Valuing Natural Capital in the Context of Ecosystem Based Management

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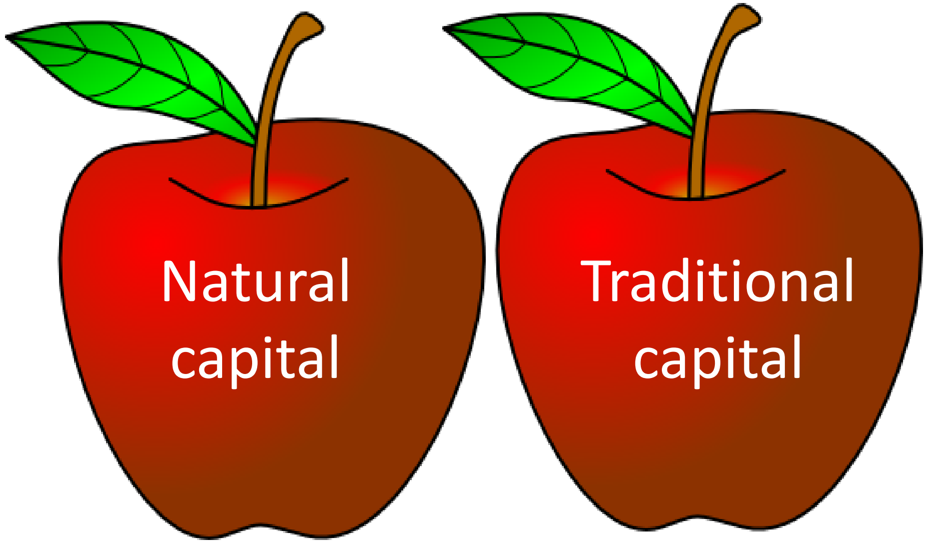
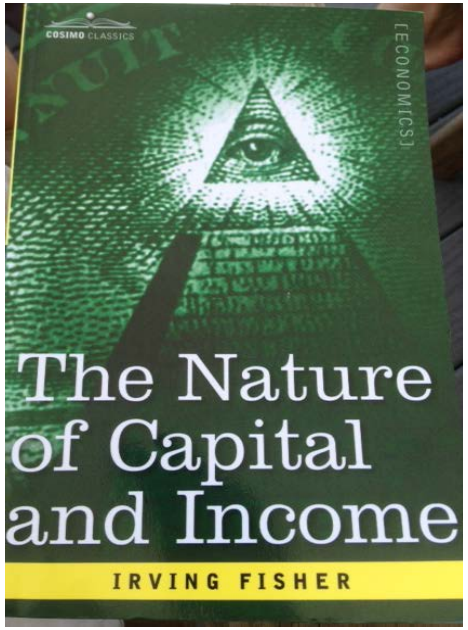
Support from the Knobloch Family Foundation & National Science Foundation

Collaborators: Josh Abbott, Seong Do Yun, Barbara Hutniczak, Ethan Addicott, Brian Reed, Jude Bayham, Lisa Pfeiffer, Erin Haacker, Whintey Boone, Simon Levin, Bonnie McCay, Kevin St. Martin, Malin Pinsky, Os Schmitz, Sam Maher, Vic Adamowicz, Yukiko Hashida



Nature as capital

"**Wealth**, then, includes all those parts of the material universe which have been appropriated to the uses of mankind. … The appropriation need not be complete; it is often only partial and for a particular purpose, as in the case of the **Newfoundland Banks**, which are appropriated only in the sense that the fishermen of certain nations have the right to take fish in their vicinity…"
I. Fisher, 1906. The Nature of Capital and Income. p4.



"**Consider income that does flow through the cash draw**"

"The nation behaves well if it treats the **natural resources as assets** which it must turn over to the next generation **increased, and not impaired, in value**; and behaves badly if it leaves the land poorer to those who come after it. That is all I mean by the phrase, Conservation of nature resources. Use them; but use them so that as far as possible our **children will be richer, and not poorer, because we have lived**."
THEODORE ROOSEVELT, speech to the Colorado Live Stock Association, Denver, Colorado, Aug. 29, 1910

A price for a capital stock

Intertemporal welfare function, $V(\boldsymbol{s}(t), \boldsymbol{x}(\boldsymbol{s}(t);\Omega);\Omega) =$
The net present value of real income (a la Fisher 1906)

- Depends on all stocks, $\boldsymbol{s}$, not just stock s^i
- Depends on the institutions, Ω, including who and what counts
- Depends on the **actual measured** economic program $\boldsymbol{x}(\boldsymbol{s};\Omega)$, which may include multiple actions
- No assumption that the economic program is optimal
- $\frac{dV}{dt} \geq 0$ is a well accepted index of sustainability

A (shadow or accounting) price for stock i is defined as $$p^i(\boldsymbol{s}(t);\Omega) \equiv \frac{\partial V(\boldsymbol{s}(t), \boldsymbol{x}(\boldsymbol{s}(t);\Omega);\Omega)}{\partial s^i(t)}$$

- The price comes from **exchange** through time
- Is the opportunity cost of leaving a little less of the stock.
- The natural capital asset price is a function of the quantities of ***all*** stocks

Wealth accounting & the change in value of natural capital in 1D

ΔV = yellow shape

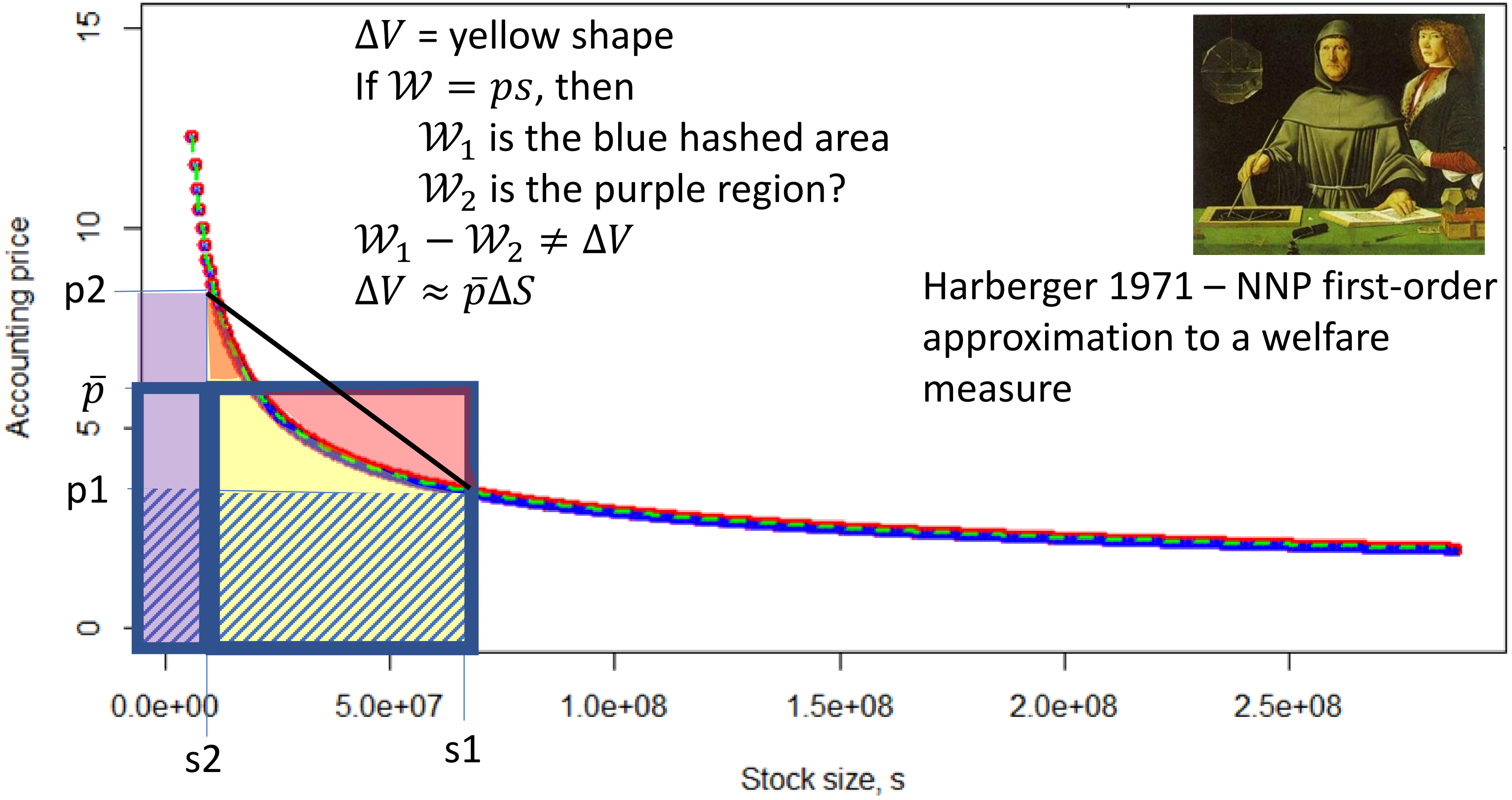
If $\mathcal{W} = ps$, then

$\mathcal{W}_1$ is the blue hashed area

$\mathcal{W}_2$ is the purple region?

$\mathcal{W}_1 - \mathcal{W}_2 \neq \Delta V$

$\Delta V \approx \bar{p}\Delta S$



Harberger 1971 – NNP first-order approximation to a welfare measure

Adapted from Fenichel et al. 2016 NCC & 2018 HEE

Wealth accounting & the change in value of natural capital in 1D

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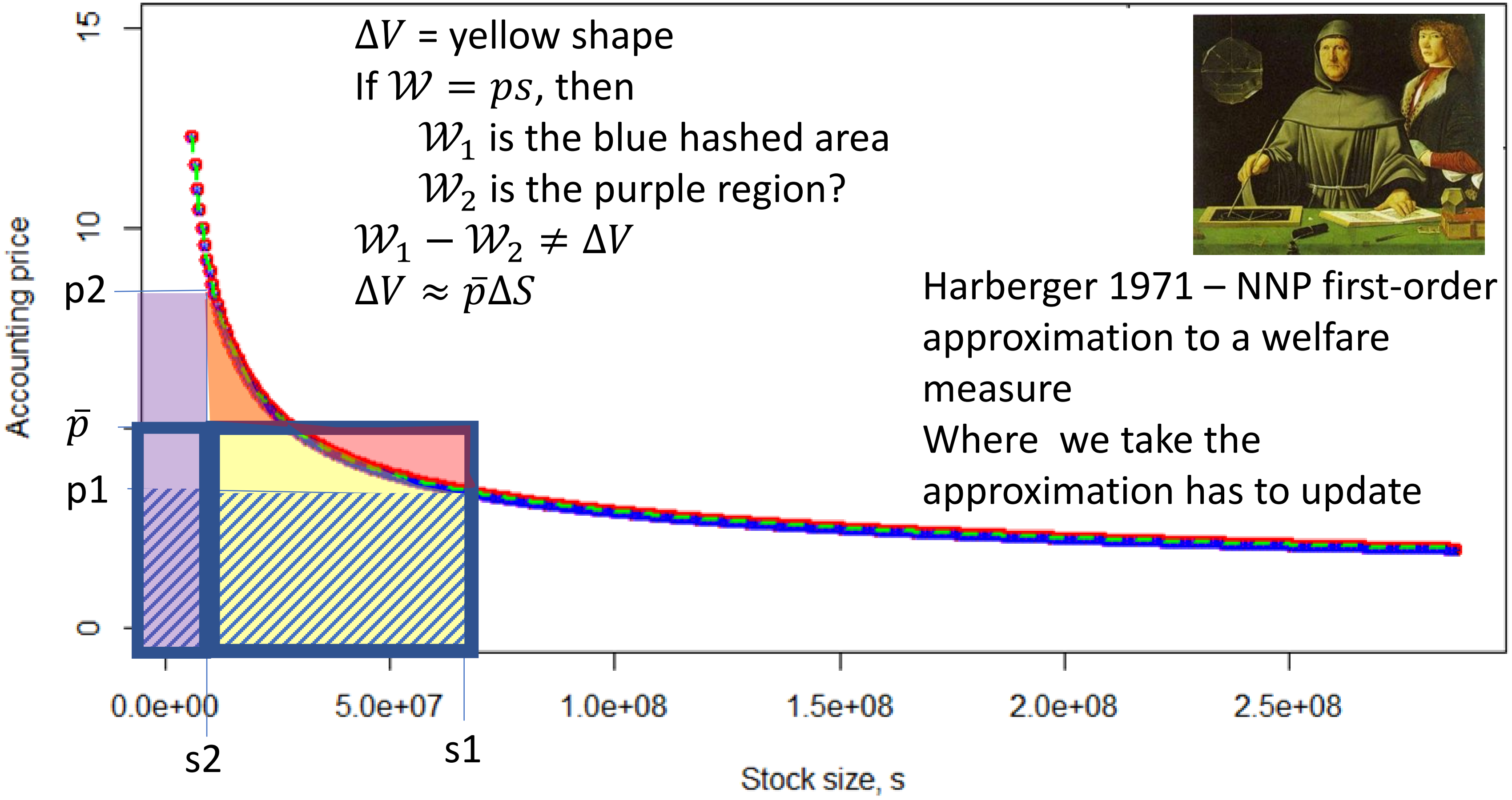
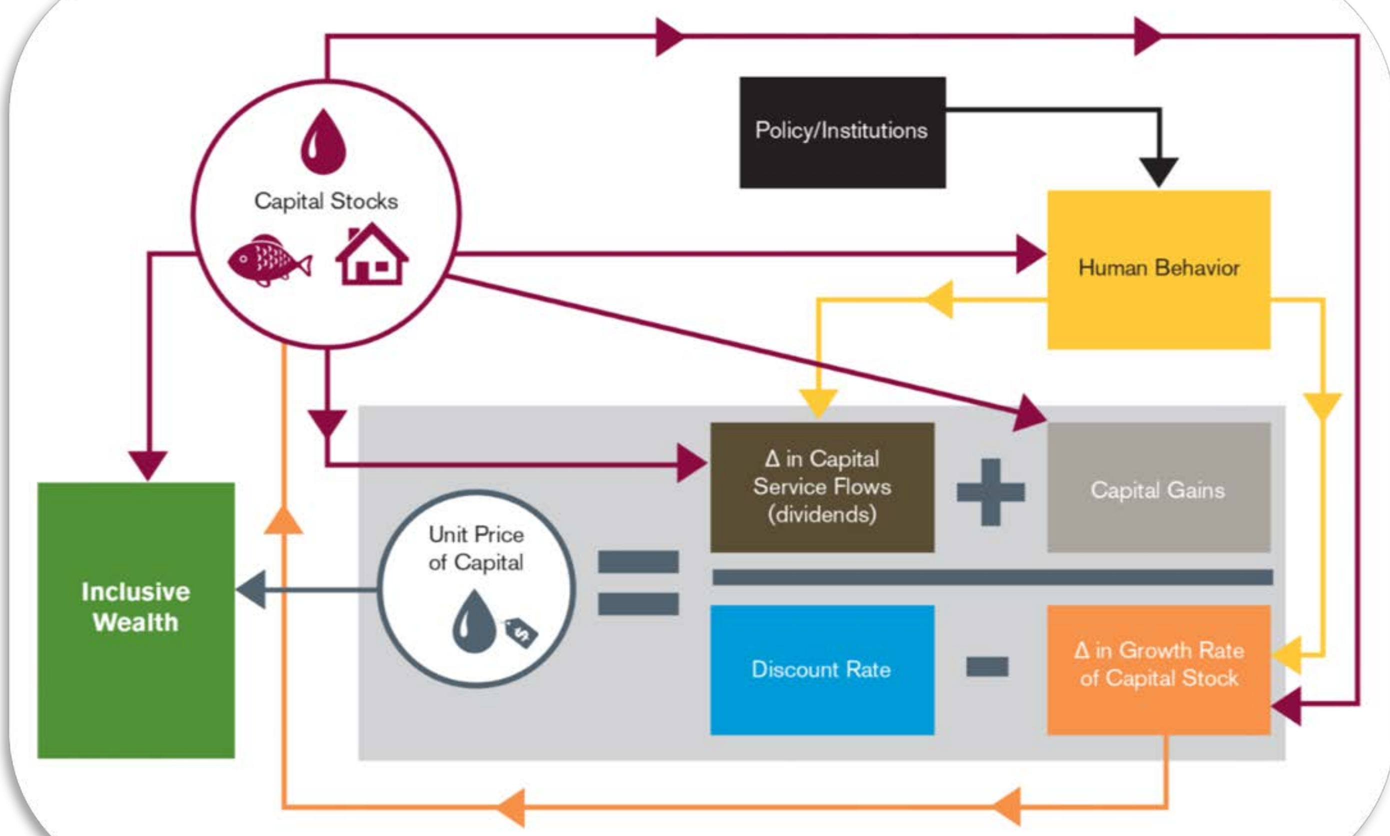


Harberger 1971 – NNP first-order approximation to a welfare measure

Where we take the approximation has to update

Natural capital can be valued symmetrically with traditional capital

Fenichel & Abbott 2014 JAERE:: Jorgenson 1963 AER



From Fenichel et al. 2016, PNAS

Most important difference from Jorgenson's work – what is observable

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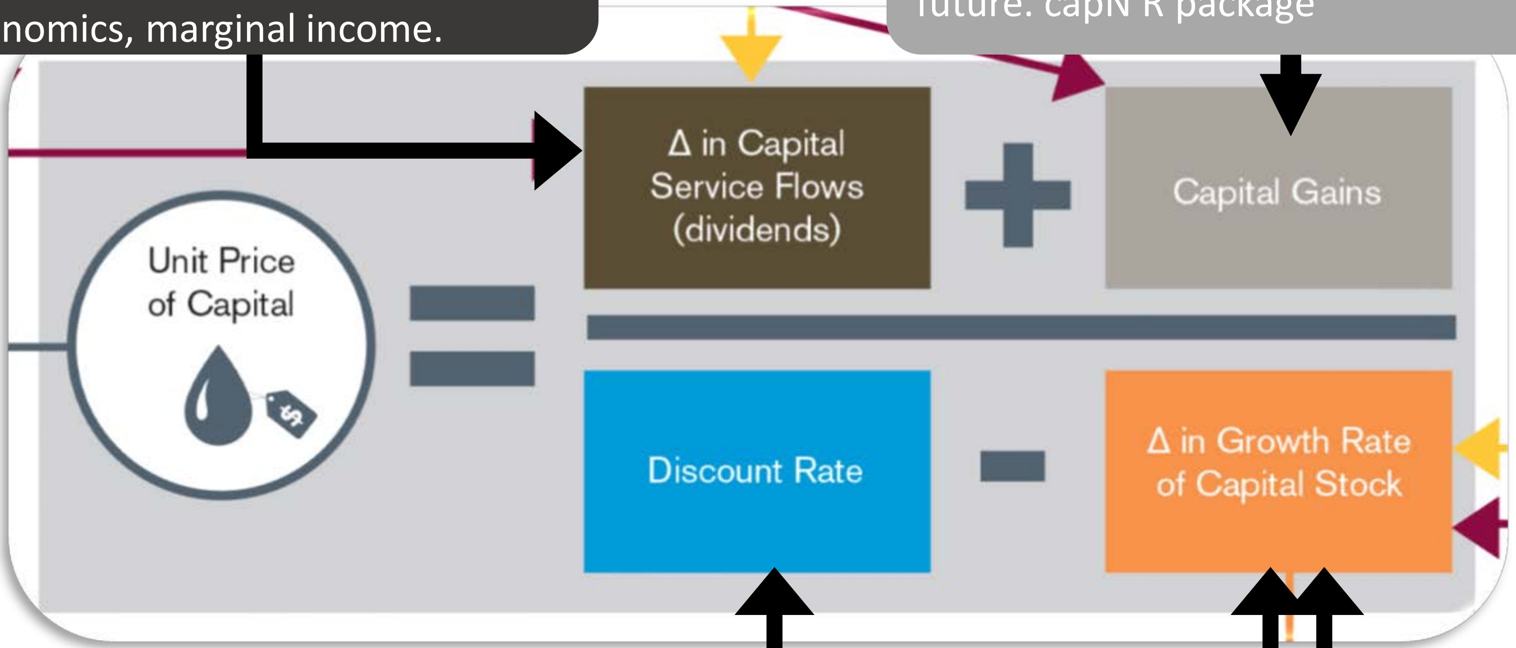
Value of extra ecosystem service flows from one more unit of stock. Market and non-market valuation economics, marginal income.

Not directly observable, use approximation. Captures forecast of the future. capN R package



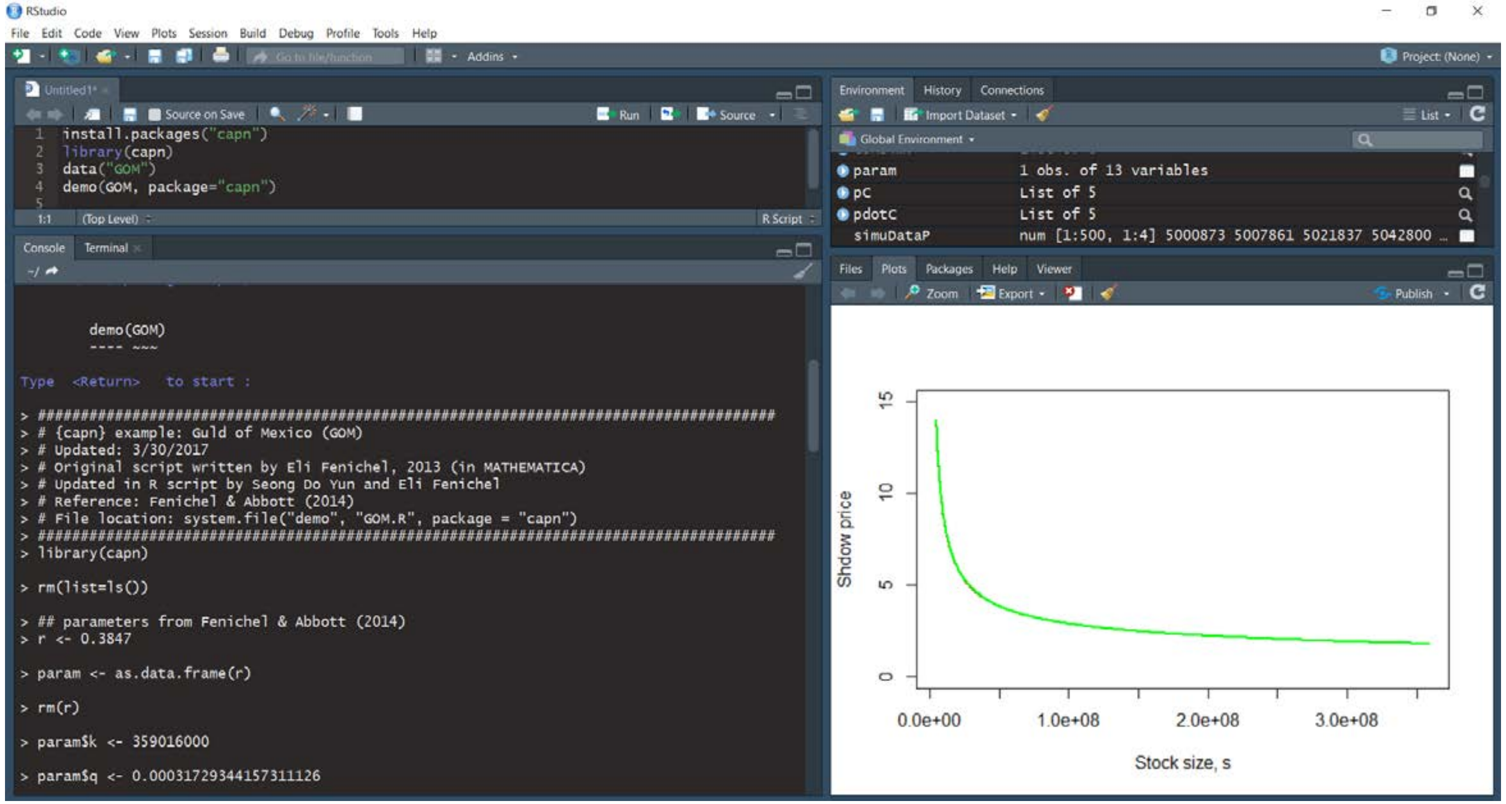
A lot has gone into this and more can, but probably want to use what a public accounting authority uses.

Productivity of the resource. Ecology and physical science.

Interface of social science, economics, and natural science. Descriptive analysis of human behavior conditioned by institutions.

Approximating asset prices for natural capital – R {capn}

- Current version of {capn} 1.0.0 has three different mathematical approximation approaches to resolve the missing capital gains terms.
- Handles multiple interacting stocks.
- Version 2.0 coming soon for stochastic shocks and uncertainty.
- Examples in package with single and multiple stocks and at https://github.com/efenichel/capn_stuff



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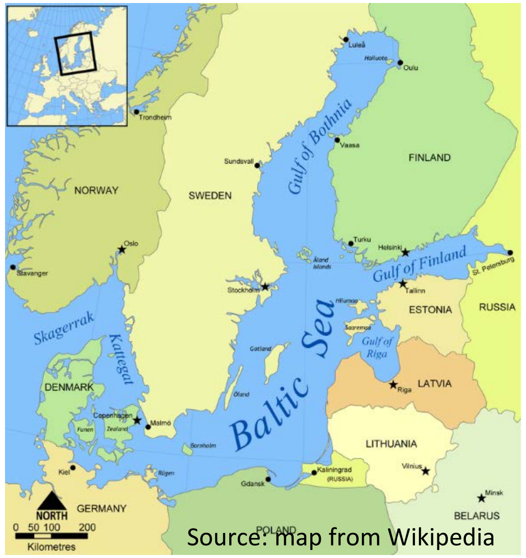
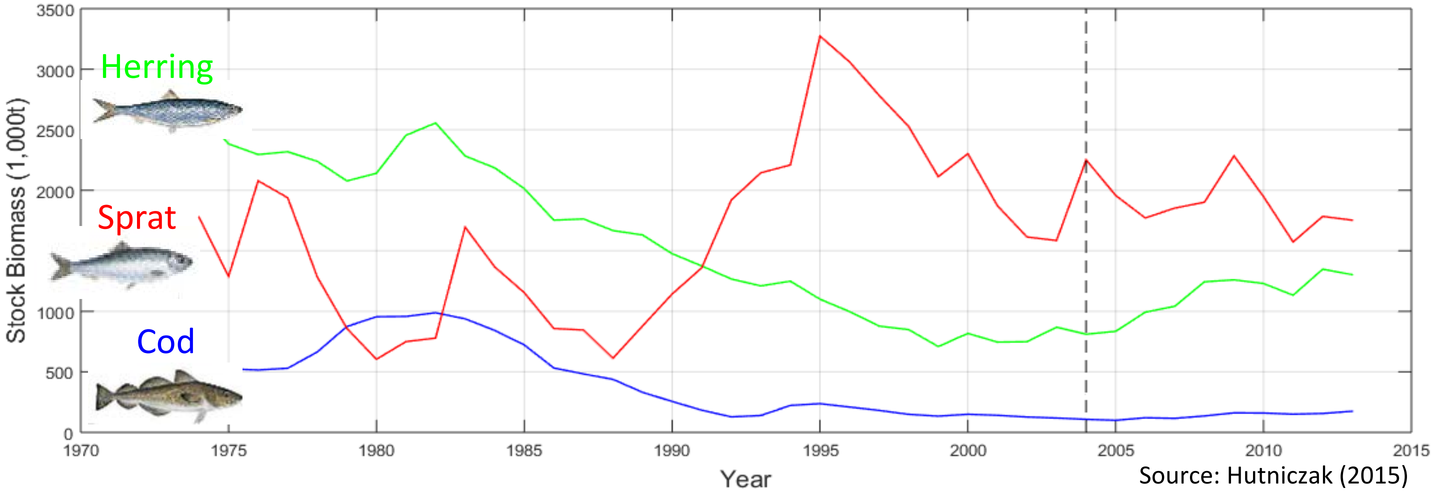
Interacting natural capital in the Baltic Sea & Connecting to EBM
A framework for human-environmental systems research that hits policy



Source: map from Wikipedia

- Cod, herring, and sprat make up 88% of the revenue (STECF, 2013)
- EU members are under the fixed share (TAC – total allowable catch) regulation.
- Depletion of cod in 1980s/1990s
- Human impacts on multispecies ecosystem
- Poland has been obligated to comply the TAC since 2004.
- Consider 2 Institutional arrangements for non-tradable individual vessel (Poland)
  - Traditionally single species stock management
  - Starting 2017 move towards ecosystem based management



Source: Hutniczak (2015)

Yun, Seong Do, Barbara Hutniczak, Joshua K. Abbott, and Eli P. Fenichel. 2017. "Ecosystem based management and the wealth of ecosystems." *Proceedings of the National Academy of Science. 114 (25):6539-6544.*

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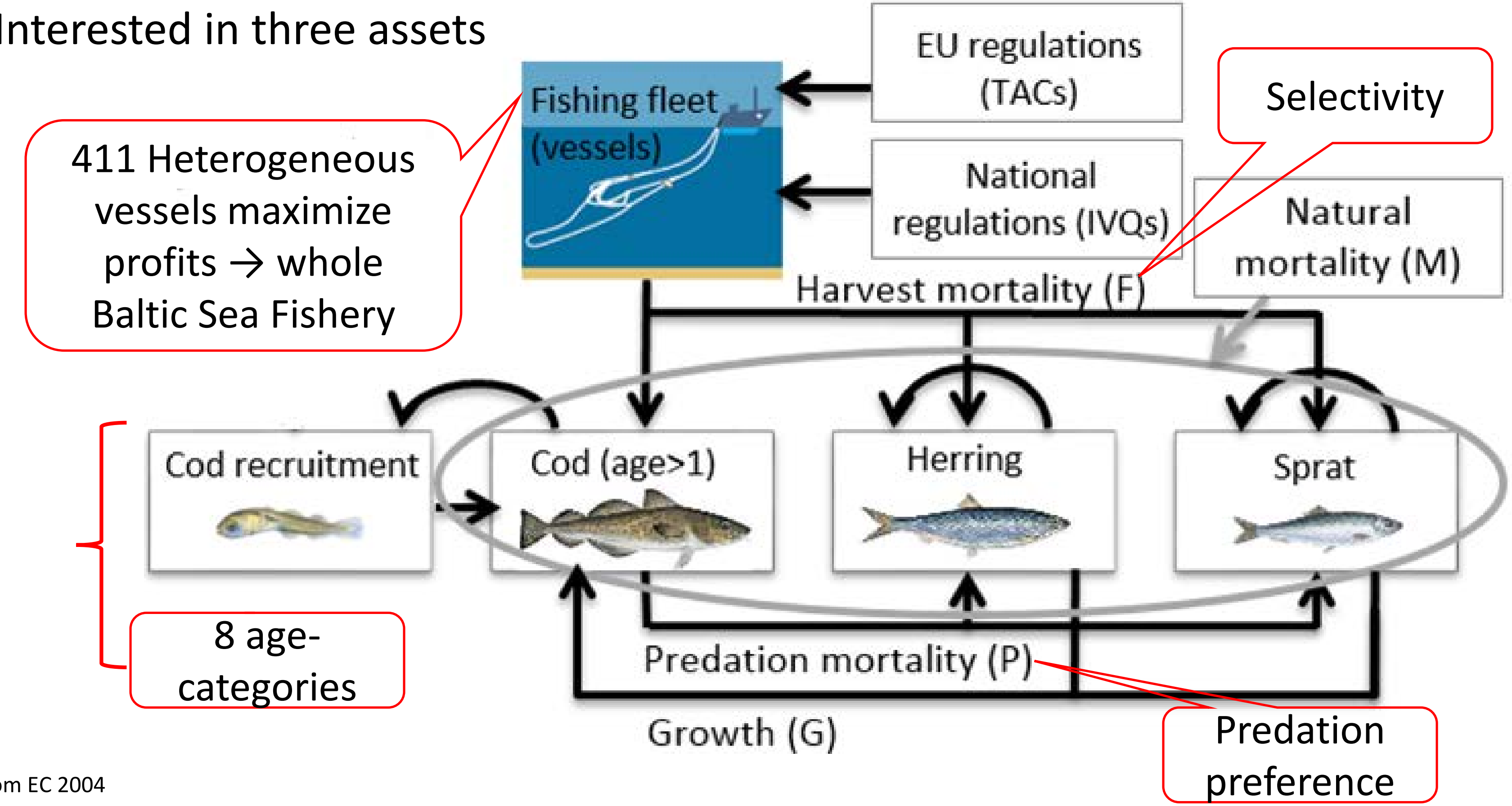
Interacting natural capital in the Baltic Sea & Connecting to EBM
A framework for human-environmental systems research that hits policy

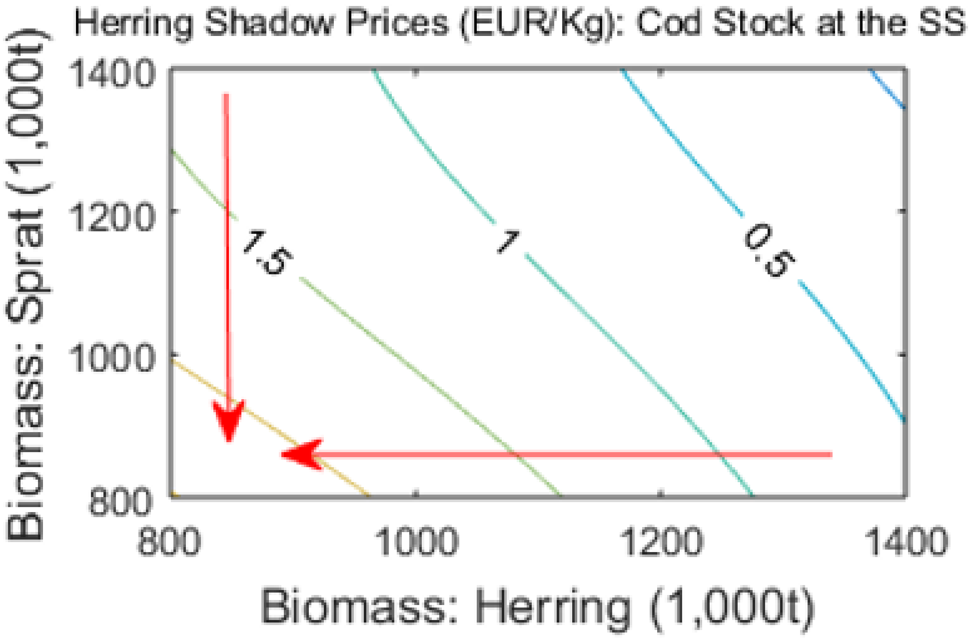
- Updated version of Hutniczak (2015)
- Representative of the complexity of many ecosystem based management models – lots of moving parts
- Interested in three assets



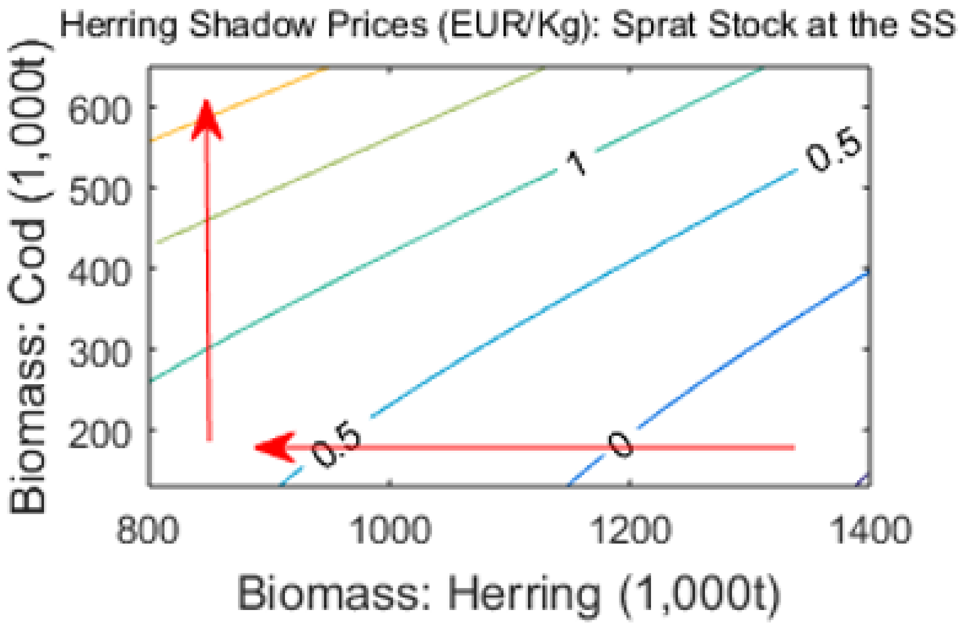
Modified from EC 2004

Cross stock capital gains effects in price – capture the limits of substitution

Price adjust as the state of the world changes
Isoclines of herring prices



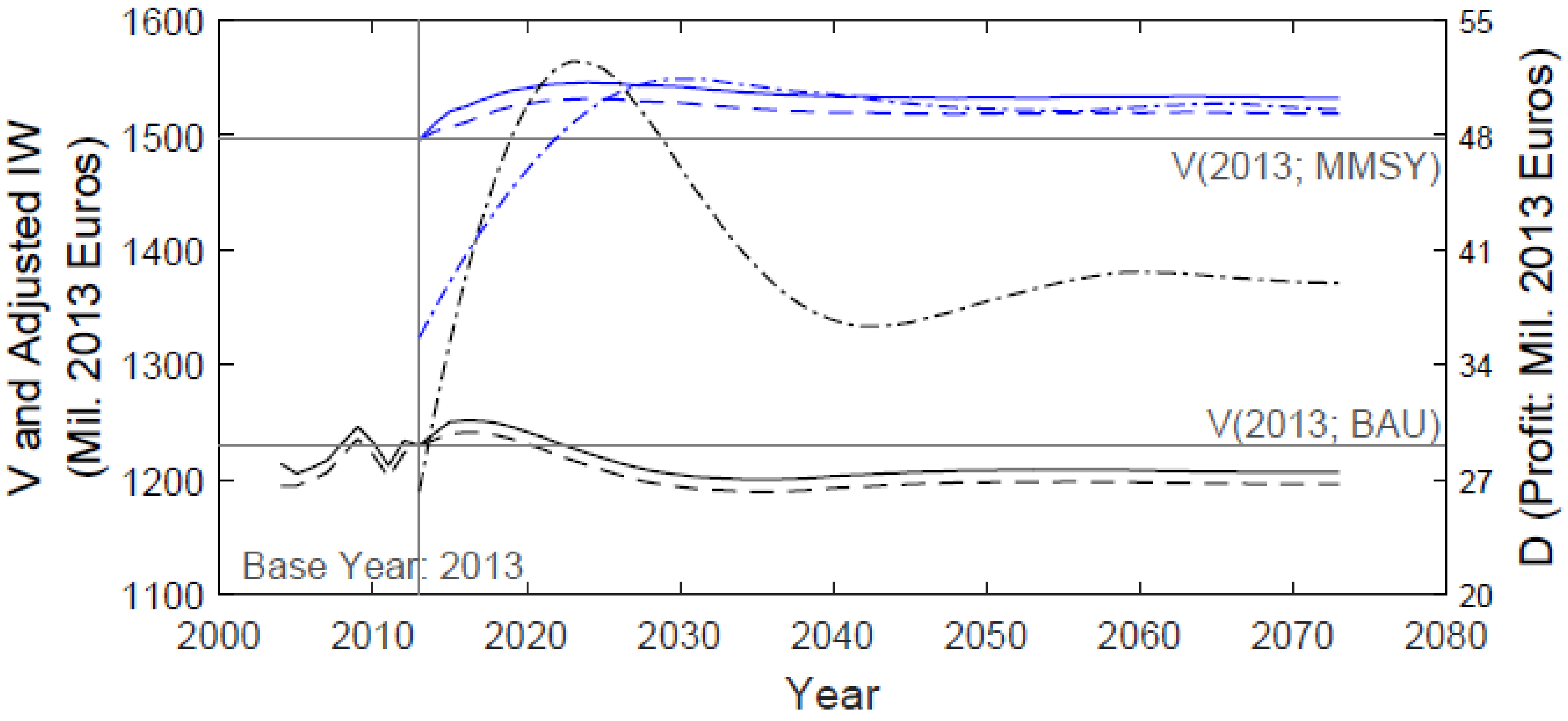
Cod fixed at the SS



Sprat is fixed at the SS

- Nonlinear effects comes through predation relation and fishing behavior!
- "+" and "-" correlation: not a weak linear index!
- Biodiversity can't be valued as a stock because of general equilibrium effects – composition matters

Using natural capital asset prices to asses institutional changes

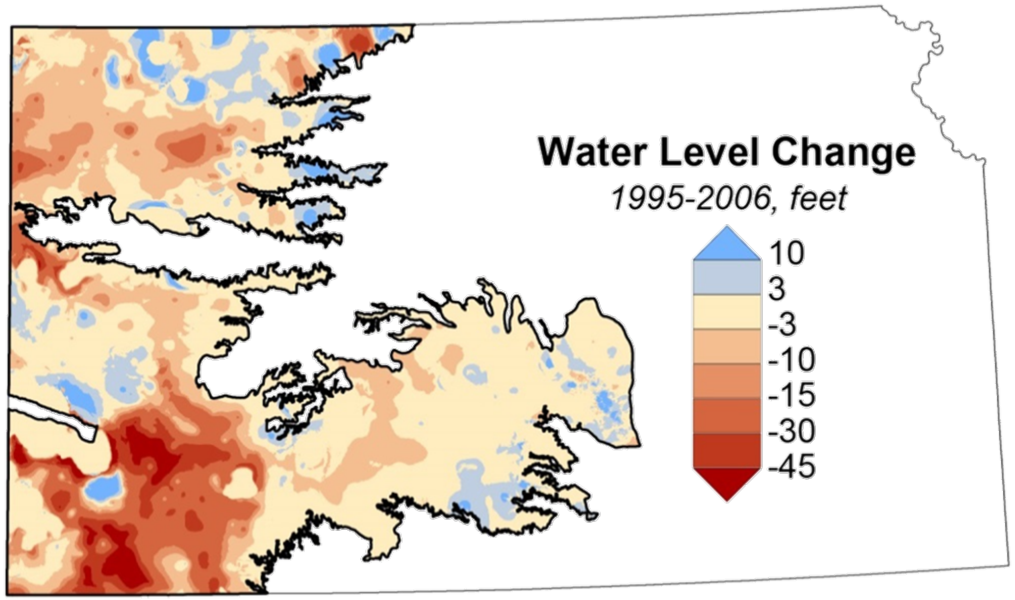


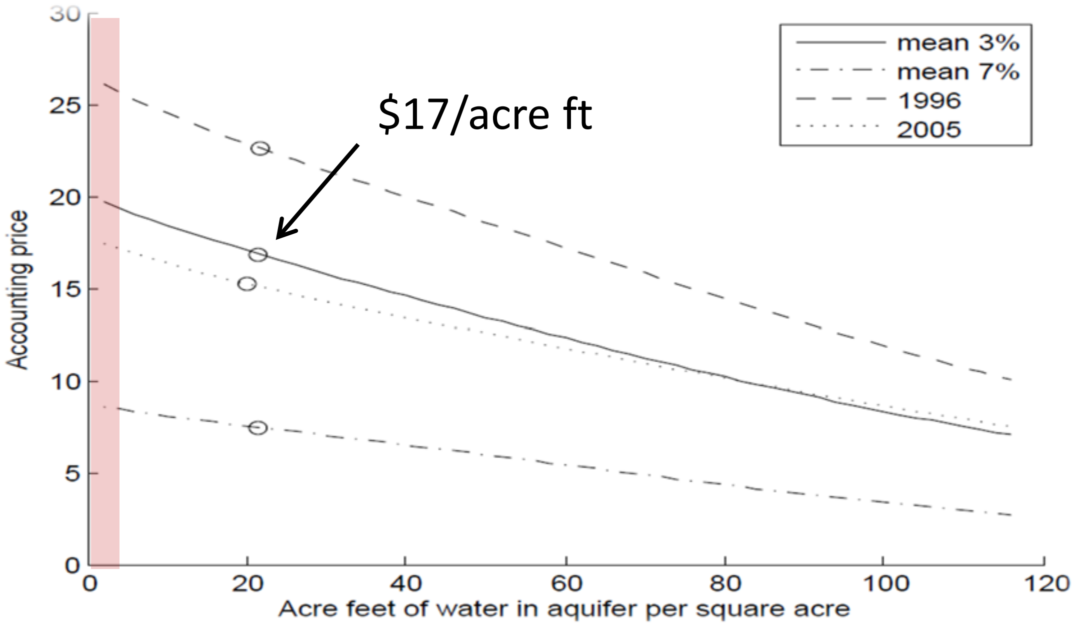
Solid line V
Dashed $\mathcal{W}$

Theory says $\Delta V \approx \Delta \mathcal{W}$, but really just focus on sign.
$\Delta \mathcal{W}$ almost always classifies ΔV correctly:

BAU gives more cod
Neither program is strictly "sustainable" both have periods of decline.

Groundwater in KS 1996-2005
Impacting the way policymakers thinks about resources





- The value KS stored in water declined between $31M/yr, (7% DR) and $110M/ yr, (3% DR),
- KS budget surplus in 2005 was $113M - sustainability is feasible, it is an investment decision.
- A lot of the drop linked to new technology and no institutional adjustment.

Fenichel, E. P., J. K. Abbott, J. Bayham, W. Boone, E. M. K. Haacker, and L. Pfeiffer. 2016. Measuring the value of groundwater and other forms of natural capital. Proceedings of the National Academy of Sciences 113:2382–2387.

More Information

ELSEVIER

Handbook of Environmental Economics

Available online 3 April 2018

In Press, Corrected Proof — Note to users

The nature of natural capital and ecosystem income*

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PNAS

Ecosystem-based management and the wealth of ecosystems

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Edited by Partha Sarathi Dasgupta, University of Cambridge, Cambridge, United Kingdom, and approved May 11, 2017 (received for review October 24, 2016)

We merge inclusive wealth theory with ecosystem-based man- or increasing "wealth"—the price-weighted sum of all societal

PNAS

Measuring the value of groundwater and other forms of natural capital

Eli P. Fenichel[a,1], Joshua K. Abbott[b], Jude Bayham[a,c], Whitney Boone[a], Erin M. K. Haacker[d], and Lisa Pfeiffer[e]

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Edited by ...

Valuing n... n wealth

https://github.com/efenichel/capn_stuff

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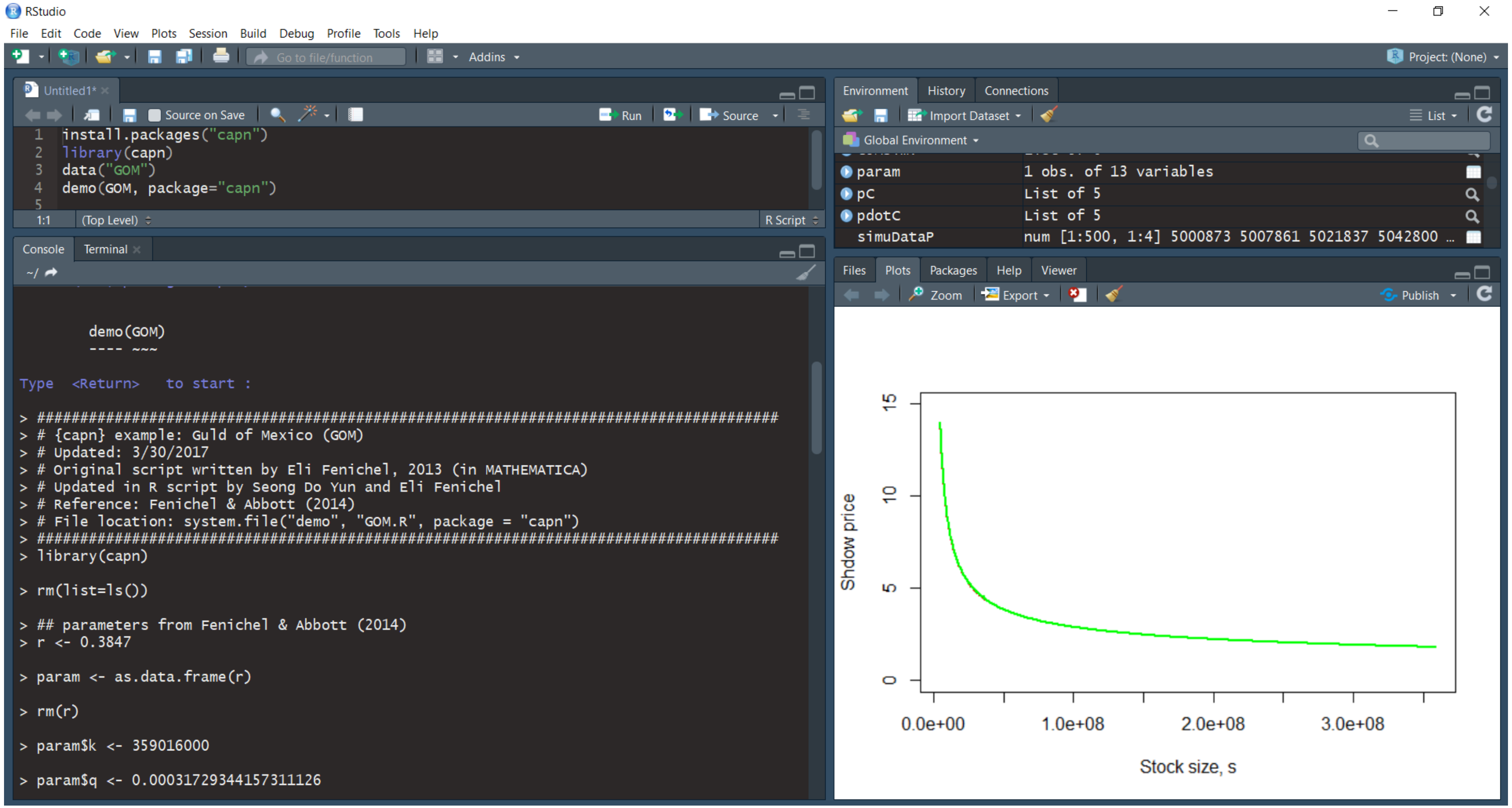
Approximating asset prices for natural capital with {capn} v1.0.0 for R



Start with install.packages("capn")

More examples and problem sets at https://github.com/efenichel/capn_stuff

Groundwater in KS 1996-2005
Fenichel et al. 2016 PNAS

Detailed hydrological measurement,

Based on Haacker et al. 2016. Groundwater. Saturated thickness and specific yield give $s(t)$.

Crop growth, yield and budget information,

Kansas State Univ. Cooperative Extension. (prices and costs, stripped of subsidies and adjusted using crop specific PPI)

Field level pumping and crop choice data,

Water Information Management and Analysis is System (previously used by Pfeiffer).

Estimate multinomial logit for planting mix,

25 planting types various combinations Alfalfa, Corn , Sorghum, Soy, Wheat, Unirrigated (fallow), gives the expected acres per field.

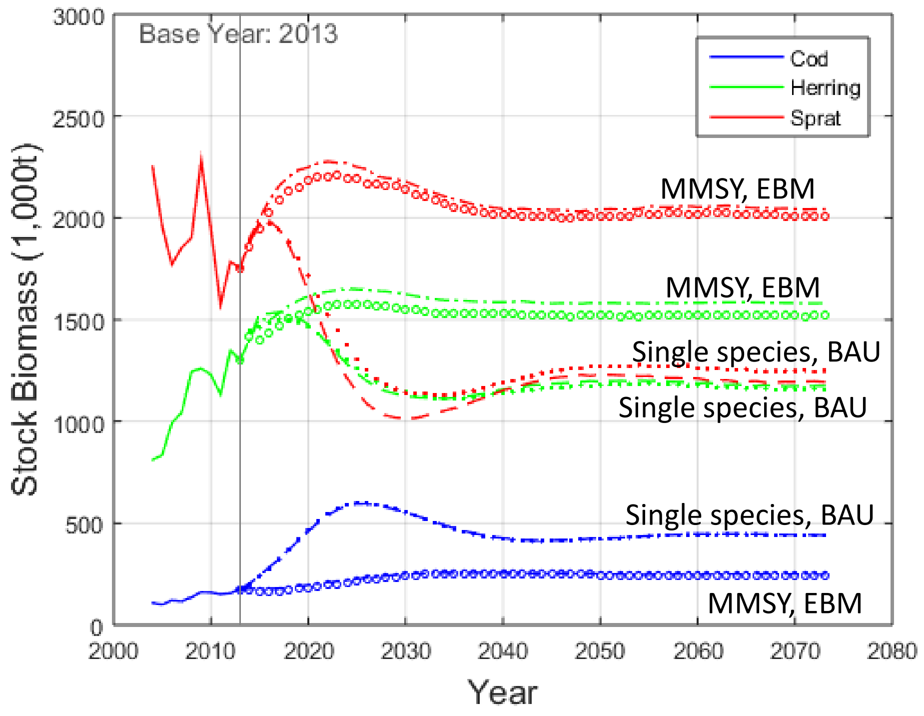
Estimate water withdrawal function per field using a selection model, as a function of stock that identifies the effects ground water, acres planted, and acres planted squared, conditional on a bunch of other covariates.

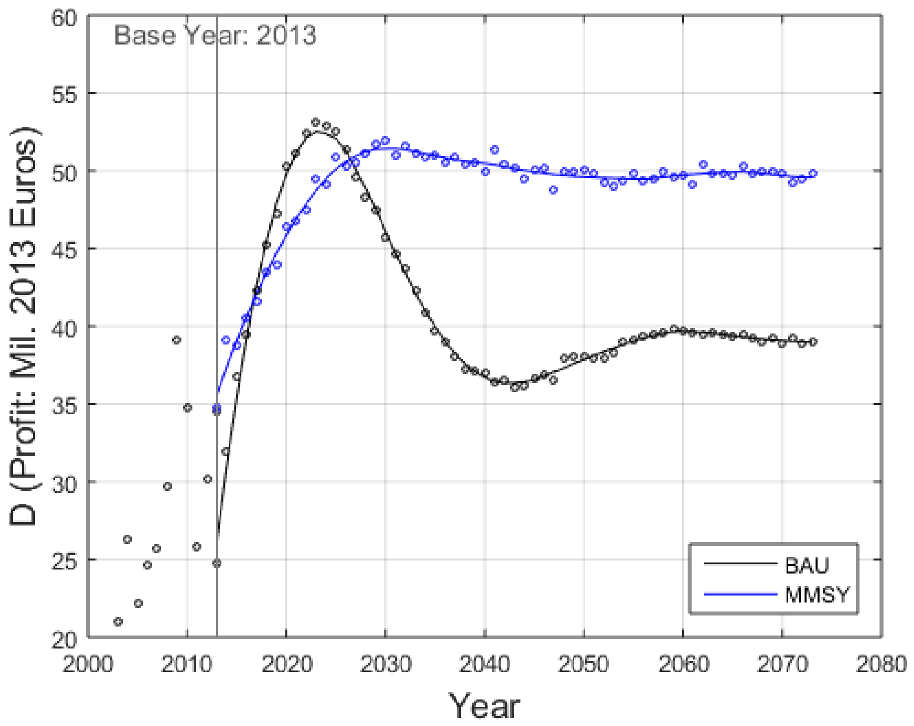
All regression highly significant.

Use OMB discount rates, prefer 3% also investigate 7%.

The simulation looks like after solving some other technical challenges

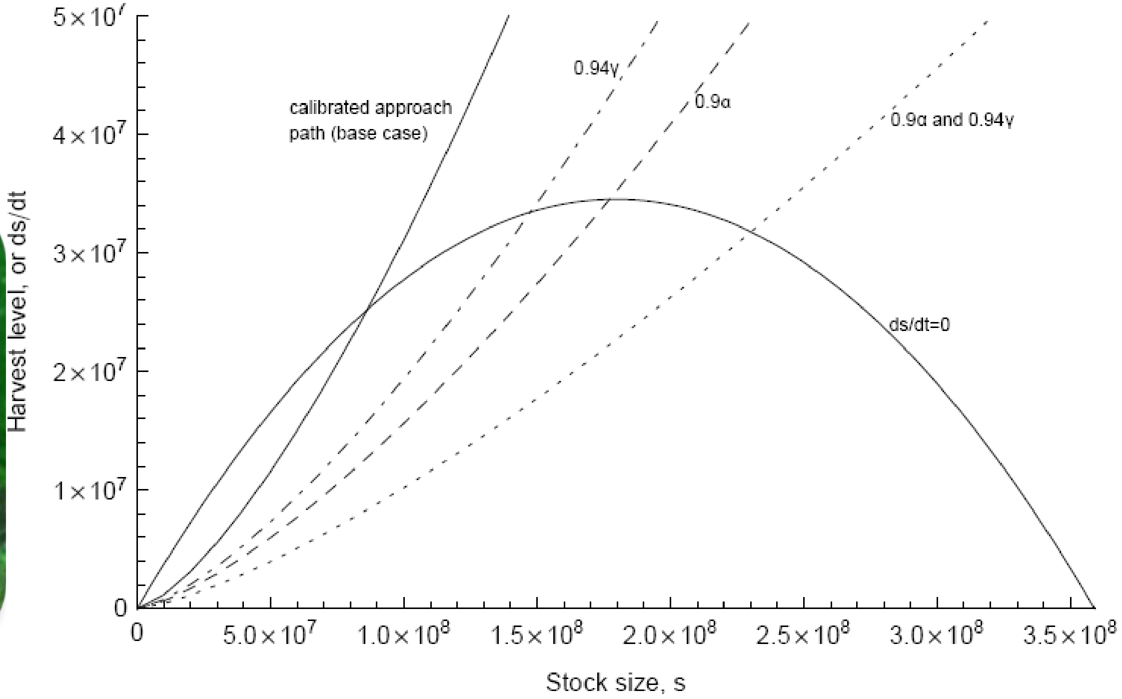
Interested in three assets, cod, herring, and sprat
Two scenarios built of target fishing mortality rates developed by ICES.
A. BAU single species MSY
B. EBM multispecies MSY



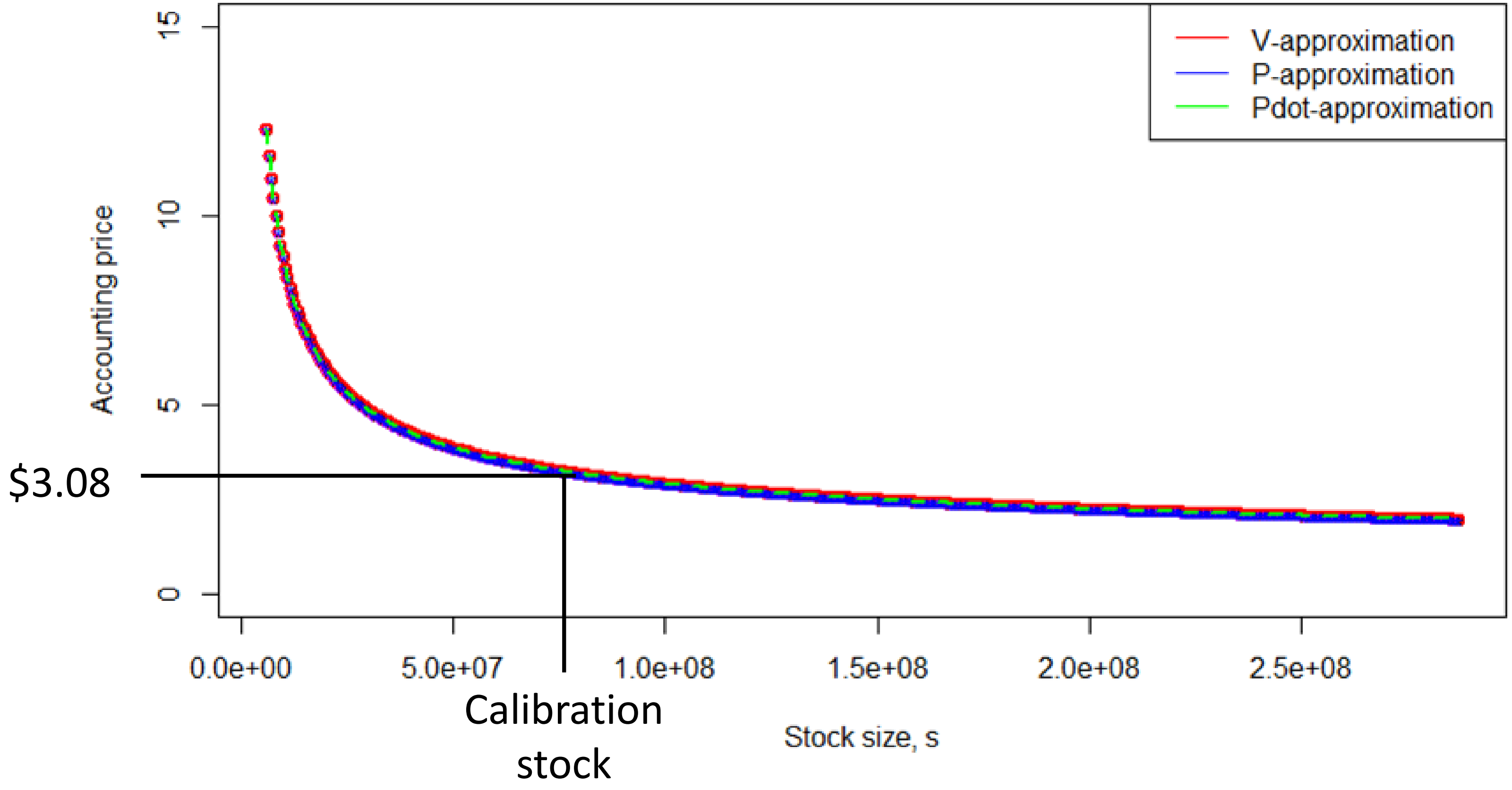


Natural Capital Asset Price for Gulf of Mexico Reef Fish c. 2005
A single stock case
Fenichel & Abbott 2014 JAERE

- 62 jointly managed species: 6 species make up most of the catch
- 1984 a Fishery management plan was enacted to rebuild stocks “on the basis of MSY modified for relevant economic, social, and ecological factors.”
- Used a complex set of regulations, entry limits, catch limits, season closures, spatial closures.
- Empirical models:
  - o Zhang & Smith 2011ReStat
  - o Zhang 2011 BE Economic Analysis & Policy

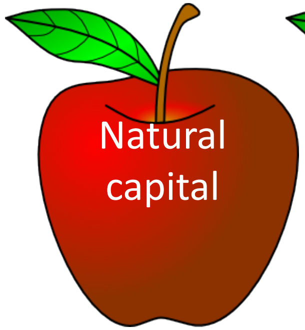


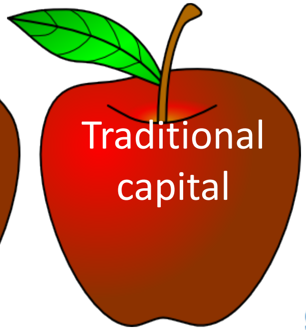
Shadow Price Curve for Gulf of Mexico Case
Multiple approaches
Based on Fenichel & Abbott 2014



Evidence from the Catch Shares Market

- Theory says ITQs should raise the value of the stock
- Red snapper ITQ shares traded at $8.73/lb (2007)
- Shows how better management institutions have increased the value of the fish for future fishing
- Like restructuring an underperforming company and seeing the share price triple
- Idealized shadow prices from optimal systems fail to value institutional "improvement"





Approximating asset prices for natural capital

Approximate the unknown functional with a S-dimensional Chebychev polynomial.

Choose M evaluation points over a bounded interval located in S dimensions.
Choose the points as the zeros of a Chebychev polynomial.

Let $V(\boldsymbol{S}^m) \approx \Phi^m(\boldsymbol{S})\beta$, which implies that $\frac{\partial V(S^m)}{\partial s^i} \approx \frac{\partial \Phi^m(\boldsymbol{S})}{\partial s^i}\beta$ and $\frac{\partial^2 V(S^m)}{\partial s^i \partial s^j} \approx \frac{\partial^2 \Phi^m(\boldsymbol{S})}{\partial s^i \partial s^j}\beta$

$$\delta V(\boldsymbol{s}) = W(\boldsymbol{s}(t), x(\boldsymbol{s}(t))) + \left[\sum_{j=1}^{S} \mu^j(\boldsymbol{s}, x(\boldsymbol{s})) V_{s^j} + \frac{1}{2}\sum_{j=1}^{S}\sum_{k=1}^{S} \Omega^{jk}(\boldsymbol{s}) V_{s^j s^k}\right]$$

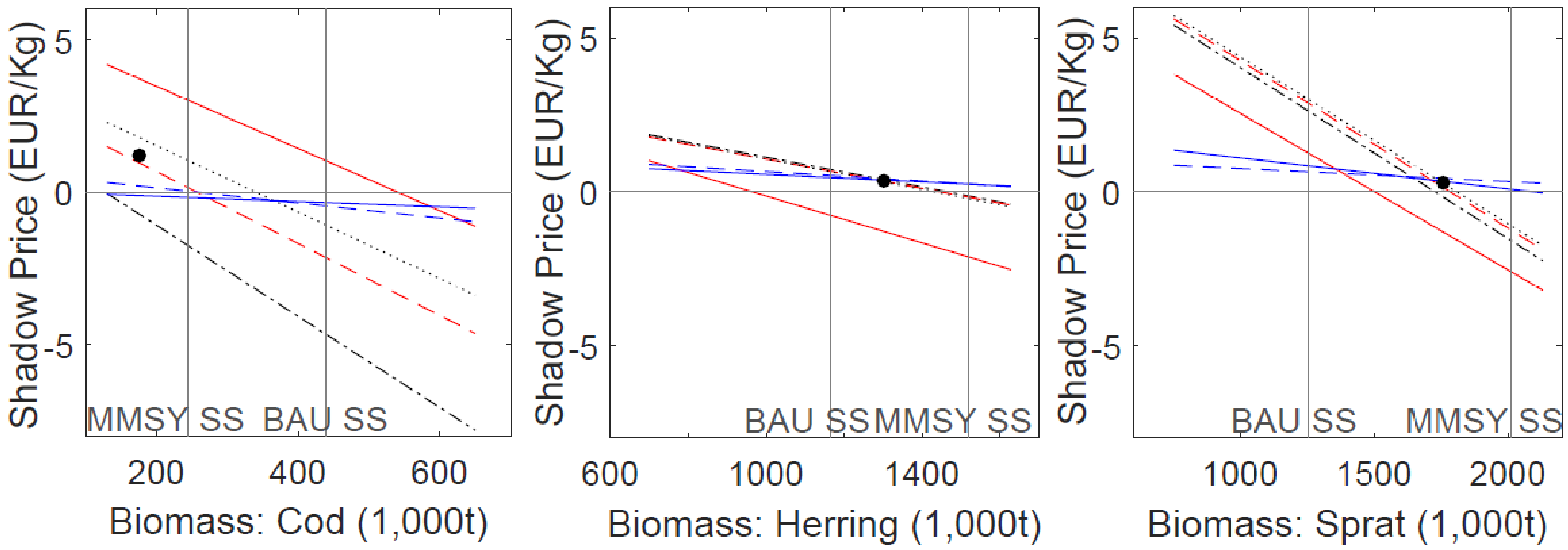
$$\Phi^m(S)\beta = W(S^m) + \left[\sum_{j=1}^{S} \mu^j(S^m)\left(\partial\Phi^m(S)/\partial s^j\right)\beta + \frac{1}{2}\sum_{j=1}^{S}\sum_{k=1}^{S}\Omega^{jk}(S^m)\left(\partial^2\Phi^m(S)/\partial s^j\partial s^k\right)\beta\right]$$

$$\beta = \left(\Psi(S)'\Psi(S)\right)^{-1}\Psi(S)'W(S)$$

$$\boldsymbol{\Psi} = \left[\Phi^m(S) - \sum_{j=1}^{S}\mu^j(S^m)\left(\partial\Phi^m(S)/\partial s^j\right) - \frac{1}{2}\sum_{j=1}^{S}\sum_{k=1}^{S}\Omega^{jk}(S^m)\left(\partial^2\Phi^m(S)/\partial s^j\partial s^k\right)\right]$$

The natural capital asset prices

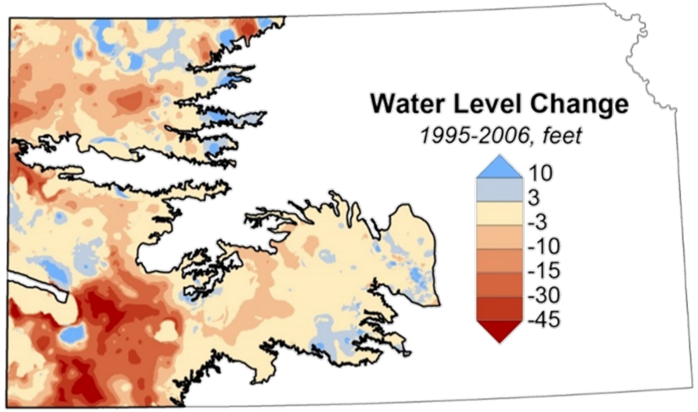
- Prices decrease in own stock (as expected)
- At 2013 stock,
  - Cod > 0
  - Herring and Sprat < 0
- BAU equilibrium cod are a liability, prey are assets
- MMSY equilibrium all are assets

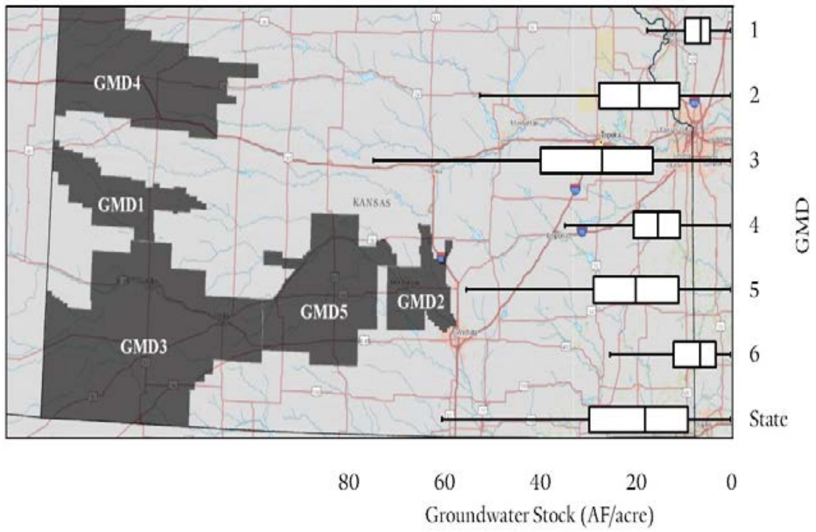


Blue EBM, Red is Single species, Dashed is steady state, solid is 2013 stock levels, Black are 80% & 110% of BAU steady state, the circle is 2013 ex-vessel price

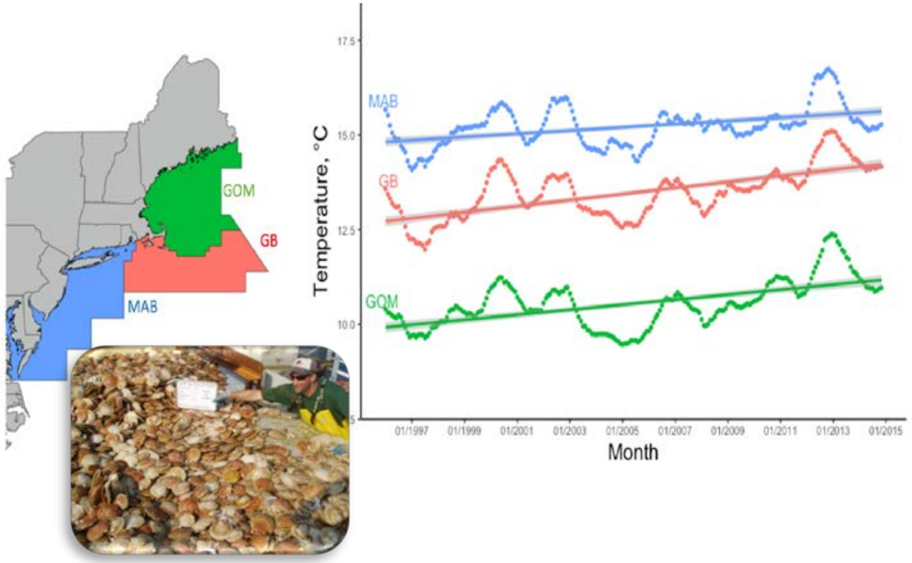
Other applications

Groundwater and spatial aggregation





Scallops and climate change (exogenous forcing)



Endangered species (caribou) and Forests beyond timber

Data Challenges

- 10 years ago I'm not sure it would have been feasible access and manage the data for this work.
- Today it is always a huge undertaking.
- Soon it might be easy and we need to be ready.
- Key challenge is that intersection of theory/ simulation modelers & empirical researchers in the sustainability space is very small.

Examples:

Gulf of Mexico – used catch & effort data for close to 30 years; non-public logbook level fishing data for behavior and costs.

Baltic Sea Example – used age structured stock data; non-public logbook fishing data on vessels, behavior, and costs.

Groundwater – a 10 year panel of every well in Kansas; crop budget data that had been lost on paper files at K-State Cooperative Extension; electricity and crop price data.

Caribou work – a mess of population data; data from oil and gas industry; management data, and a lot of guess work.

Forestry project – high resolution remote sensing; tax records; plot level data; landowner level data…

Measuring the value of natural capital and sustainability is a purposeful interdisciplinary endeavor, where disciplines have comparative advantages.

Key Challenges (and some thoughts)

1. Dynamics that not autonomous in time
2. Aggregation across multiple weakly interacting system
3. Dimensionality challenges
4. Stochasticity or uncertainty in the economic program
5. Endogenous institutional change
6. Interactions between natural and other forms of capital

Wealth accounting moving to higher dimensions

If we choose a good $\bar{p}$, then changes in wealth are essential changes in intertemporal wellbeing

1D case $\Delta V \approx \Delta \mathcal{W} = \bar{p}\Delta S$ if $\bar{p} > 0$, the direction of the change is the directional change of the sole stock

A case with trivial many stocks where only one stock changes non-trivially

$$\Delta \mathcal{W} = \sum_{i \neq j} \bar{p_i} \Delta s_i + \int_{s_j(t)}^{s_j(t+\epsilon)} p_j\left(\xi, \boldsymbol{s}_{-\boldsymbol{j}}(t); \phi\right) d\xi$$

How to deal with multiple non-trivial changes in stocks? Order or integration can matter. What do we need to know? Do we need all the price curves or could we get point and elasticity measures?

Deriving asset prices for natural capital

Assume a behavioral equilibrium - people respond in predictable ways to changes in stocks.

Recognize that the economic program must be recovered empirically.

$W_{s^i}\big(\boldsymbol{s}(\tau), \boldsymbol{x}(\boldsymbol{s}(\tau))\big) \equiv W^*_{s^i} = \frac{\partial W}{\partial s^i} + (\nabla_{\boldsymbol{x}} W)' \frac{d\boldsymbol{x}}{ds^i}$, similar for f

Generalize $\dot{\boldsymbol{s}} = G^i(\boldsymbol{s}) - f^i\big(\boldsymbol{s}, \boldsymbol{x}(\boldsymbol{s})\big)$ as

$ds^i = \mu^i\big(\boldsymbol{s}, \boldsymbol{x}(\boldsymbol{s})\big)dt + \sigma^i(\boldsymbol{s})dZ^i \; \forall i$ allows for a stochastic process in G.

Once the economic program is substituted in, just a function $\boldsymbol{s}$.

$Cov\left(ds^i, ds^j\right) = \Omega^{ij}(\boldsymbol{s})\mathrm{dt}$

This means

$$V\big(\boldsymbol{s}(t)\big) = \mathbb{E}\left[\int_t^\infty e^{-\delta(\tau-t)} W\left(\boldsymbol{s}(\tau), \boldsymbol{x}\big(\boldsymbol{s}(\tau)\big)\right) d\tau\right]$$

Deriving asset prices for natural capital

Apply Ito's lemma

$$dV(\boldsymbol{s}) = \left[\sum_{j=1}^{S} \mu^j\left(\boldsymbol{s}, \boldsymbol{x}\left(\boldsymbol{s}\right)\right) V_{s^j} + \frac{1}{2}\sum_{j=1}^{S}\sum_{k=1}^{S}\Omega^{jk}(\boldsymbol{s})V_{s^j s^k}\right] dt + \sum_{j=1}^{S}\sigma^j(\boldsymbol{s})V_{s^j}dZ^j$$

Taking the expectation and dividing by dt

$$\frac{dV}{dt} = \frac{\mathbb{E}_t[dV]}{dt} = \left[\sum_{j=1}^{S} \mu^j\left(\boldsymbol{s}, \boldsymbol{x}\left(\boldsymbol{s}\right)\right) V_{s^j} + \frac{1}{2}\sum_{j=1}^{S}\sum_{k=1}^{S}\Omega^{jk}(\boldsymbol{s})V_{s^j s^k}\right]$$

In the, deterministic case this simplifies to

$$\frac{dV(\boldsymbol{s})}{dt} = \sum \frac{\partial V}{\partial s^i}\frac{ds^i}{dt} = \sum p\dot{s}$$

We all know $\frac{dV(\boldsymbol{s})}{dt} = \delta V(\boldsymbol{s}) - W\left(\boldsymbol{s}(t), \boldsymbol{x}\left(\boldsymbol{s}(\boldsymbol{t})\right)\right)$

Setting $\frac{dV}{dt} = \frac{dV}{dt}$

Deriving asset prices for natural capital

$$\delta V(\boldsymbol{s}) = W\left(\boldsymbol{s}(t), x(\boldsymbol{s}(t))\right) + \left[\sum_{j=1}^{S} \mu^{j}\left(\boldsymbol{s}, \boldsymbol{x}(\boldsymbol{s})\right) V_{s^j} + \frac{1}{2}\sum_{j=1}^{S}\sum_{k=1}^{S} \Omega^{jk}(\boldsymbol{s}) V_{s^j s^k}\right]$$

This is a current value Hamiltonian or fundamental asset equation

Take the partial with respect to the stock and isolate $V_{s^i} = p^i$

$$p^i(\boldsymbol{s}) = \frac{\boxed{W_{s^i}} + \boxed{\left(\frac{\partial p^i}{\partial s^i}\mu^i + \sum_{j\neq i}^{S}\frac{\partial p^j}{\partial s^i}\mu^j\right) + \sum_{j\neq i}^{S} p^j \mu^j_{s^i} + \frac{1}{2}\sum_{j}^{S}\sum_{k}^{S}\left(\Omega^{jk}_{s^i}\frac{\partial p^j}{\partial s^k} + \Omega^{jk}\frac{\partial^2 p^j}{\partial s^k \partial s^i}\right)}}{\boxed{\delta} - \boxed{\mu^i_{s^i}}}$$

A single stock $$p(s) = \frac{W_s + [\mu(s) + \sigma_s(s)]p_s + \frac{1}{2}\sigma^2(s)p_{ss}}{\delta - \mu_s(s)}$$

A single stock deterministic case $p(s) = \frac{W_s(s,x(s)) + \dot{p}}{\delta - \left(G_s(s) - f_s(s,x(s))\right)}$ this is Jorgenson's value of invested capital if W_s is constant and $\dot{p} = 0$

Deriving asset prices for natural capital

$$p^i(s) = \frac{\boxed{W_{s^i}} + \boxed{\left(\frac{\partial p^i}{\partial s^i}\mu^i + \sum_{j\neq i}^S \frac{\partial p^j}{\partial s^i}\mu^j\right) + \sum_{j\neq i}^S p^j \mu^j_{s^i} + \frac{1}{2}\sum_j^S \sum_k^S \left(\Omega^{jk}_{s^i}\frac{\partial p^j}{\partial s^k} + \Omega^{jk}\frac{\partial^2 p^j}{\partial s^k \partial s^i}\right)}}{\boxed{\delta} - \boxed{\mu^i_{s^i}}}$$

Focus in on capital gains

$$\left(\frac{\partial p^i}{\partial s^i}\mu^i + \sum_{j\neq i}^S \frac{\partial p^j}{\partial s^i}\mu^j\right) + \sum_{j\neq i}^S p^j \mu^j_{s^i} + \frac{1}{2}\sum_j^S \sum_k^S \left(\Omega^{jk}_{s^i}\frac{\partial p^j}{\partial s^k} + \Omega^{jk}\frac{\partial^2 p^j}{\partial s^k \partial s^i}\right) =$$

$$\underbrace{\underbrace{\left(\frac{\partial p^i}{\partial s^i}\mu^i + \sum_{j\neq i}^{S} \frac{\partial p^j}{\partial s^i}\mu^j\right)}_{\text{Own and cross-price effect}} + \underbrace{\sum_{j\neq i}^{S} p^j \mu^j_{s^i}}_{\text{Cross-stock effect}}}_{\text{Deterministic terms}} + \underbrace{\frac{1}{2}\sum_{j=1}^{S}\left(\sigma^{2j}_{s^i}\frac{\partial p^j}{\partial s^j} + \sigma^{2j}\frac{\partial^2 p^j}{\partial s^j \partial s^i}\right)}_{} + \underbrace{\frac{1}{2}\sum_{j=1}^{S}\sum_{k\neq j}^{S}\left(\Omega^{jk}_{s^i}\frac{\partial p^j}{\partial s^k} + \Omega^{jk}\frac{\partial^2 p^j}{\partial s^k \partial s^i}\right)}_{}$$

Risk sensitivity term, investing in stock i impacts the sensitivity to stocks in any asset in S.

This is not directly related to risk preferences from W. Can come from curvature in biophysical dynamics or economic program

Portfolio effects and work through covariance.
Term vanishes if all COVs = 0.
If investing in stock i increase concavity in the j and k dimension, the then positive correlation, reducing the asset price.