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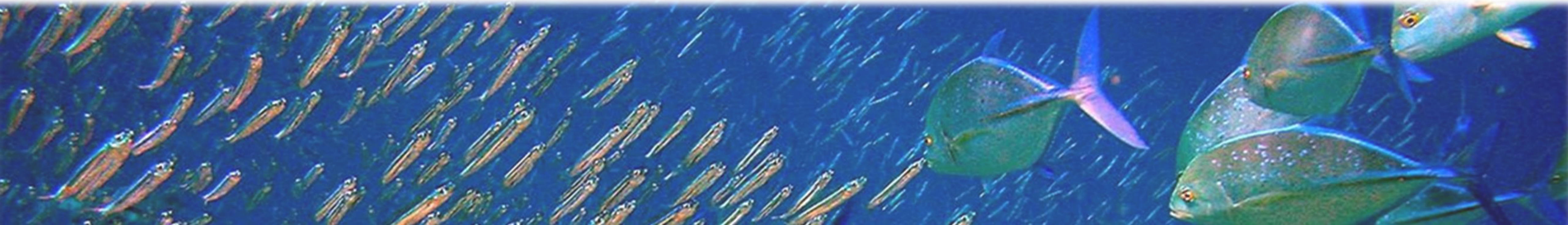
Sustainability Criteria
Using Bioeconomic Models to Avoid Surprises

Martin D. Smith

3 Days MESSH Keynote Address Part 1

Sète, France

January 26, 2023



Overarching Theme

Bioeconomic modeling is necessary for empirical analysis of fisheries data

- Models prevent us from drawing spurious inferences
- Models guard against bad policy decisions based on spurious inferences

Outline

- Iconic bioeconomic models of the fishery
  - Introduces 5 well-known models
  - Summarizes main insights
  - Highlights some surprises and a few empirical examples
- In-depth Application: Fishery Collapse Revisited (Li and Smith *MRE* 2021)
  - Applies the iconic models to the debate about catch-based metrics
  - Shows that catch-based metrics are **highly misleading** and perform even worse than previous critics have suggested

Iconic bioeconomic models

Biological Management of Fisheries

1. Maximum Sustainable Yield

Unmanaged Fisheries

2. Static Open Access Gordon *JPE* (1954) and Copes *SJPE* (1970)
3. Dynamic Open Access V. Smith *AER* (1968) and *JPE* (1969)

Economic Management of the Fishery

4. Maximum Economic Yield Clark and Munro *JEEM* (1975), Clark (1976)
5. Optimal Escapement Reed JEEM (1979)

1. Biological Management: Maximum Sustainable Yield

Biological Management – Maximum Sustainable Yield

$$H = F(X)$$ Harvest takes the net biological growth F(X)

$$\max_{\{X\}} H = F(X)$$ Maximize sustainable harvest

$$F'(X) = 0$$ Take derivative of net biological growth, set to 0, solve for target stock, plug back into F(X), and solve for target harvest

Example: Logistic growth

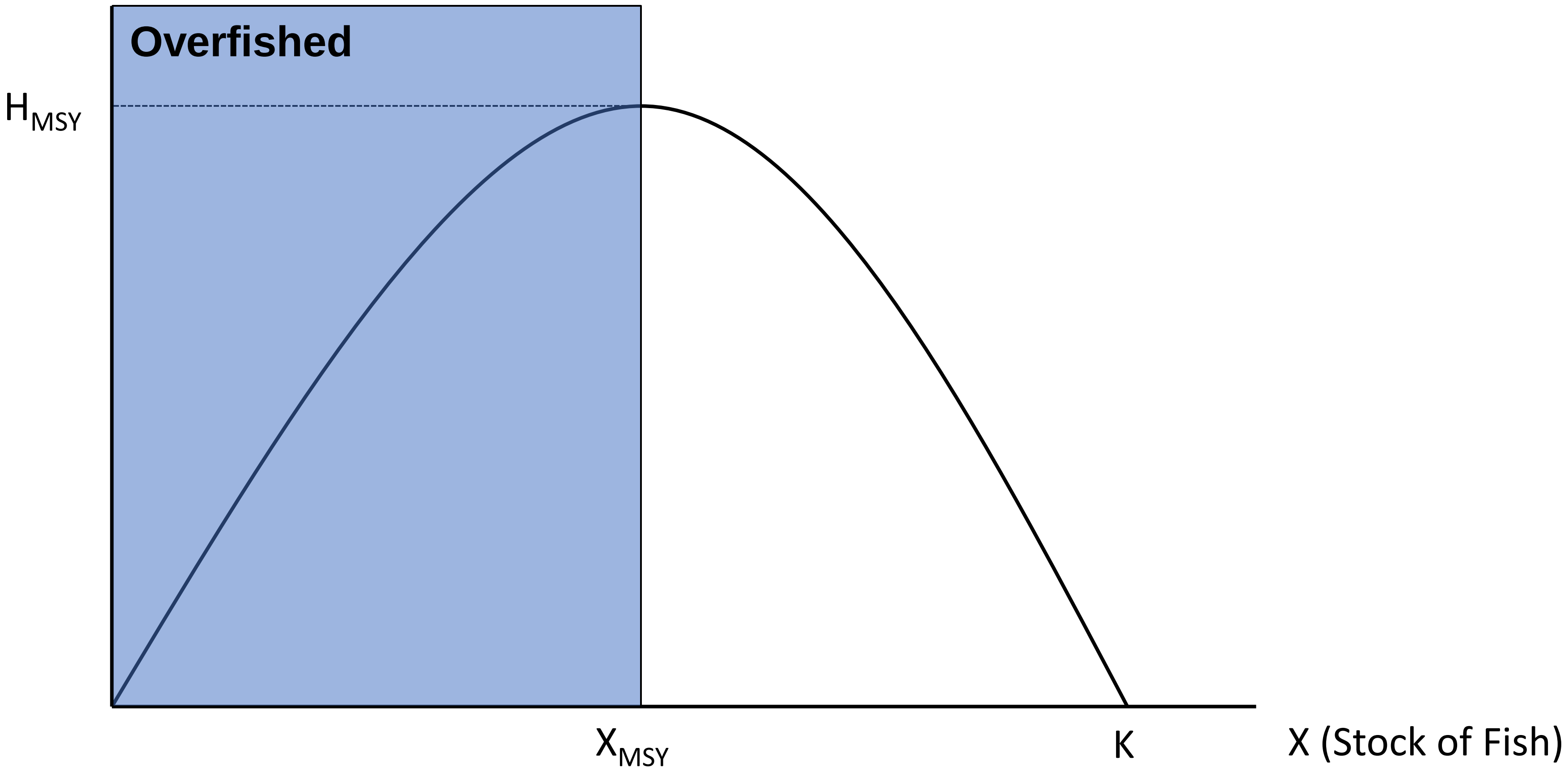
$$F(X) = rX\left(1 - X/K\right)$$

$$F'(X) = r - 2r\,X/K = 0$$

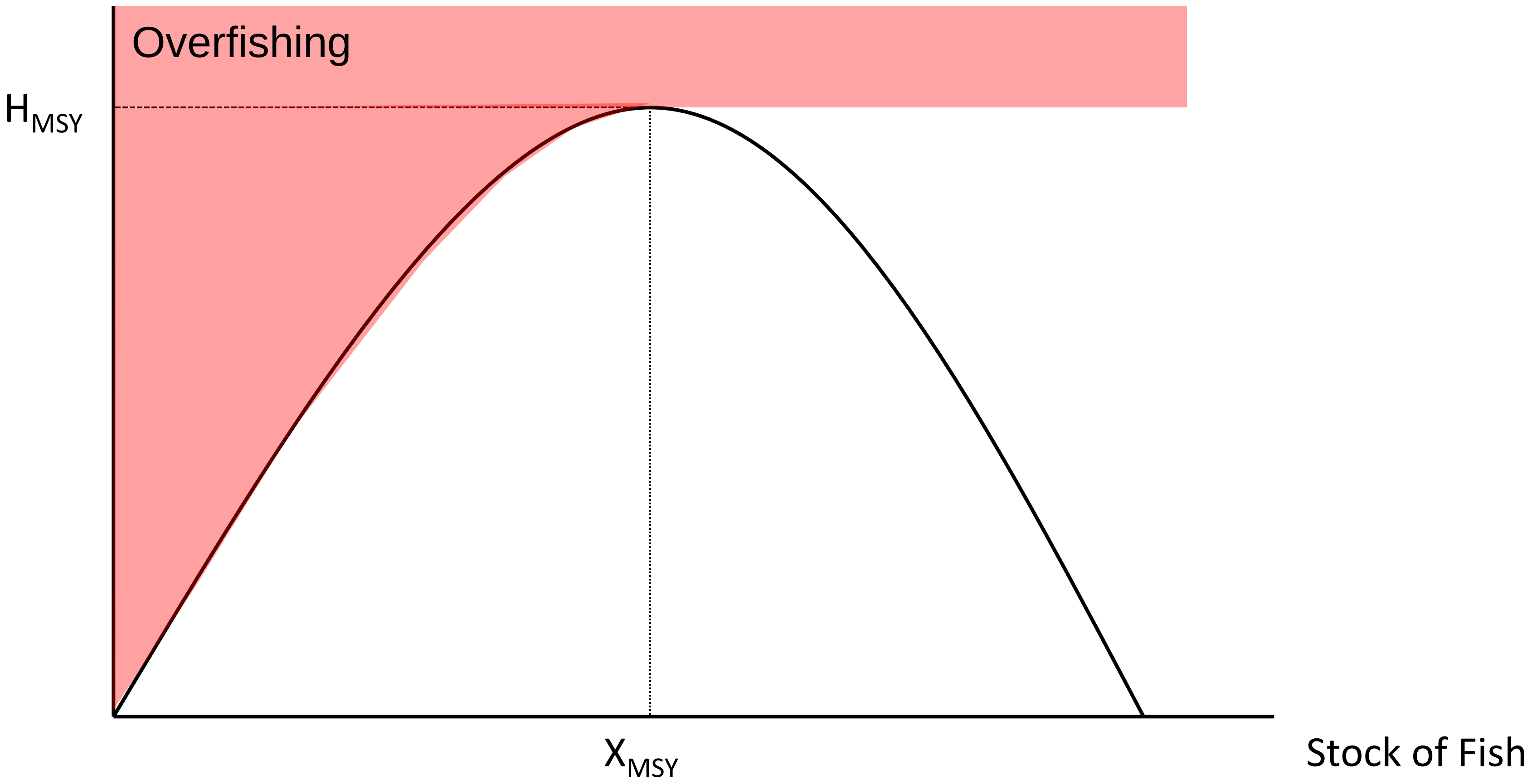
$$X_{MSY} = \frac{K}{2}$$

$$H_{MSY} = \frac{rK}{4}$$

Defining “Overfished”

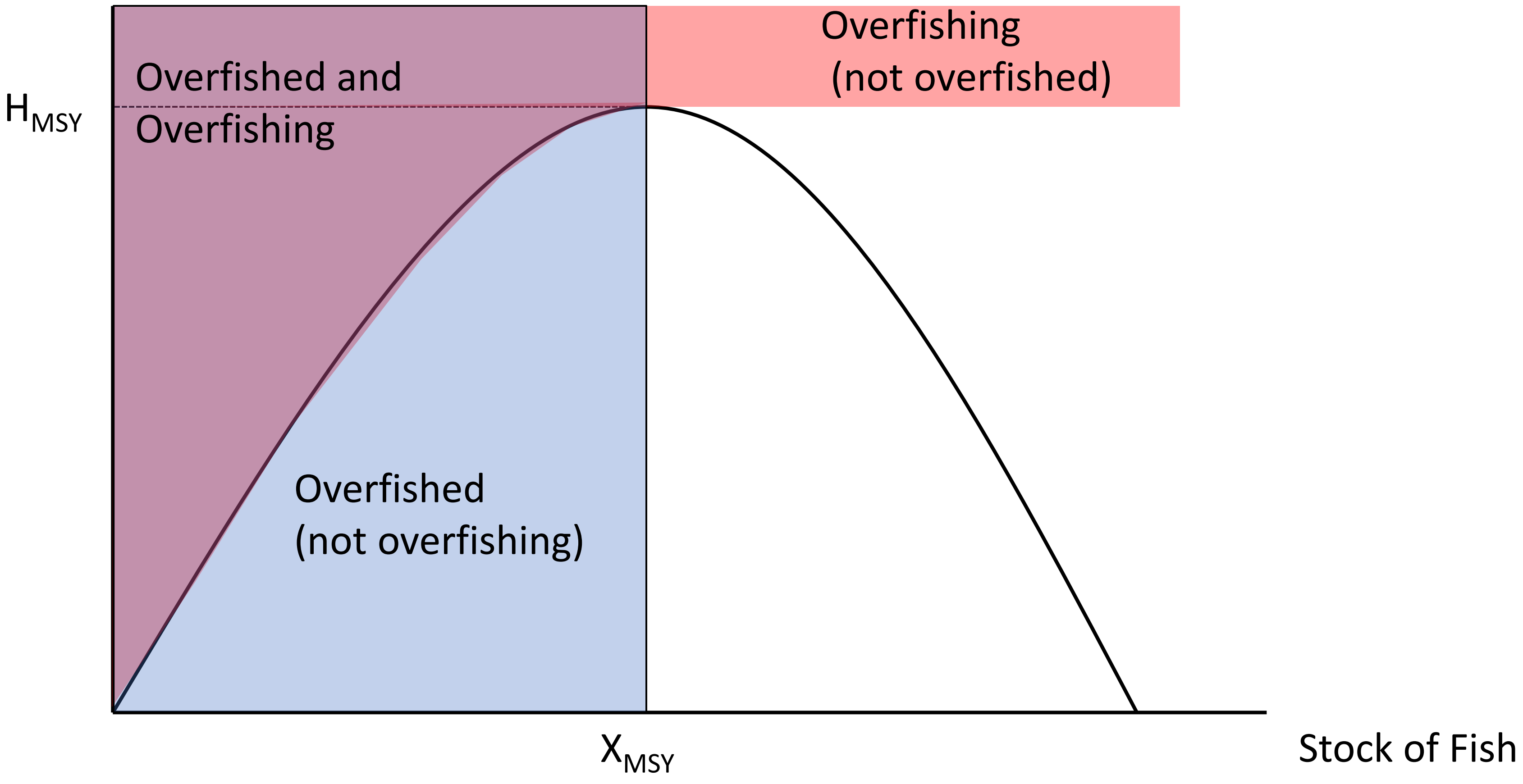


Defining "Overfishing"



Overlap is “overfished” and “overfishing”

Surprise: could be overfished but not overfishing or overfishing and not overfished



2. Unmanaged Fishery: Static Open Access

Unmanaged Fishery: Static Open Access

Gordon (1954, *Journal of Political Economy*)

$$H = qEX$$

Harvest proportional to fishing effort (E) and the fish stock (X)

$$F(X) = rX\left(1 - X/K\right) = H$$

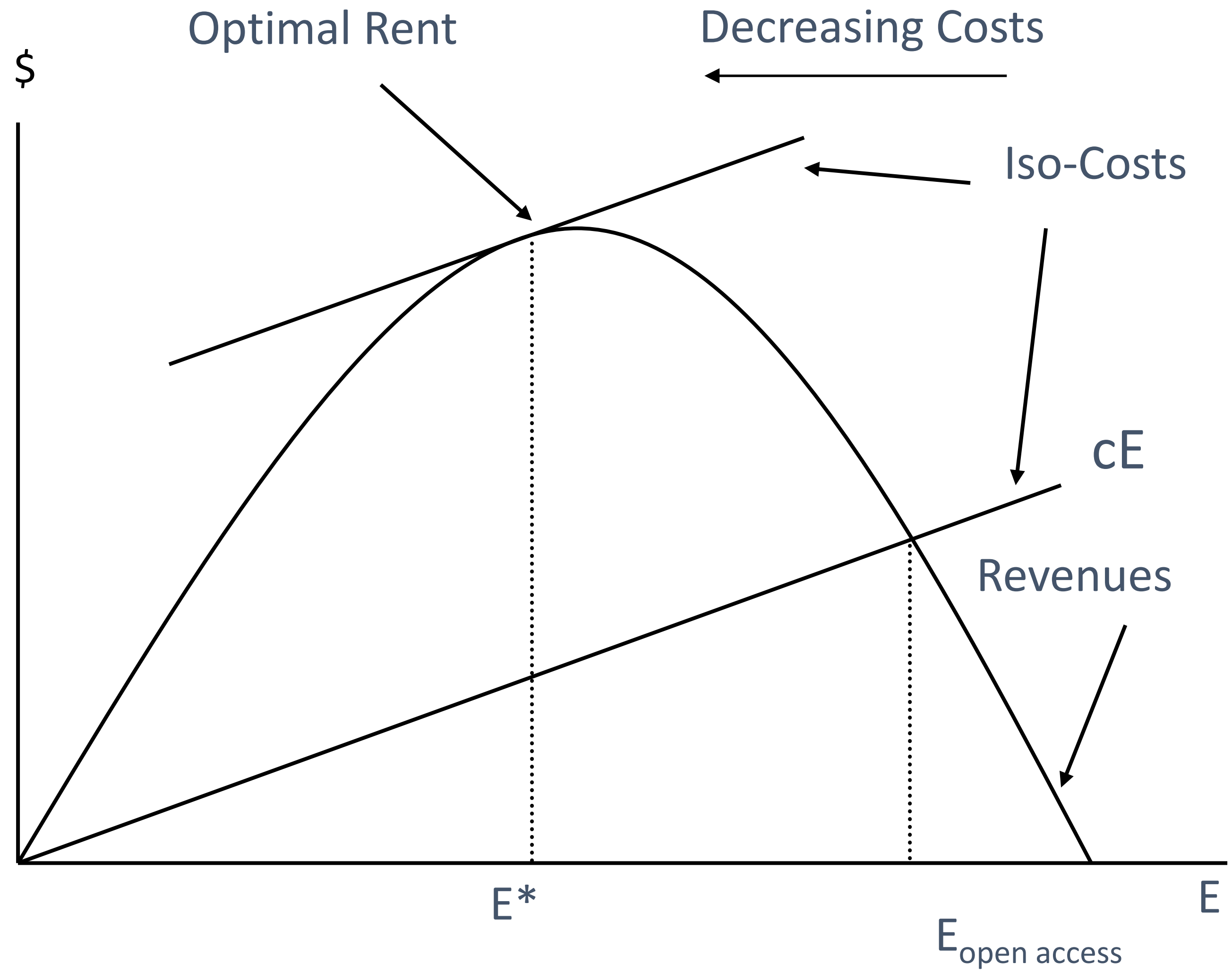
Harvest extracts the net biological growth F(X)

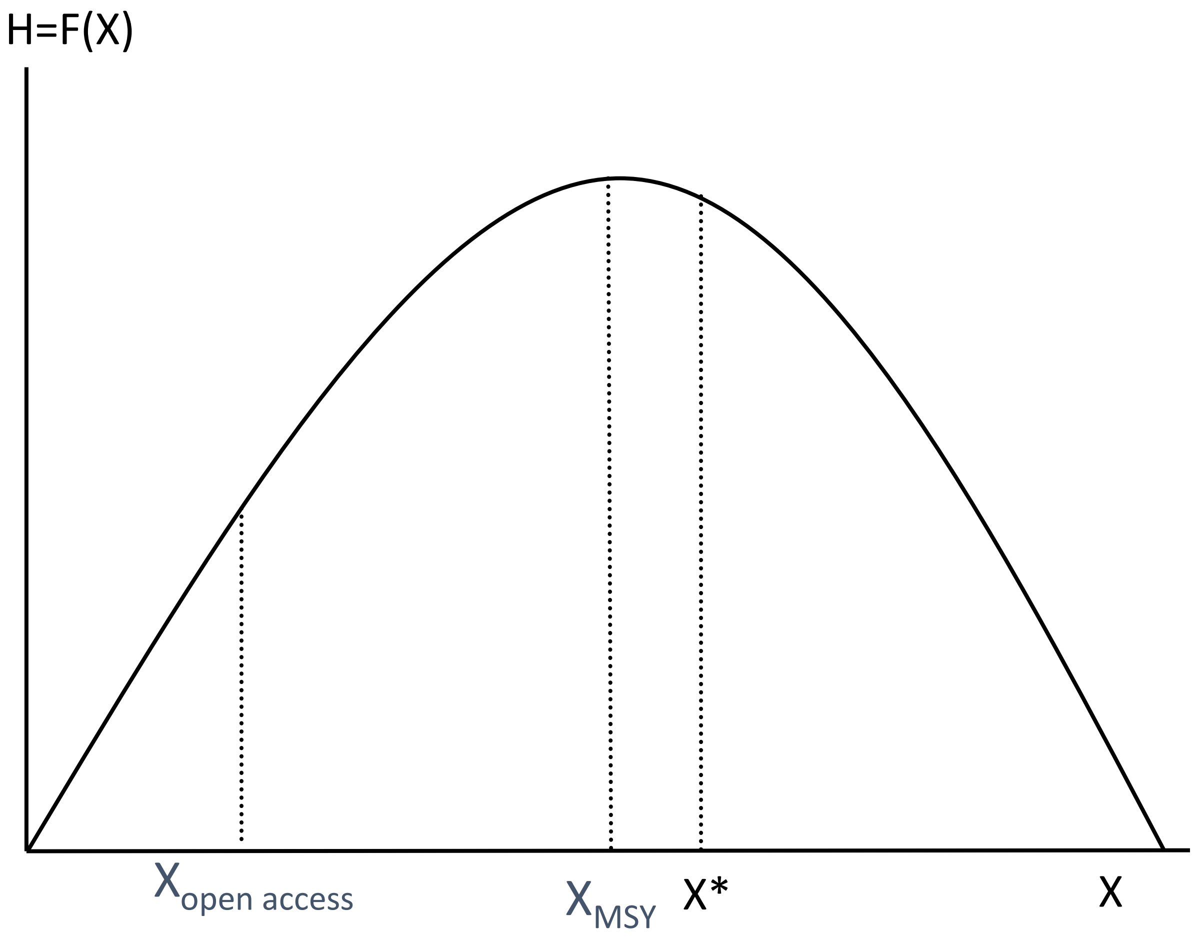
$$\pi = PH - cE = 0$$

Rent (profit) = Revenue – Cost = 0 (in equilibrium)

3 implications of Gordon (1954)

- Excess economic costs (rent dissipation)
- Biological overexploitation
- Surprise: MSY not optimal

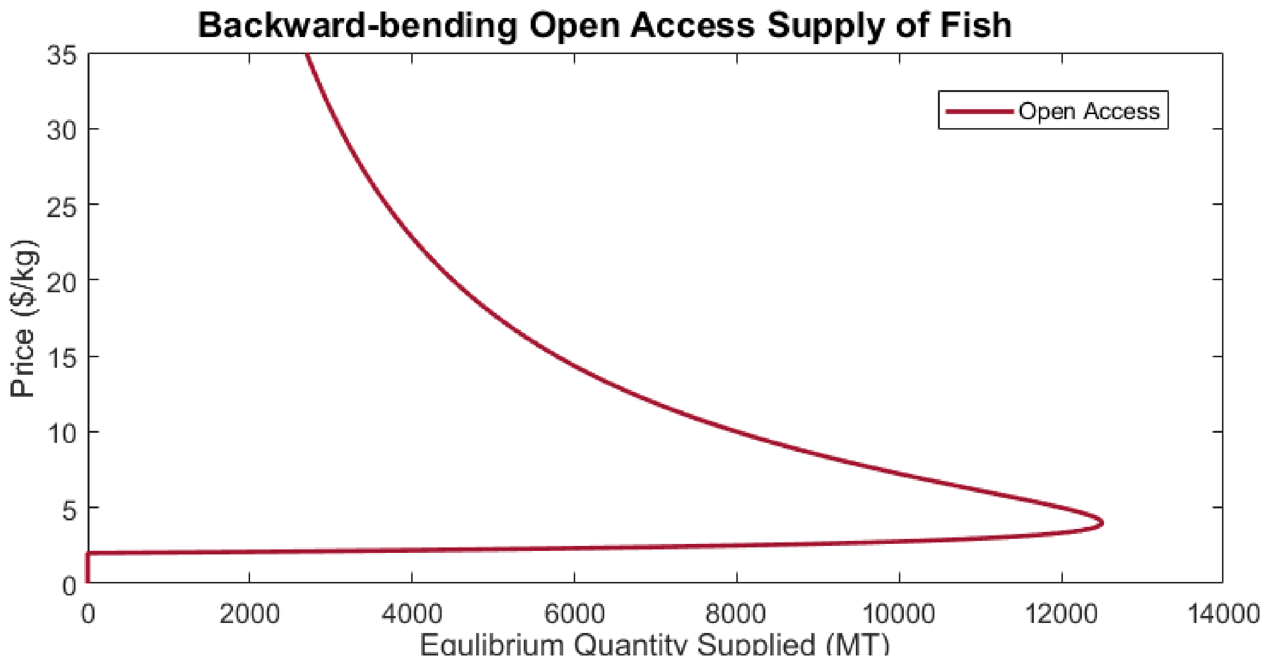




Unmanaged Fishery: Static Open Access

An empirical implication of Gordon (1954) is the backward-bending supply of fish Copes (1970)

$$H_{SS} = r\frac{c}{Pq}\left(1 - \frac{c}{PqK}\right)$$



Surprise: Higher price can actually decrease the long-run supply of fish!

Application: Backward-bending supply of bluefin tuna with age structure

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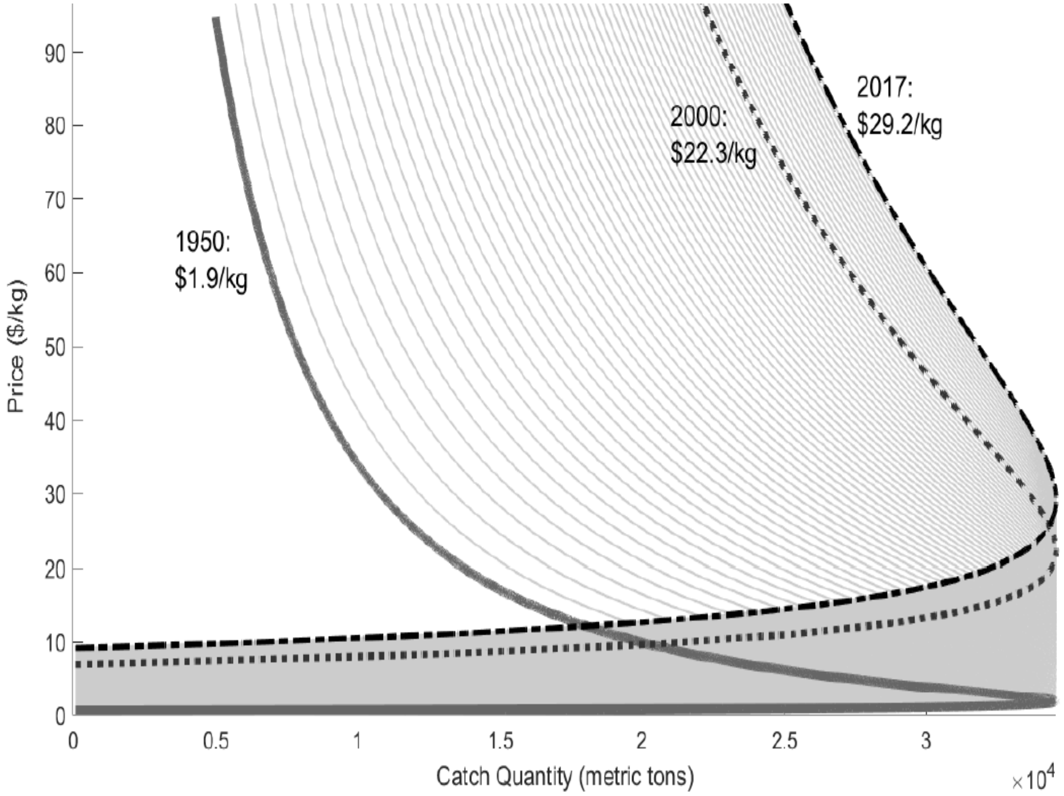


An Age-Structured Backward-Bending Supply of Fish: Implications for Conservation of Bluefin Tuna

Qingran Li, Julia Bronnmann, Rachel Karasik, Martin F. Quaas, and Martin D. Smith

J. Assoc. of Env. And Res. Economists 2021

- Surprise: Multiple bends are theoretically possible with age structure
- We find just one backward-bending price, but it increases over time
- **Both market context and management drive outcomes in the fishery!**

3. Unmanaged Fishery: Dynamic Open Access

Unmanaged Fishery: Dynamic Open Access

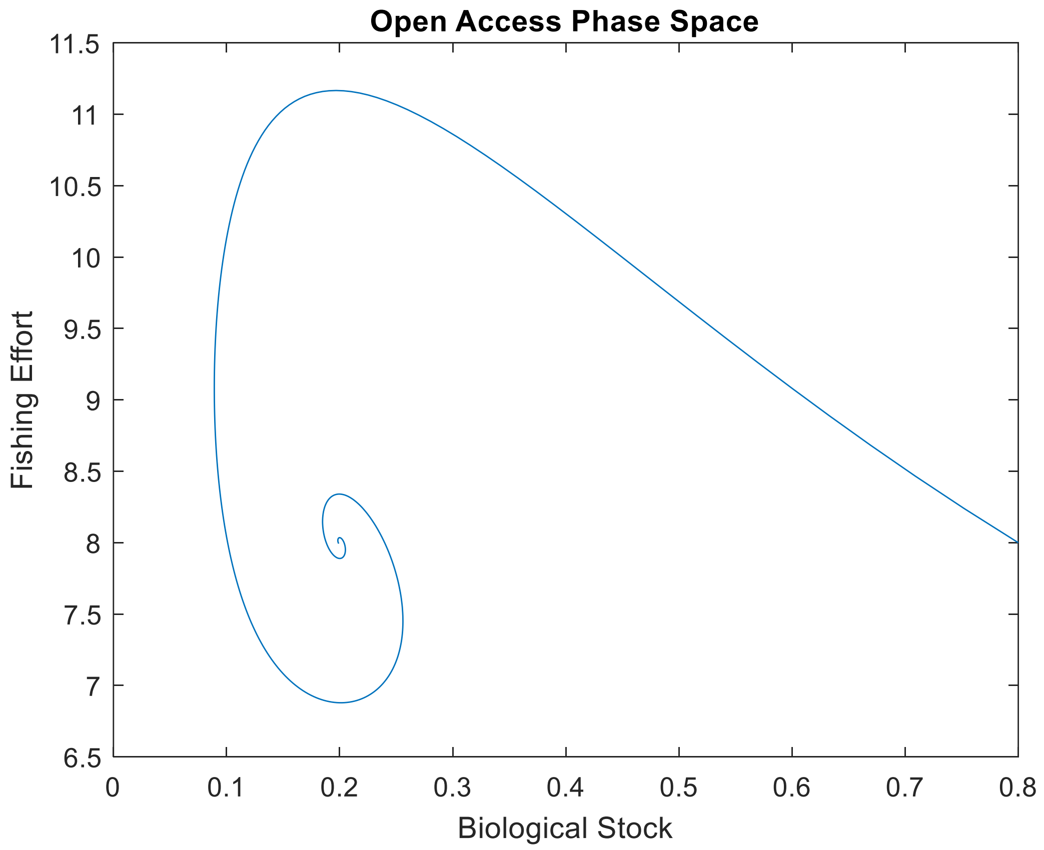
V. Smith *AER* (1968) and *JPE* (1969)

- Models stocks dynamics
- Models entry/exit based on Gordon zero-rent equilibrium
- Only one additional parameter – the economic speed of adjustment
- 2 ODEs
- Stable focus (spiraling) equilibrium in continuous time

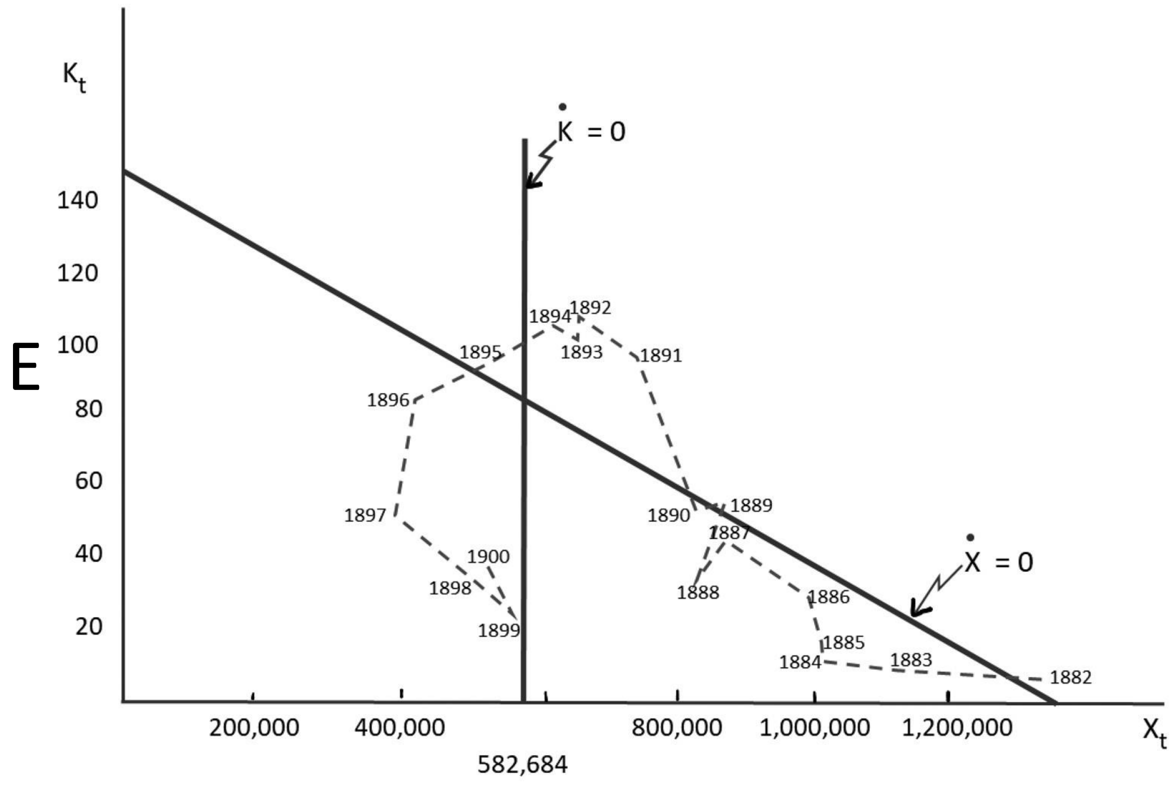
$$\dot{x}(t) = rx(t)\left[1 - \frac{x(t)}{k}\right] - qE(t)x(t)$$

$$\dot{E}(t) = \gamma\left[pqE(t)x(t) - cE(t)\right]$$

Speed of adjustment



Unmanaged Fishery: Dynamic Open Access



Wilen *MRE* (2018)

Diving the time series into bins, "the correlation coefficients between fleet size and catch-per unit-effort (the stock proxy) in each bin are: -0.94, -0.75, -0.98, 0.96, and -0.82."
Abbott, Sanchirico, and Smith *MRE* (2018)

Could wrongly conclude Malthusian spiral and have draw the opposite policy conclusions (see Smith *Science* 2014 critique of Brashares et al. *Science* 2014)

Surprise: Fishing effort and the fish stock can be negatively or positively correlated

4. Optimal Dynamic Management: The Maximum Economic Yield

Optimal Dynamic Management – The Maximum Economic Yield

- Clark and Munro *JEEM* (1975)
- Maximize present value rents (profits) subject to stock dynamics
- The solution defines the Maximum Economic Yield (MEY) stock and harvest (or effort) levels

The Optimal Control Problem

$$\max \int_0^{\infty} e^{-\delta t} \pi\left(H(t), X(t)\right) dt$$

$$s.t.$$

$$\dot{X}(t) = F\left(X(t)\right) - H(t)$$

The Present Value Hamiltonian

$$\tilde{\mathrm{H}} = \pi\left(H(t), X(t)\right) + \tilde{\lambda}(t)\left[F\left(X(t)\right) - H(t)\right]$$

First Order Necessary Conditions

$$\frac{\partial \tilde{\mathrm{H}}}{\partial H} = \frac{\partial \pi}{\partial H} - \tilde{\lambda}(t) = 0$$

$$-\frac{\partial \tilde{\mathrm{H}}}{\partial X} = \dot{\tilde{\lambda}}(t) - \delta \tilde{\lambda}(t) = -\frac{\partial \pi}{\partial X} - \tilde{\lambda}(t) F'\left(X(t)\right)$$

Transversality

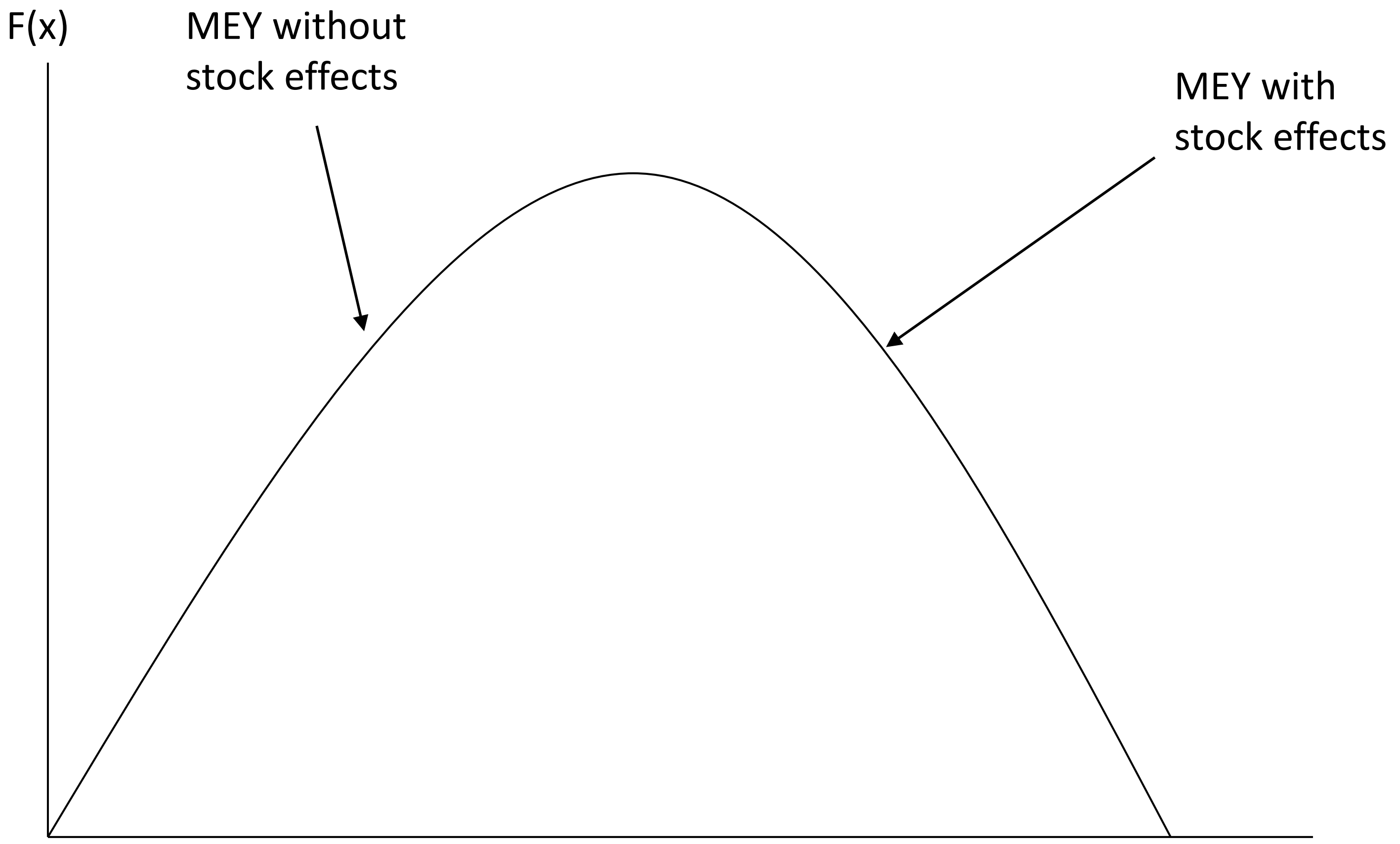
$$\lim_{t \to \infty} \tilde{\lambda}(t) X(t) = 0$$

Optimal Dynamic Management – The Maximum Economic Yield

$$\delta = F'(X) + \frac{\frac{\partial \pi}{\partial X}}{\frac{\partial \pi}{\partial H}}$$

Fundamental Equation of Renewable Resource Economics

- Growth rate of financial capital equals growth rate of natural capital + stock effect
- Stock effect depends on whether a large stock reduces costs or the stock has non-market value
- **Surprise: MEY stock could be larger or smaller than MSY (economic management could be more conservationist than biological management)**



5. Optimal Stochastic Dynamic Management: The Reed Model

Optimally managed fishery – stochastic recruitment

- Reed *JEEM* (1979)

$$R(t+1) = Z(t)f\big(S(t)\big)$$

- Escapement-based management often used for anadromous fish

$$\mathrm{E}PV = E\left\{\sum_{t=0}^{\infty}\left[\frac{1}{(1+\delta)^t}\int_{S(t)}^{R(t)}\left(p-\frac{c}{qx}\right)dx\right]\right\}.$$

- **Surprise: under some plausible conditions, optimal management involves a constant escapement of fish each year**

$$f'(S)\cdot\left(p-\frac{c}{f(S)}\right)\Big/\left(p-\frac{c}{S}\right) = 1+\delta.$$

$$H^*(t) = \max\left\{Z(t-1)f\big(S(t-1)\big) - S^*, 0\right\}$$

Application
Fishery Collapse Revisited

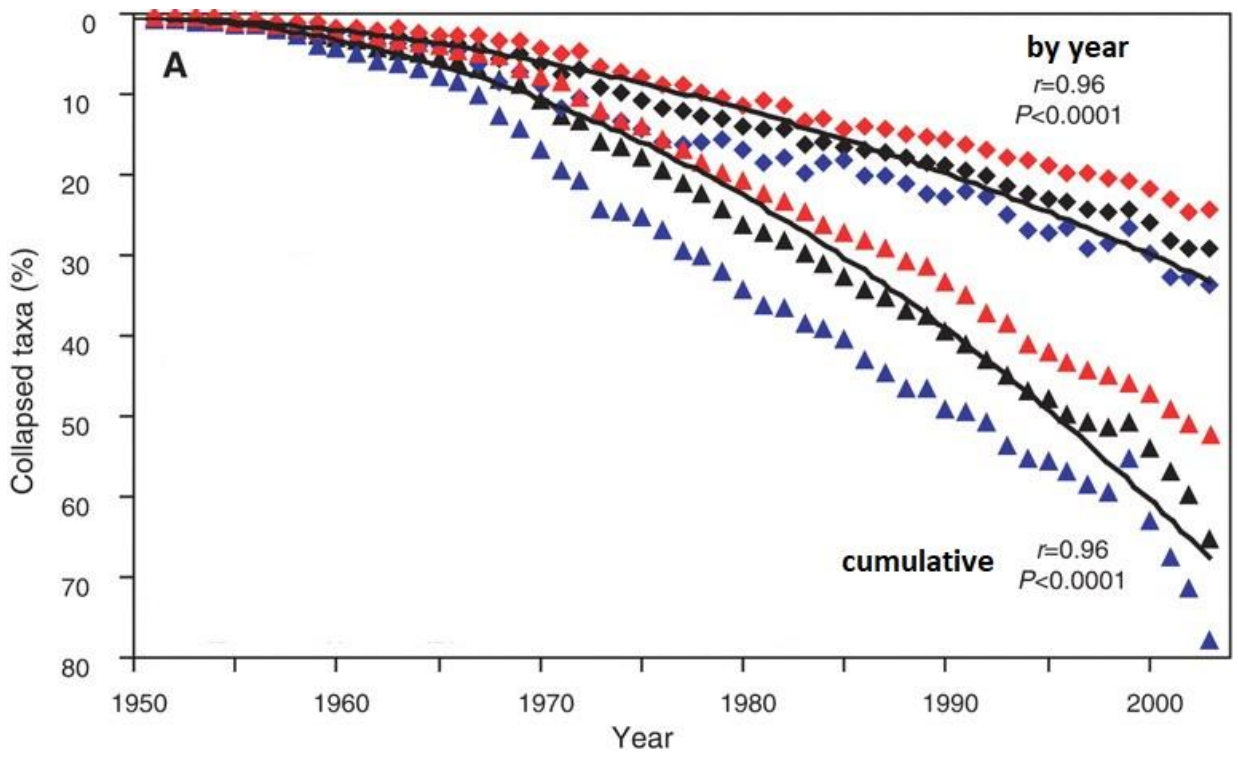
Qingran Li (Clarkson University), Martin D. Smith

Marine Resource Economics, *36*(1), pp.1-22, 2021.

Ignoring economic incentives and institutions generates misleading predictions about resource scarcity

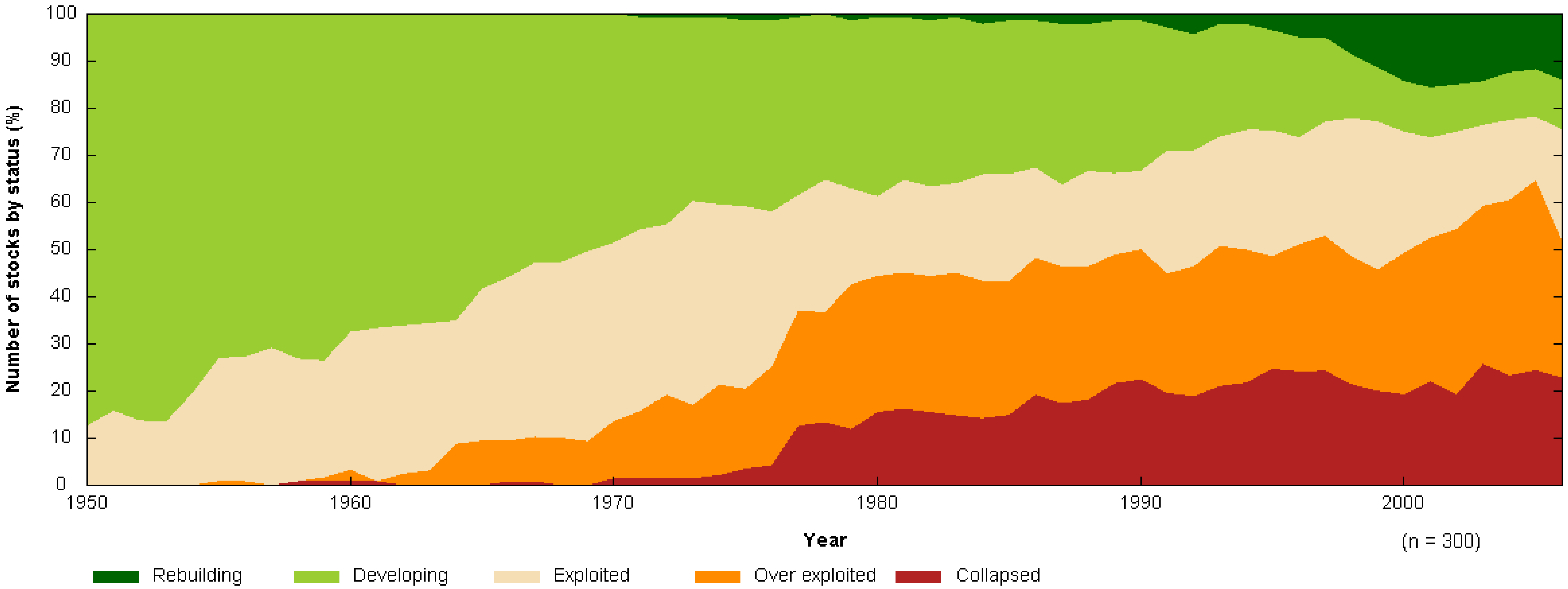
- By extrapolating path "*global collapse of all taxa currently fished by 2048*" (Worm et al, 2006)

- **Fishery collapse** is defined by a **10%-rule**: catches dropping below 10% of the recorded maximum



Source: Figure 3A – "Trajectories of collapsed fish and invertebrate taxa over the past 50 years" (Worm et al, 2006)

Stock status plots still use catch-based metrics



Source: Sea Around Us, http://www.seaaroundus.org/stock-status-plots-method/
Accessed 3/20/20

History and debate about catch-based metrics and the 10% rule

- Froese and Kesner-Reyes (2002) and the FAO
- Based on catch records only
- Critics
  - Stochastic process (Wilberg and Miller Science 2007; Branch et al. 2011)
  - Assessment models (Carruthers et al. 2012)
  - Empirical comparison to assessed fisheries (Branch et al. 2011)
- Pauly, Hilborn, and Branch debate in *Nature* 2013

COMMENT

ENERGY Shale gas and oil will run out faster than champions predict p.307 | ANTHROPOLOGY Napoleon Chagnon sets the record straight p.310 | BIOGRAPHY A flattering life of impish physicist Freeman Dyson p.311 | HEALTH Iran needs international help to fight HIV epidemic p.314

Does catch reflect abundance?

Researchers are divided over the wisdom of using estimates of the amount of fish hauled in each year to assess the health of fisheries.

POINT

Yes, it is a crucial signal

The only data available for most fisheries are the weight of fish caught each year, insists Daniel Pauly.

COUNTERPOINT

No, it is misleading

Many factors as well as abundance determine the hauls of fishermen, warn Ray Hilborn and Trevor A. Branch.

Why should policy scientists care?

- the 10%-rule defining collapse is highly influential
  - Worm et al. (2006) highly cited (4,303 cites in GS as of 3/24/20), cited specifically for collapse result 39% of the time and more often in fisheries and policy journals (Branch *PLoS One* 2013)
  - Still has prominent proponents, e.g. D. Pauly and Sea Around Us
- Economists use the 10%-rule as an outcome measure in **empirical** analyses that make **causal claims about policy**
  - Catch shares (Costello et al., *Science* 2008, *Annual Rev Res Econ* 2010)
  - Subsidies (Sakai, *Land Econ* 2017)
  - Trade (Erhardt, *JAERE* 2018; Eisenbarth, JEEM 2022)
- Arguments **for** and **against** the 10%-rule are **not** grounded in **bioeconomic theory**
  - Human agency, institutions, and behavior are ignored in catch-based metrics
  - Ignoring institutions and human can reverse conclusions about fisheries management (Smith and Wilen *JEEM* 2003; Smith, Zhang, and Coleman *JEEM* 2008) and ability to draw causal inferences about policy (Ferraro, Smith, and Sanchirico *PNAS* 2019)

What we do

- Evaluate the performance of the 10% rule in a series of numerical experiments that account for how institutions, economic incentives, and biological factors shape the catch data generating process

- Show conditions under which the 10% rule generates false negatives **and** false positives by simulating dynamic paths of catch records when the true stock status is known

- Conclude that all results based on the 10% rule are rendered **meaningless** because they fail to condition on critical institutional, economic, and biological factors

Experimental Design

- For a given institutional arrangement and biological and economic parameters:
  - Simulate the dynamic path of fishing effort, catch, and stock
  - Compare the catch in each period to the maximum historic catch in all previous periods
  - Evaluate performance of the 10% rule when the true fishery is "collapsed" (< =10% of carrying capacity) or "not collapsed"
  - **False negative** means true fishery is collapsed in steady state but 10% rule fails to identify it
  - **False positive** means true fishery is not collapsed in steady state but 10% rule does flag it

- 3 institutional types
  - Dynamic open access
  - Optimal management using MEY
  - Rebuilding fisheries to target MSY

Rebuilding experiments based on MSY management

- Simulate pure open access fishery with non-collapsed but overfished steady state
- Save maximum harvest
- Choose maximum constant harvest rate that enables rebuilding to MSY level within 5 (or 10) years
- Check for false positives

Open access experiments

- **Non-dimensionalized** V. Smith *AER* (1968) model with logistic growth

  - Harvest: $H(t) = qE(t)X(t)$

  - Stock-Effort dynamics:

$$\dot{X}(t) = rX(t)\big(1 - X(t)\big) - H(t)$$

$$\dot{E}(t) = \gamma\big(pH(t) - cE(t)\big)$$

- A “collapsed” fishery at 10% of carrying capacity, i.e. $X_\infty = \frac{c}{pq} = 0.1$

Optimally managed fishery - deterministic

Clark and Munro *JEEM* (1975)

$$\max \int_0^\infty e^{-\delta t}\big(pH(t) - cE(t)\big)\,dt$$

$$\text{s.t. } 0 \le E(t) \le E^{max}$$

$$\dot{X}(t) = rX(t)\big(1 - X(t)\big) - H(t)$$

$$H(t) = qE(t)X(t)$$

Most Rapid Approach defined by the optimal steady-state stock (X^*) (MEY Stock), effort (E^*) (MEY Effort), and the *bang-bang* control rule:

$$E(t) = \begin{cases} 0 \;\; if \;\; X(t) < X^* \\ E^* \;\; if \;\; X(t) = X^* \\ E^{\max} \;\; if \;\; X(t) > X^* \end{cases}$$

Check for false positives

Optimally managed fishery – stochastic recruitment

- Reed *JEEM* (1979)

$$f(S) = \theta S/(1 + (\theta - 1)S).$$

- Simulate fisheries under optimal escapement with different amounts of stochasticity

$$f'(S) \cdot \left(p - \frac{c}{f(S)}\right) / \left(p - \frac{c}{S}\right) = 1 + \delta.$$

Solve implicit function for S*

- Check for false positives when harvest falls below 10% rule

$$H^*(t) = \max\{Z(t-1)f\big(S(t-1)\big) - S^*, 0\}$$

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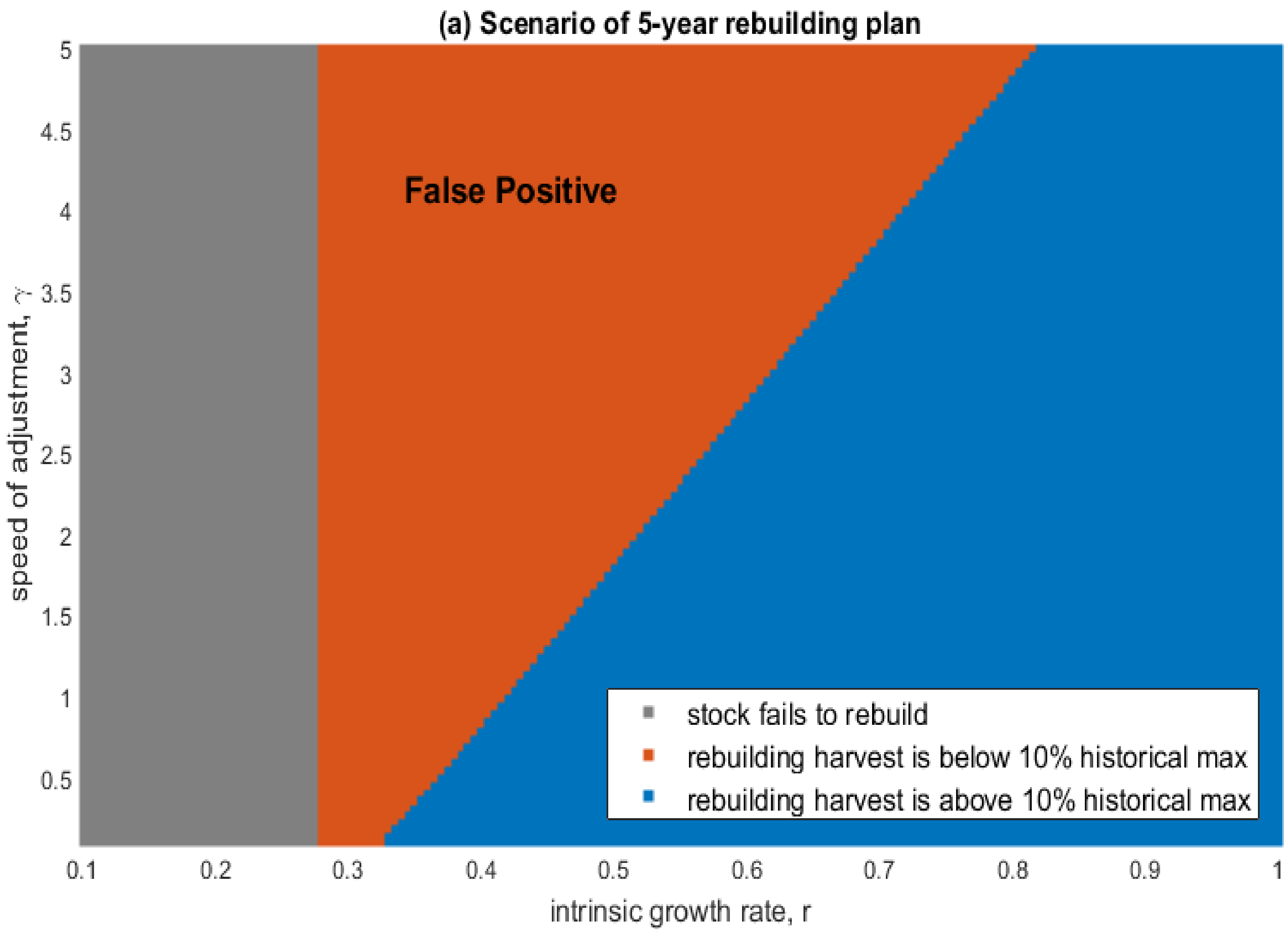
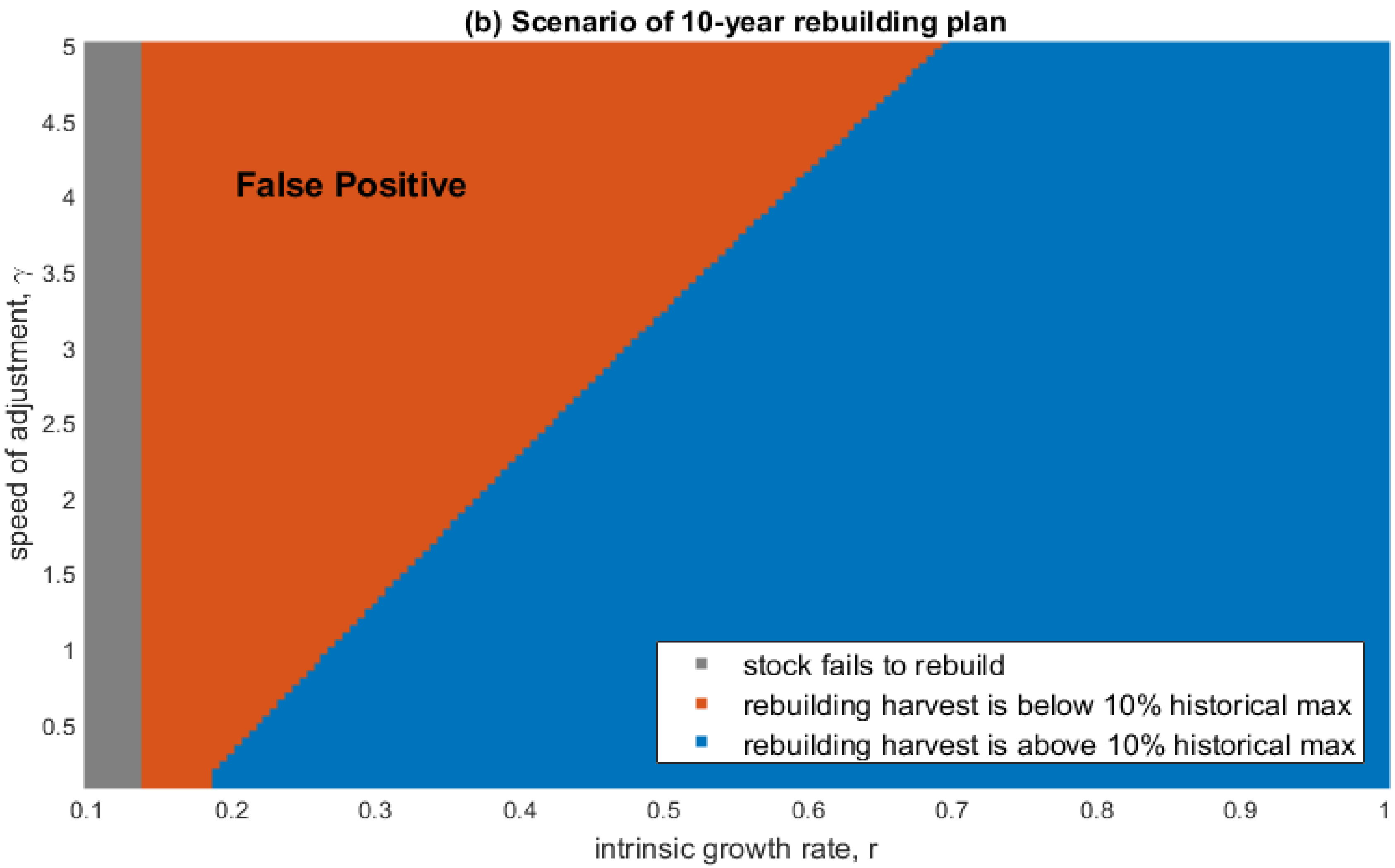
Results – rebuilding to MSY

False positives with 5-year rebuilding plan

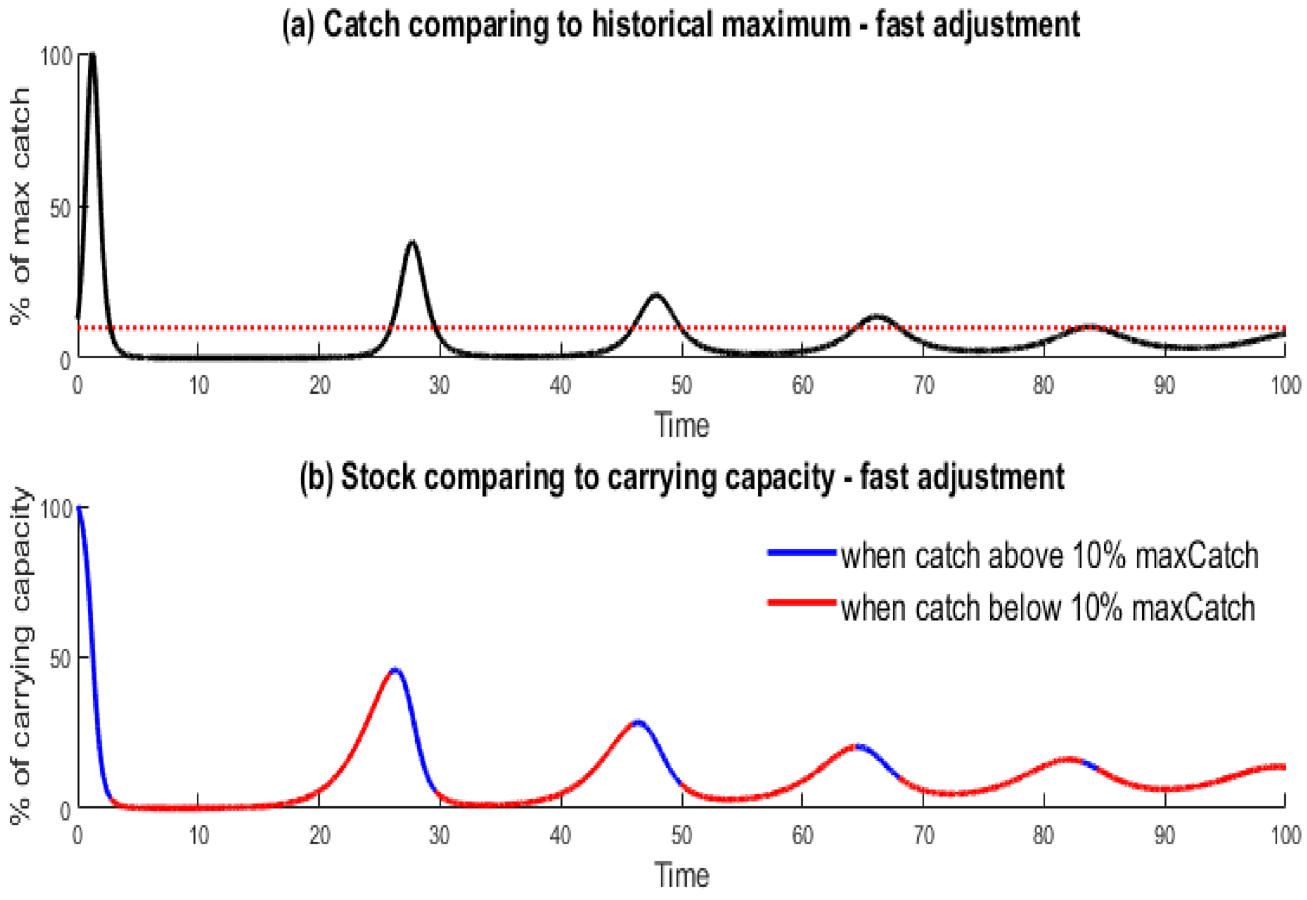


False positives with 10-year rebuilding plan



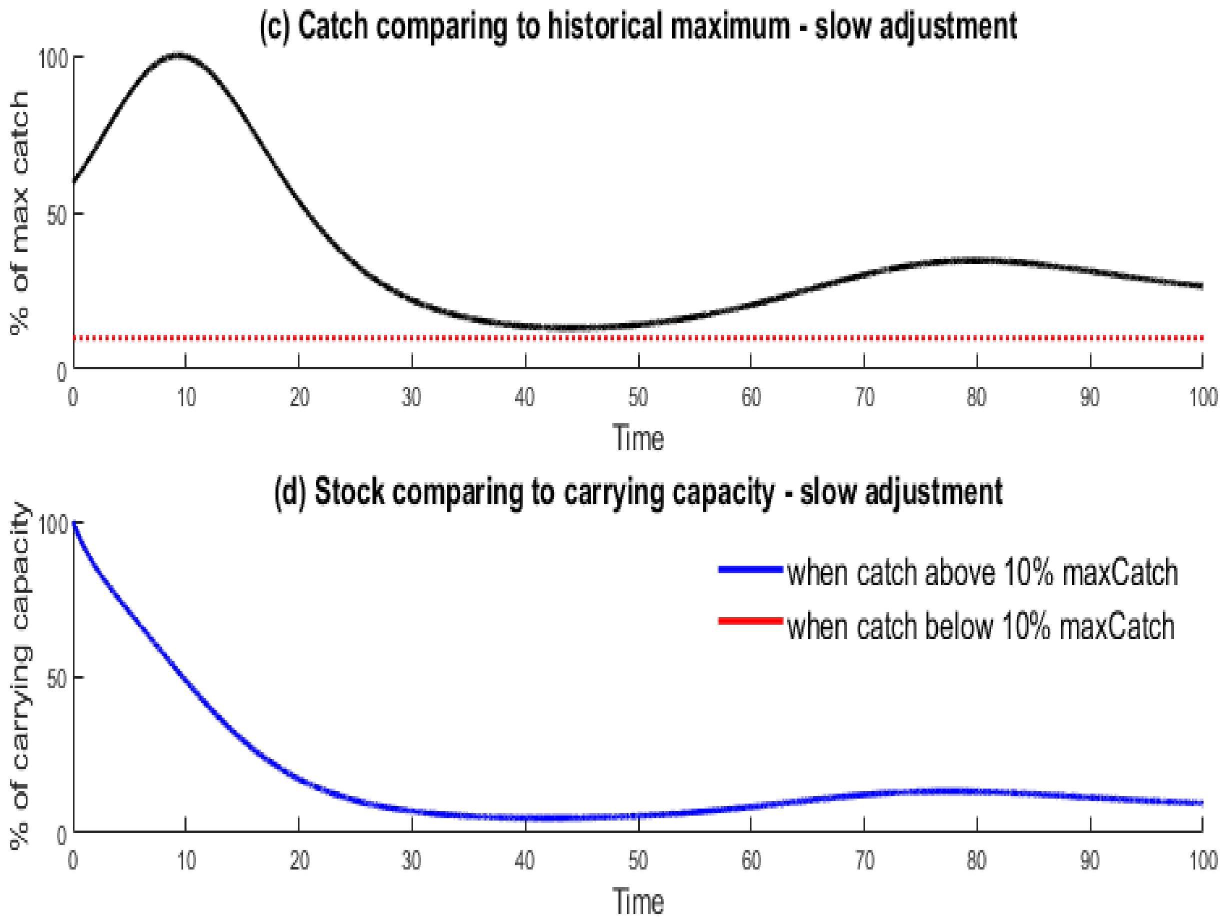
Results – Pure open access when actual fishery is **collapsed** in steady state

The 10% rule can generate false negatives in pure open access fisheries along the approach path

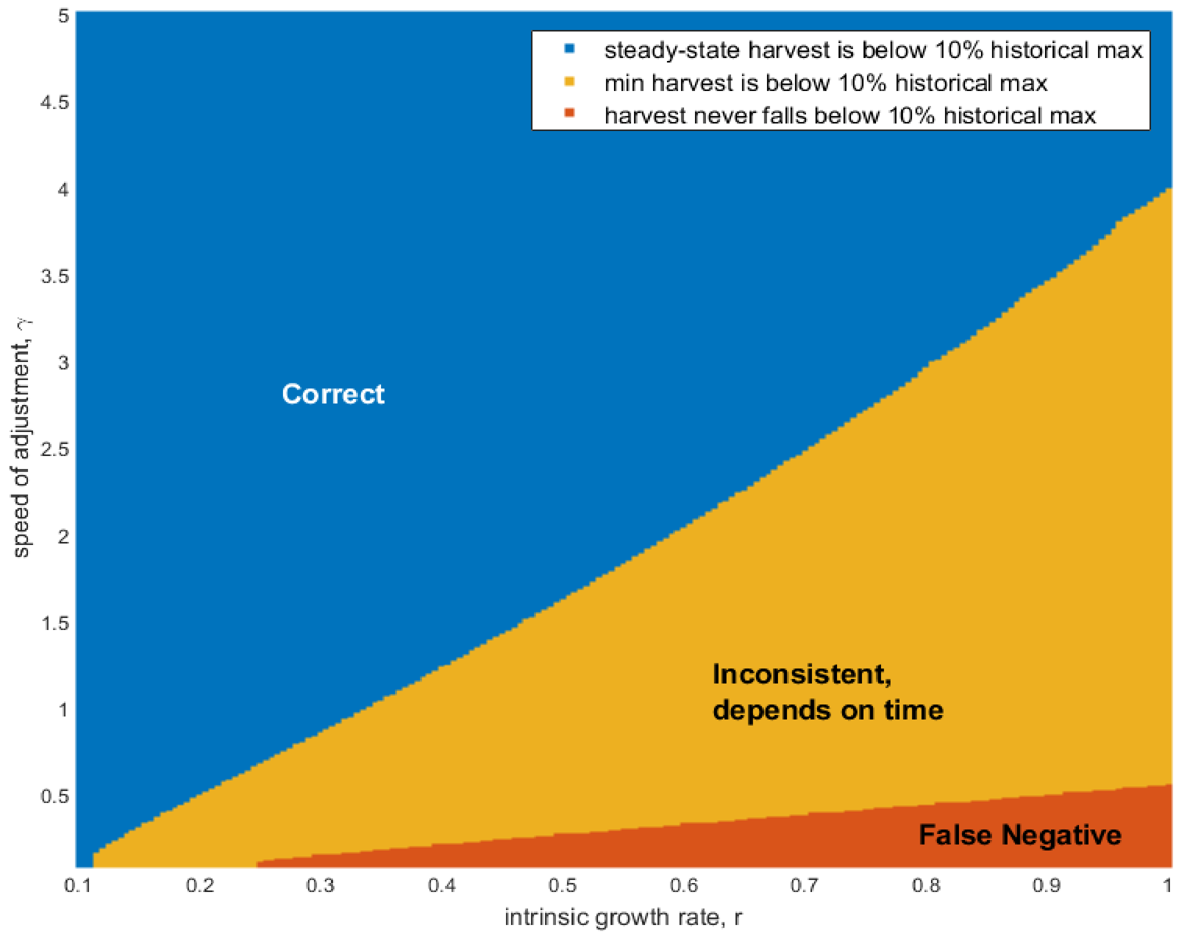


The 10% rule generates false negatives in pure open access fisheries when economic adjustment is slow

Surprise:
Did not change the steady state and performance changed dramatically

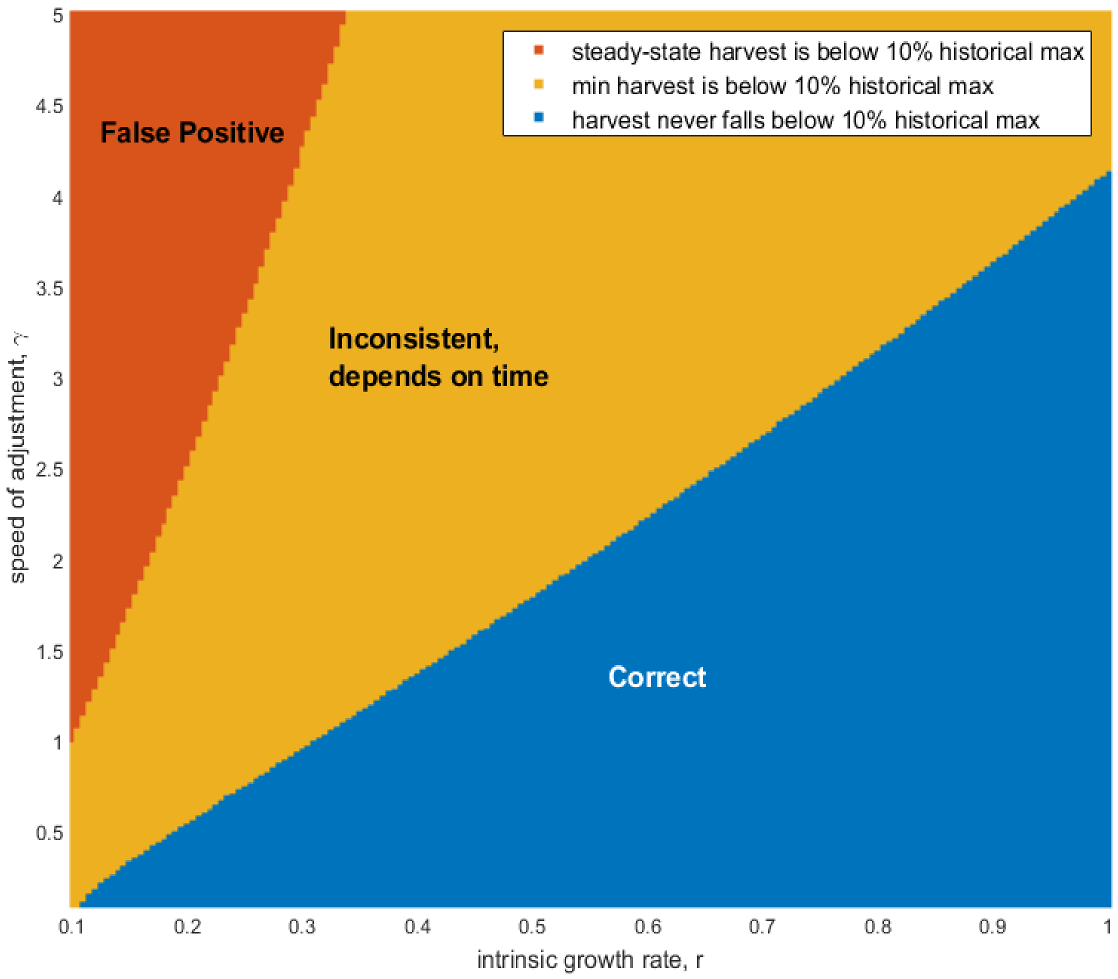


False negatives more likely with high intrinsic growth or slow speed of adjustment



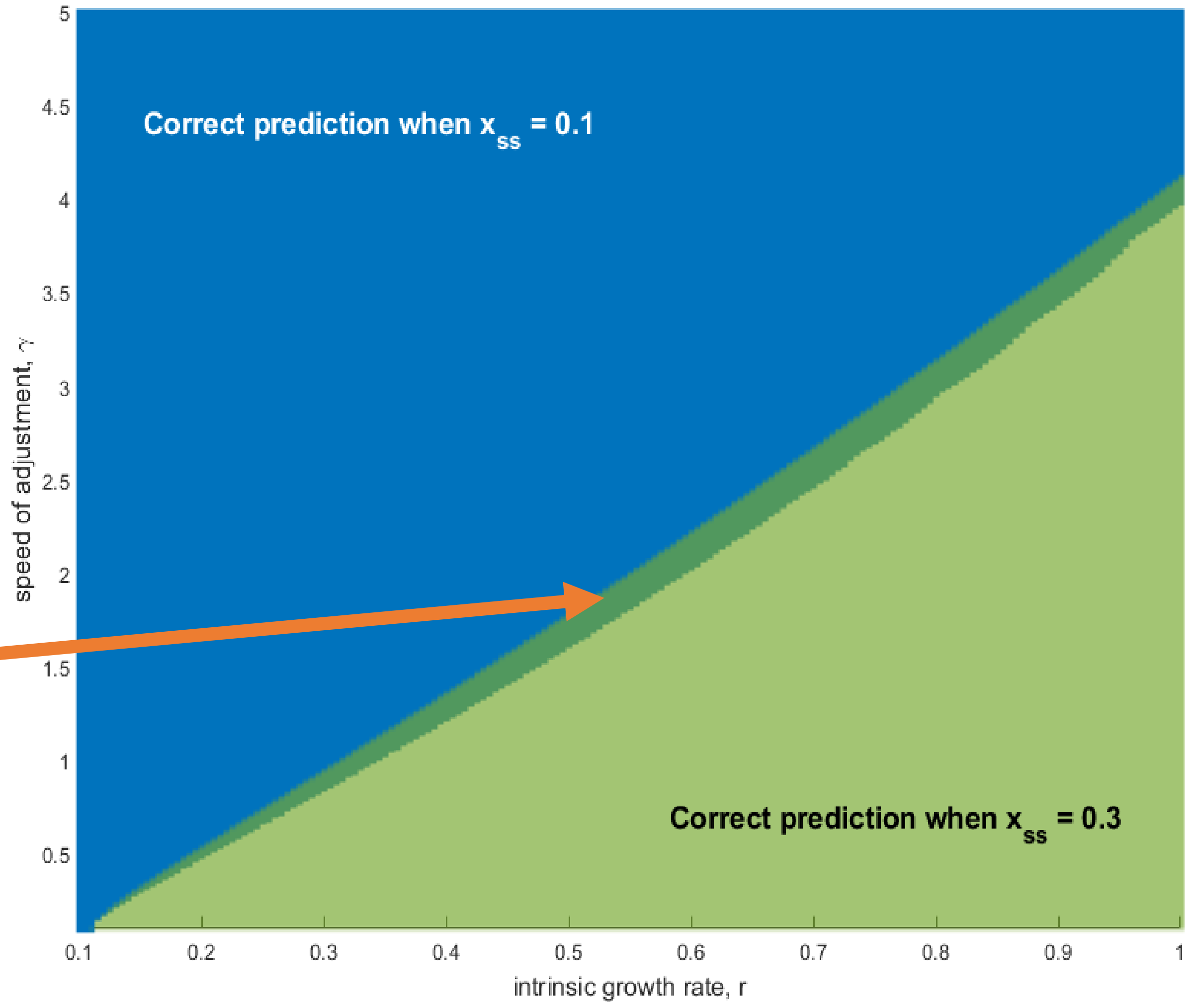
Results – Pure open access when actual fishery is **not collapsed** in steady state

False positives more likely with low intrinsic growth or fast speed of adjustment



Surprise: the 10% rule is unable to decipher true status of the fishery

Very thin region of overlap



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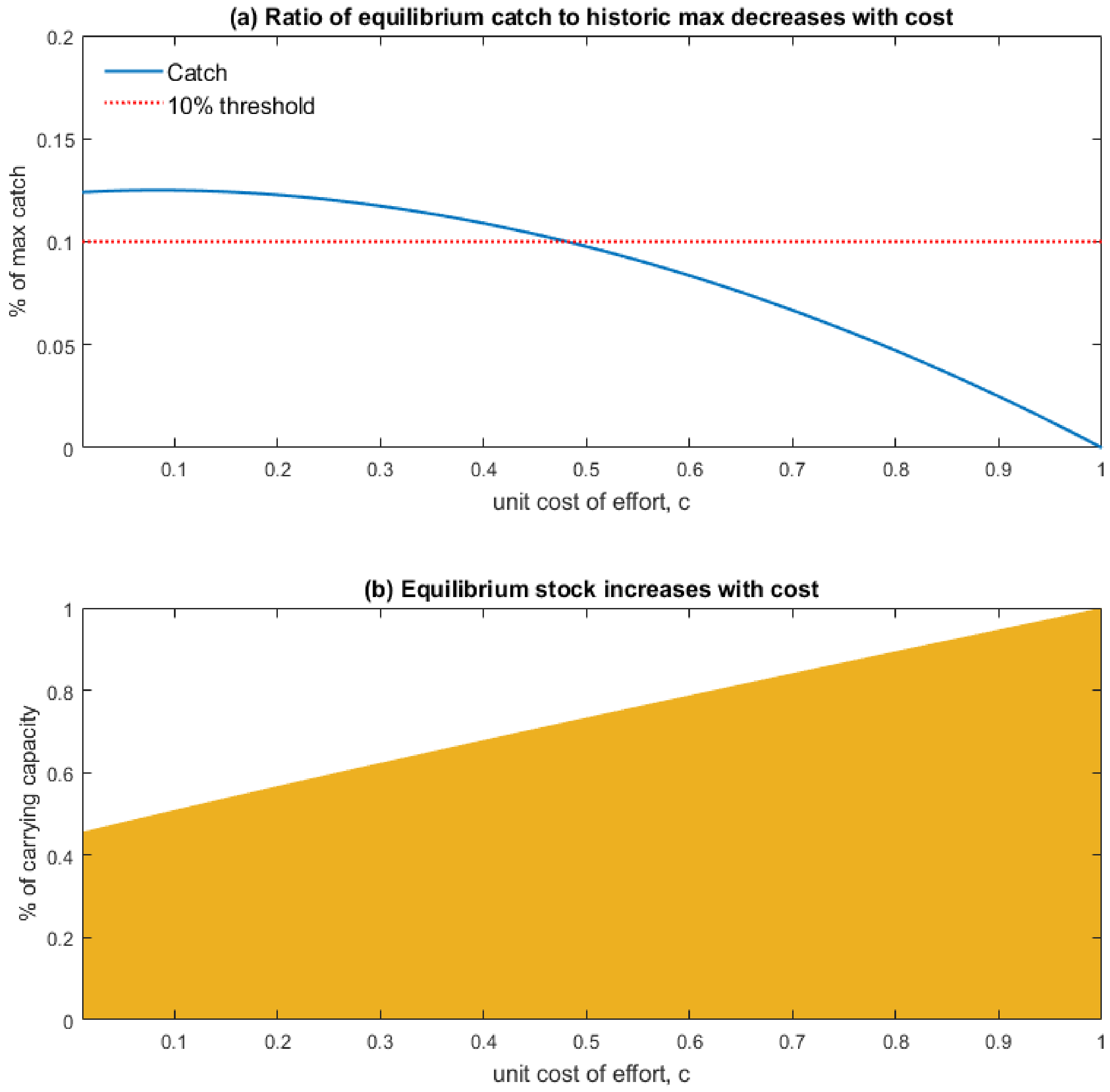
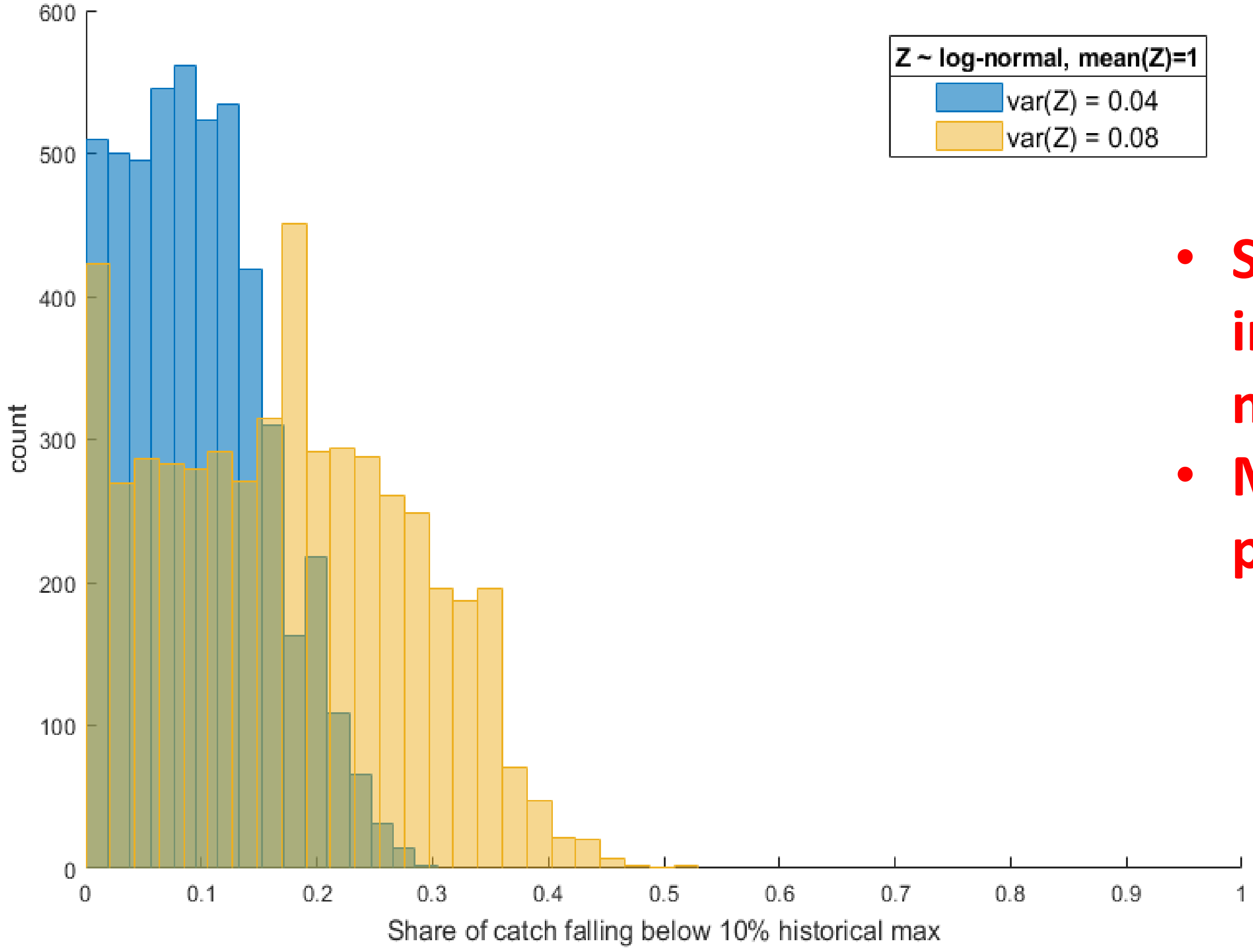
Results – optimal management

Surprise: False positives common under optimal management

Maximum catch based on
Most Rapid Approach Path
to the optimal steady state



Optimally managed stochastic fisheries – false positives



- **Surprise: false positives are baked into optimal dynamic stochastic management**
- **More stochasticity worsens the problem**

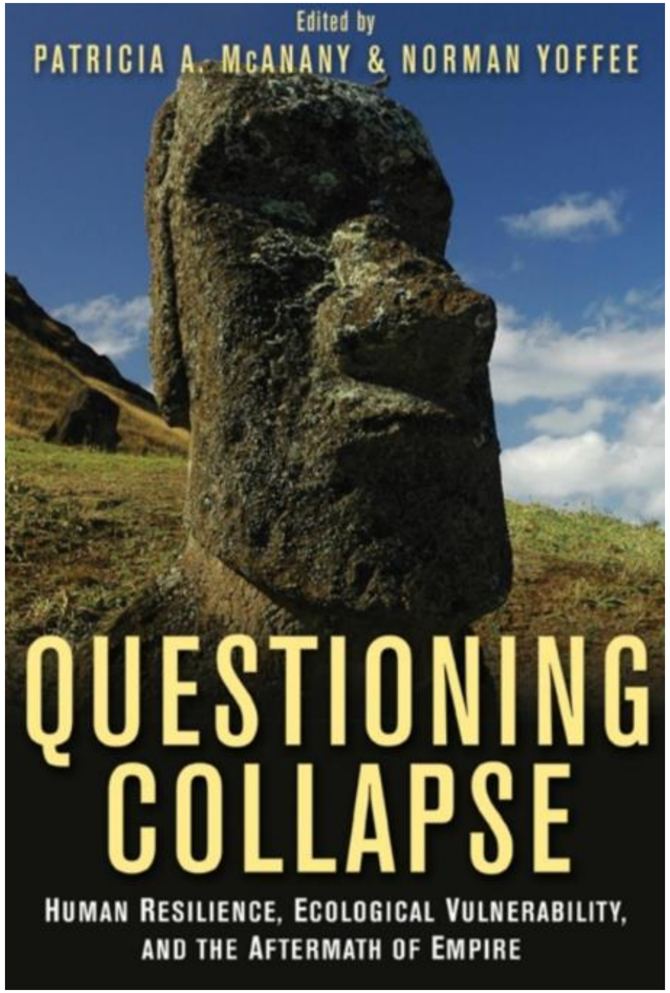
Discussion

Implications of findings

- 10% rule useless for stock status plots
- 10% rule useless as an outcome measure in comparative work
- Serious questions about other catch-based metrics that fail to condition on institutional and economic factors
- Need to redo or re-evaluate empirical findings based on the 10% rule

Reflections on “collapse”

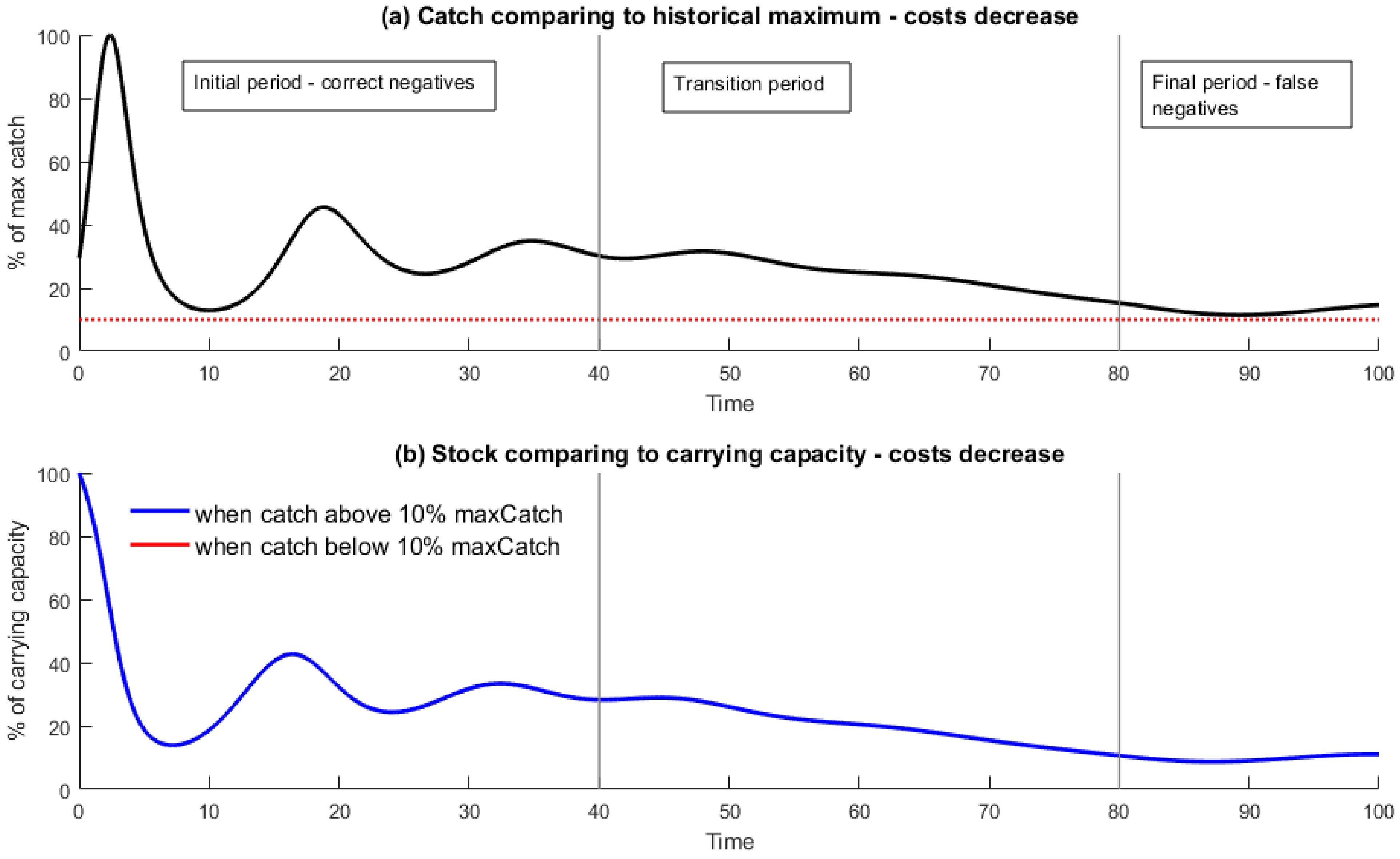
- Jared Diamond’s definition: “By collapse, I mean a drastic decrease in human population size and/or political/economic/social complexity, over a considerable area, for an extended time” (2005, p. 3).
- Diamond’s findings debunked by historians and archeologists
- From McAnany and Yoffee (2010):
  - “might these abandoned places, in many cases, be just as accurately viewed as part of a successful strategy of survival, part of human resilience?” (p. 6).
  - “ societies modify their practices in response to perceived crises” (p. 12)



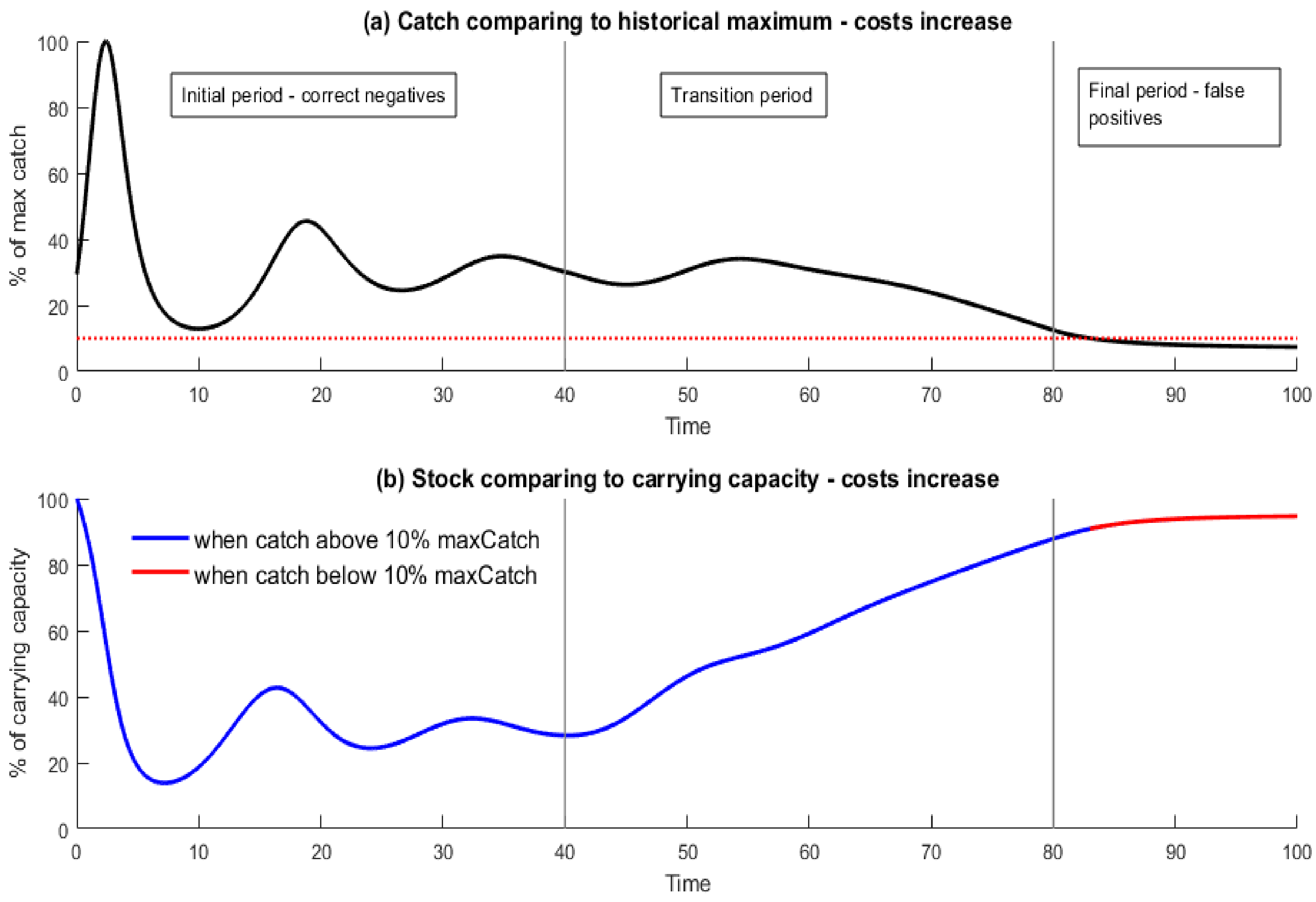
Questions

Supplementary Slides

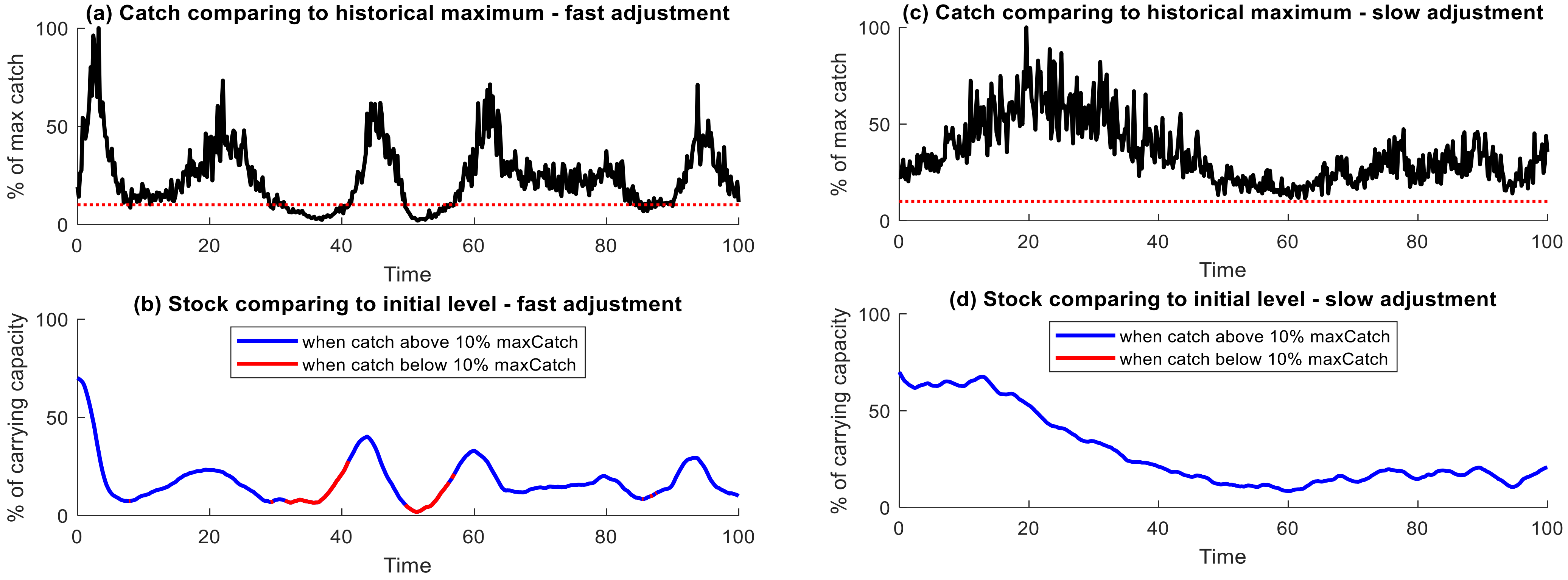
Decreasing costs – false negatives after



Increasing costs – false positives after



Add stochasticity to open access (process and observation error)

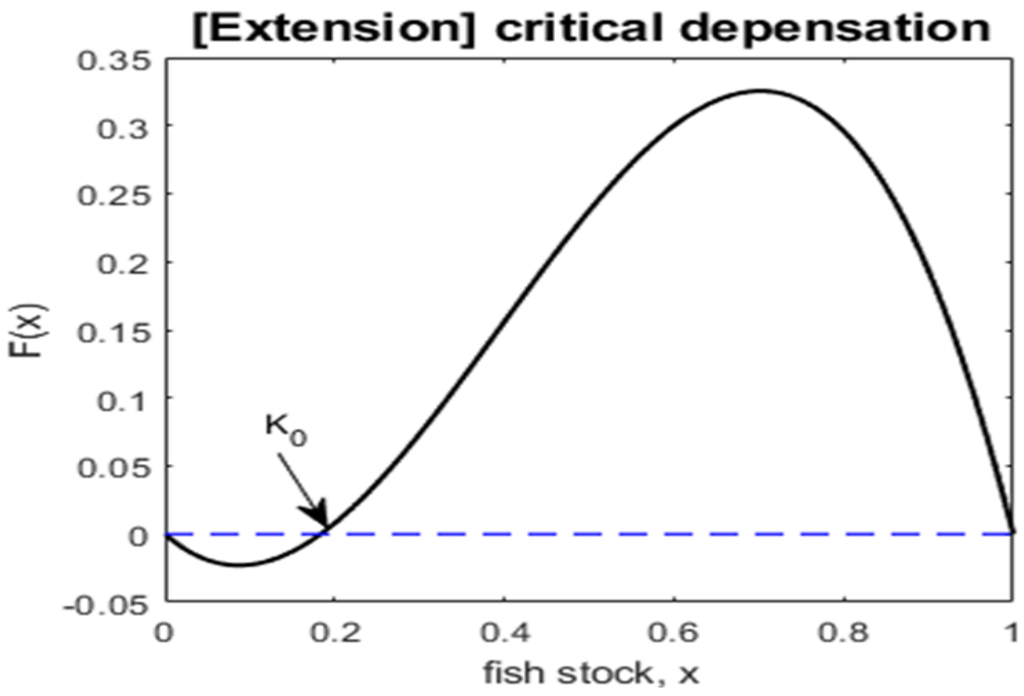


Results – extensions to pure open access

Extensions to open access

Introduce **critical depensation** in the stock dynamics

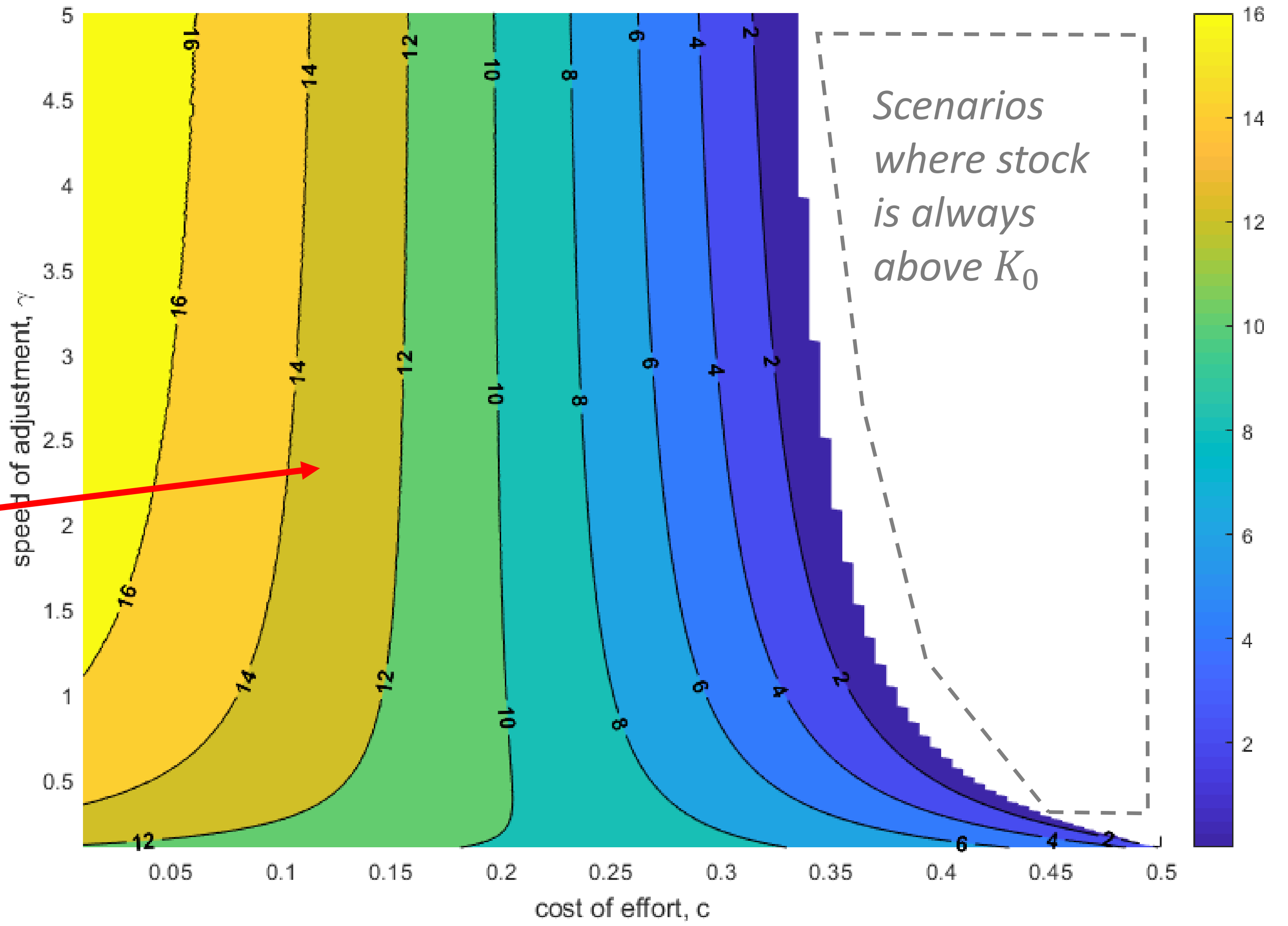
- A fishery that crosses the critical threshold (K_0) on an **extinction** path should be diagnosed as **collapsed**



Percent of maximum catch when stock crosses the point of no return

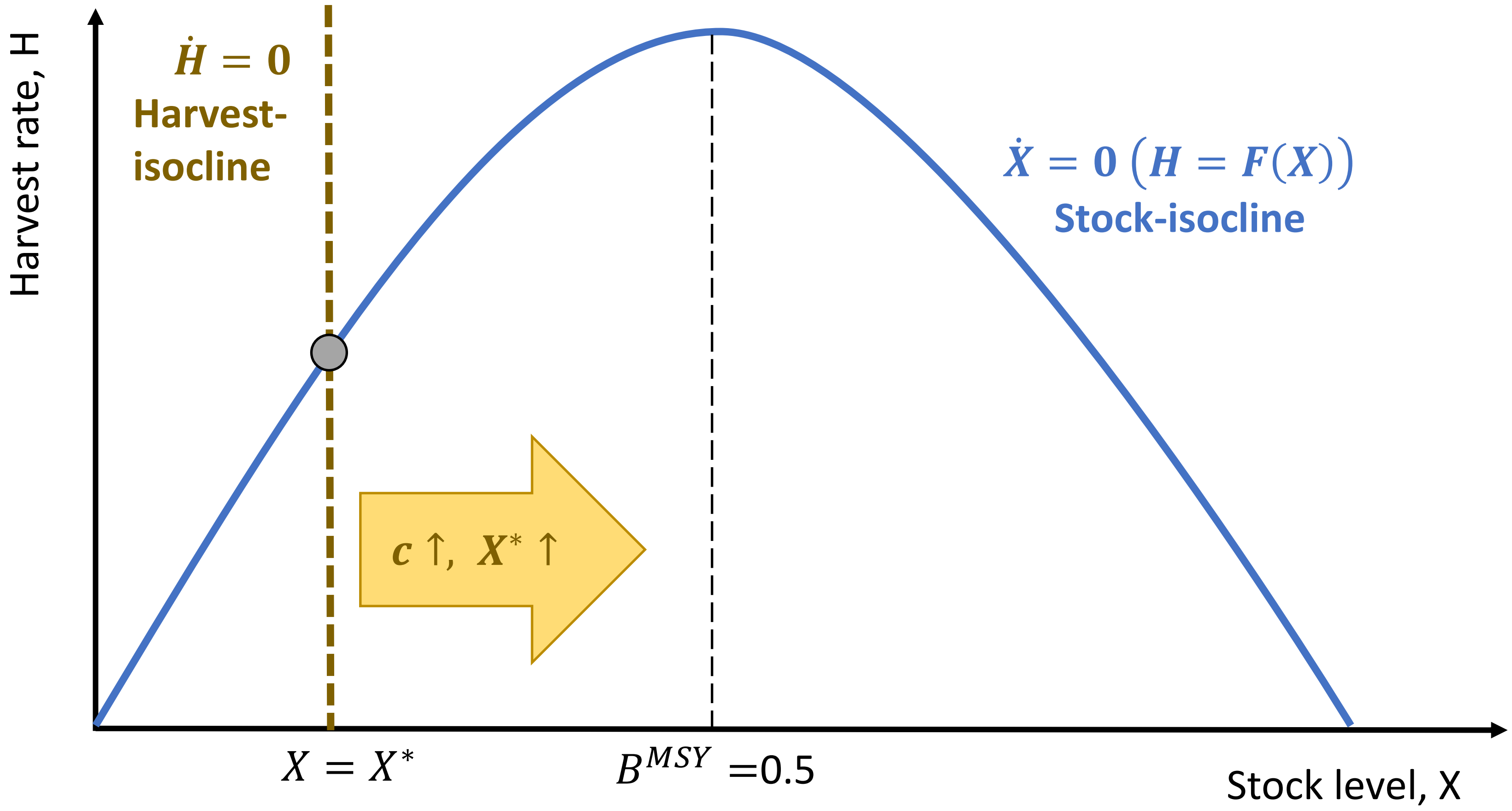
Surprise: the 10% rule fails when it is needed most!

With low cost, the 10% rule is too late to avoid extinction

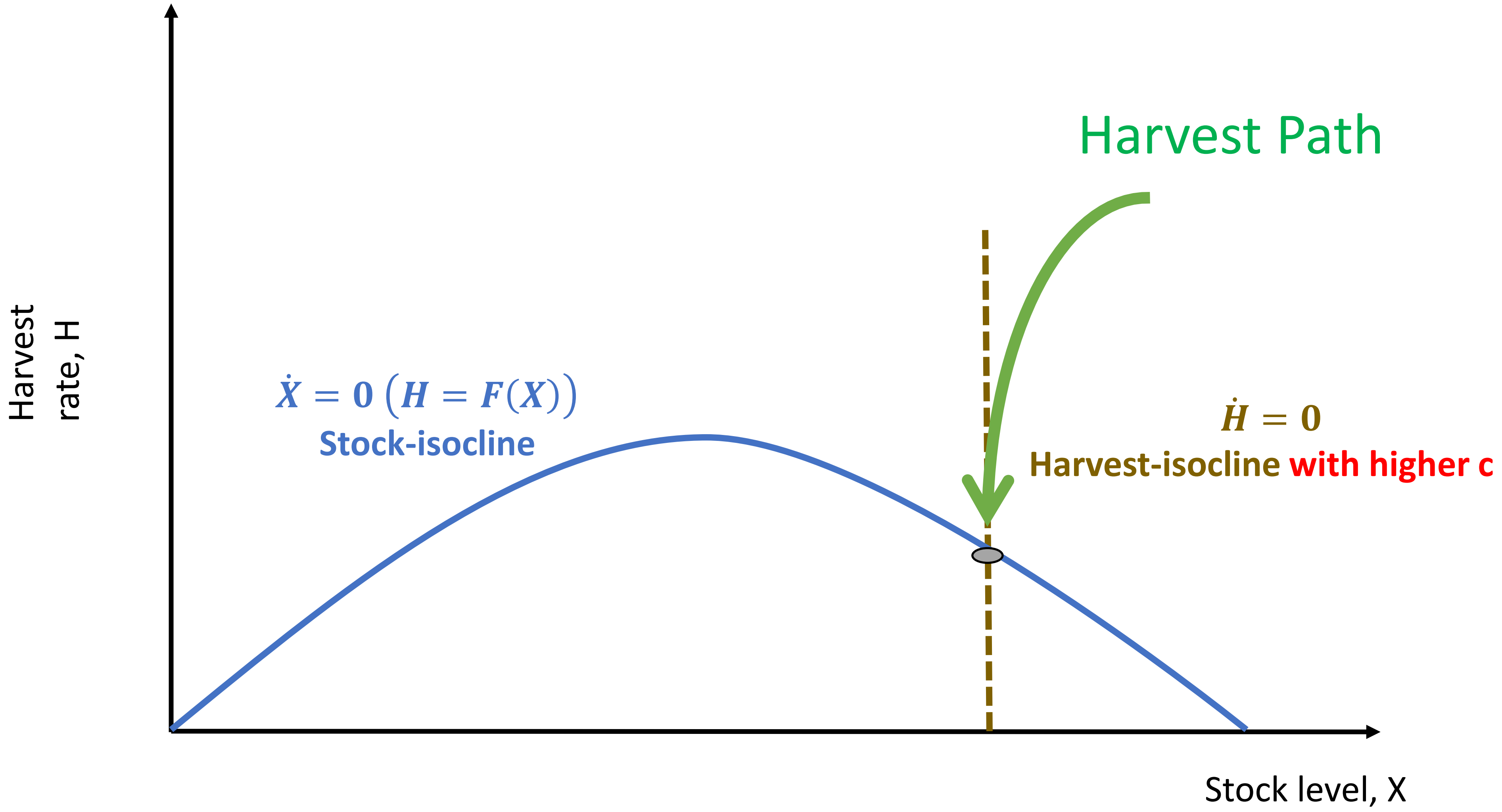


Supplementary slides for Num Exp.2

- Optimal steady-state $X^* = \frac{1}{4}\left[\left(\frac{c}{pq} + 1 - \frac{\delta}{r}\right) + \sqrt{\left(\frac{c}{pq} + 1 - \frac{\delta}{r}\right)^2 + \frac{8c\delta}{pqr}}\right]$, $H^* = F(X^*)$

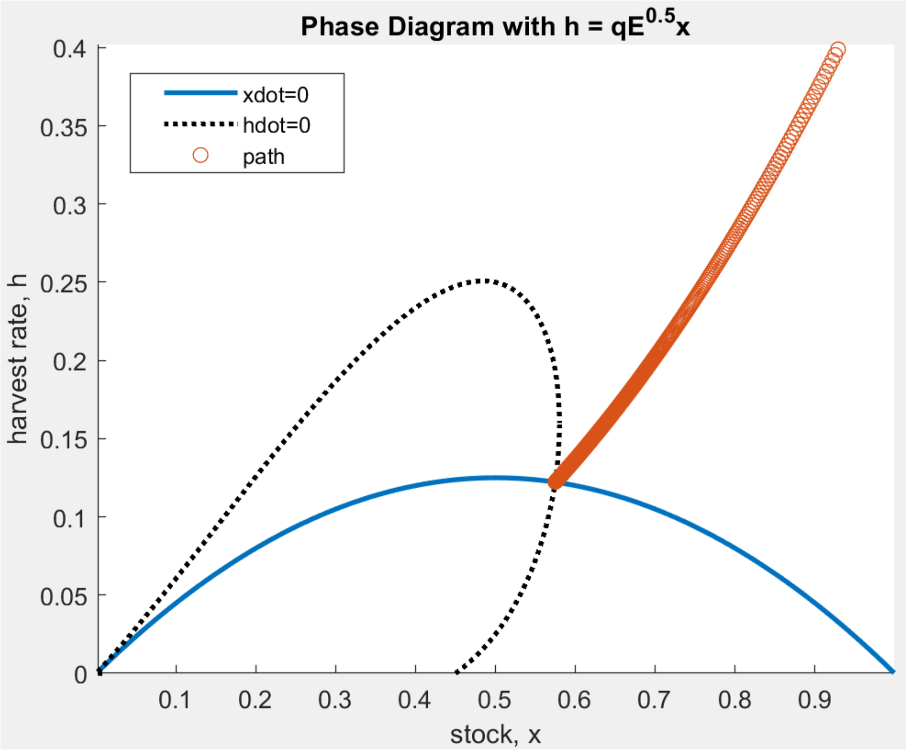


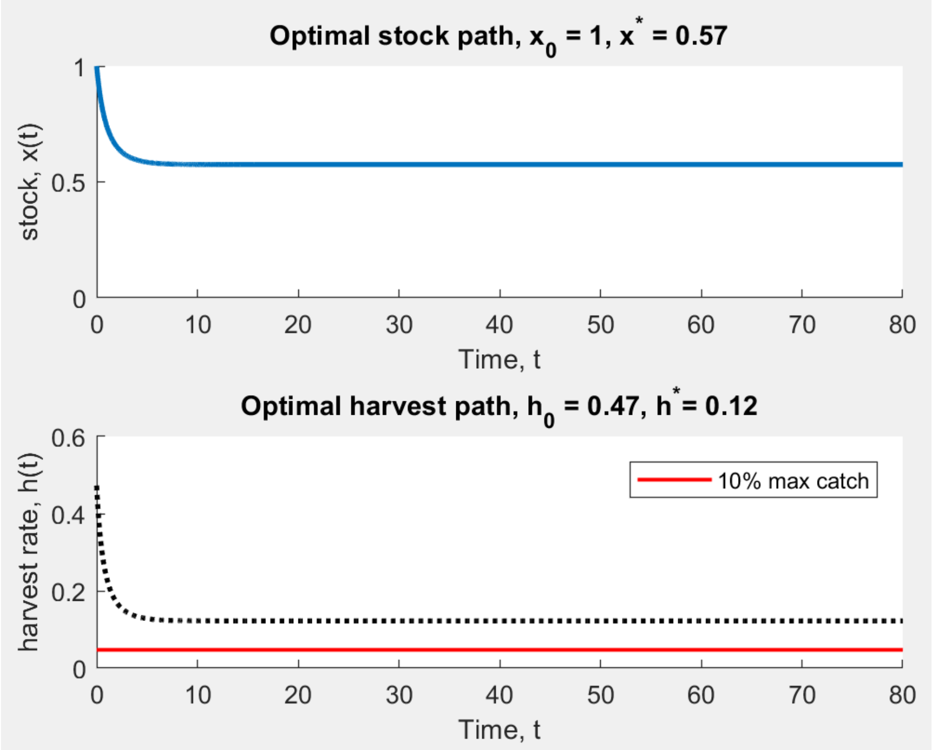
High harvest along the approach path



Optimal management with Cobb-Douglas

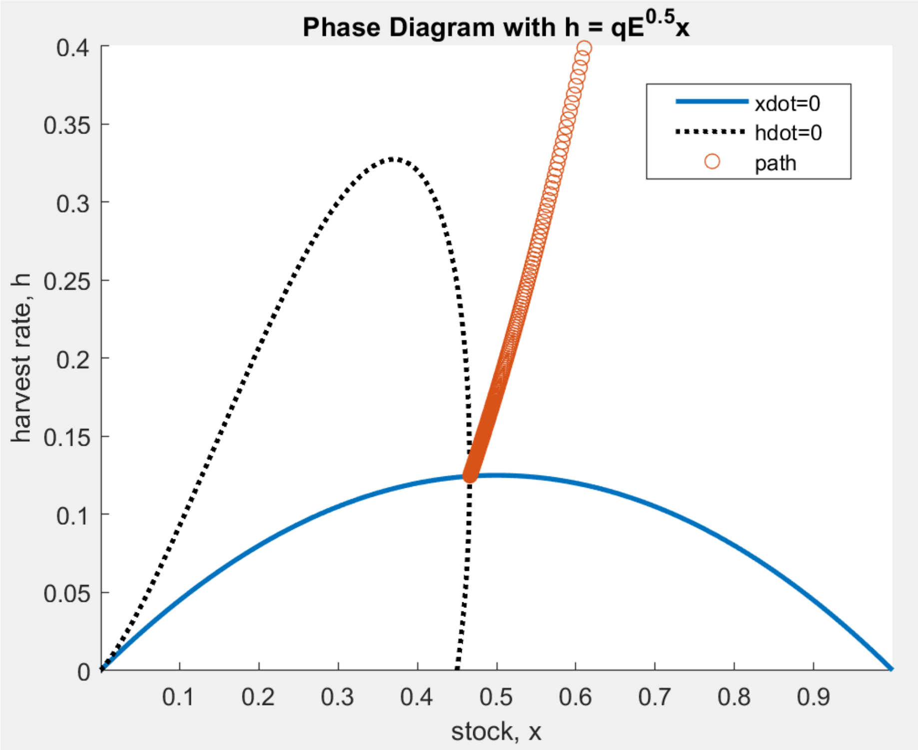
- High cost scenario with c = 0.5

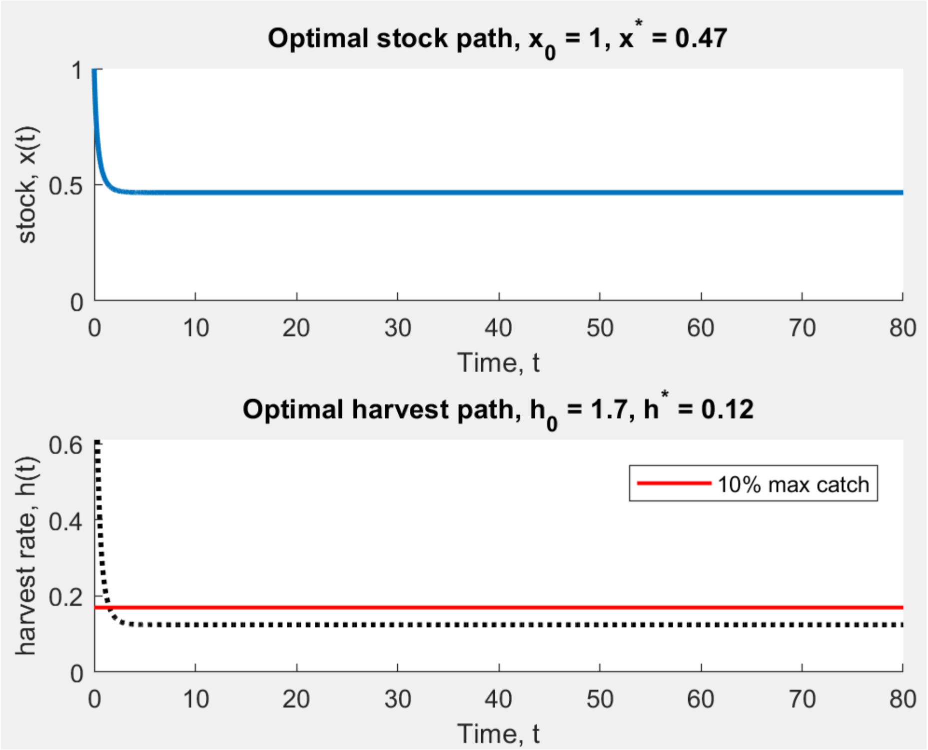




Optimal Management with Cobb-Douglas

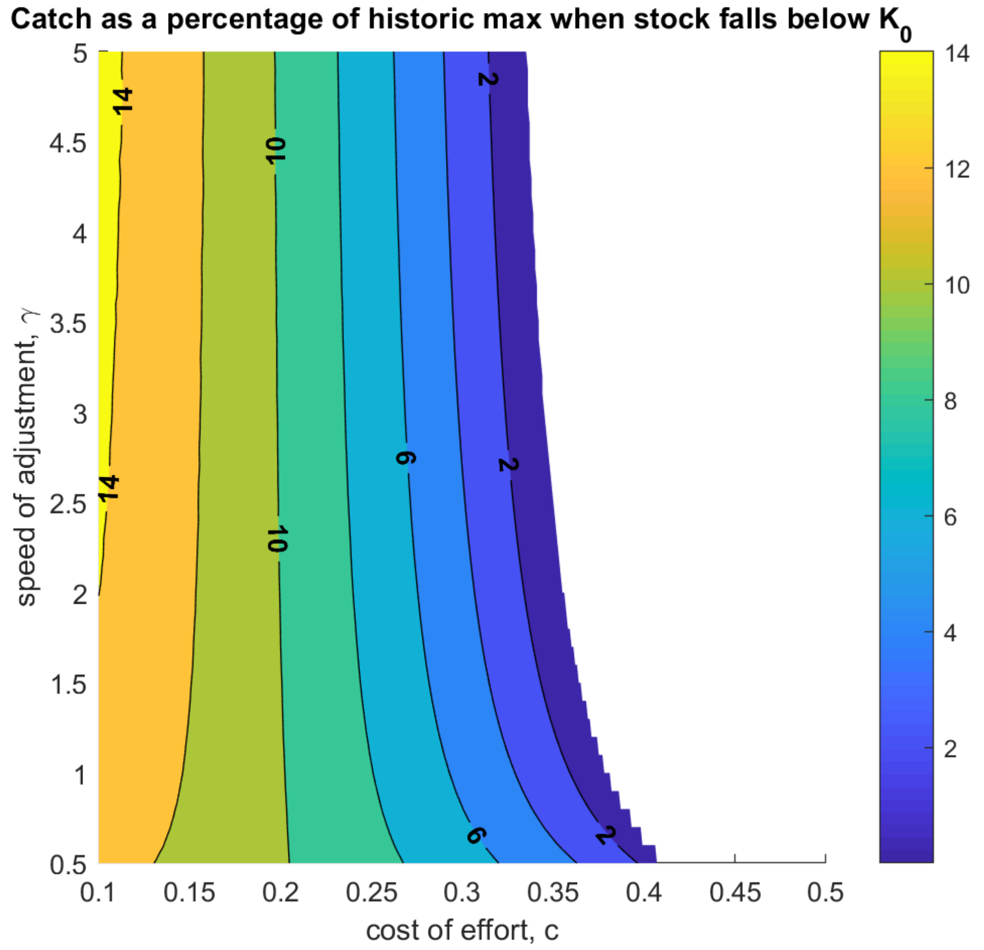
- Low cost scenario with c = 0.05





Different thresholds of critical depensation

Critical depensation threshold K0 = 0.05



Critical depensation threshold K0 = 0.2