Valuing Natural Capital in the Context of Ecosystem Based Management

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Natural capital

Traditional 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...”

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

- Depends on all stocks, \( s \), not just stock \( s^i \)
- Depends on the institutions, \( \Omega \), including who and what counts
- Depends on the actual measured economic program \( x(s; \Omega) \), 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 \( p^i(s(t); \Omega) = \frac{\partial V(s(t), x(s(t); \Omega); \Omega)}{\partial s^i(t)} \)

- 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

\[ \Delta V = \text{yellow shape} \]

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
\[ \Delta V = \text{yellow shape} \]

If \( W = p_s \), then

- \( W_1 \) is the blue hashed area
- \( W_2 \) is the purple region?

\[ W_1 - W_2 \neq \Delta V \]

\[ \Delta V \approx \bar{p}\Delta S \]

Harberger 1971 – NNP first-order approximation to a welfare measure
Where we take the approximation has to update

Adapted from Fenichel et al. 2016 NCC & 2018 HEE
Natural capital can be valued symmetrically with traditional capital
Fenichel & Abbott 2014 JAERE:: Jorgenson 1963 AER

Most important difference from Jorgenson’s work – what is observable
Value of extra ecosystem service flows from one more unit of stock. Market and non-market valuation economics, marginal income.

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

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

Δ in Capital Service Flows (dividends)

Unit Price of Capital

Discount Rate

Δ in Growth Rate of Capital Stock

Capital Gains

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](https://github.com/efenichel/capn_stuff)
Interacting natural capital in the Baltic Sea & Connecting to EBM
A framework for human-environmental systems research that hits policy

- 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: map from Wikipedia

Hunting (2015)
- Cod, herring, and sprat make up 88% of the revenue (STECF, 2013)
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Source: Hutniczak (2015)

Heterogeneous vessels maximize profits → whole Baltic Sea Fishery

8 age-categories

411 Heterogeneous vessels maximize profits → whole Baltic Sea Fishery

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

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

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

The nature of natural capital and ecosystem income*

Eli P. Fenichel, Joshua K. Abbott, and Seong Do Yun

Available online 3 April 2018
In Press, Corrected Proof — Note to users

More Information

Handbook of Environmental Economics

Ecosystem-based management and the wealth of ecosystems

Seong Do Yun*, Barbara Hutniczak, Joshua K. Abbott, and Eli P. Fenichel

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Edited by Kanta Sato, Nippon Medical School, Tokyo, Japan, and approved May 11, 2017 (received for review October 24, 2016)

We merge inclusive wealth theory with ecosystem-based management—increasing “wealth”—the price-weighted sum of all societal goods and services—by management of ecosystems.

Measuring the value of groundwater and other forms of natural capital


School of Forestry and Environmental Studies, Yale University, New Haven, CT 06520; School of Sustainability, Arizona State University, Tempe, AZ 85287; College of Agriculture, California State University, Chico, CA 95929; and Department of Geological Sciences, Michigan State University, East Lansing, MI 48824.

Edited by: https://github.com/efenichel/capn_stuff

Get rights and content
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](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 2011 ReStat
  o Zhang 2011 BE Economic Analysis & Policy
Shadow Price Curve for Gulf of Mexico Case
Multiple approaches
Based on Fenichel & Abbott 2014

$3.08
• 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 Chebyshev polynomial.

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

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

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

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

\[
\beta = (\Psi(S)' \Psi(S))^{-1} \Psi(S)' W(S)
\]

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

*Water Level Change 1995-2006, feet*

**Scallops and climate change**
(exogenous forcing)

**Endangered species (caribou) and Forests beyond timber**
• 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 \( \Delta V \approx \Delta W = \bar{p} \Delta S \) 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

\[
\Delta W = \sum_{i \neq j} \bar{p}_i \Delta S_i + \int_{s_j(t)}^{s_j(t+\epsilon)} p_j(\xi, s_{-j}(t); \phi) \, d\xi
\]

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

Recognize that the economic program must be recovered empirically.

\[ W_{si}(s(\tau), x(s(\tau))) \equiv W^*_s = \frac{\partial W}{\partial s_i} + (\nabla_x W)' \frac{dx}{ds_i}, \] similar for \( f \)

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

\[ ds^i = \mu^i(s, x(s))dt + \sigma^i(s)dZ^i \] \( \forall i \) allows for a stochastic process in \( G \).

Once the economic program is substituted in, just a function \( s \).

\[ Cov(ds^i, ds^j) = \Omega^{ij}(s)dt \]

This means

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

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Apply Ito’s lemma

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

Taking the expectation and dividing by \( dt \)

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

In the deterministic case this simplifies to

\[ \frac{dV(s)}{dt} = \sum \frac{\partial V}{\partial s^i} \frac{ds^i}{dt} = \Sigma p \dot{s} \]

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

Setting \( \frac{dV}{dt} = \frac{dV}{dt} \)
Deriving asset prices for natural capital

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

This is a current value Hamiltonian or fundamental asset equation

Take the partial with respect to the stock and isolate \( V_{si} = p^i \)

\[
p^i(s) = \left[ W_{si} + \left( \frac{\partial p^i}{\partial s^i} \mu^i + \sum_{j \neq i}^{S} \frac{\partial p^i}{\partial s^i} \mu^j \right) \right] + \sum_{j \neq i}^{S} p^j \mu^j_s + \frac{1}{2} \sum_{j}^{S} \sum_{k}^{S} \left( \Omega_{s}^{jk} \frac{\partial p^i}{\partial s^k} + \Omega_{s^k}^{jk} \frac{\partial^2 p^i}{\partial s^k \partial s^i} \right)
\]

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 \( p(s) = \frac{W_s(s, x(s)) + \dot{p}}{\delta - (\dot{g}_s(s) - f_s(s, x(s)))} \) this is Jorgenson’s value of invested capital if \( W_s \) is constant and \( \dot{p} = 0 \)
Deriving asset prices for natural capital

\[ p^i(s) = W^i_s + \left( \frac{\partial p^i}{\partial s^i} \mu^i + \sum_{j \neq i}^S \frac{\partial p^j}{\partial s^i} \mu^j \right) + \sum_{j \neq i}^S p^j \mu^j_s + \frac{1}{2} \sum_j^S \sum_k^S \left( \Omega^{jk}_s \frac{\partial p^i}{\partial s^k} + \Omega^{jk}_s \frac{\partial^2 p^i}{\partial s^k \partial s^l} \right) \]

Focus in on capital gains

\[ \left( \frac{\partial p^i}{\partial s^i} \mu^i + \sum_{j \neq i}^S \frac{\partial p^j}{\partial s^i} \mu^j \right) + \sum_{j \neq i}^S p^j \mu^j_s + \frac{1}{2} \sum_j^S \sum_k^S \left( \Omega^{jk}_s \frac{\partial p^i}{\partial s^k} + \Omega^{jk}_s \frac{\partial^2 p^i}{\partial s^k \partial s^l} \right) = \]

- **Own and cross-price effect**
- **Cross-stock effect**
- **Deterministic terms**
- 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.