$ in steady state**. Look at the Figure:
  - if $g_S < 0$, then $S_{SS} > S_{MSY}$.

Thus, **the steady-state (second-best) level of fish stock, S_{SS}, is greater than the level of fish stock that supports the MSY, S_{MSY}.**

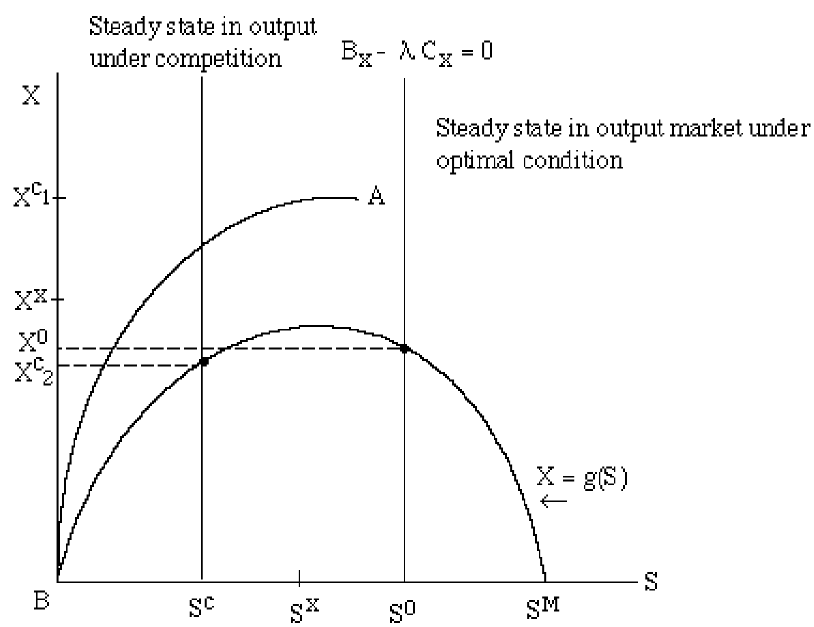
Note that **the steady-state (second-best) level of fish harvest, X_{SS}, is less than X_{MSY}.**

Open Access and Competitive Behavior

When a resource has open access, each fisherperson believes that any fish he/she does not catch will simply be caught by another fisher, so that the gains to keeping higher stocks will not be realized anyway.

Therefore, **under competition**:
(1) Stock is smaller than optimal.
(2) Output may be greater or smaller than is optimal.
(3) Social cost associated with extra harvesting will outweigh benefits from extra fish in cases where open access output is greater than optimal output.

There can be more than one steady state.



Steady State Outcomes: Optimal vs. Competition

Open Access (cont.)

Under competition, if MC is relatively small and demand is big, there may be a period when $X^c > X^x$ and the resource can be depleted, for example, when $X^c = X^{c1}$.

The MC may be increasing as S declines and the possible output stock combinations under competition will follow the line AB and the steady stock with X = S = 0 is at B.

When the open access outcome does not involve a steady state, the fish stock can be sent to zero through extinction.

If the marginal harvesting cost $\rightarrow \infty$ as the stock approaches zero, a steady state may be reached with a very small stock level.

If C_X is substantial and under the optimal solution λ / C_x is small, competitive outcomes will not be far away from optimal outcome.

Several intervention policies:

- Standards limiting the catch.
- An output tax of λ.
- Tax on fishing effort (can be placed on labor or on the number of boats)
- Moratorium on Fishing
- Change Length of Fishing Season
- Regulations on Technology (i.e., no gill-netting)

Renewable Resource Management in Steady-State

Consider a price-taking fishing industry with:

- Fish Stock (in biomass units): S
- Growth Function of Fish Stock: $g(m, n, S) = mS - nS^2/2$.
  - m might represent availability of food in the ecosystem
  - n might represent the number of predators (a constant)
- Fish Harvest (in biomass units): X
- Total Benefits of Harvest: $B(X) = P*X$
- Total Costs of Harvest: $C(X, S) = \frac{bX}{S}$

Note: the larger the fish stock, the lower the cost of fish harvest.

the fishery's economic problem can be stated as:

$$\max_{X,S} \; B(X) - C(X, S) \qquad \text{subject to: } g(m, n, S) = X$$

note: we can find several important quantities without solving the optimization problem:

Maximum Sustainable Stock

occurs where $g(m,n,S) = 0 \Rightarrow S_{mss} = 2m/n$

Stock Level that Supports Maximum Sustainable Yield

occurs where $dg/dS = 0 \Rightarrow S_{msy} = m/n$.

Maximum Sustainable Yield

substitute S_{msy} into $g(m,n,S) \Rightarrow X_{msy} = g(m,n,S_{msy}) = m^2/2n$

Optimal Steady-State Stock and Harvest Levels

$L = B(X) - C(X, S) + \lambda\ [g(m, n, S) - X]$

The FOC's:

$$\frac{dL}{dX} = \frac{dTB(X)}{dX} - \frac{dTC(X,S)}{dX} - \lambda = 0 \qquad P - b/S - \lambda = 0$$

$$\frac{dL}{dS} = -\frac{dTC(X,S)}{dS} + \lambda \frac{dg(m,n,S)}{dS} = 0 \qquad -(-bX)/S^2 + \lambda\ [m - nS] = 0$$

$$\frac{dL}{d\lambda} = g(m,n,S) - X = 0 \qquad [mS - nS^2/2] - X = 0$$

Solving for Steady-State Stock Level

Solve FOC (3) for X. Plug the resulting expression for X into FOC (2) to get:

(4) $-[-b(m/S - n/2)] + \lambda\ [m - nS] = 0$

Putting aside expression (4) for the moment, solve FOC (1) for λ:

(5) $\lambda = P - b/S$

Now plug λ into (4) and solve for S* to get:

(6) $S^* = m/n + b/2P$

Optimal Steady-State (cont.)

Solving for Steady-State Harvest Level

plug the expression for S* into FOC (3) and simplify:

$$(7) \qquad X^* = \frac{m^2}{2n} - \frac{nb^2}{8P^2}$$

- As the price of fish increase, the optimal harvest level increases towards X_{MSY}
- As the cost of harvesting decreases through improved technology, X* increases
- As the number of predators increases, the fish stock decreases, which implies that the optimal harvest, X* decreases
- As the available food in the ecosystem increases, X* increases

Thus, to increase our fish harvest:

- Subsidize investment in new technology
- Remove predator species
- Add fish food into the ecosystem.

Solving for Steady-State User Cost

substitute S* back into FOC (1):

$$(8) \qquad \lambda^* = P - \frac{b}{\frac{m}{n} + \frac{b}{2P}}$$

Open Access Market Failure

Under open access competition, fishers ignore the user cost component of FOC (1) and instead harvest until:

$P - dTC/dX = 0$ or $P = b/S$

=> the steady-state stock under open access competition, Sc, is:

(11) $Sc = b/P$

In steady-state, $g(m,n,S) = mS - nS^2/2 = X$:

(12) $X = mS - nS^2/2$

Substituting (11) into (12) => open access harvest level:

(13) $$X_c = \frac{mb}{P} - \frac{nb^2}{[2P^2]}$$

open access competition results in too little stock (i.e., Sc < S*), and too little harvest (i.e., Xc < X*).

A Harvest Tax to Correct Open Access Market Failure

· market failure occurs because private firms ignore user costs
=> set a tax per unit of harvest equal to the user cost at the optimal harvest level.

(14) tax per unit = $$\lambda^* = P - \frac{b}{\frac{m}{n} + \frac{b}{2P}}$$

Shifting the Growth Function - Fish Feeding

Various management activities can be undertaken to influence the growth of resources.

Let the growth equation be denoted g(S, A), where 'A' is a variable representing the level of feeding. (dg/dA > 0).

Assuming that the price per unit of feed is denoted by v, total cost becomes:

$$(15)\quad C(X,S,A) = C(X,S) + vA$$

The Lagrangian expression for this problem is:

$$(17)\quad \max_{X,S,A,\lambda} \quad L = B(X) - C(X, S) - vA + \lambda\left[g(S, A) - X\right]$$

The FOC's:

$$(18)\quad \frac{dL}{dX} = \frac{dB}{dX} - \frac{dC}{dX} - \lambda = 0$$

$$(19)\quad \frac{dL}{dS} = -\frac{dC}{dS} + \lambda\frac{dg}{dS} = 0$$

$$(20)\quad \frac{dL}{d\lambda} = g(S,A) - X = 0$$

we also have a new first-order condition:

$$(21)\quad \frac{dL}{dA} = \lambda\frac{dg}{dA} - v = 0\ .$$

This new condition says that we should increase feeding until the VMP of feeding (λ dg/dA) is equal to the price of feed v.