Comprehensive Fishery Wealth: A Bioeconomic, Ecosystem-Based Approach to Measuring Fisheries Sustainability

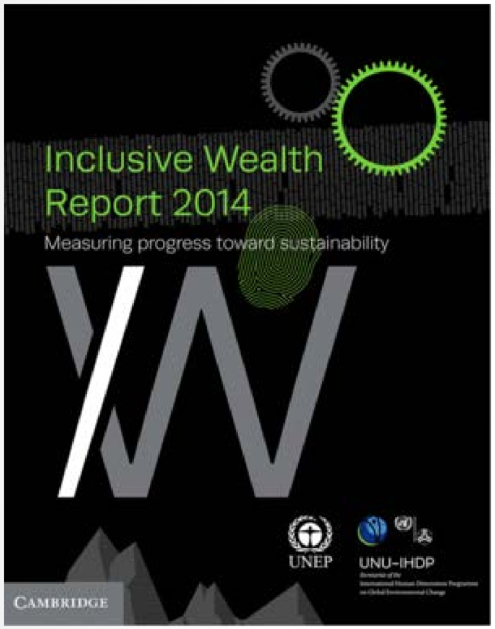
Joshua Abbott
Arizona State University
jkabbott.faculty.asu.edu

Eli Fenichel
Yale University

ASU SCHOOL of SUSTAINABILITY

Yale SCHOOL OF FORESTRY & ENVIRONMENTAL STUDIES

Comprehensive (inclusive) wealth & shadow prices



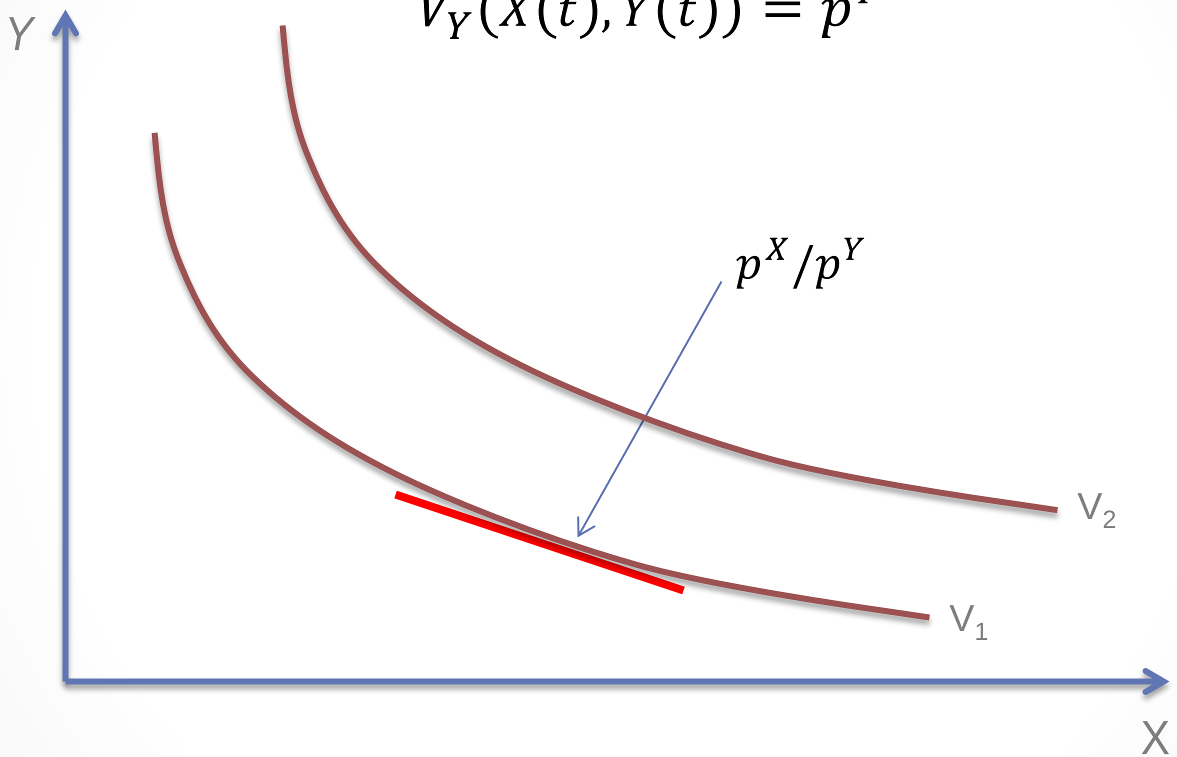
- Increasingly used in sustainable development literature
- Define *V(X,Y)* as the *value function*
  - o Predicted NPV of welfare given capital stocks
  - o Contingent on imperfect institutions (kakatopia)
- If sustainability is defined as non-declining *V(X,Y)*
- Then sustainable development is consistent with non-declining "genuine/inclusive" wealth over time
  - o Wealth is a linear index (price X quantity)
  - o Capital prices must be "forward looking"
    - V_X or V_Y

Partha Dasgupta. 2004. Human Well-Being and the Natural Environment. Oxford University Press.
Arrow, K.J., Dasgupta, P. and Maler, K.-G. 2003. Evaluating projects and assessing sustainable development in imperfect economies. Environmental and Resource Economics. 26, 647-685.

$$V\big(X(t),Y(t)\big) = \int_t^{\infty} e^{-\delta(\tau-t)} W\big(X(\tau),Y(\tau)\big)\, d\tau$$

$$V_X(X(t),Y(t)) = p^X$$

$$V_Y(X(t),Y(t)) = p^Y$$



$$Comprehensive\ Wealth = p^X X + p^Y Y$$

$$Comprehensive\ Investment = p^X dX + p^Y dY$$

Paul R. Ehrlich and Lawrence H. Goulder. 2007. “Is Current Consumption Excessive? A General Framework and Some Indications for the United States.” *Conservation Biology* 21(5): 1145-1154.

Comprehensive fishery wealth?

- Premise: assess management success by its ability to maintain (or grow) wealth in the system
- There are precursors to this (WAVES Partnership, Rashid's work)
- Relevant capital stocks:
  - Trophically related species
    - Harvest and non-harvested
  - Vessel capital
  - Human capital
- Advantages:
  - Tight connection of ecosystem dynamics, human behavioral feedbacks, and normative criteria of evaluation into a single meaningful index
  - Rigorous conceptual foundation in economic sustainability
- Disadvantage:
  - The shadow prices are rarely observable
    - Missing markets, market failures, etc.
  - There is much ad hocery in the literature

Toward better shadow prices

Fenichel, E.P. and J.K. Abbott. "Natural Capital: From Metaphor to Measurement." *Journal of the Association of Environmental and Resource Economists* 1(1): 1-27.

- Available on JSTOR (open access)

- We develop a rigorous asset pricing equation for natural capital
  - Rooted in capital theory (Jorgenson 1963)
  - Explicitly incorporates feedbacks between people and natural capital stocks (and vice versa)
- Apply in a single stock case (GOM reef fish)
  - Another application to groundwater (in preparation)
- We extend to multiple interacting capital stocks here
  - Trophically connected species

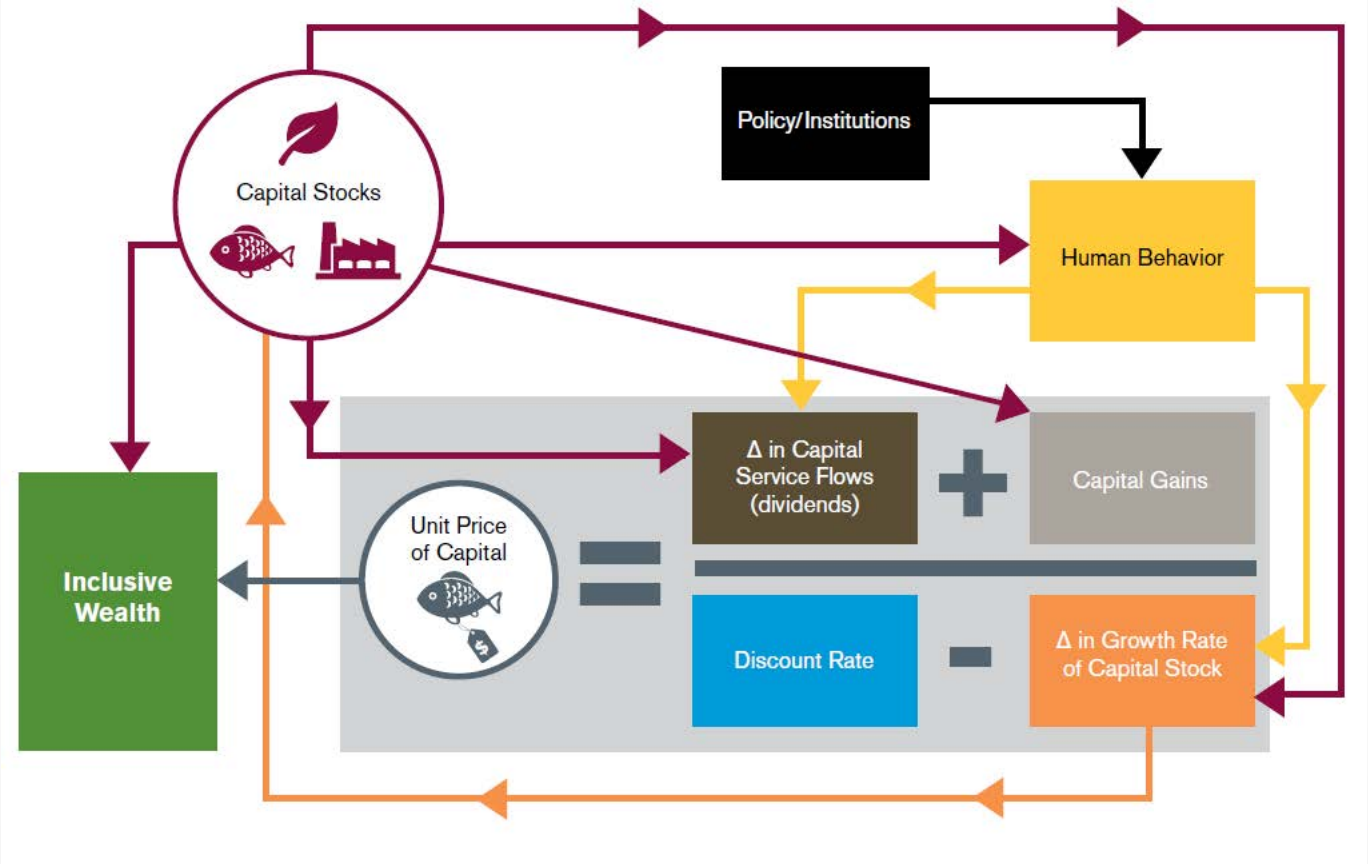
Brief derivation (2 species)

- The building blocks
  - Instantaneous net benefits: $W(X,Y,E^X,E^Y) = \pi^X(X,E^X) + \pi^Y(Y,E^Y)$
  - Capital (stock) dynamics: $\dot{X} = f^X(X,Y) - h^X(X,E^X)$, $\dot{Y} = f^Y(X,Y) - h^Y(Y,E^Y)$
  - Human (fisher) behavior: $E^X(X,Y)$ and $E^Y(X,Y)$
    - The "economic program" or "policy function"
    - NOT optimized!
    - A function of capital stocks only (not time)
- Start with the Hamilton-Jacobi-Bellman condition
  - Substitute out $E^X(X,Y)$ and $E^Y(X,Y)$
  - $\delta V(X,Y) = H^*(X,Y) = W(X,Y) + p^X\dot{X} + p^Y\dot{Y}$
  - Holds even in the absence of dynamic optimization!
- Differentiate HJB condition to obtain

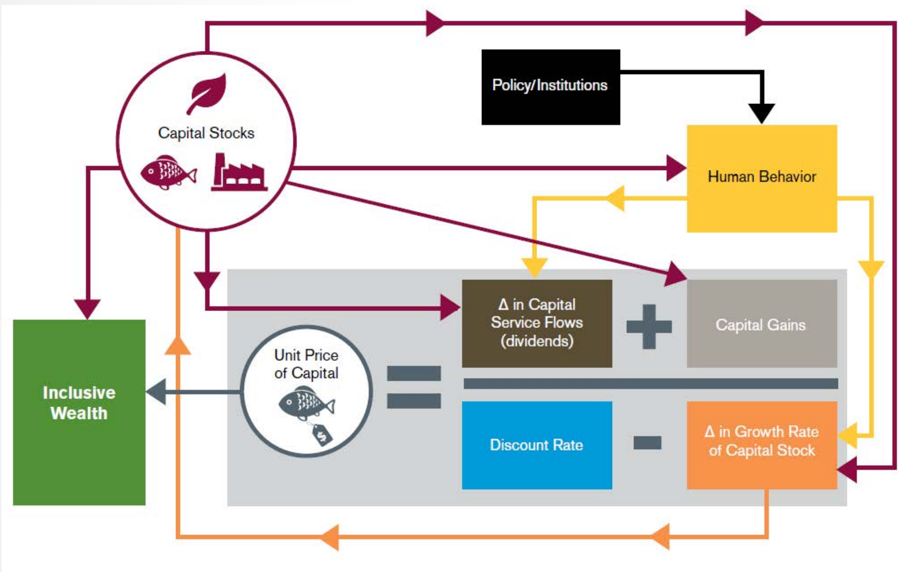
$$p^X(X,Y) = \frac{W_X + \dot{p}^X + p^Y\dot{Y}_X}{\delta - \dot{X}_X}$$

$$p^Y(X,Y) = \frac{W_Y + \dot{p}^Y + p^X\dot{X}_Y}{\delta - \dot{Y}_Y}$$

$$p^X(X,Y) = \frac{W_X + \dot{p}^X + p^Y \dot{Y}_X}{\delta - \dot{X}_X}$$



Dealing with capital gains



- Everything but capital gains is estimable with enough ecological and economic data
- But capital gains can be very important away from the steady state.
- Capital gains are completely defined given the assumed economic program and capital dynamics!
- We use polynomial collocation approaches to close the gap
  1. Approximate $p^i(X,Y)\ i = X,Y$

  OR

  2. Approximate $V(X,Y)$ using HJB condition

Proof of concept: predator/prey

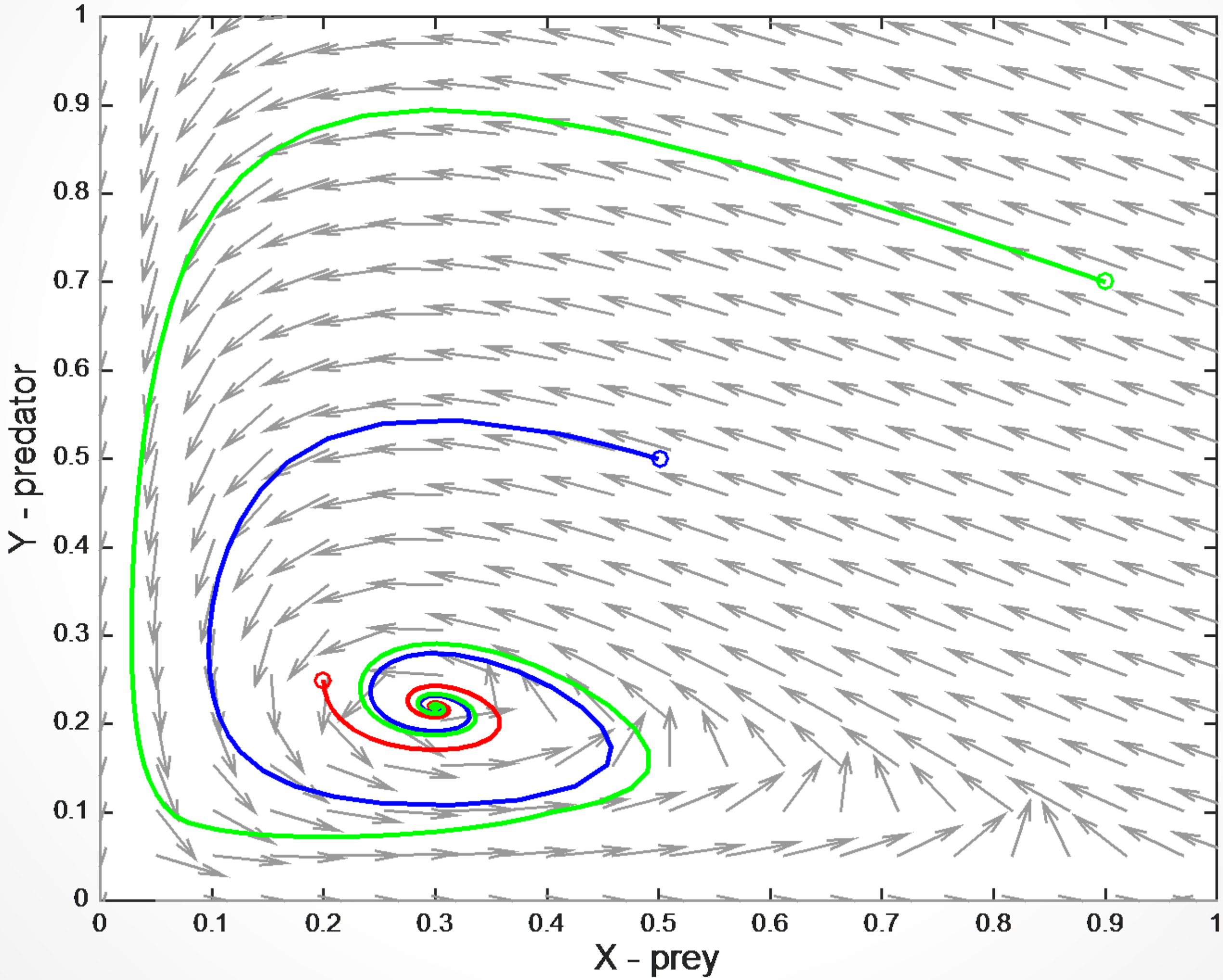
- Not calibrated to any real-world data (yet)
- Ecological model
  - Prey: logistic growth with Type I predation
  - Predator: Lotka-Volterra
- Economic model
  - Benefits derive solely through harvest of predator and prey (no non-use value)
  - Fixed market prices for predator and prey
  - Stock-dependent harvest costs (Schaefer)
- Management
  - Linear, univariate harvest control rules
  - No harvest if the fishery isn't profitable
- Two main scenarios
  1. Marketable predator & non-marketable prey
  2. Nuisance predator & marketable prey

Collocation procedure

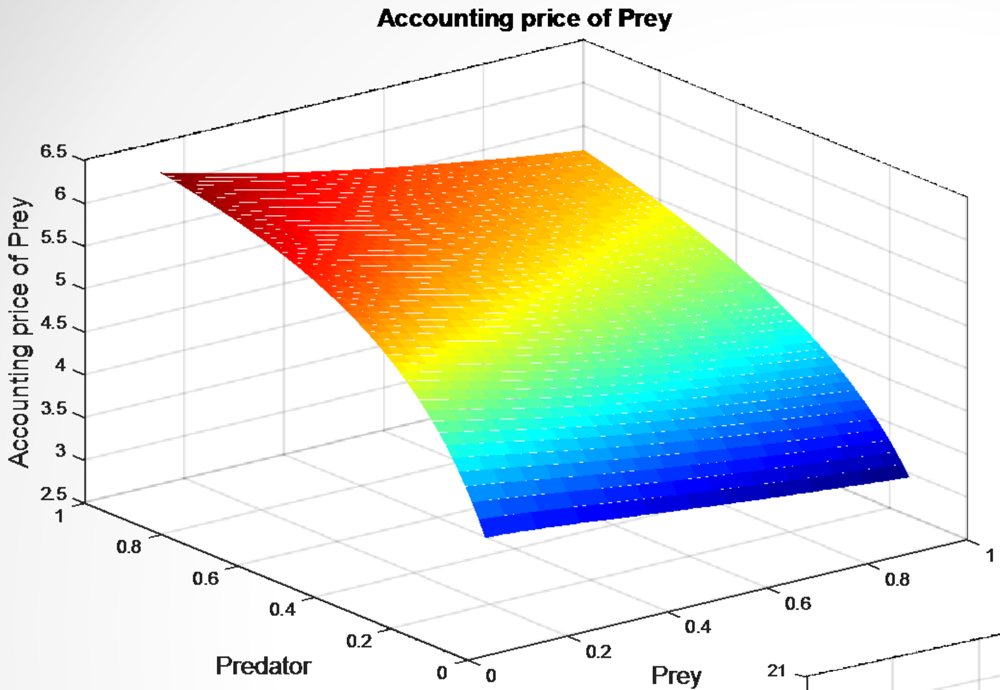
- Approximate value function *V(X,Y)* with *Φ(X,Y)*
- We collocate by exploiting the HJB condition
  - $\Phi(X,Y)=W(X,Y)+\Phi_X * dX/dt+\Phi_Y * dY/dt$
- Define *Φ(X,Y)* as the tensor product of two univariate Chebychev polynomial basis matrices
  - Chebychev polynomials are orthogonal
  - 20^{th} order polynomial in 1 dimension = 400 degree polynomial in 2 dimensions
- The calibration task is to define the coefficients of the polynomial
  - Evaluation points = the tensor product of the underlying univariate Chebychev nodes
  - Just identified system (evaluation points = # coefficients) -> approximation is exact at evaluation points
- We find the coefficients using numerical methods for fixed-point problems (Broyden's method) using MATLAB

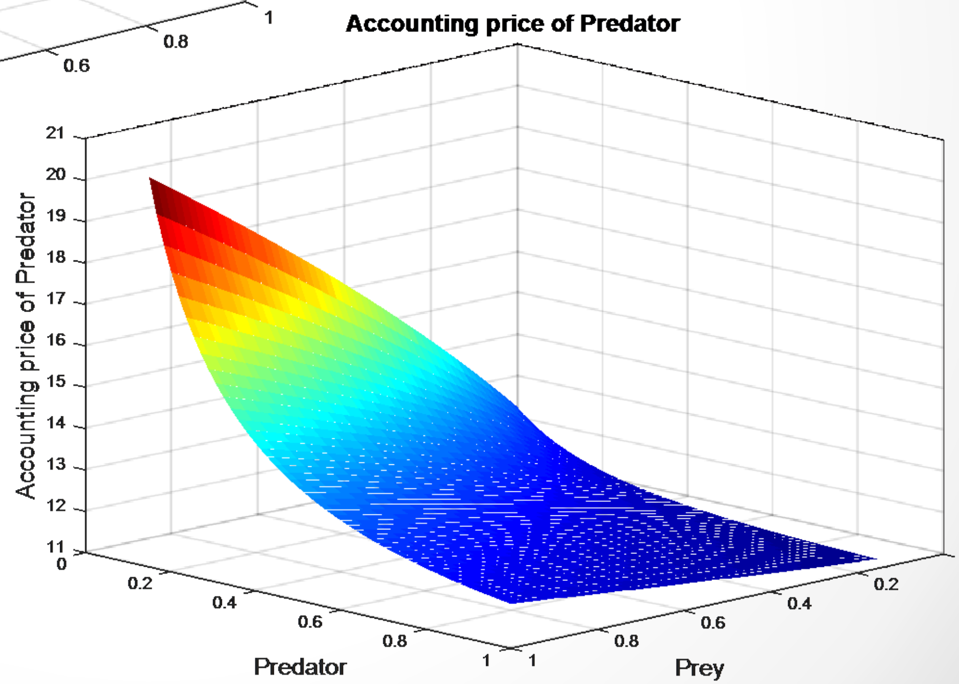
Case 1:

Valuable predator, “worthless” prey

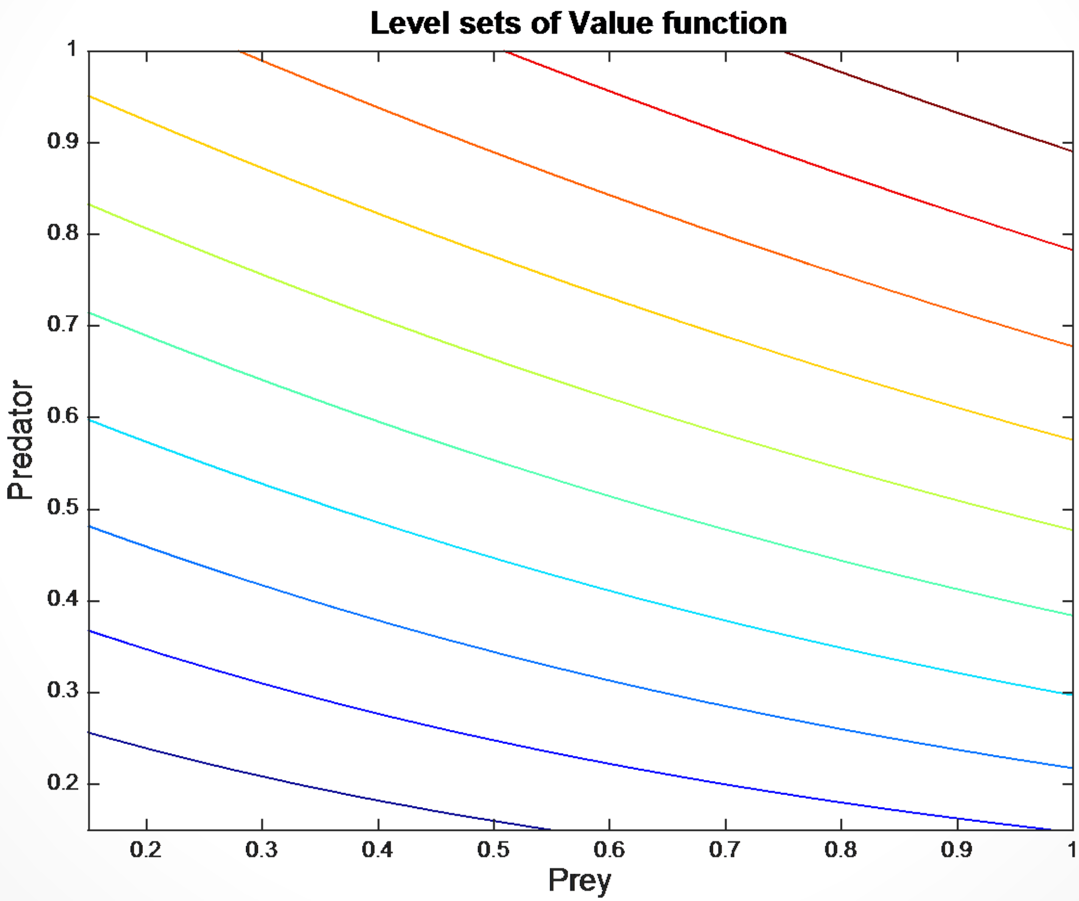


Shadow values

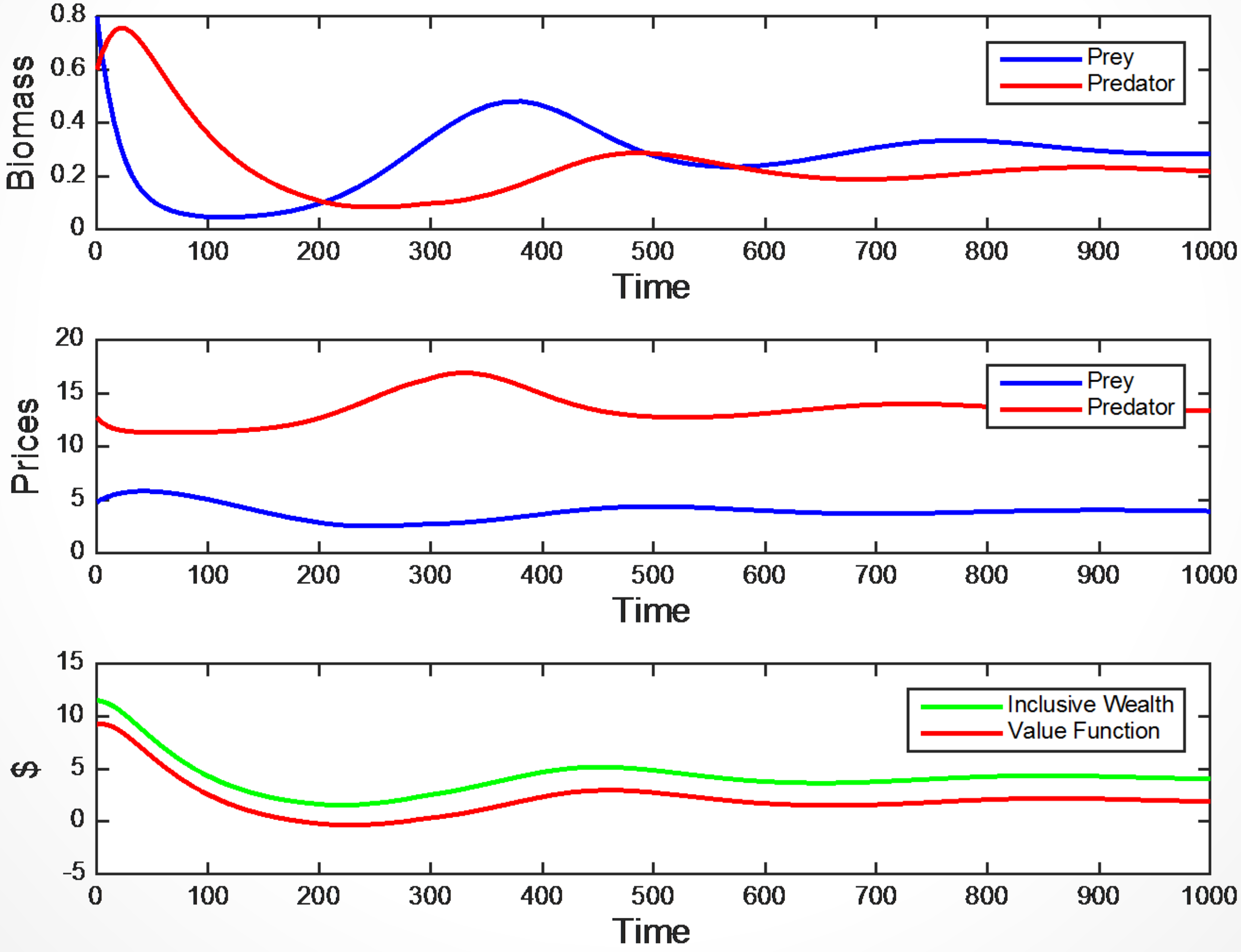




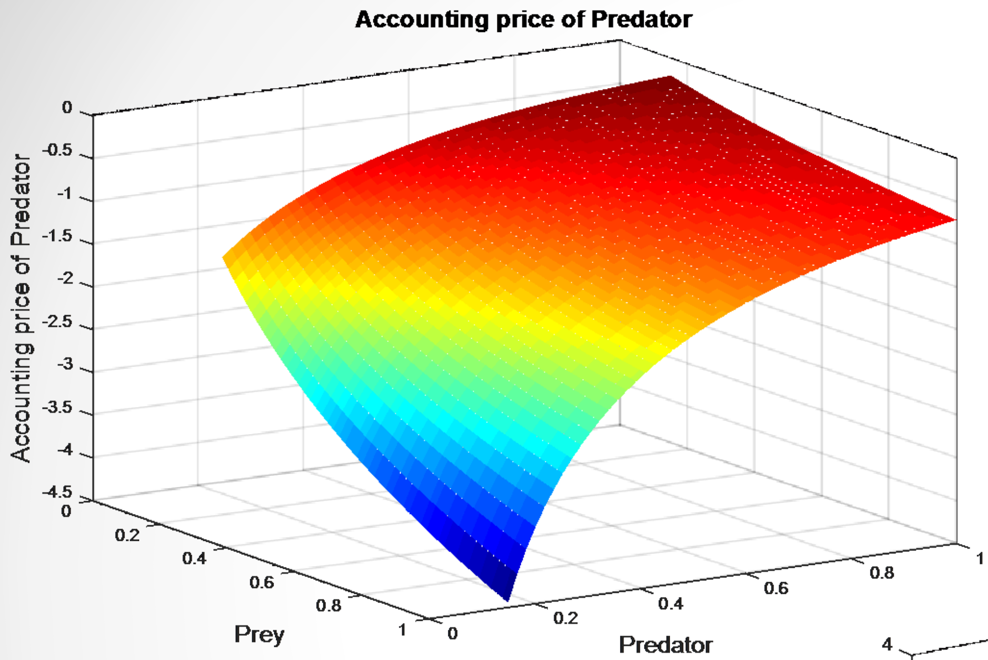
Assessing substitutability

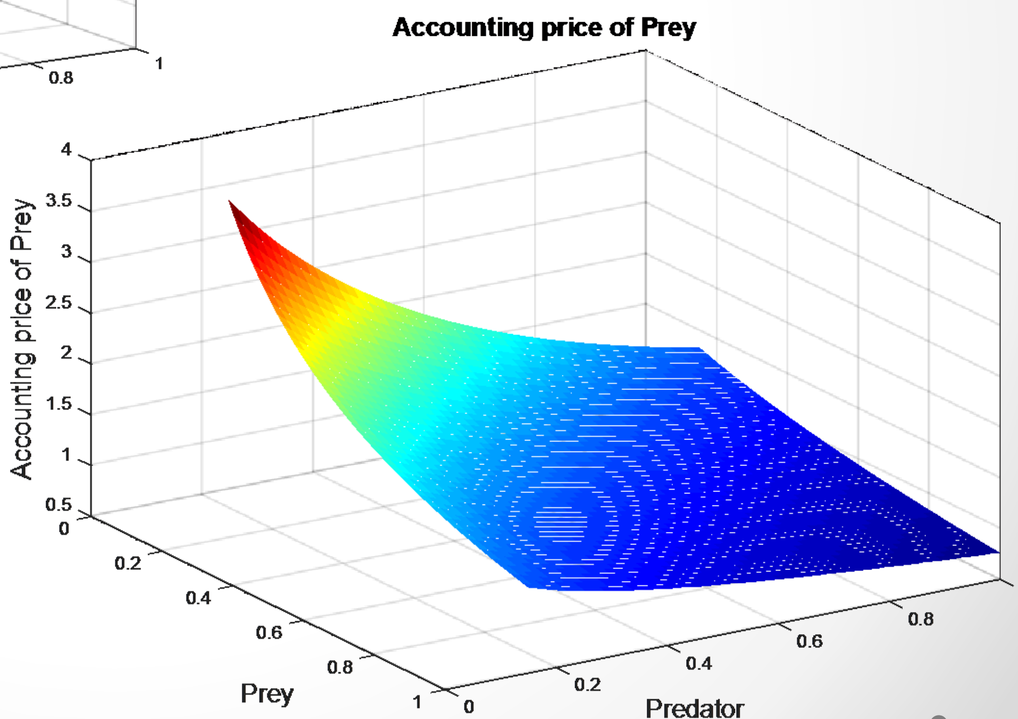


Simulation: from highly "enriched" state



Case 2: "nuisance" predator, valuable prey





Moving forward

- Applications to two real-world test cases
    - Working with EcoPath/EcoSim inputs
    - Chesapeake Bay with Basia Hutniczak and Doug Lipton
    - Bering Sea groundfish (arrowtooth flounder, cod, pollock) with Stephen Kasperski and Alan Haynie
- Extensions
    - Incorporating vessel capital
    - Stochastic shocks in population dynamics and/or human behavior feedbacks
    - Non-autonomous capital dynamics
    - Exploring potential gains in computational efficiency for large state spaces

Thank you!

% error of value function approximation