Ecosystem-based approaches to Natural Capital Provision: A Natural Capital Approach to Caribou Conservation

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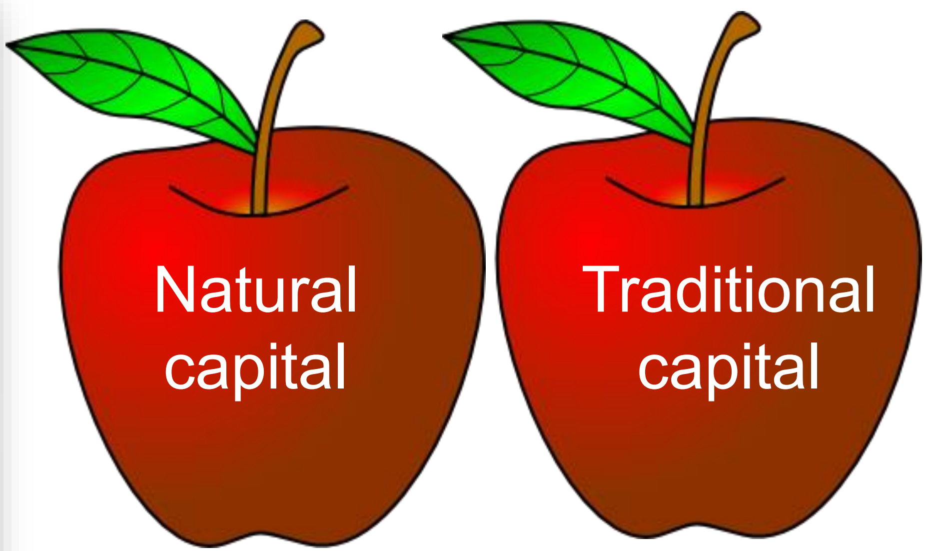


Sustainability, Conservation & Natural Capital

"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 natural 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

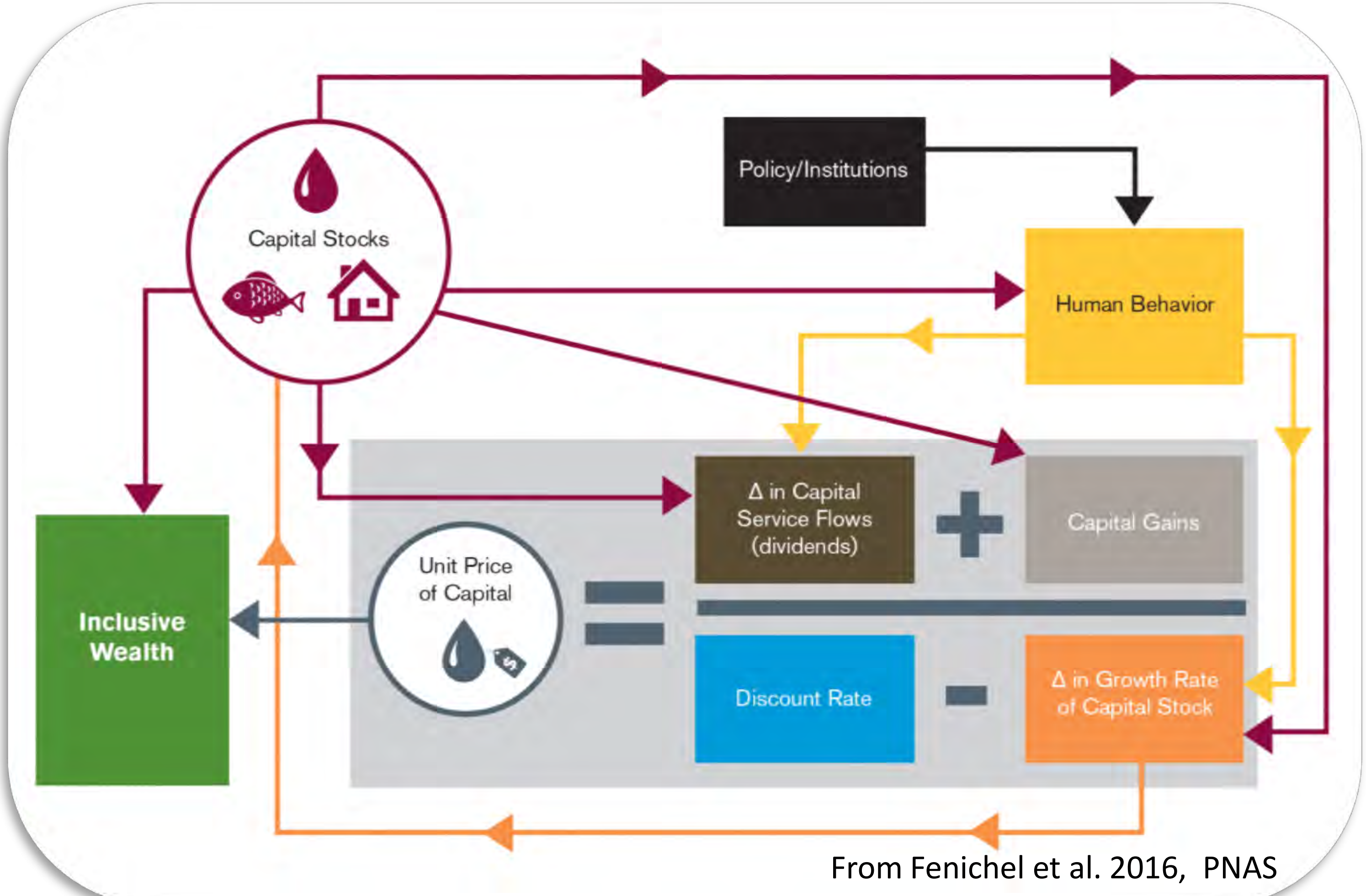
Use this as the starting point: assume ESA or SARA were meant as instruments to realize this vision.

Putting Conservation in the Context of Sustainability

- Inclusive wealth is the sum value of capital assets including natural capital.
- Sustainability is non-declining (conservation of) wealth, broadly defined.
- Conservation – saving opportunities for later.
- Wildlife provides opportunities for "real income" – Krutilla.

Natural capital can be valued symmetrically with traditional capital

Fenichel & Abbott 2014 JAERE:: Jorgenson 1963 AER



From Fenichel et al. 2016, PNAS

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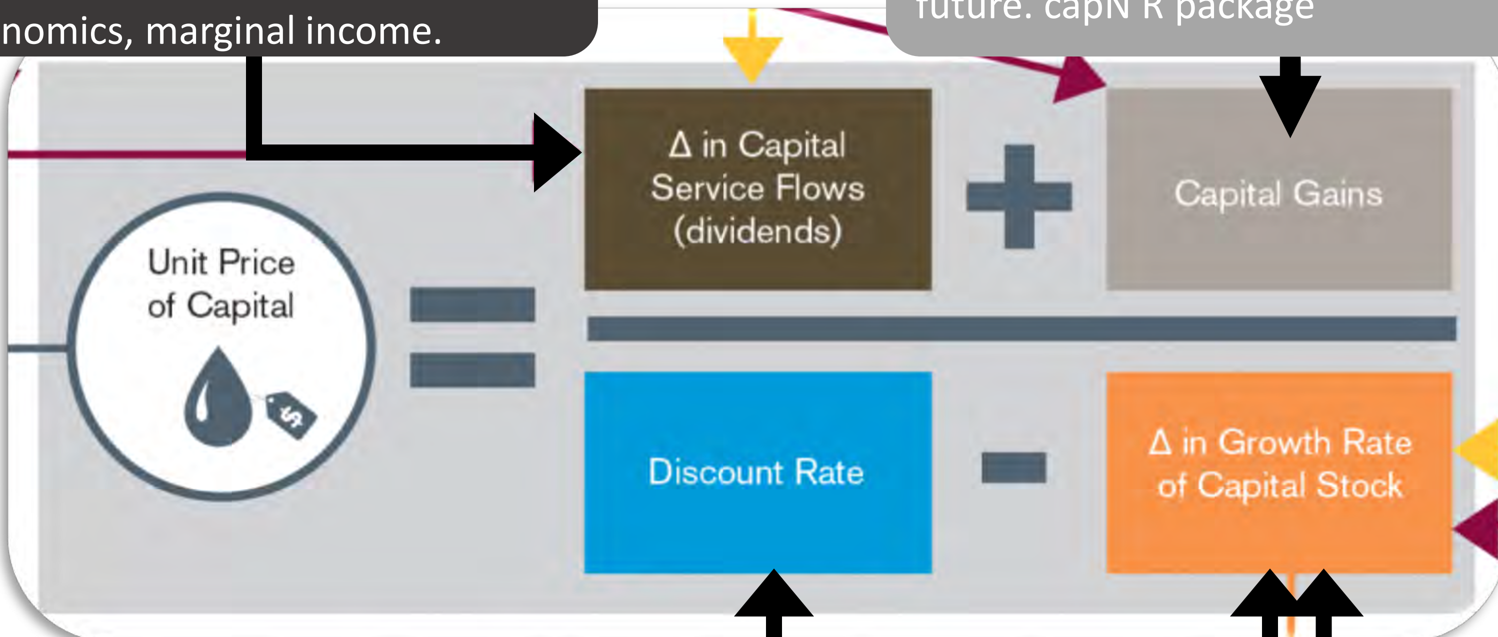
Value of extra ecosystem service flows from one more unit of stock. Market and non-market valuation economics, marginal income.

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.

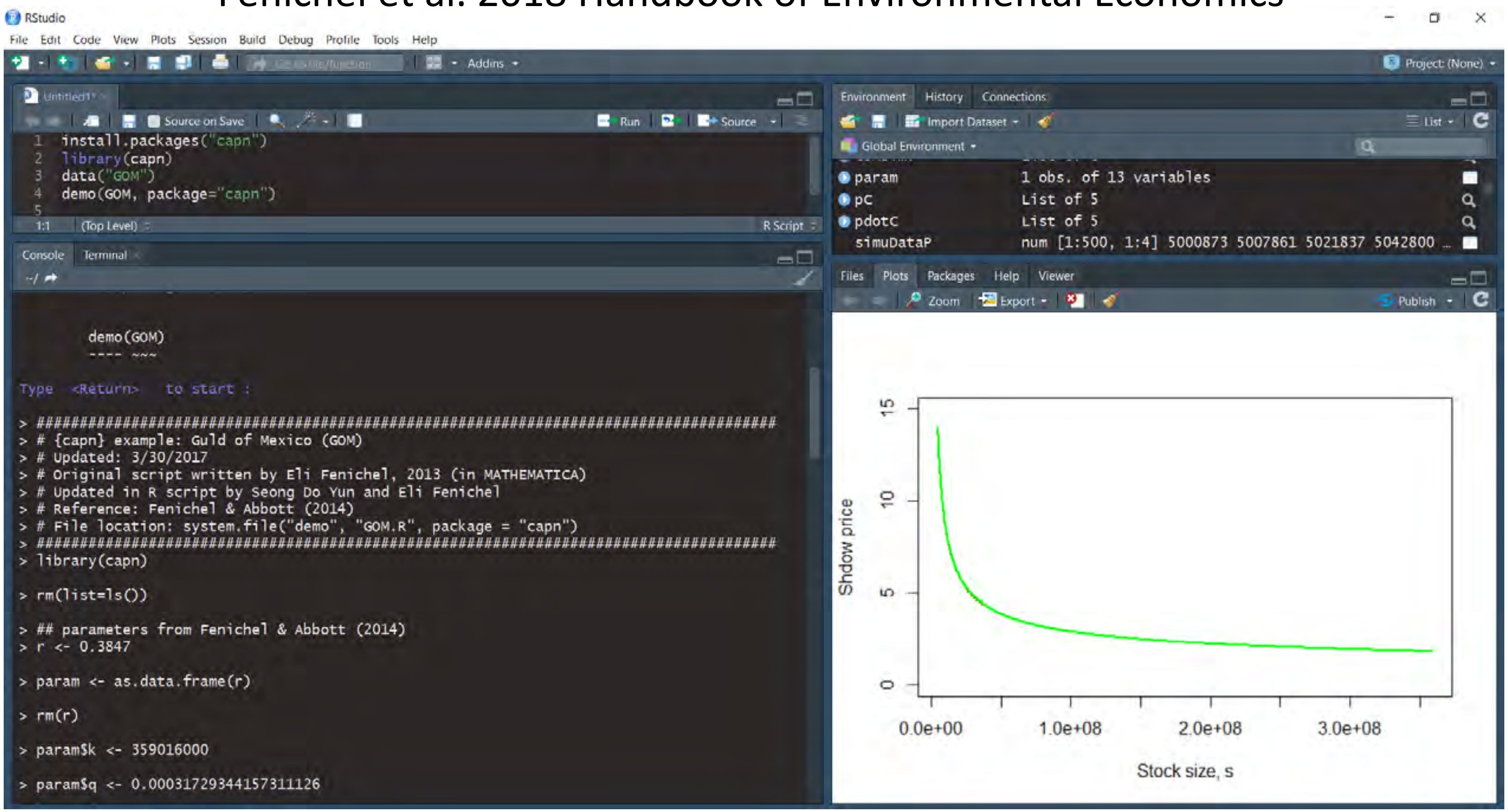
The 3 deterministic (2 stochastic) parts of capital gains

I. **Deterministic terms**
   A. Own price effects
      i. Classic capital gains term.
      ii. Captures how a change in a stock impacts its own scarcity.
   B. Cross-price effects
      i. General equilibrium or feedback effects.
      ii. Relates to where assets are complements or substitutes.
   C. Cross-stock effects
      i. Bio-physical interactions effect.
      ii. Real capital stocks can impact the physical change in other stocks

II. **Stochastic effects (own and portfolio effects)**
   A. Endogenous risk
      i. Thought of as a self-protection effect
      ii. How changes in a stock impact the variance and co-variances conditional on the curvature of the intertemporal welfare function
   B. Endogenous risk aversion effect
      i. Prudence, precaution, or self-insurance effect
      ii. How changes in the stock impact the curvature of the intertemporal welfare function

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

Implements functional approximation approaches documented in help and Fenichel et al. 2018 Handbook of Environmental Economics



Start with install.packages("capn")

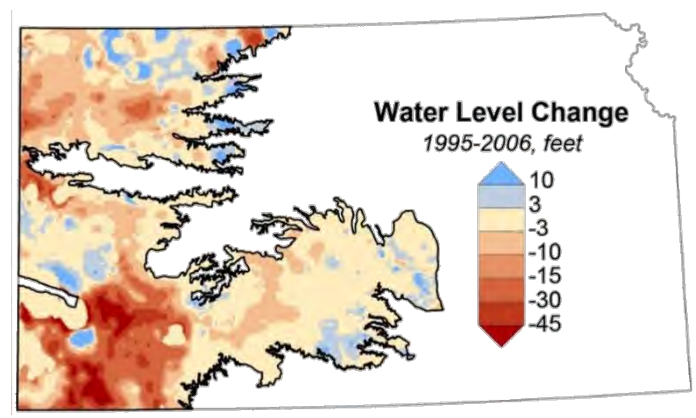
More examples and problem sets at https://github.com/efenichel/capn_stuff

Interested – get your phone and take a picture of this slide.

Natural capital asset pricing in practice

- Fenichel and Abbott 2014 JAERE – Commercial Gulf of Mexico reef fish
  - Pre ITQ shadow price ~ $3/lb - Post ITQ, $8/lb.
  - **Better management institutions increase the value of the fish.**
  - The value of **management institutions capitalized through asset prices** – like the value of firm management capitalized through a share price.

- Fenichel et al. 2016 PNAS – Kansas Groundwater
  - On average $17/ acre foot of water in the ground
  - If groundwater is a trust fund the, Kansas lost $110M/ yr, (3% discount rate) between 96-05.
  - **Brings the tradeoffs being made into focus.**
  - **Upon seeing this, Kansas farmers suggested that they needed to be better job conserving water.**

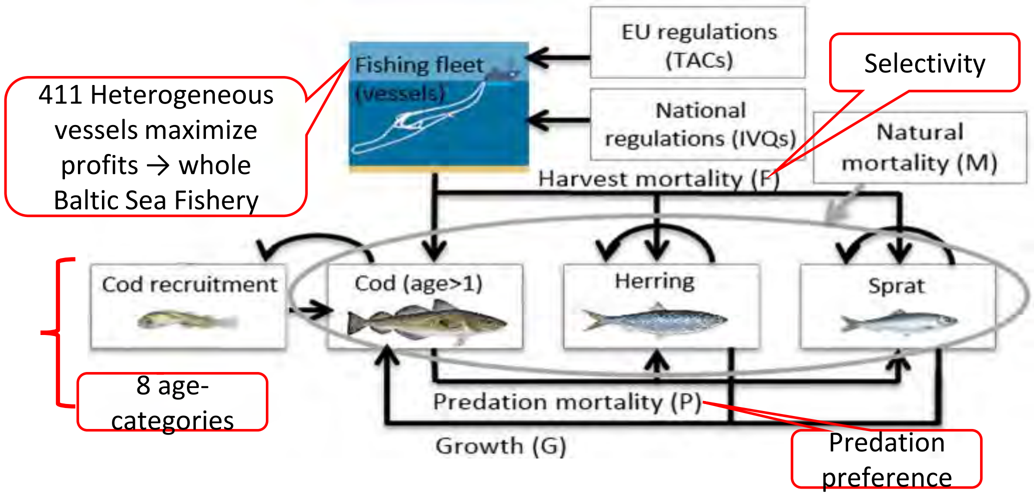


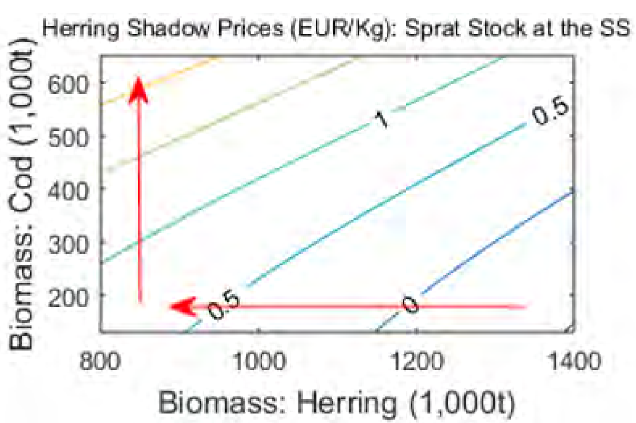
Natural capital asset pricing for an ecosystem

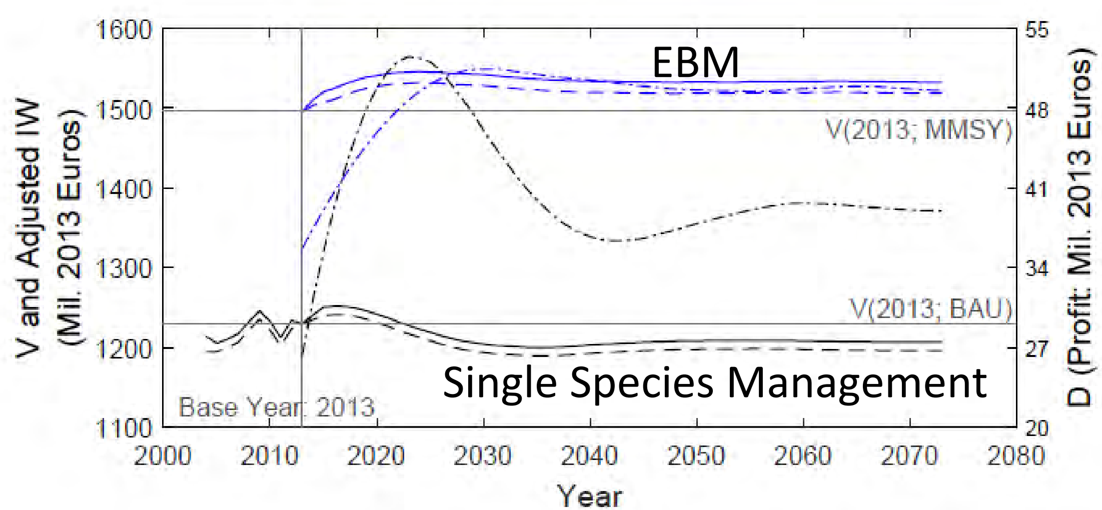
Yun et al. 2017 PNAS

- Focusing on ecological interactions leads to the natural capital asset prices reflecting substitution and complementarity relationships.

- A switch from single-species management to ecosystem based management (EBM) leads to about a 30% in asset values.

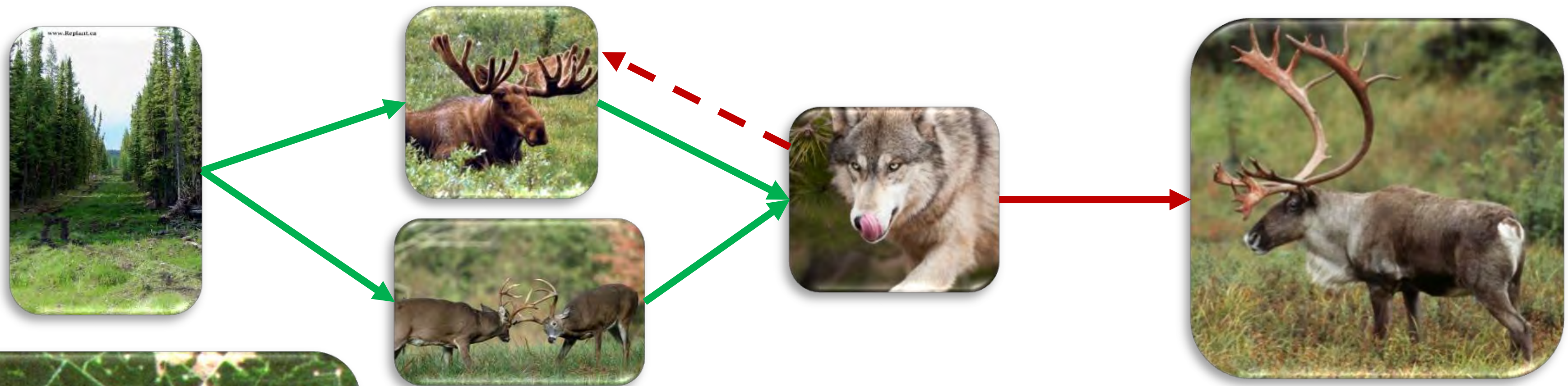


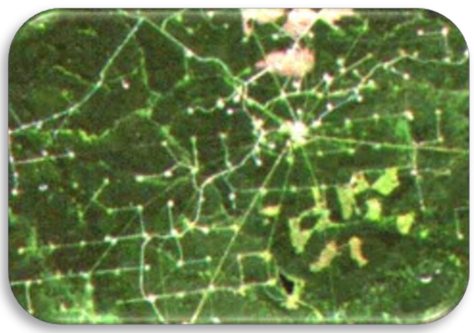




Natural capital asset pricing for caribou

Woodland caribou are an iconic, cultural important, and "endangered" species in Alberta, Canada.



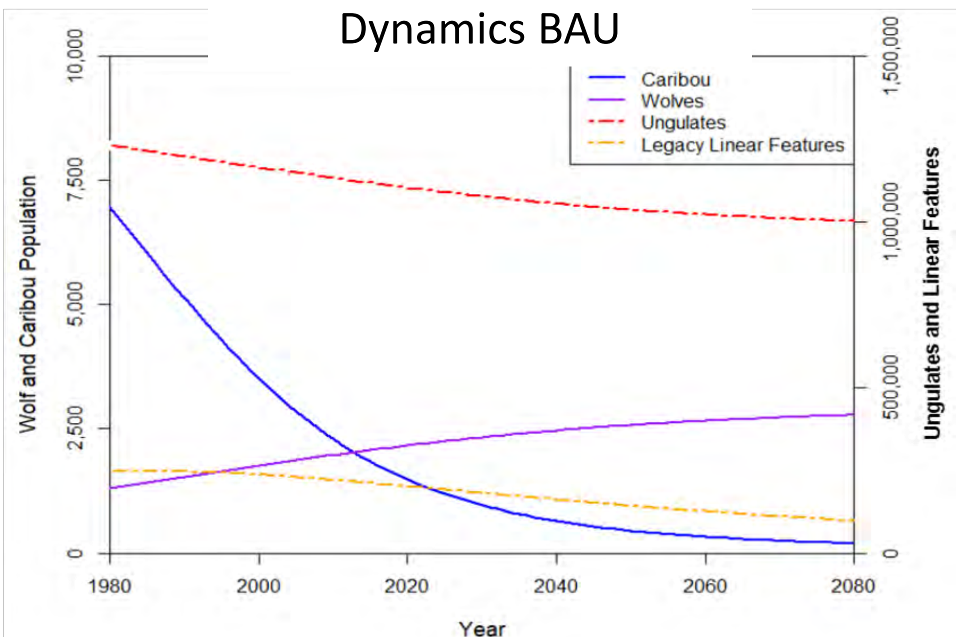


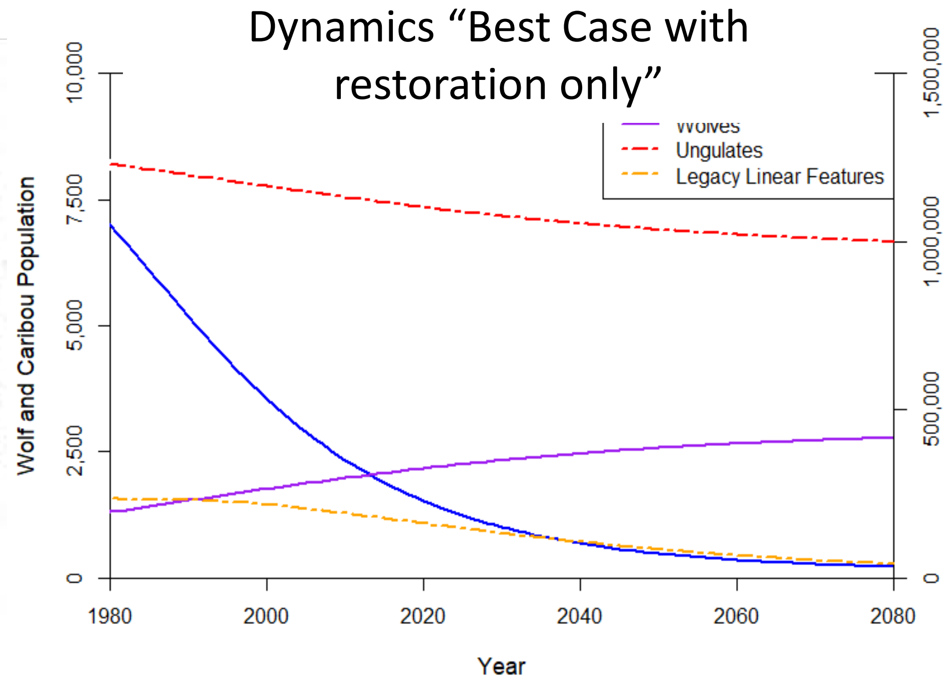
Collective action and concern for caribou has lead to voluntary linear feature restoration at a cost to the oil and gas industry.

Observe a baseline level of restoration.

Use ecological dynamics and linear feature restoration to impute a (lower bound) on a natural capital asset price for caribou.

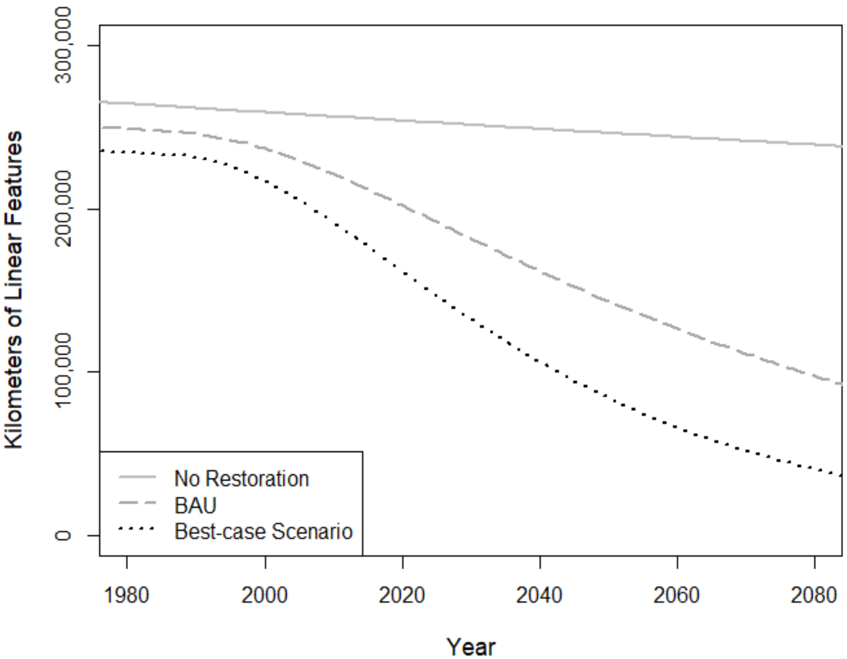
System Dynamics & Habitat Restoration

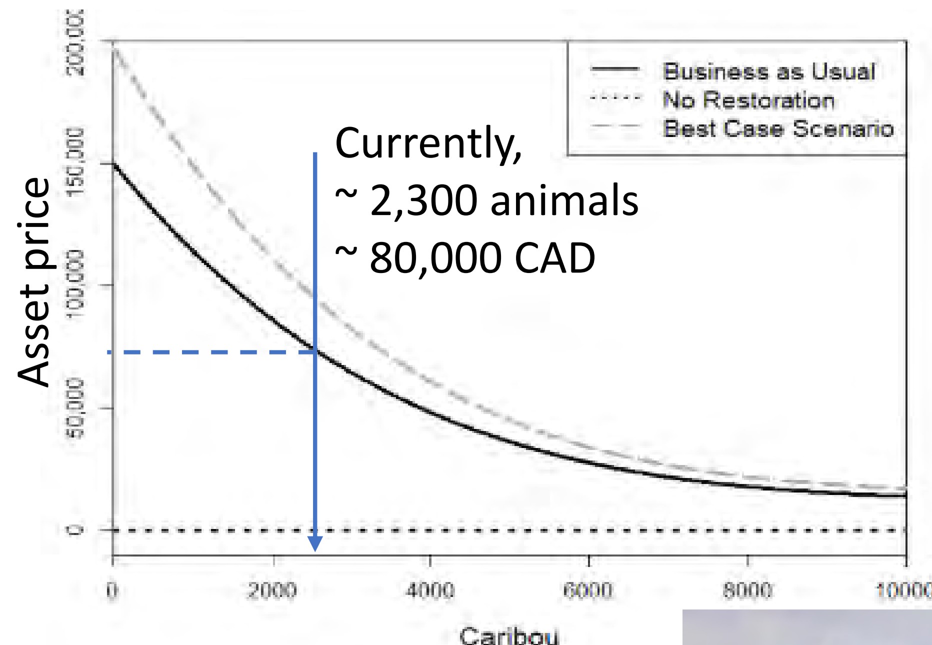


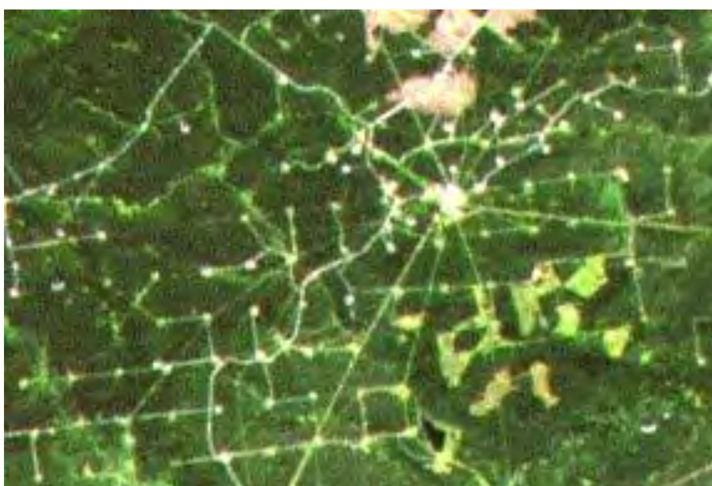


- Ignore spatial and herd structure
- Consider four stocks:
  - Caribou, wolves, ungulates, and linear features (traditional seismic lines).
  - Focus on predator-prey interactions including wolf pack structure.
  - Empirical data to infer the economic program and restoration rates.
- "Dividends" oil and gas net revenue based on landscape management less restoration costs. Forestry is in variant to Caribou so it is ignored.
- Parameterize with the best data, which in some cases is not great
  - Results are qualitative and give orders of magnitude.

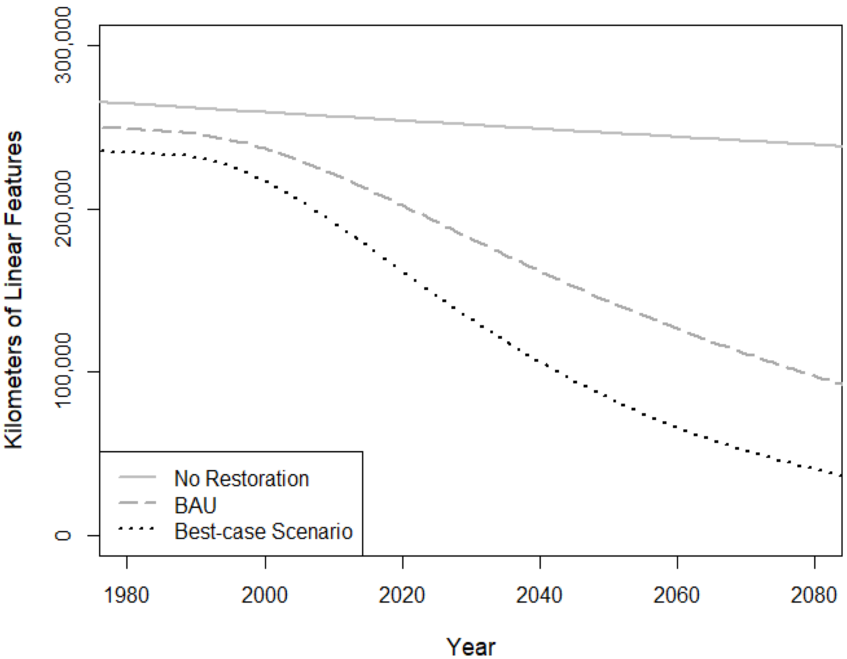
Revealed natural capital asset price of caribou, using capn for R

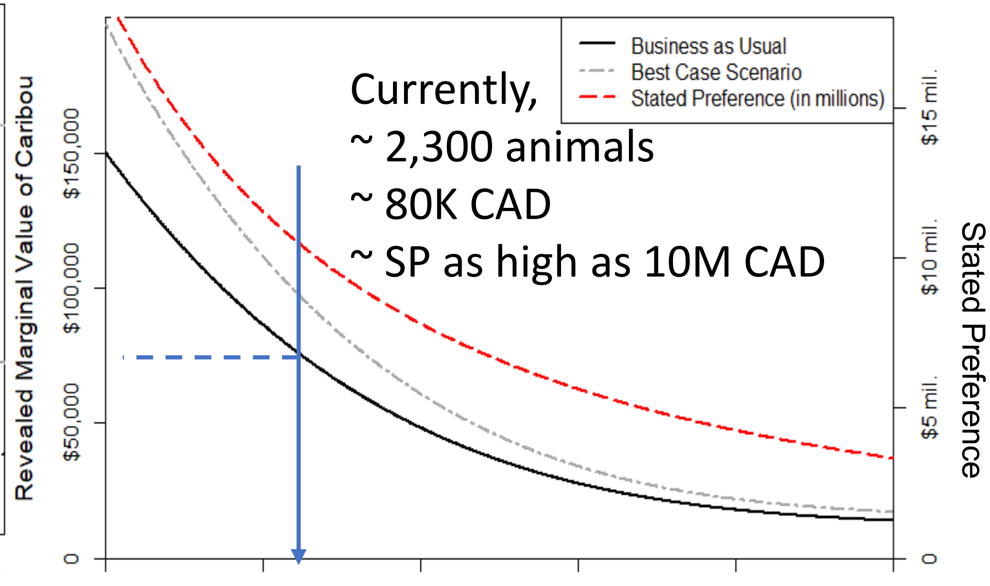


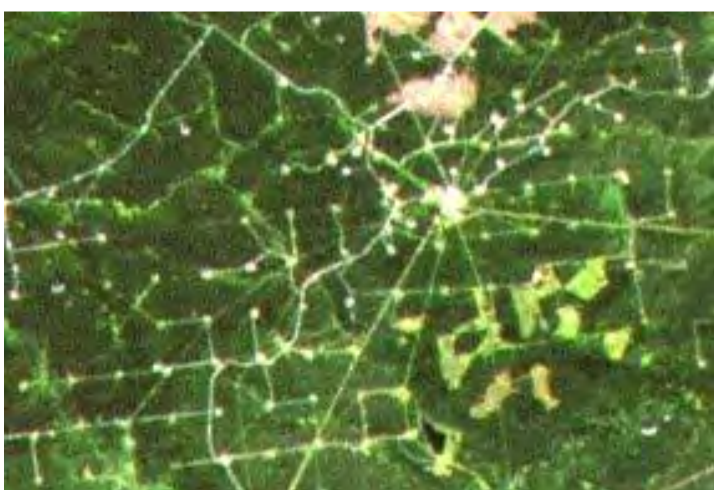




Revealed natural capital asset price of caribou, using capn for R

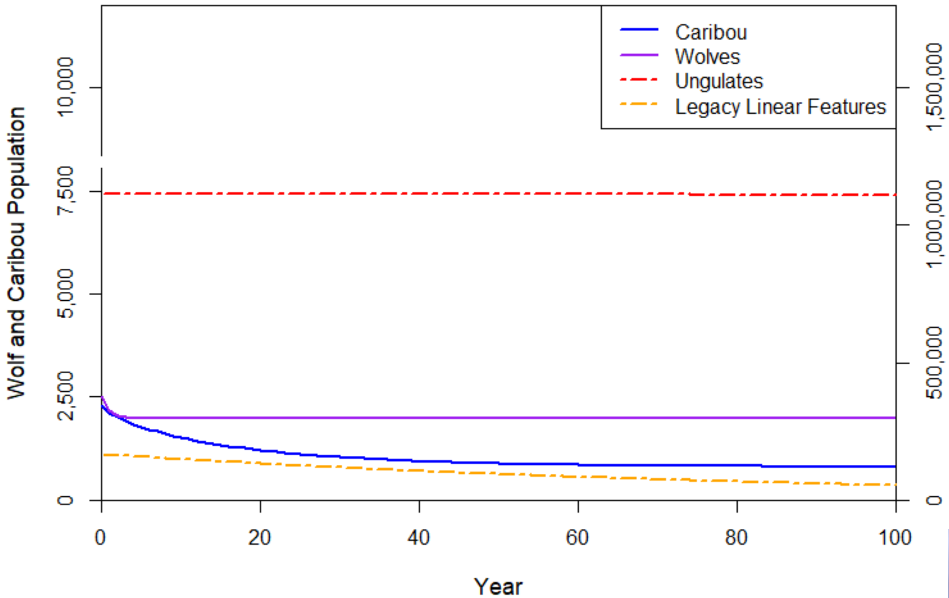




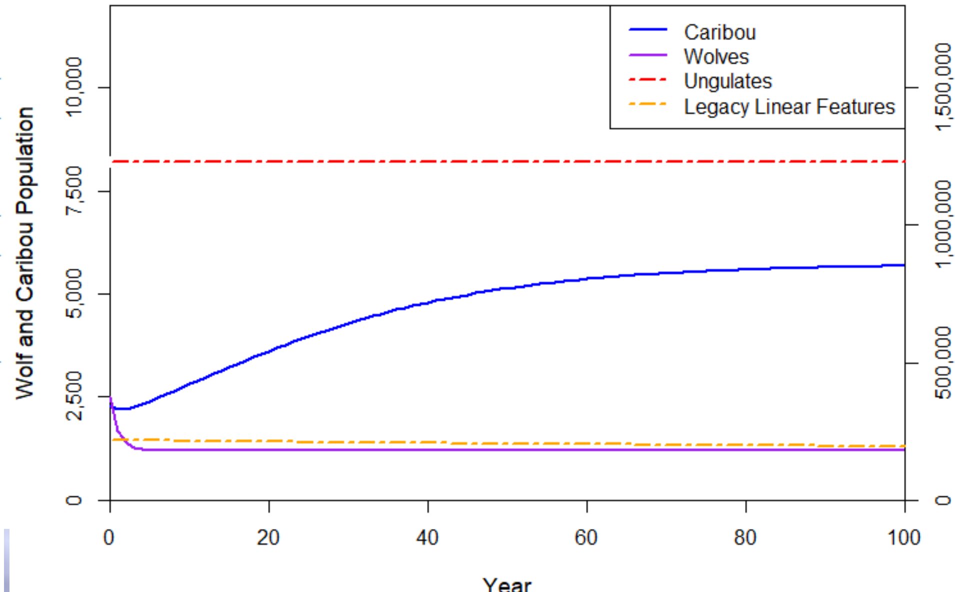


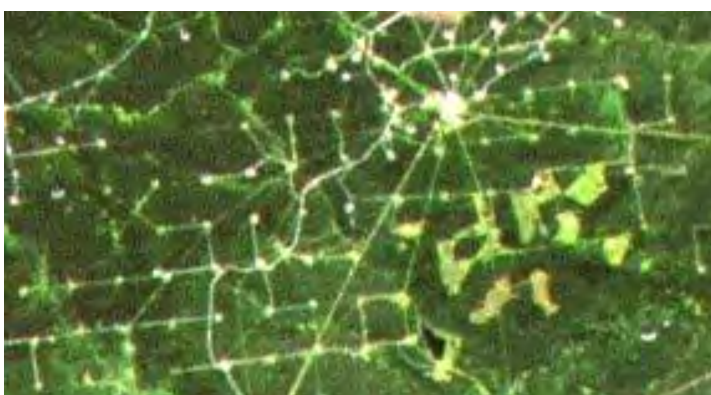
Other Scenarios: Hypothetical Alternative Economic Programs

Wolf cap to achieve non-declining ecosystem wealth

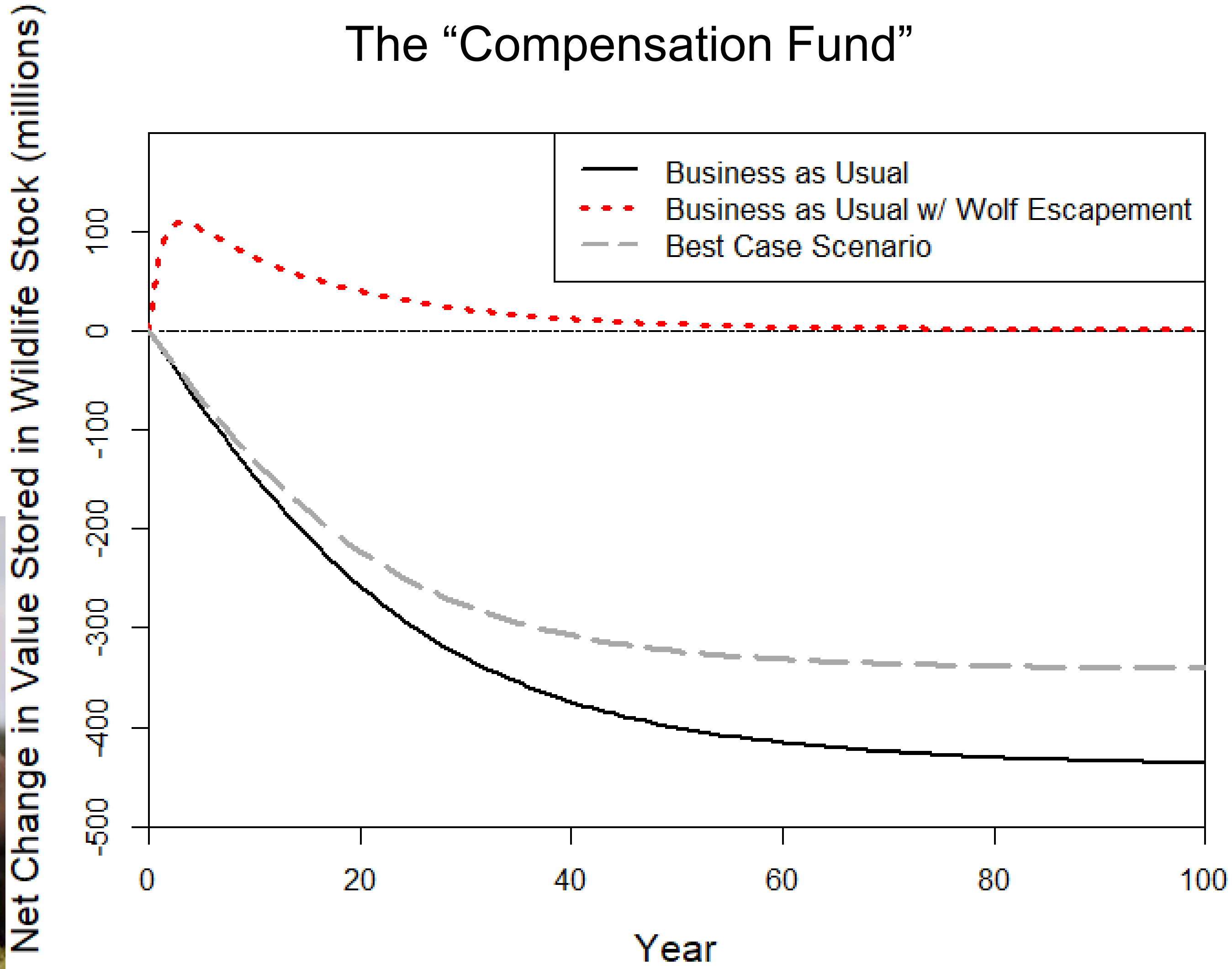


Wolf cap to achieve "recover" caribou (~1200 wolves)



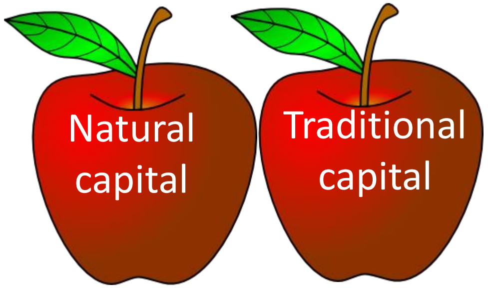


Ecosystem Conservation and Sustainability



Take away messages

- **Sustainability means conservation of capital wealth** including natural capital like caribou.
- Based on current *revealed* behavior, some restoration and no wolf cap, the **marginal caribou is worth on the order of $80K CAD**, which is low compared to *stated* willingness to pay.
    - If the revealed value is low, then maybe learn from the famers in Kansas and consider "better" caribou conservation.
    - If the revealed value is high, then maybe all is good.
- On the **current trajectory** the sustainability would require a **compensation fund** of at least **$400M CAD**.
- Remember management changes capitalize through assets – ecosystem management changes capitalize through natural capital.
- Applications to fish, caribou, groundwater, and forests.



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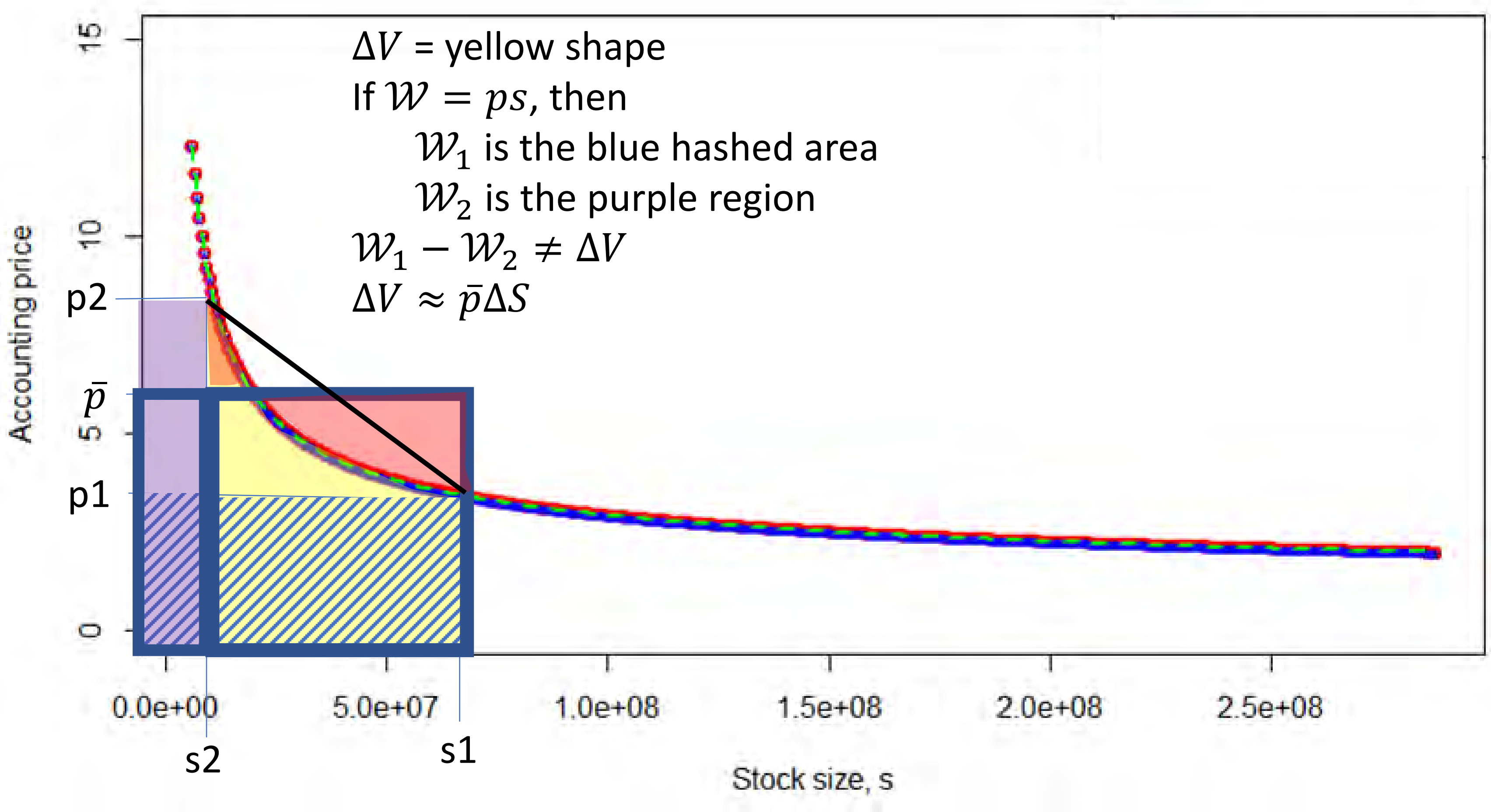
Research Directions

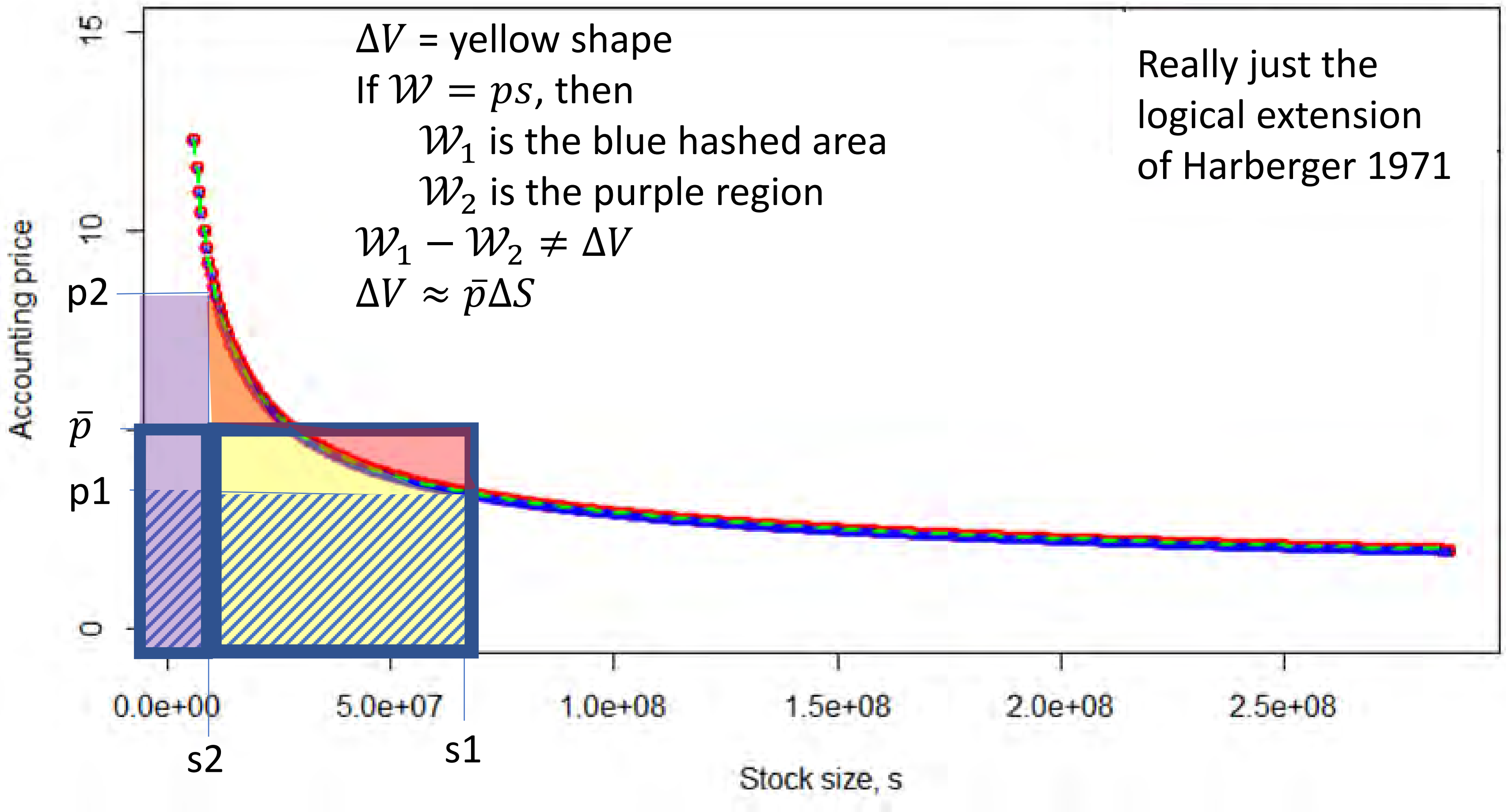
- Focused multi-disciplinary research to jointly understand the human behaviors, net benefits, and ecological dynamics.
    - Ecological dynamics are often sufficiently well understood, but certainly could be improved – greater ecological challenge is defining tractable stocks.
    - The economic program and feedback rules are not well understood.
    - Valuing "dividends" remains a challenge.
- Need to look at human-ecological systems with real data (if simplified models) not hypothetical situations.
- Need to understand the difference between accounting for performance and benefit-cost analysis.
- Consider that people acting like they care – Samuelson revealed preferences.
- Realize that imperfect markets still express value.
- Policy design that rewards firms for boosting increases in wildlife wealth – means we need measurement.

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



Adapted from Fenichel et al. 2016 Nature Climate Change

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

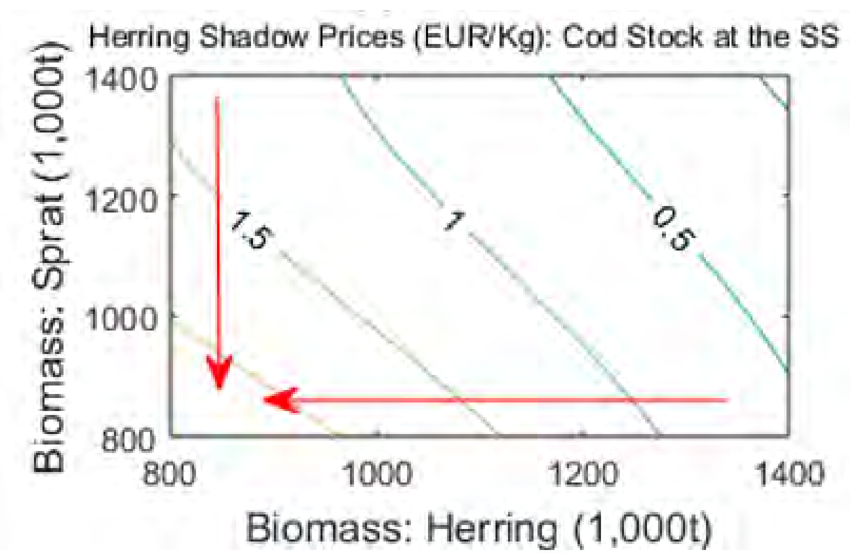


Adapted from Fenichel et al. 2016 Nature Climate Change

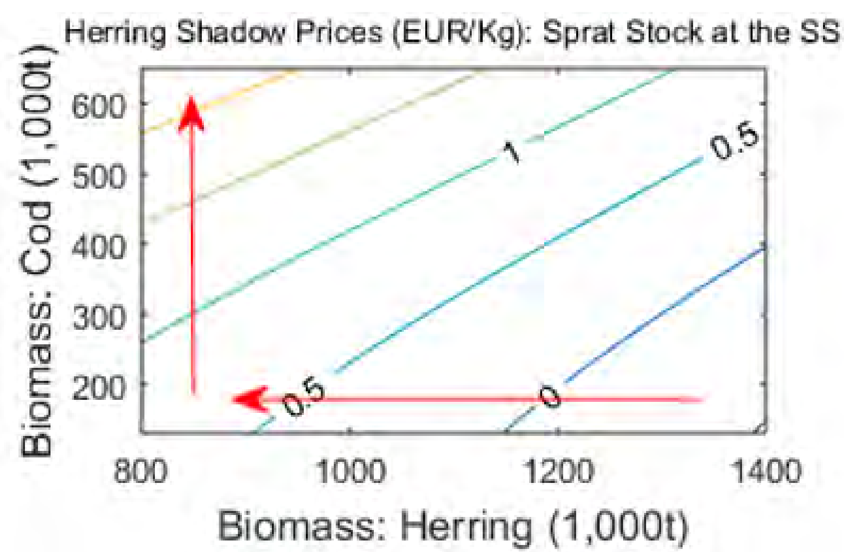
Cross stock effects in price (cross partial of value function) – capture the limits of substitution

Stocks i and j are only complements if $V_{s^i s^j}(\mathbf{s}) = \frac{\partial p^i(\mathbf{s})}{\partial s^j} > 0$

By the implicit function theorem $\frac{ds^j}{ds^i} = -\left(\frac{V_{s^i s^i}}{V_{s^i s^j}}\right)$, so upward sloping contours in state space indicate complements



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!

Deriving asset prices for natural capital

The forecastable behavioral equilibrium allows

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

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

Define

$p^i(\boldsymbol{s}) \equiv \partial V(\boldsymbol{s})/\partial s^i$

Deriving asset prices for natural capital

Apply Ito's lemma

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

Taking the expectation and dividing by dt

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

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

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Deriving asset prices for natural capital

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

This is a current value Hamiltonian or fundamental asset equation

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

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

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

Deriving asset prices for natural capital

Deterministic terms

Own and cross-price effect

Cross-stock effect

Stochastic terms or a "portfolio term"

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

Endogenous risk: effects of changes is s^i on the variances or covariances as valued through the curvature of the intertemporial welfare function

Endogenous risk aversion or "prudence": effects of perturbing s^i on the curvature of the value function (third derivative of the intertemporal welfare function) – a type of self-insurance.

Upshot: shadow prices are linked deterministically through biophysical & economic interaction and stochasticially through covariances.

Approximating asset prices for natural capital

Asset value equation

$$V(s) = \delta^{-1}\left(W\big(\boldsymbol{s}, \boldsymbol{x}(\boldsymbol{s})\big) + \boldsymbol{p}\big(\boldsymbol{s}(t)\big)'\dot{\boldsymbol{s}}\right)$$

Or

Shadow price

$$p^i(\boldsymbol{s}) = \frac{W_{s^i}(\boldsymbol{s}, \boldsymbol{x}(\boldsymbol{s})) + \frac{\partial p^i}{\partial s^i}\dot{s}^i + \sum_{j \neq i}\left(\frac{\partial p^j}{\partial s^i}\dot{s}^j + p^j \frac{\partial \dot{s}^j}{\partial s^i}\right)}{\delta - \left(G^i_{s^i}(\boldsymbol{s}) - f^i_{s^i}\big(\boldsymbol{s}, \boldsymbol{x}(\boldsymbol{s})\big)\right)}$$

For a single stock

$$p(s) = \frac{W_s + \dot{p}}{\delta - \left(G_s(s) - f_s\big(s, x(s)\big)\right)} = \frac{W_s + p_s\dot{s}}{\delta - \left(G_s(s) - f_s\big(s, x(s)\big)\right)}$$

Approximating asset prices for natural capital

Approximator	Information used to identify coefficients	Other tradeoffs
V (multi-state and stochastic)	$W(s)$, $\dot{s}$, Ω^{jk}	Easily handles multi-dimensional problems, approximations are decidedly non-targeted. Solves the aggregation problem. Can be modified for cases when $x(s) \notin \mathbb{C}^1$
$V_s(s) = p(s)$ (deterministic, better for single stock)	$W_s(s)$ and $\dot{s}_s$	Makes use of marginal effects, which are often what are estimated empirically. Approximations not targeted.
$V_{ss}\dot{s} = \dot{p}(s)$ (deterministic probably single stock)	$W_s(s)$, $W_{ss}(s)$, $\dot{s}_s$, $\dot{s}_{ss}$	Make use of more information than p approximator, but that means we must be more confident in that additional information. Requires twice differentiability especially in $\dot{s}$. If $\dot{s}_{ss} \approx 0$, relies heavily on $W_{ss}(s)$ rather than $W_s(s)$. Gives targeted approximation.

- Yun, Hutniczak, Abbott, & Fenichel, 2017. Ecosystem based management and the wealth of ecosystems. *PNAS 114, 6539.*
- Fenichel, Abbott, & Yun. *forthcoming*. "The nature of natural capital and ecosystem income." In Handbook of Environmental Economics edited by V. K. Smith, P. Dasgupta and S Pattanayak. North Holland.

Approximating asset prices for natural capital

Need a way of approximating unknown functions
A way to explore all possible simulations at once.

$$p^i(\boldsymbol{s}) = \frac{W_{s^i}(\boldsymbol{s}, \boldsymbol{x}(\boldsymbol{s})) + \frac{\partial p^i}{\partial s^i}\dot{s}^i + \sum_{j \neq i}\left(\frac{\partial p^j}{\partial s^i}\dot{s}^j + p^j \frac{\partial \dot{s}^j}{\partial s^i}\right)}{\delta - \left(G^i_{s^i}(\boldsymbol{s}) - f^i_{s^i}(\boldsymbol{s}, \boldsymbol{x}(\boldsymbol{s}))\right)}$$

or

$$\delta V(\boldsymbol{s}) = W\big(\boldsymbol{s}, \boldsymbol{x}(\boldsymbol{s})\big) + \Big(\boldsymbol{G}(\boldsymbol{s}) - \boldsymbol{f}\big(\boldsymbol{s}, \boldsymbol{x}(\boldsymbol{s})\big)\Big)' \boldsymbol{p}(\boldsymbol{s})$$

1. Replace the unknown function with an approximating function (e.g., a polynomial): $\mu\big(s(t)\big) = \sum_{n=0}^{N-1} \beta_n \phi_n(s(t))$
2. Substitute in $x(s)$ so that the RHS is only a function of stock value
3. Choose a finite number of evaluation points of $\boldsymbol{s} \in \mathbb{R}^N$
4. Three ways to approximate: $V \approx \mu$ so that $p^i = V_{s^i} \approx \mu_s$;
   $p \approx \mu$, which leads to $\dot{p} = \mu_s \dot{s}$;
   $\dot{p} \approx \mu$, which leads to a messier expression
5. Algebraic solutions for the parameter vector.

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 $\frac{\partial^2 V(S^m)}{\partial s^i \partial s^j} \approx \frac{\partial^2 \Phi^m(\boldsymbol{S})}{\partial s^i \partial s^j}\beta$

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

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

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

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

Connection to dynamic programming

Consider the problem, assume that problem is not linear in u

$$V(s) = \max_{u \in \mathbb{R}} \int_{t=0}^{\infty} e^{-\delta\tau} W(s(\tau), u(\tau))\, d\tau \text{ s.t. } \dot{s} = G(s) - f(s,u),\ s(0)$$

We would write out

$$\delta V = H(x,u) = W(s,u) + \lambda\big(G(x) - f(x,u)\big) = W(s,u) + V_s\big(G(s) - f(s,u)\big)$$

F.O.C.

$$W_u - \lambda f_u = 0 \rightarrow u(s, V_s)$$

Write

$$\delta V(s) = W(s, u(s, V_s) + V_s\left(G(s) - f\big(s, u(s, V_s)\big)\right)$$

Approximate $V(s)$ and $V_s(s)$ with $\Phi\beta$ and $\Phi_s\beta$
Calculate at as least as any values of s as the length of β.
Need to recover β to make the HJB hold, but β enters nonlinearly
Minimize on error function or used a fixed point solver

capn

- Creates N-dimensional Chebychev basis functions.
- Lay out a node array.
- Handles parameter flows.
- Provides efficient solutions to the generalized inverse problem when there is a closed form based on the type of problem.
- Manages simulation inputs.
- Provides some Demos

- Much of this can also be done in the Matlab compecon library.
- We know of people doing it in excel.