Fisheries Management under Cyclical Population Dynamics

by

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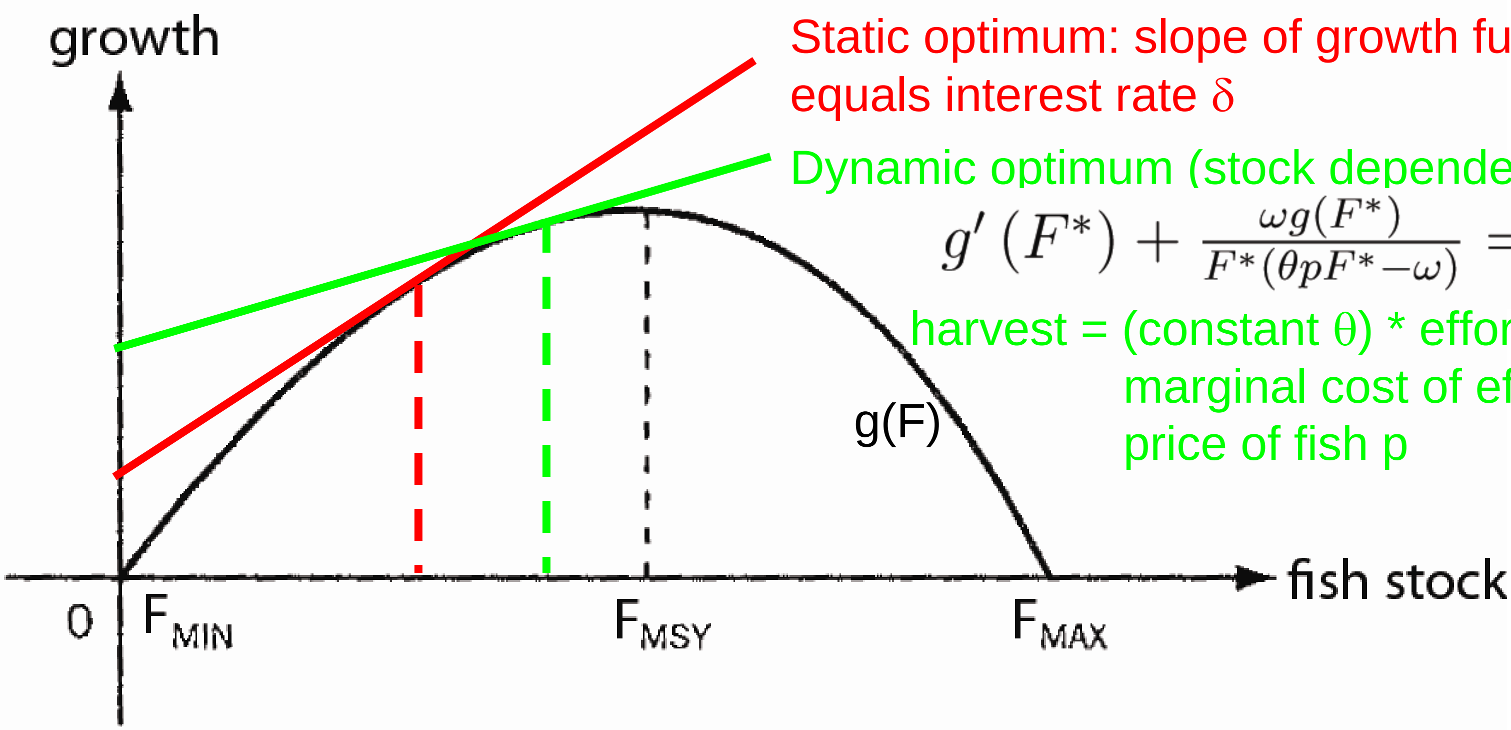
Motivation I

- Two recent reports find that fisheries are seriously overexploited (in contrast to Stratton report from 1969)
  - Pew Oceans Commission, *State of America's Oceans: Charting A Course for Sea Change*
  - U.S. Oceans Commission, *A Blueprint for the 21st Century*
- Traditional wisdom: open-access leads to overexploitation
  - Individual transferable quotas, restricted access
- Establishment of 200-mile zones around countries
  - Includes more than 85% of fish stock

Gordon-Schaefer Model

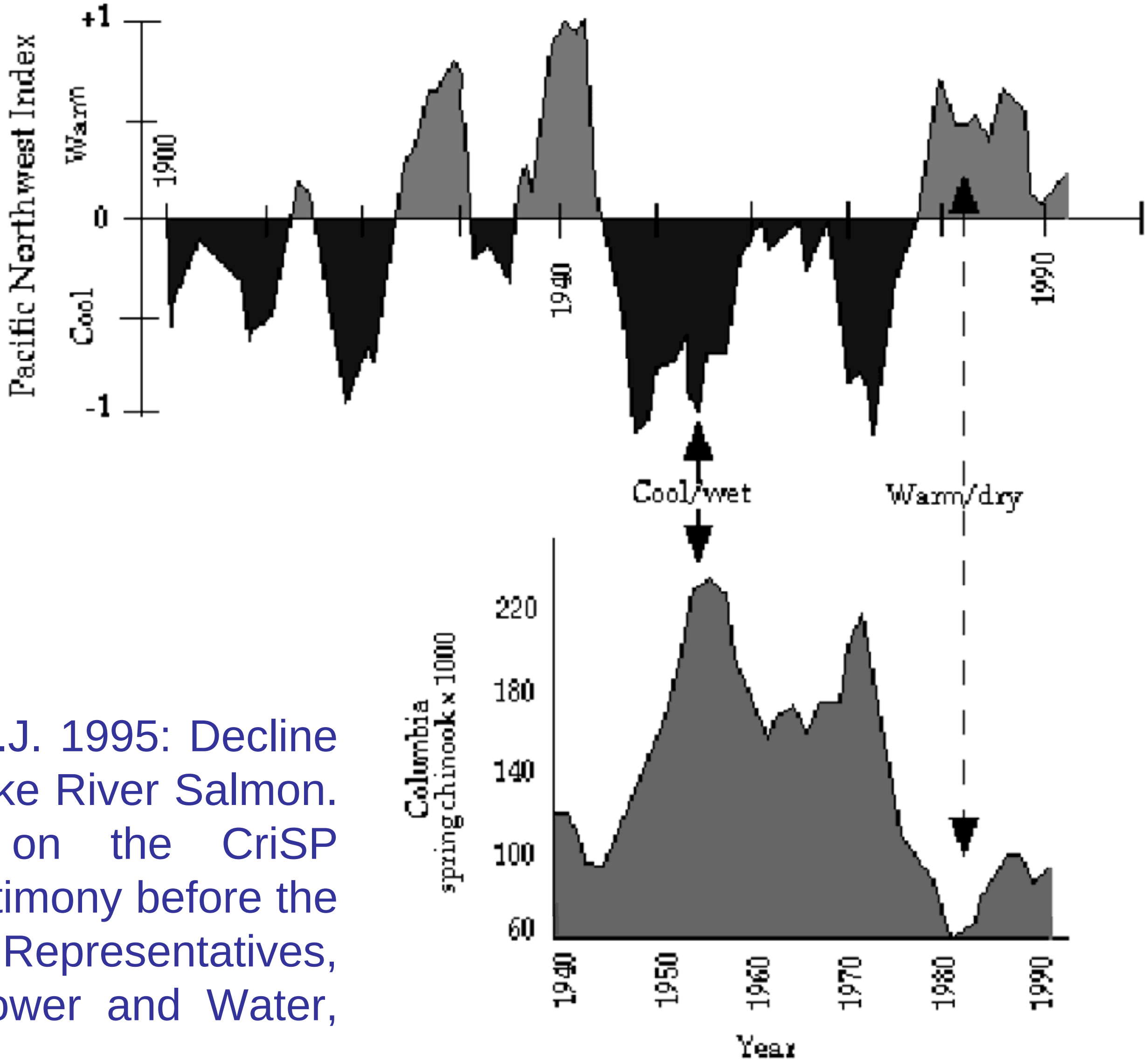


$$g'\left(F^*\right) + \frac{\omega g(F^*)}{F^*(\theta p F^* - \omega)} = \delta$$

Motivation II

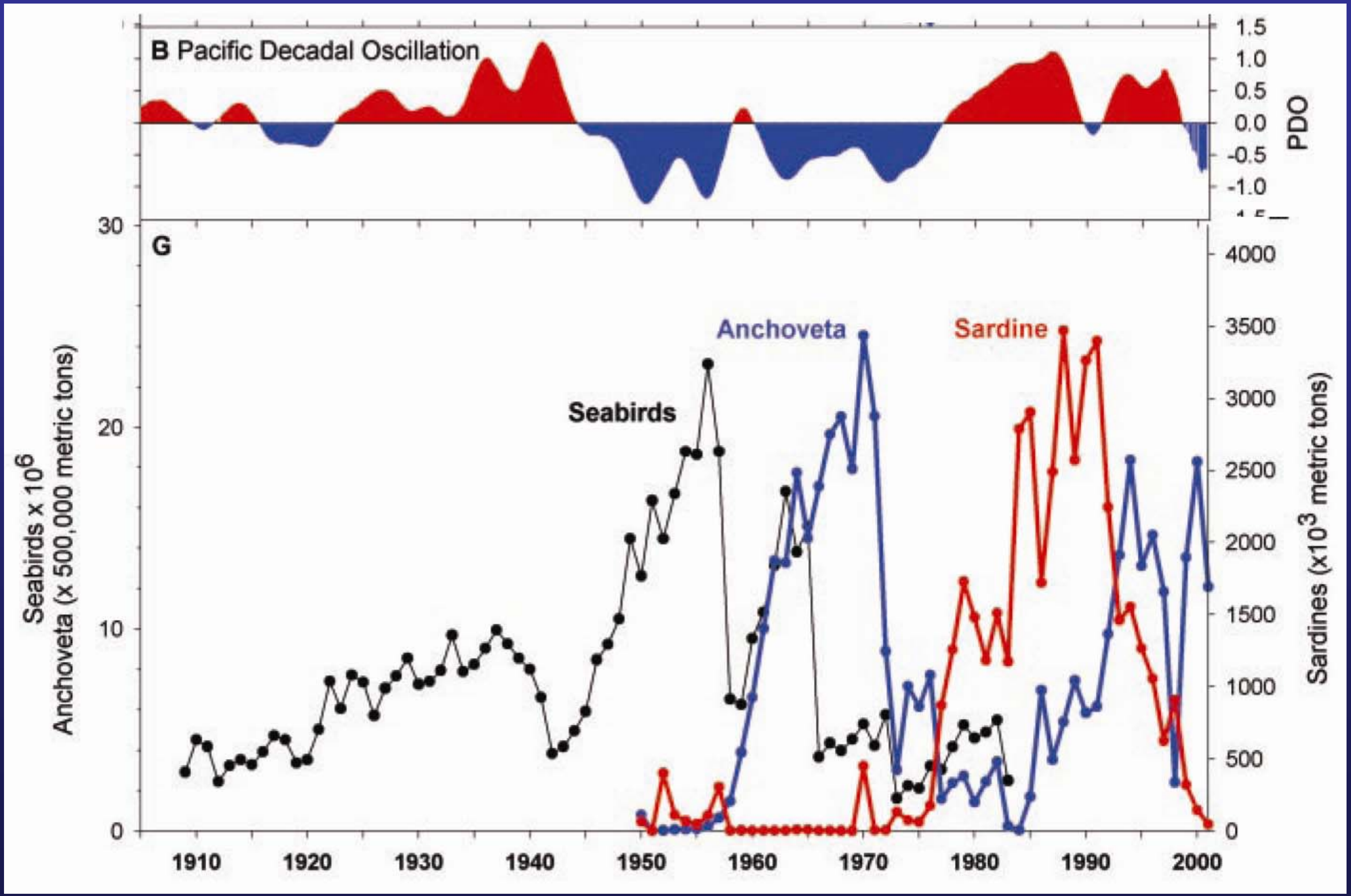
- Economists have addressed uncertainty
  - Focus predominantly on i.i.d. error terms
  - Bad outcomes and good outcomes balance out
    - Several **consecutive** bad outcomes are unlikely
  - Uncertainty has limited effects
    - Strongest effect of stock uncertainty, Sethi et al. (forthcoming)
- Recent evidence that there are systematic fluctuations independent of fishing efforts
  - Cycles: El Nino, Pacific Decadal Oscillation
  - Prey fish (short-lived) are more impacted that long-lived predators

Evidence from Pacific Northwest



Source: Anderson, J.J. 1995: Decline and Recovery of Snake River Salmon. Information based on the CriSP research project. Testimony before the U.S. House of Representatives, Subcommittee on Power and Water, June 3.

Evidence from California



Source: Chavez et al: From Anchovies to Sardines and Back: Multidecadal Change in the Pacific Ocean (2003)

Idea Behind Paper

- Focus of this paper
  - Systematically oscillating growth rates / carrying capacity
  - Implications for maximizing economic rent
    - Model with stock-independent cost
    - Model with stock-dependent cost
  - Extend analysis to multi-species models
- Earlier studies
  - Parma (1990)
    - Non-stationary stock recruitment
  - Costello, Polasky, and Solow (2001)
    - Examine resource management with prediction biological conditions

Outline

Models with Time-Varying Parameters:

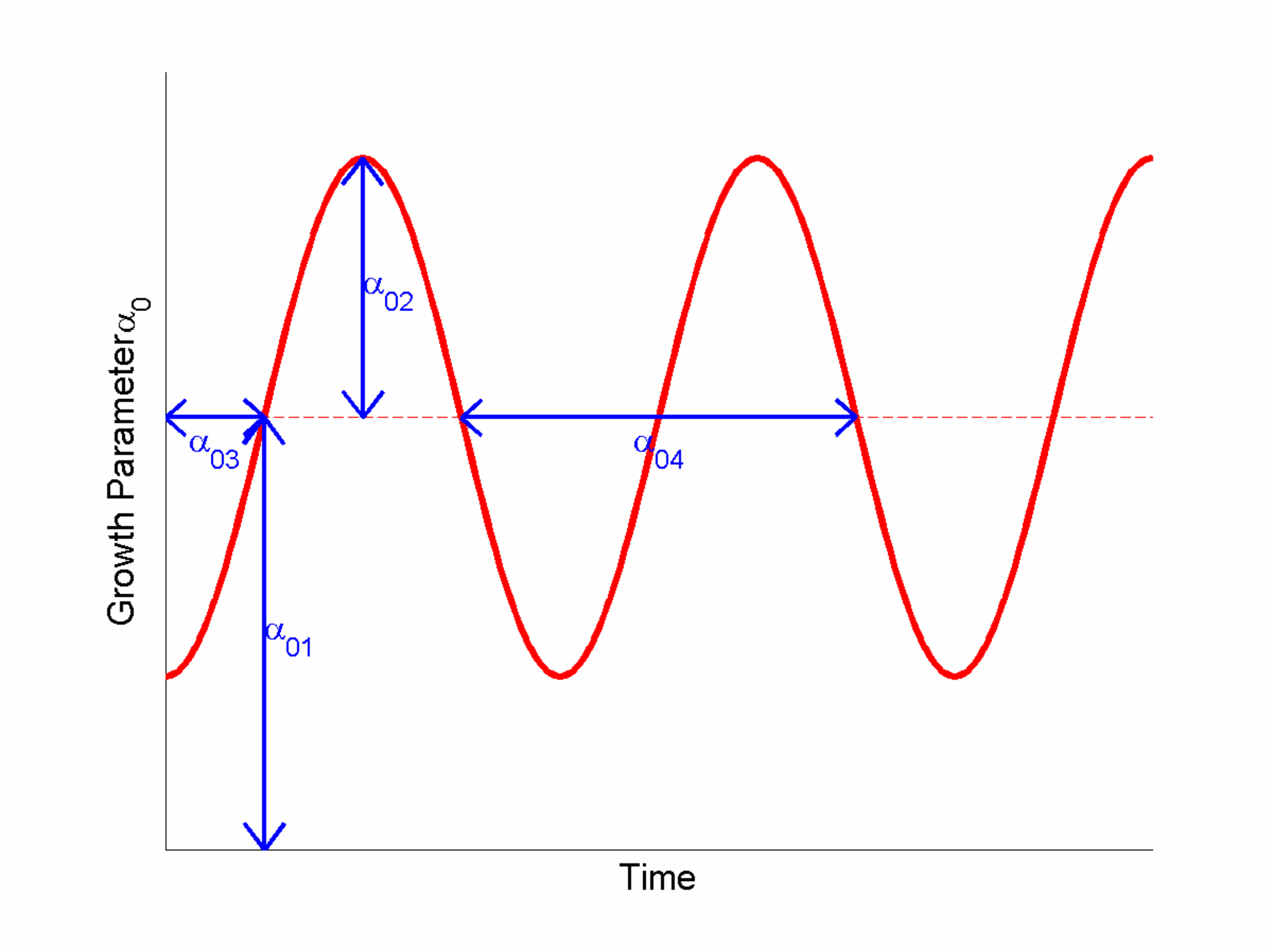
1) Single-Species Model: Stock-independent harvest cost

2) Single-Species Model: Stock-dependent harvest cost

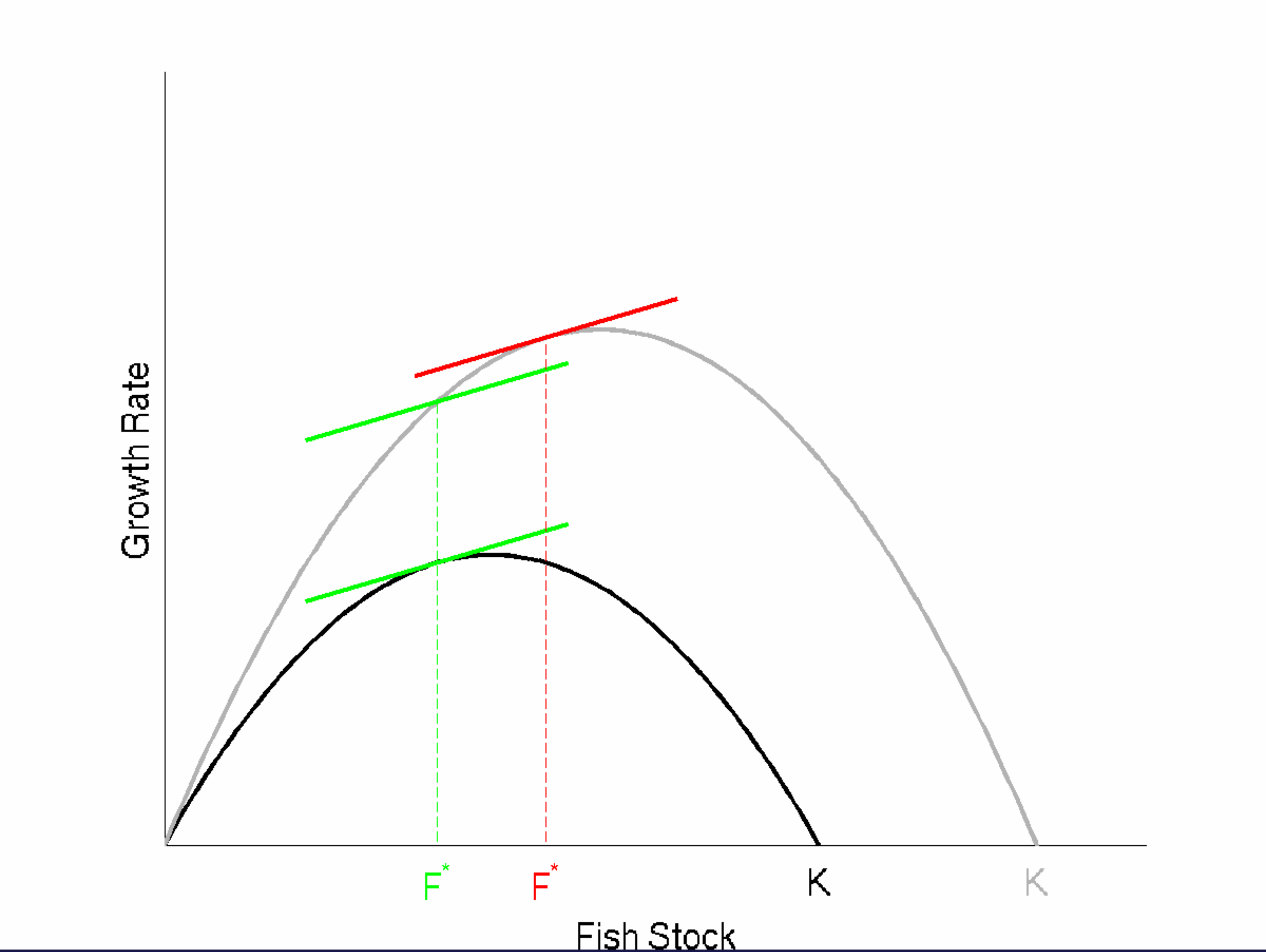
3) Multi-Species Model: Stock-independent harvest cost

Conclusions

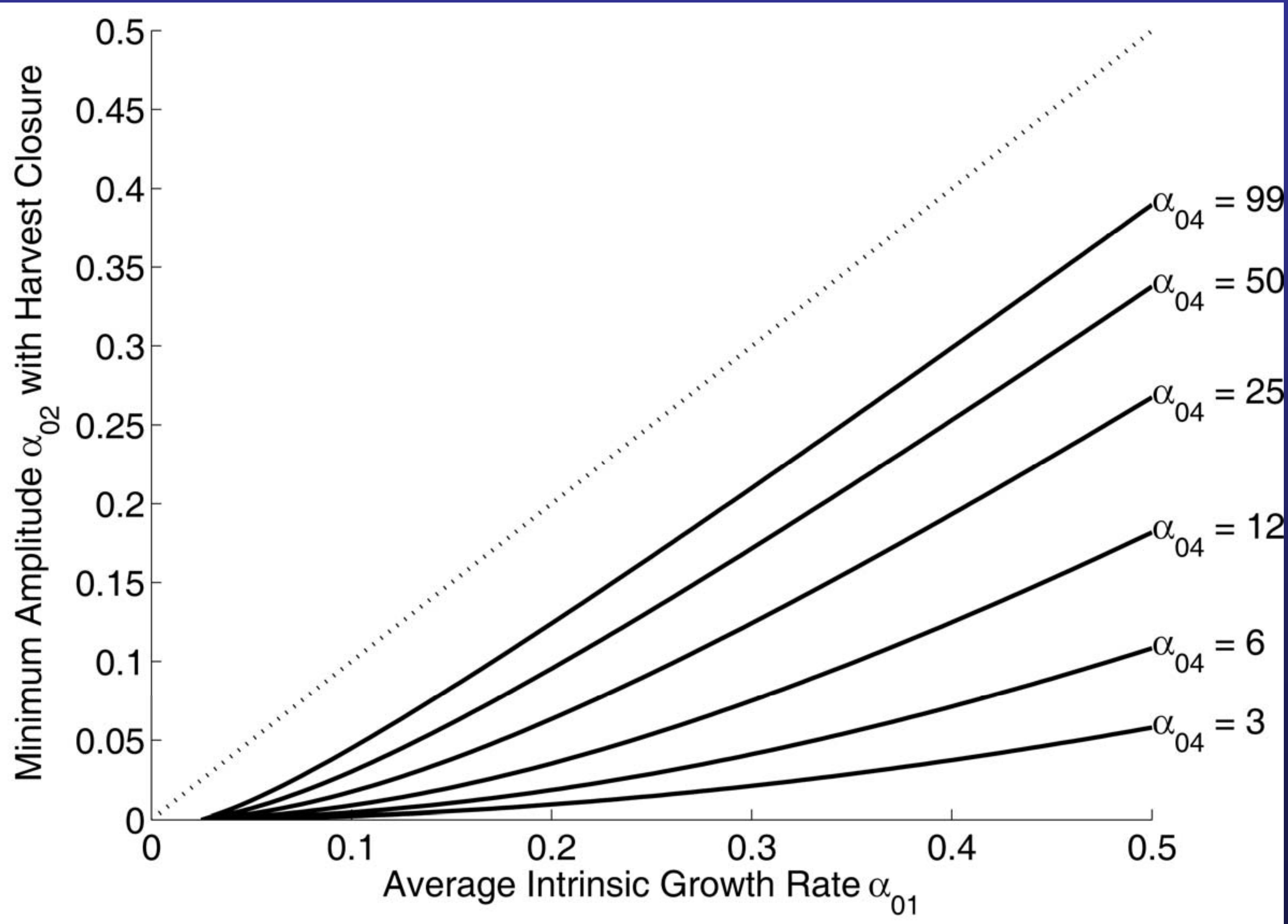
Oscillating Growth Rates



Cyclical Fluctuations in Growth Rate



Harvest Closures



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Single-Species Model

$$\max_{h(t)} \int_0^\infty e^{-\delta t}\left[ph(t) - \omega\frac{h(t)}{\theta F(t)}\right]dt \qquad \text{s.t.} \quad \dot{F}(t) = [\alpha_0(t) + \alpha_1 F(t)]\, F(t) - h(t)$$

Where

F: fish stock
p: price of fish
h: harvest rate
ω: cost of effort
e: effort
θ: effort factor, $h = \theta F e$
δ: discount factor
α_0, α_1: parameters of growth function

Derivation of Optimal Stock Level

$$F^*(t) = \frac{\theta p\left[\delta - \alpha_0(t)\right] + \alpha_1\omega}{4\alpha_1\theta p} + \sqrt{\left(\frac{\theta p\left[\delta - \alpha_0(t)\right] + \alpha_1\omega}{4\alpha_1\theta p}\right)^2 - \frac{\delta\omega}{2\alpha_1\theta p}}$$

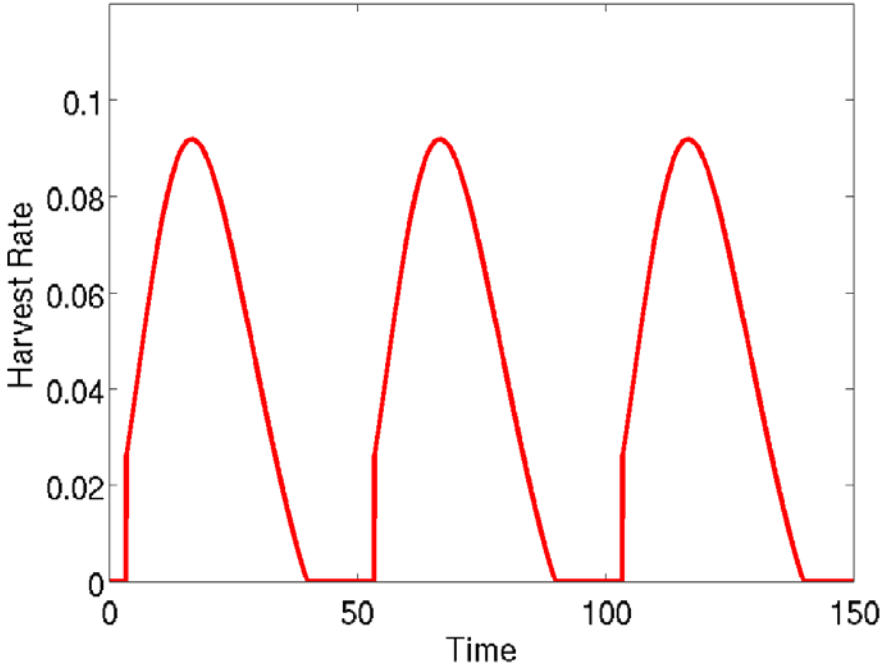
- Dynamic optimum is given by logistic growth function g(F)

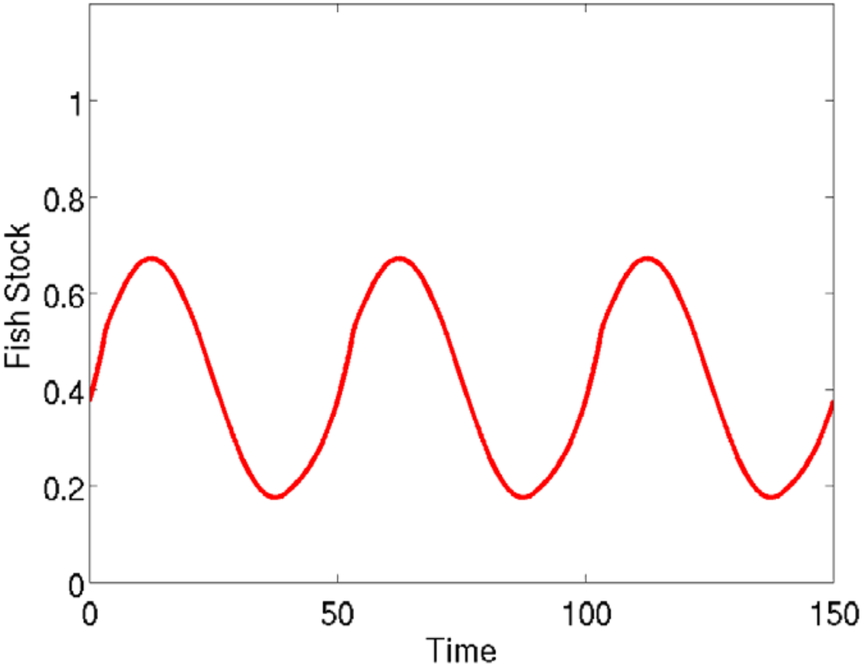
$$g'\left(F^*\right) + \frac{\omega g(F^*)}{F^*(\theta p F^* - \omega)} = \delta$$

- The optimal stock level is
  - increasing in the growth parameters α_0, α_1 and cost of effort ω
  - decreasing in the interest rate δ, effort factor θ and price of fish p.

Oscillating Growth Rates

Optimal Harvest Rate



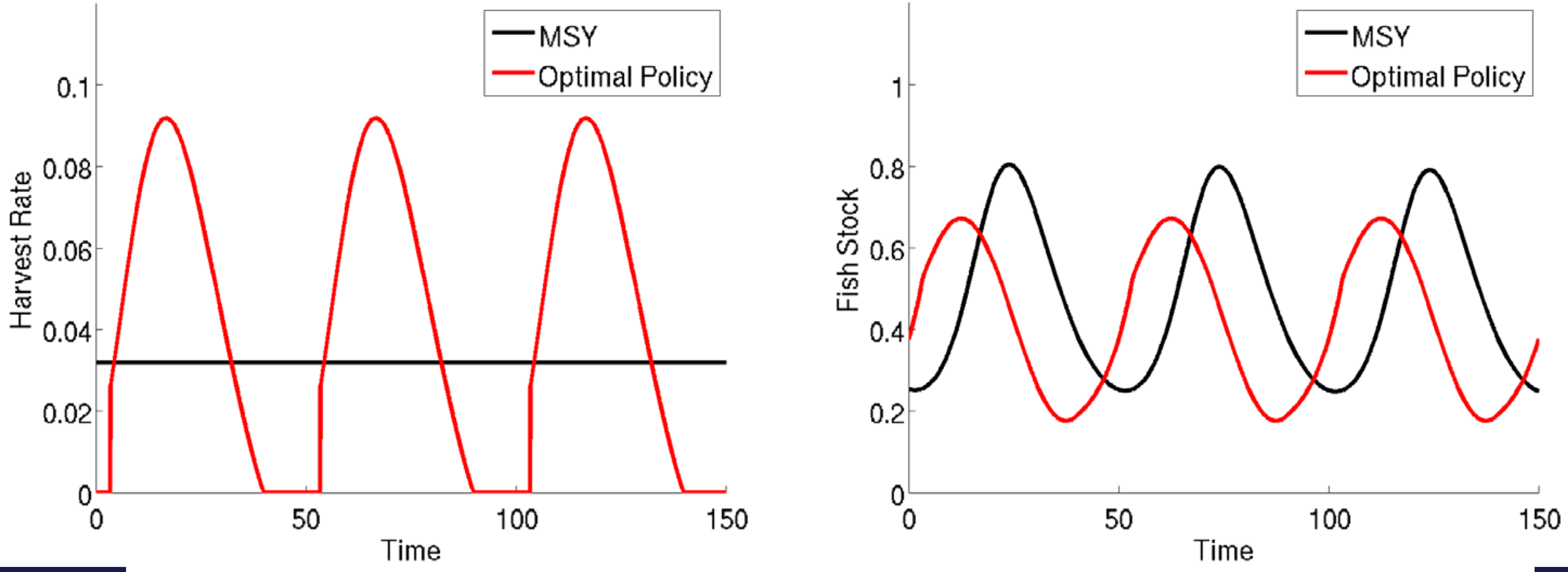


$$\text{growth rate}: \quad \dot{\mathrm{F}} = \left[0.15 + 0.075\sin\left(\frac{2\pi t}{50}\right) - 0.15F\right]F$$

price $p = 225$, cost of effort $\omega = 2$, effort factor $\theta = 1$, interest rate $\delta = 2.5\%$

Oscillating Growth Rates

Maximum Sustainable Harvest



$$\text{growth rate: } \dot{\mathrm{F}} = \left[0.15 + 0.075\sin\left(\frac{2\pi t}{50}\right) - 0.15F\right]F$$

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When is it best to wait?

- Reduce harvest when there is a big return on investment, i.e., on up-cycle
  - In reality fishermen often argue that conditions are getting better and one should hence increase harvest quotas, but this the opposite of the optimum.
- Harvest is zero if growth rate is less than change in the optimal desired stock level.

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Models with Time-Varying Parameters:

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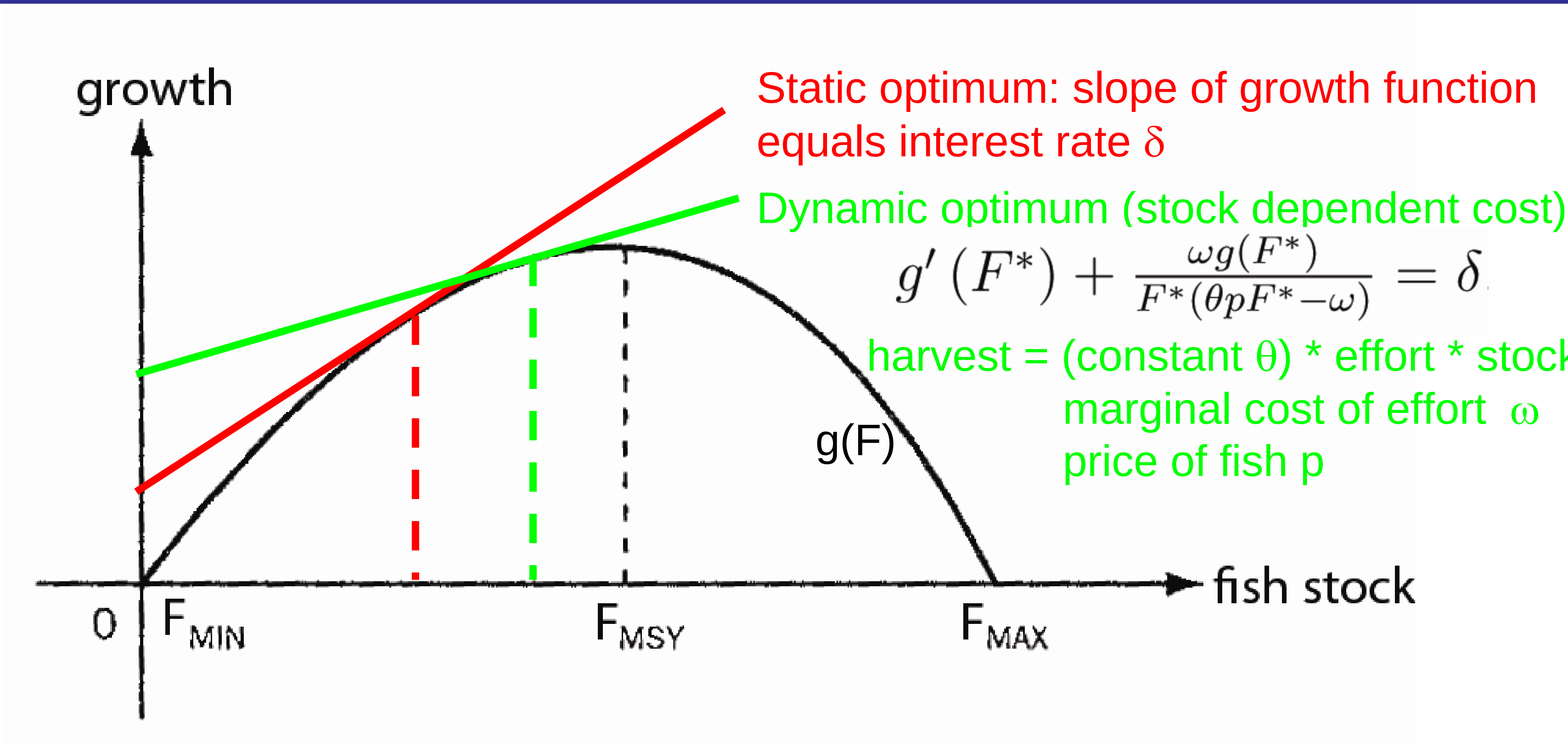
2) Single-Species Model: Stock-dependent harvest cost

Comparison to traditional management rules

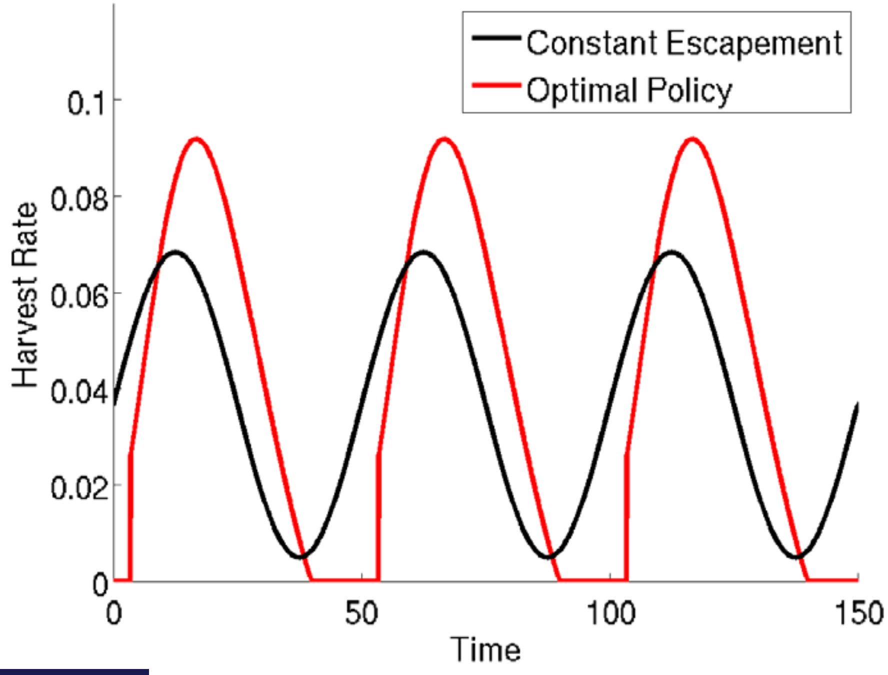
3) Multi-Species Model: Stock-independent harvest cost

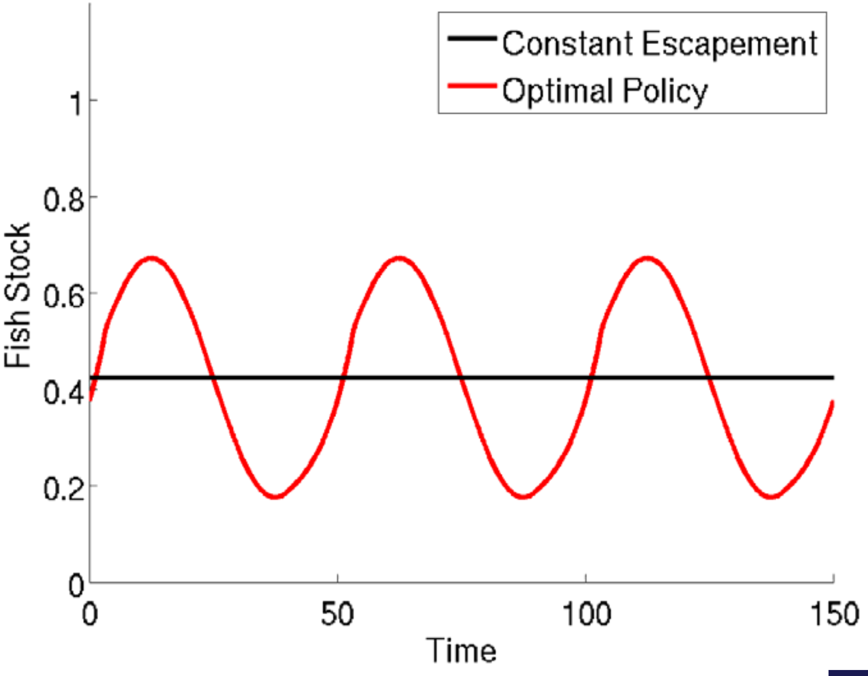
Conclusions

Comparison to Traditional Models



Oscillating Growth Rates
Using a Constant Target Stock





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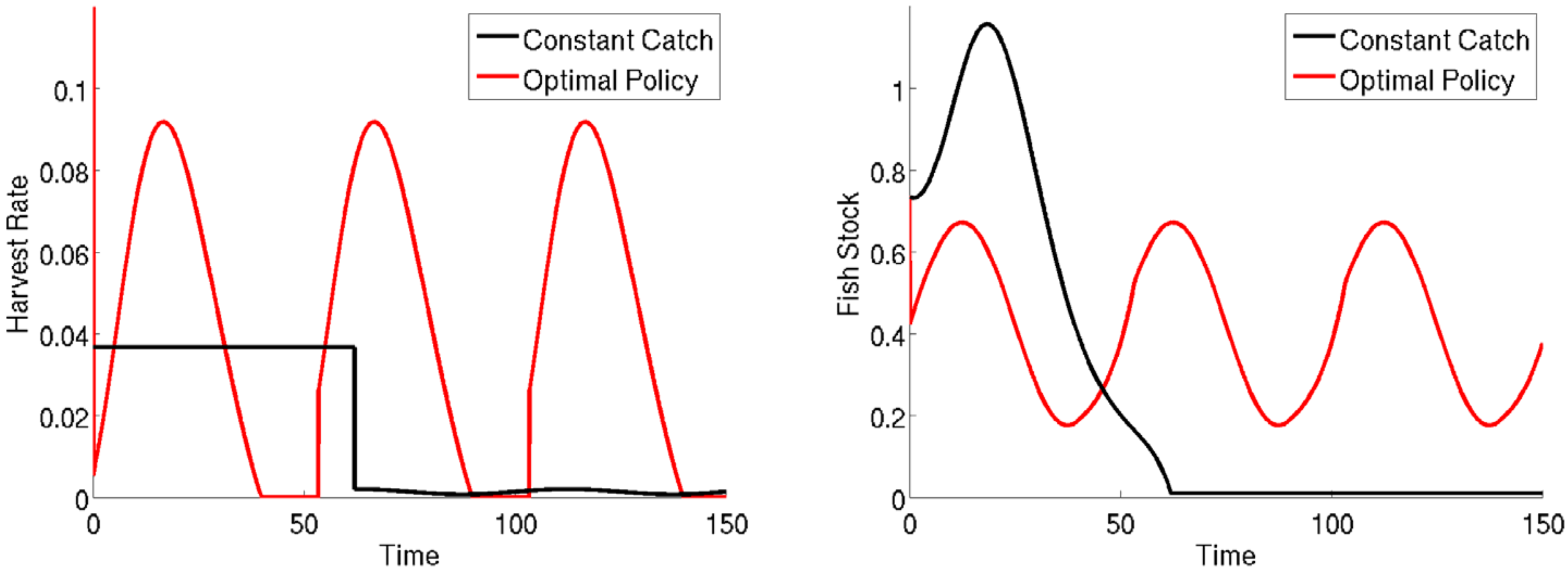
Oscillating Growth Rates

Harvest Quota – Based on Average Growth

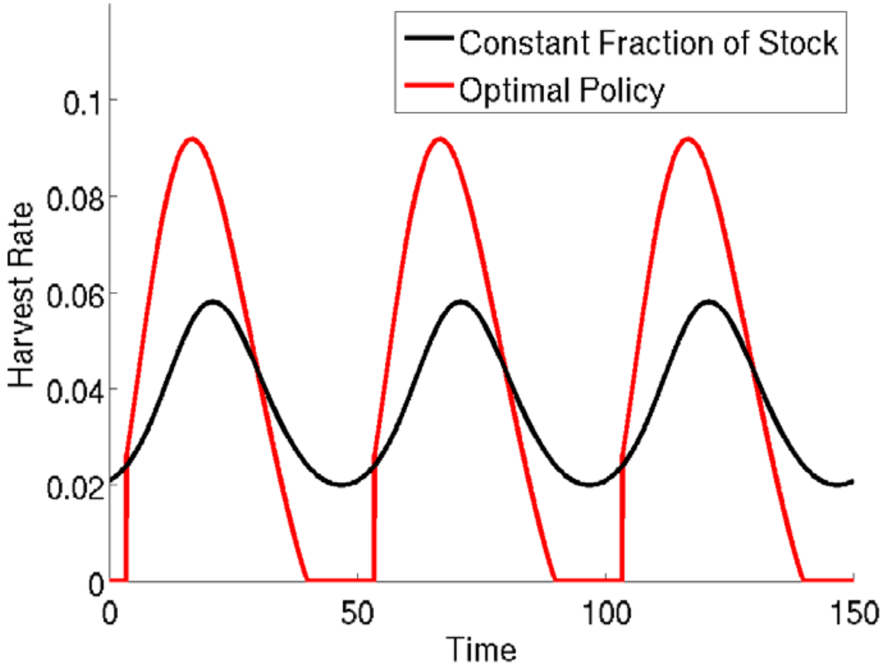


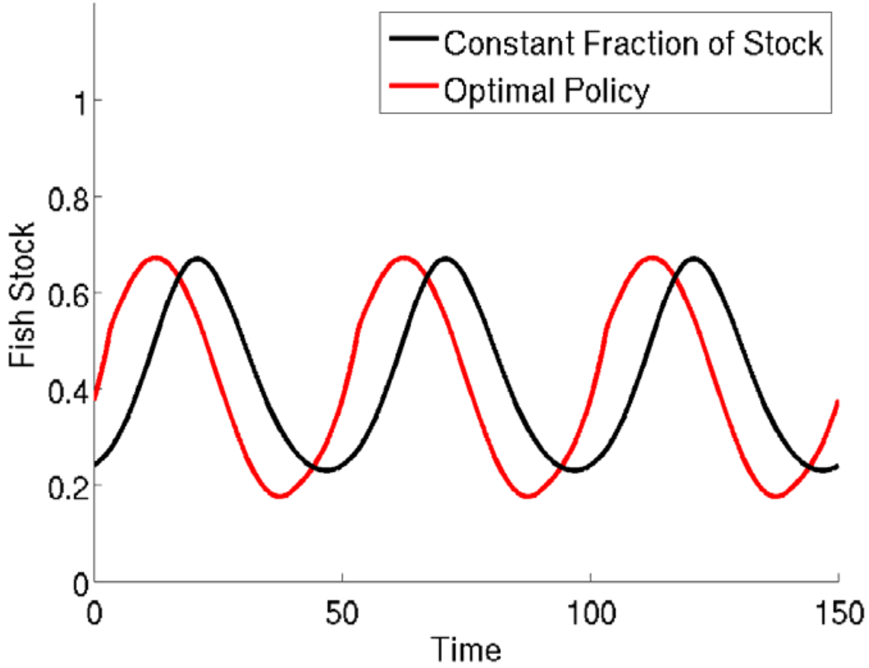
$$\text{growth rate}: \quad \dot{\mathrm{F}} = \left[0.15 + 0.075\sin\left(\frac{2\pi t}{50}\right) - 0.15F\right]F$$

price $p = 225$, cost of effort $\omega = 2$, effort factor $\theta = 1$, interest rate $\delta = 2.5\%$

Oscillating Growth Rates

Fraction of Stock – Based on Average Growth



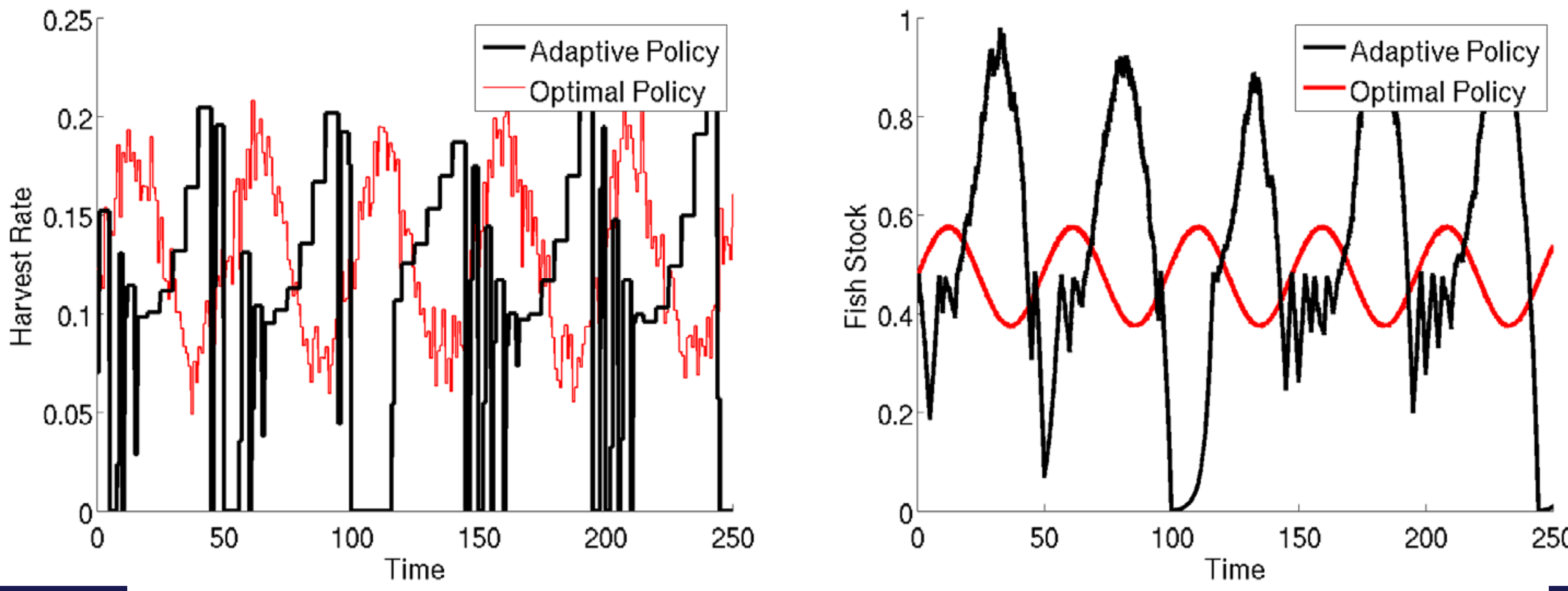


$$\text{growth rate: } \quad \dot{\mathrm{F}} = \left[0.15 + 0.075\sin\left(\frac{2\pi t}{50}\right) - 0.15F\right]F$$

price $p = 225$, cost of effort $\omega = 2$, effort factor $\theta = 1$, interest rate $\delta = 2.5\%$

Optimal Harvest Policy

Random Growth Rates - Lagged Government Policy
Using 20-year Lag, 5-year Reauthorization



$$\text{growth rate}: \quad \mathrm{dF} = \left[0.5 + 0.1\sin\left(\frac{2\pi t}{49}\right) - 0.5F\right]Fdt + \sigma F dW(t)$$

price $p = 500$, cost of effort $\omega = 0.5$, effort factor $\theta = 1$, interest rate $\delta = 2.5\%$, $\sigma = 0.03$

Outline

Models with Time-Varying Parameters:

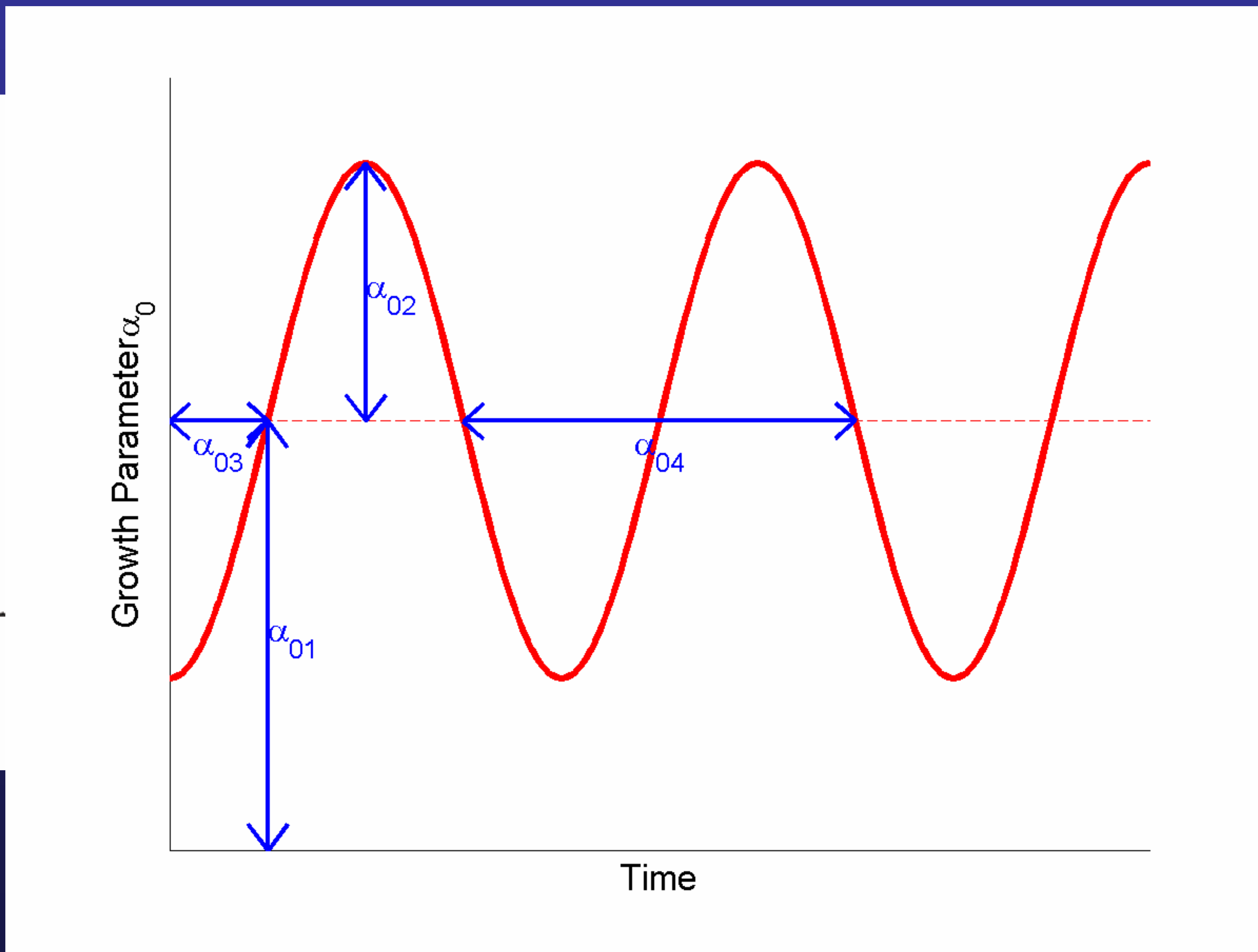
1) Single-Species Model: Stock-independent harvest cost

2) Single-Species Model: Stock-dependent harvest cost
   Estimating periodicity

3) Multi-Species Model: Stock-independent harvest cost

Conclusions

Difficulty of Estimating Periodicity



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cost):

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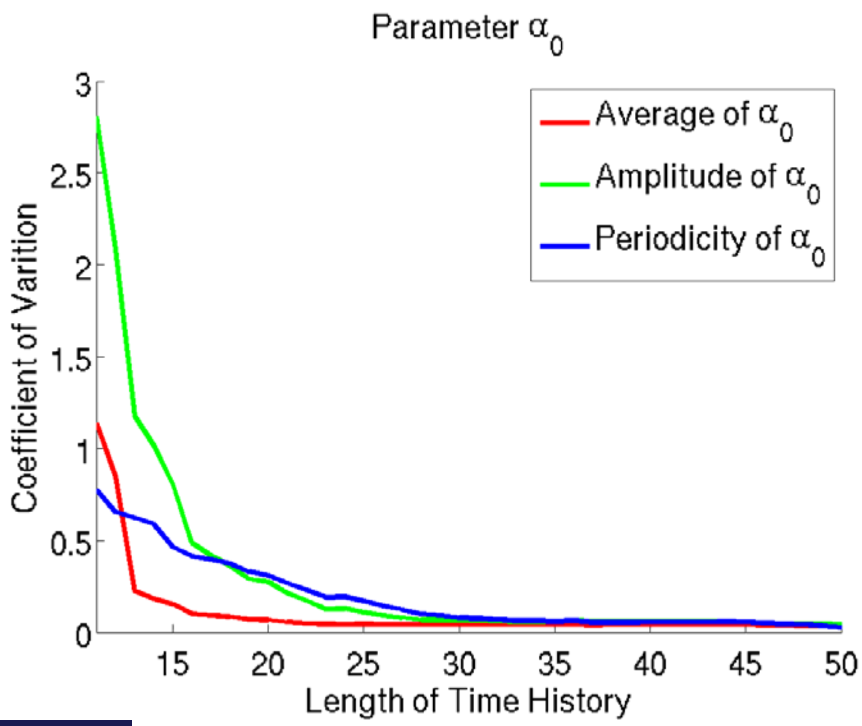
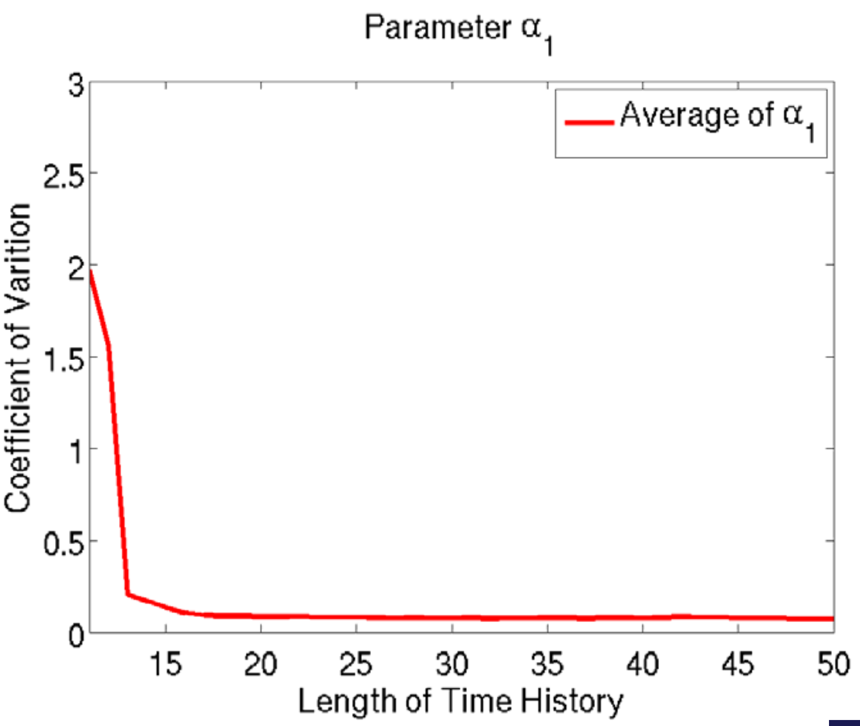
Estimating Periodic Parameters





$$\text{growth rate}: \quad \mathrm{dF} = \left[0.5 + 0.1\sin\left(\frac{2\pi t}{50}\right) - 0.5F \right] F dt + \sigma F dW(t)$$

price $p = 500$, cost of effort $\omega = 0.5$, effort factor $\theta = 1$, interest rate $\delta = 2.5\%$, $\sigma = 0.01$

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Multi-Species Model
(3 fish species i = 1,2,3)

$$\max_{h_i(t)} \int_0^\infty e^{-\delta t} \left[p_1 h_1(t) - \omega \frac{h_1(t)}{\theta_1 F_1(t)} + p_2 h_2(t) - \omega \frac{h_2(t)}{\theta_2 F_2(t)} + p_3 h_3(t) - \omega \frac{h_3(t)}{\theta_3 F_3(t)} \right] dt$$

$$\text{s.t.} \quad \dot{F}_1(t) = [\alpha_{10} + \alpha_{11} F_1(t) + \alpha_{12} F_2(t) + \alpha_{13} F_3(t)]\, F_1(t) - h_1(t)$$

$$\dot{F}_2(t) = [\alpha_{20} + \alpha_{21} F_1(t) + \alpha_{22} F_2(t) + \alpha_{23} F_3(t)]\, F_2(t) - h_2(t)$$

$$\dot{F}_3(t) = [\alpha_{30} + \alpha_{31} F_1(t) + \alpha_{32} F_2(t) + \alpha_{33} F_3(t)]\, F_3(t) - h_3(t)$$

Where

F_i: fish stock

h_i: harvest rate

e_i: fishing effort

θ_i: effort factor, $h_i = \theta_i F_i e_i$

α_{ij}: parameters of growth function

p_i: price of fish

δ: discount factor

ω_i: cost of effort

Multi-Species Model

- System has unique stable equilibrium if
  - A is invertible

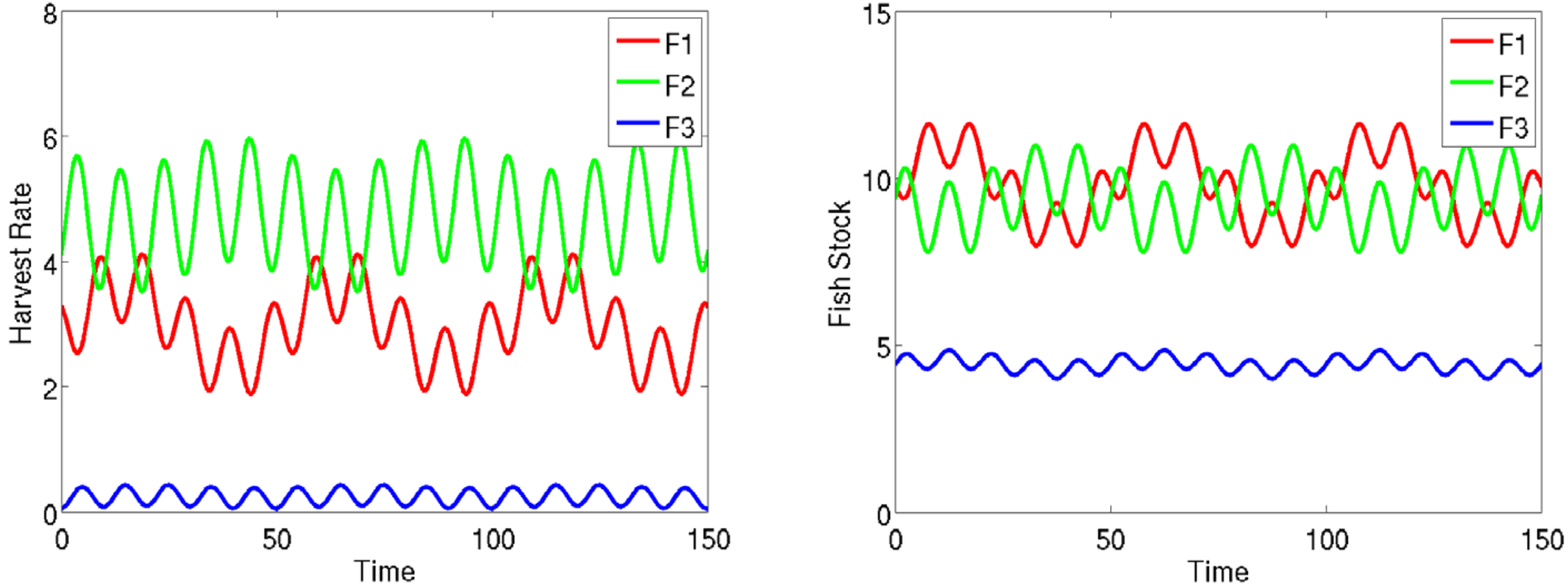
$$\underbrace{\begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{23} & \gamma_{33} \end{bmatrix}}_{\mathbf{A}} \begin{bmatrix} F_1(t) \\ F_2(t) \\ F_3(t) \end{bmatrix} = \underbrace{\begin{bmatrix} -\alpha_{10} \\ -\alpha_{20} \\ -\alpha_{30} \end{bmatrix}}_{\mathbf{b}}$$

  - A_F of linearized system has three negative eigenvalues

$$\begin{bmatrix} \dot{F}_1(t) \\ \dot{F}_2(t) \\ \dot{F}_3(t) \end{bmatrix} \approx \underbrace{\begin{bmatrix} \alpha_{11}\widehat{F_1} & \alpha_{12}\widehat{F_1} & \alpha_{13}\widehat{F_1} \\ \alpha_{21}\widehat{F_2} & \alpha_{22}\widehat{F_2} & \alpha_{23}\widehat{F_2} \\ \alpha_{31}\widehat{F_3} & \alpha_{32}\widehat{F_3} & \gamma_{33}\widehat{F_3} \end{bmatrix}}_{\mathbf{A_F}} \begin{bmatrix} F_1(t) \\ F_2(t) \\ F_3(t) \end{bmatrix}$$

Multi-Species Model

Optimal Economic Harvest



Notes: The left graph displays the optimal harvest rate while the right graph shows the resulting stock size. The intrinsic growth rates of the two prey fish oscillate according to $\alpha_{10} = 0.8 + 0.04 \sin\left(\frac{2\pi t}{50}\right)$, $\alpha_{20} = 1 + 0.05 \sin\left(\frac{2\pi t}{10}\right)$. The economic parameters are $\theta_1 = \theta_2 = \theta_3 = 1, \omega = 50$, and $p_1 = p_2 = 100, p_3 = 500$.

Implications of Periodic Fluctuations

- Interactions between various species transmit fluctuations to other species

- Relatively small fluctuations in one species can build up in the system
  - Optimal harvest rates vary drastically even though stock size is rather constant
  - Classical rule which bases harvest on stock size is misleading

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- Large biological literature suggesting
  - Periodic fluctuations in growth rates
- Implications for optimal management of fisheries
  - Time-invariant rules will be misleading and suboptimal
    - Harvest closures optimal when conditions improve most rapidly
  - Adaptive policies can bring the system to the brink of extinction
  - Selective fish-specific harvesting quotas will not necessarily protect a species
- Requirement to manage system as a whole