Management issues for complex ecosystems

Learning from coral reefs and boreal forests

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Introduction

- How do people use natural resources? Can we predict their use?
- How can we derive as much welfare as possible from using ecosystem resources?
- How can we use resources produced within ecosystems without jeopardizing future opportunities to use them?

Relevant literature

- Economic papers:
  - Resource models
    - Gordon-Scott-Clark
    - Faustmann-Pressler-Ohlin
  - Shallow lake models
    - Carpenter, Brock and Hansson (1999)
    - Mäler, Xepapadeas & de Zeeuw (2000)
    - Brock & Starrett (2000)
    - Wagener (2001)
- Ecological modeling:
  - Schaeffer
  - Holling (1959, 1973)
  - Scheffer (1998) and Carpenter & Cottingham (1998)

Two case studies

- Aquatic ecosystems used for fisheries: coral reefs.
  - Dominant characteristic in the model: flipping between coral dominated and algae dominated states.
- Forest ecosystems used for timber and recreation: boreal forests.
  - Dominant characteristic in the model: convex concave conifer growth.

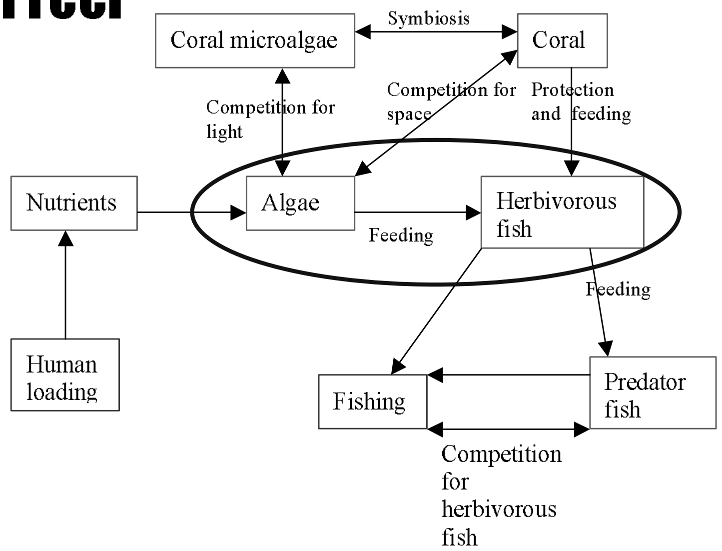
Coral reefs / boreal forests

- natural resources and ecosystem services:
  - Fisheries, fish nurseries, nutrient sink, recreation.
  - Timber, berries and mushroom, hunting, CO_2 sink, recreation.
- complex dynamic systems:
  - High level of biodiversity, complex species interactions.
  - Few dominating species.
- sensitivity to external change:
  - Bleeching, eutrophication, overfishing.
  - Overbrowsing, fire, pests.
- several stability states.
  - coral dominated / algae dominated.
  - Birch / pine.

Motivation

- Fisheries on coral reef / timber = important sources of income.
- Traditional models.
  - Fisheries: Schaeffer type models (Gordon 1954, Scott 1955).
  - Forestry: Faustmann-Pressler-Ohlin models (1849-1921).
  - One species, logistic growth: fisheries models derive optimal harvest/forestry models derive optimal rotation period.
  - Cannot explain the ”surprises” that have occurred in coral reef recently (bleaching, eutrophication followed by coral death). Are not adapted to new regulations on boreal forests.
- The models used are less unrealistic: more than one species and complex growth (sigmoid/convex-concave).

A simple coral reef



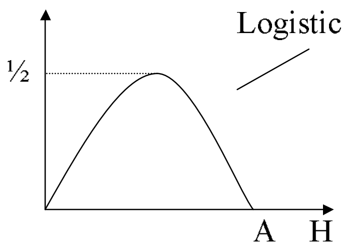
An even more simple coral reef

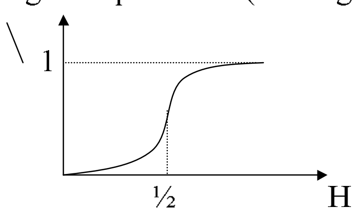
Nutrient load   Natural death rate   Consumption rate

Algae $\dot{A} = n - dA - eAH$

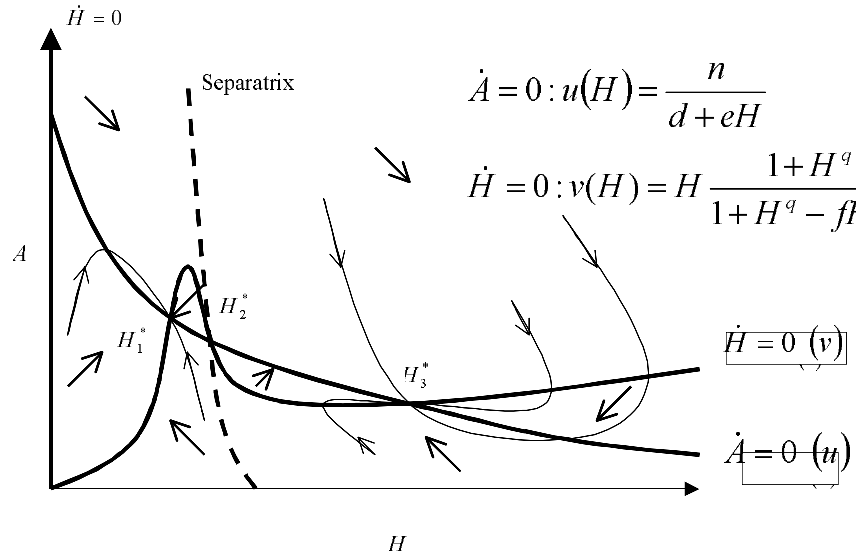
Predation rate   Curvature parameter

Fish $$\dot{H} = \underbrace{H\left(1-\frac{H}{A}\right)}_{\text{Logistic growth}} - \boxed{f\underbrace{\frac{H^q}{1+H^q}}_{\text{Sigmoid predation (Holling III)}}}$$





Phase diagram



$$\dot{A} = 0 : u(H) = \frac{n}{d + eH}$$

$$\dot{H} = 0 : v(H) = H\,\frac{1 + H^q}{1 + H^q - fH^{q-1}}$$

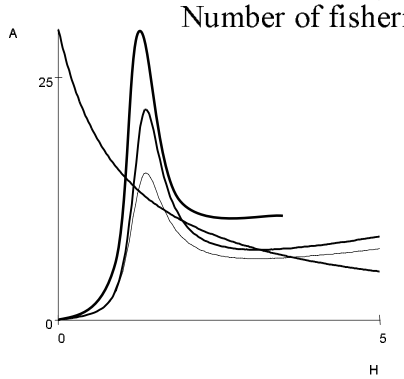
The effects of fishing

$$\dot{H} = H\left(1 - \frac{H}{A}\right) - f\,\frac{H^q}{1 + H^q} - K\eta EH$$

Fishing effort

Catchability coefficient

Number of fishermen



Total harvest is: $h(t) = K\eta EH$

- More algae in steady state.
- Increased flipping risk towards the algae-dominated states.
- Bifurcation towards one algae-dominated steady state.

Endogenous fishing

- A fisherman's profit from harvesting at time *t*:

$$\Pi(E,H) = p\eta EH - C(E)$$

Constant price

Cost of fishing effort

- $C'(E)>0$ and $C''(E)>0$.

Management options

- Open access:
  - several profit maximizing actors.
  - no institutional access restrictions to the reef.
  - Fishermen enter the market as long as some positive profit can be made.
- Sole ownership:
  - A profit maximizing sole owner
  - Fishing effort is the control variable
  - Perfect knowledge about coral reef dynamics

Management options

➲ Open access

$$\dot{A} = n - dA - eAH$$
$$\dot{H} = H\left(1 - \frac{H}{A}\right) - f\frac{H^q}{1+H^q} - K\eta EH$$
$$\dot{K} = \phi\left(p\eta EH - C(E)\right)$$
$$p\eta H = C'(E)$$

➲ Sole ownership

$$\max_{E\in\Xi} \int_0^\infty \left(p\eta EH - C(E)\right)e^{-\rho t}dt$$
$$\text{s.t. } \dot{A} = n - dA - eAH$$
$$\dot{H} = H\left(1 - \frac{H}{A}\right) - f\frac{H^q}{1+H^q} - \underbrace{E\eta H}_{h}$$

Dynamic systems

Open access

$$\begin{cases} \dot{A} = n - dA - eAH \\ \dot{H} = H\left(1 - \frac{H}{A}\right) - f\frac{H^q}{1+H^q} - K\eta E^o(H)H \\ \dot{K} = \phi\left(p\eta E^o(H)H - C\left(E^o(H)\right)\right) \end{cases}$$

Sole Owner-ship

$$\begin{cases} \dot{A} = n - dA - eAH \\ \dot{H} = H\left(1 - \frac{H}{A}\right) - f\frac{H^q}{1+H^q} - E^*(H,\lambda_H)\eta H \\ \dot{\lambda}_A = \lambda_A\rho + \lambda_A(d + eH) - \lambda_H\frac{H^2}{A^2} \\ \dot{\lambda}_H = \lambda_H\left(\rho - 1 + \frac{2H}{A} + fp\frac{H^{q-1}}{\left(1+H^q\right)^2}\right) + \lambda_A eA - (p - \lambda_H)E^*(H,\lambda_H)\eta \end{cases}$$

return

Steady states

- Open access

$$E^o = E^o(H^o)$$

$$A^o = \frac{n}{d + eH^o}$$

$$H^0 = \frac{C(E^o(H^o))}{p\eta E^o(H^o)}$$

$$K^o = \frac{1}{\eta E^o(H^o)}\left(1 - \frac{H^o}{n}(d + eH^o) - f\frac{(H^o)^{q-1}}{1+(H^o)^q}\right)$$

- Sole ownership
  - No analytical solutions
  - Typically there are several steady states
  - Dependence on initial conditions
  - Skiba points

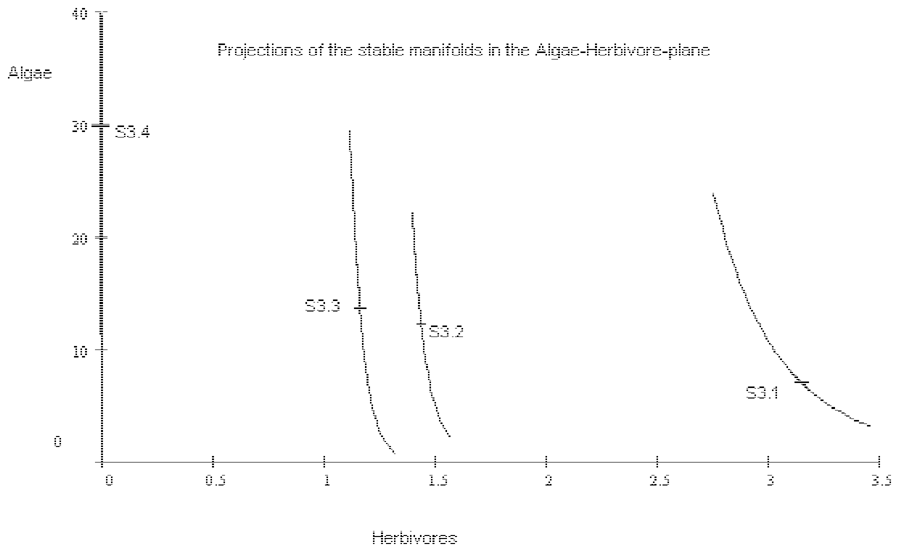
return

Steady states

The feasible steady states (positive populations) are in bold.

System	name	A	H	λ_A	λ_H	K
SYS1		-5.335	-6.623			
	H_3^*	**6.466**	**3.64**			
	H_2^*	**11.315**	**1.651**			
	H_1^*	**13.378**	**1.243**			
	H_0^*	**30**	**0**			
SYS2	$S2$	**15.836**	**0.894**			**10.976**
		284.164	-0.89443			-76.082
SYS3		$-1.431E+3$	-1.021	$-3.795E-3$	7.212	
		-104.155	-1.288	$-3.422E-3$	5.997	
		-4.975	-7.03	$1.861E-3$	$-5.602E-3$	
	$S3.1$	**7.243**	**3.142**	**9.44E − 4**	**0.021**	
	$S3.2$	**12.307**	**1.438**	**8.43E − 4**	**0.152**	
	$S3.3$	**13.883**	**1.161**	**1.69E − 5**	**5.272E − 3**	
	$S3.4$	**30**	**0**	**0**	**0**	
		34.881	-0.14	$5.29E-4$	28.925	

Stable manifolds in sole-ownership



Comparison of the phase diagrams in (A,H) -plane

Let $\zeta(H) = H(1 + H^q)$ and $\xi(H) = 1 + H^q - fH^{q-1}$

$$u(H) = \frac{N}{d + eH}$$ $\dot{A} = 0$ curve, common to all

$$v(H) = \frac{\zeta(H)}{\xi(H)}$$ $\dot{H} = 0$ curve natural ecosystem

$$w(H) = \frac{\zeta(H)}{\xi(H) - K\eta E^o (1 + H^q)}$$ $\dot{H} = 0$ curve open access

$$z(A, H, \dot{\lambda}) = \frac{\zeta(H)}{\xi(H) - E^*(H, \lambda_H(A, H, \dot{\lambda}))\eta(1 + H^q)}$$

$\dot{H} = 0$ curve sole ownership

A three species boreal forest

a_{ij}= Interaction coefficients

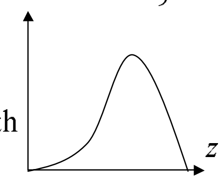
G = Natural species growth

Logistic growth

$$\left.\begin{array}{ll} \boxed{\text{moose}} & \dot{x} = x - x^2 + a_{xy}xy + a_{xz}xz \equiv G_x(x,y,z) \\ \boxed{\text{birch}} & \dot{y} = r_y y - y^2 - a_{yx}xy - a_{yz}z \equiv G_y(x,y,z) \\ \boxed{\text{pine}} & \dot{z} = \boxed{r_z z^2 - z^3} - a_{zx}xz - a_{zy}y \equiv G_z(x,y,z) \end{array}\right\} SYS1$$

Natural growth rates

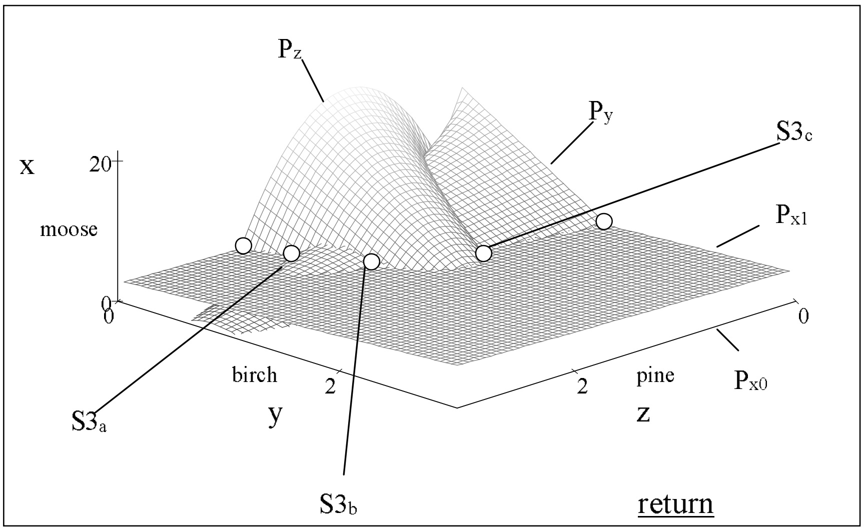
Convex-concave growth



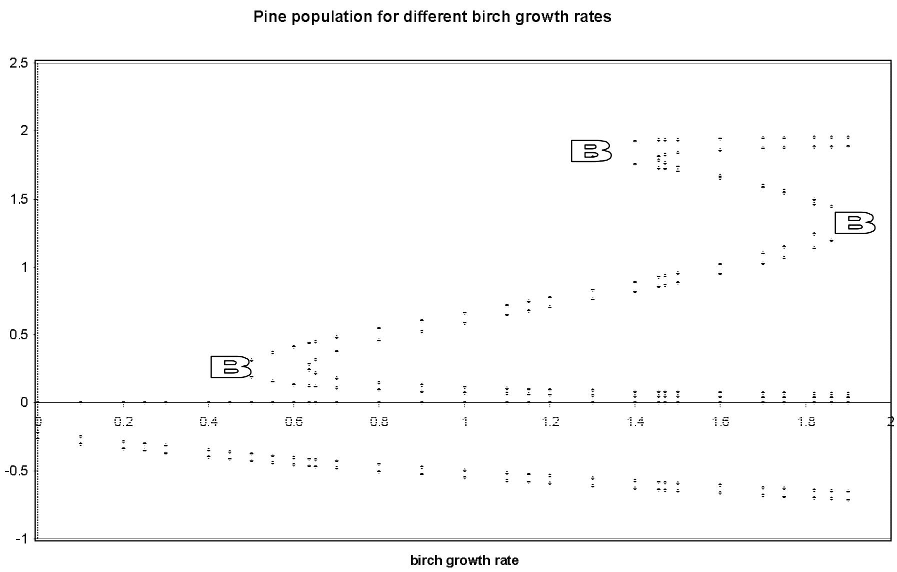
Ecosystem Simulations

- Up to 15 different steady states.
  - 4 interior states, only one stable.
  - 11 boundary states of which several are stable.
- Solution: $\forall T_j, T_{j+1}$ and $i \in \{x, y, z\}$: $\varphi_i\left(x_{T_j}, y_{T_j}, z_{T_j}, T_{j+1}\right)$
- Separatrices between the basins of attraction of the different stable states (show phase diagram).
- For some parameter values bifurcations occur in which some steady states appear or disappear (show bifurcation diagram).

Phase diagram



Bifurcation diagram



The multiple-use problem

Weights in the welfare function

$$B(h,x,y,z) = K_x\Omega_x(h_x) + K_y\Omega_y(h_y) + K_z\Omega_z(h_z) + K_e\Omega_e(x,y,z)$$

Private profits from harvesting species

Environmental benefit from the forest

$$\max_h \int_0^{+\infty} B(h,x,y,z)e^{-\rho t}\,dt$$

Net benefits from forestry (private /social)

$$\begin{aligned} \text{st} : \dot{x} &= G_x(x,y,z) - h_x \\ \dot{y} &= G_y(x,y,z) - h_y \\ \dot{z} &= G_z(x,y,z) - h_z \end{aligned}$$

harvests

x, y, z positive

The optimal rotation problem

- Present value of forestland:

$$V_z = \sum_{j=0}^{+\infty}\left(\left(\varphi_z\left(x_{T_j}, y_{T_j}, z_{T_j}, T_{j+1}\right)p_z e^{-\rho(T_{j+1}-T_j)} - C\right)e^{-\rho T_j}\right)$$

Solution to the ecosystem ODE at time T_{j+1} = present value for harvesting at T_{j+1} when previous harvest was T_j

Harvesting cost

- The company's problem: $\max_{T_j} V_z$

General management rules for forestry: multiple use

- condition for optimal harvests:

$$K_i \frac{\partial \Omega_i \left(h_i^*\right)}{\partial h_i} = \lambda_i, \text{ or } h_i^* = 0, \forall i \in \{x, y, z\}$$

- In steady state the adjoined equations imply.

$$\rho \lambda_{\mathrm{j}} = K_e \frac{\partial \Omega_e}{\partial j} + \sum_{i \in \{x,y,z\}} \lambda_i \frac{\partial G_i (x, y, z)}{\partial j}, \forall j \in \{x, y, z\}$$

- Simulations show.
  - four interior steady states: two saddle points, two unstable.
  - If environmental value is accounted for, more steady states.
  - Bifurcations for some parameter values (more or fewer steady states).
  - Skiba points/manifolds.

General management rules for forestry: whole stand harvesting

- *Proposition: (modified Faustmann-Pressler-Ohlin): A forest stand shall be harvested each time the marginal net benefit from delaying the harvest equals the interest on the net benefit of harvesting at that time.*

$$\frac{\partial z_{T_j}}{\partial T_j} p_z + \left(\frac{\partial z_{T_{j+1}}}{\partial x_{T_j}} \frac{\partial x_{T_j}}{\partial T_j} + \frac{\partial z_{T_{j+1}}}{\partial y_{T_j}} \frac{\partial y_{T_j}}{\partial T_j} + \frac{\partial z_{T_{j+1}}}{\partial z_{T_j}} \frac{\partial z_{T_j}}{\partial T_j} \right) p_z e^{-\rho (T_{j+1} - T_j)} = \rho \left(z_{T_j} p_z - C \right)$$

- So the harvesting time depends on the stocks of other species in the ecosystem and on how the growth of the species to harvest is modeled.

General management rules for forestry: whole stand harvesting

- If pine growth is convex-concave one may have several optimal harvesting time (See Ready, Bergland & Romstad).
- Simulations show that the harvest size is crucial for the ecosystem's potential to recover.
- If harvest is too large pine becomes extinct.
- Accounting for other species implies that harvest must be smaller to avoid extinction.

What do we learn?

- Harvesting costs determine the open access ecosystem conditions. The ecosystem determines the number of fishermen.
- We must deal with multiple steady states and Skiba points in sole-ownership/continuous harvesting cases.
- The rotation period must account for other species and there may be several optimal ones.

Open access

- ➲ A steady state exists iff there is some fish stock for which the average cost of effort equals the market value of the total available fish stock.
- ➲ The steady state is unique if the average cost is monotonous.
- ➲ Traditional results on open access are reinforced. Overexploitation leads typically to a unique algae dominated steady state. The steady state levels of **algae, fish and effort remain as if there were no threshold effects**.
- ➲ Threshold effects imply **fewer fishermen/vessels**.

Sole ownership/continuous harvest

- ➲ *Proposition: Suppose $\rho>0$, then the system of equations of motion for the optimized ecosystem is either **unstable** or has the instability characterized by the **saddle point property** in the neighborhood of a steady state. (See Kurz).*
  - Ecosystem complexity does **not** affect this property.
- ➲ *Proposition: If the system has **several steady state**, all of them are characterized by the **saddle** path property if the **discount rate** is **small** enough. If the **discount rate** is **large** enough all steady states are **unstable**. For values of the discount rate in between, some steady states are unstable, the others are saddle points.*
  - Accounting for ecosystem complexity affects the number of steady states and the dynamics of the optimized ecosystem.

Sole ownership/continuous harvest

- The threshold term should affect steady state levels of fish and algae stocks and their number.
- The optimal path/steady state is not obvious.
  - Multiple steady states / Skiba points.
  - Dependence on initial conditions.
- Exogenous changes can result in crossing a Skiba manifold.
- Policy recommendation for sole owners cannot rely on marginal rules only. One must know all future costs and benefits to determine the optimal steady state.
- These results can probably be obtained even if pine has no complex growth but is affected by a species with complex dynamics.

Sole ownership/optimal rotation

- The optimal rotation period depends on other species dynamics.
- There may be several optimal rotation periods if the dynamics are complex.
- Not accounting for other species may increase the risk of depletion of the harvested species.

Tasks for policy makers

➲ Solve the inefficiency problems related to open access.

➲ Find the optimal path when there are several candidate steady states.

➲ Detect the risks of flipping early to increase management opportunities.

➲ Cope with model uncertainty.

➲ Skiba points.