Ecological Economics of Water Quality: Mud and Precaution

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Overview of the Lecture

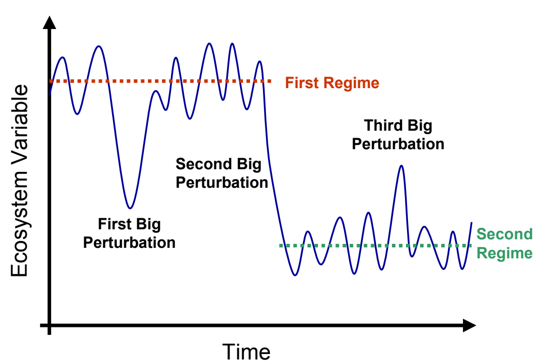
Ecological regime shifts, thresholds and resilience

Eutrophication (over-fertilization) of lakes, rivers, oceans

A model for the ecological economics of eutrophication

Uncertain thresholds and the challenge of learning

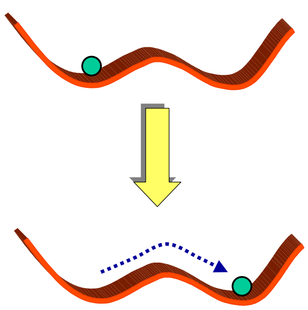
Regime shifts and the precautionary principle

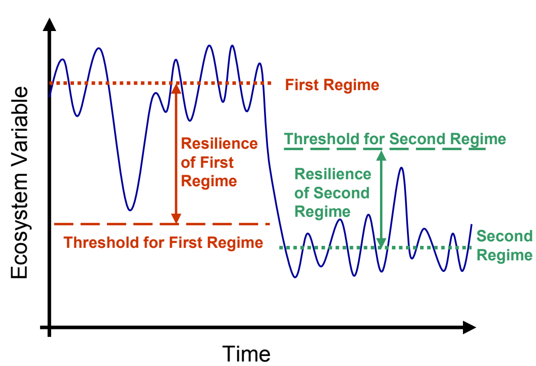


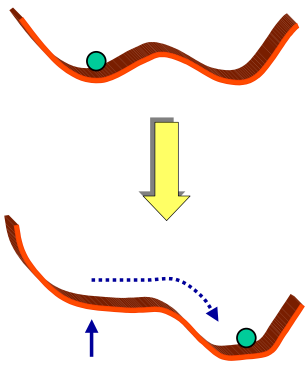
Exogenous (forced from outside)?

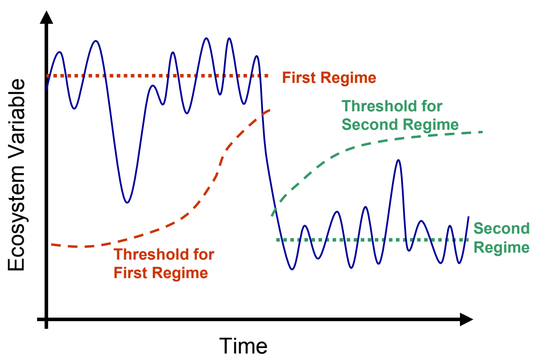
Or endogenous (result of internal dynamics)?

Or both?









Ecosystem Type	Alternative State 1	Alternative State 2	References
Freshwater Systems	Clear Water Benthic Vegetation	Turbid Water Blue-green algae	*Carpenter 2001* *Scheffer et al. 2001*
	Oligotrophic macrophytes and algae	Cattails and blue green algae	*Gunderson 2001*
	Game fish abundant	Game fish absent	*Post et al. 2002*
Marine Systems	Hard coral	Fleshy Algae	*Nyström et al. 2000*
	Kelp forests	Urchin dominance	*Estes and Duggins 1993*
	Seagrass beds	Algae and muddy water	*Gunderson 2001*
	Fish stock abundant	Fish stock depleted	*Walters and Kitchell 2001, Steele 1998*
Rangelands	Grass structure	Shrub structure	*Walker 1993*
Forests	Pest outbreak	No pest	*Holling 1986*
	Pine Trees dominate	Hardwood plants dominate	*Peterson in press*
	Birch-Spruce succession	Pine dominance	*Danell et al. in review*
Arctic Systems	Grass dominated	Moss dominated	*Zimov et al. 1995*

Scheffer et al. 2001, Nature 413: 591-596; Folke et al. 2002, Ambio 31: 437-440

Atlantic Thermohaline Circulation*

Warming climate ->

Rapid melting of arctic ice ->

Meltwater floats above the Gulf Stream ->

Heat from Gulf Stream cannot reach the atmosphere ->

Rapid cooling of Europe

*Taylor, K. 1999. Rapid climate change. *American Scientist*, **87**, 320-327

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Example: Eutrophication of Lakes

Eutrophication = Over-enrichment of freshwater with mineral nutrients, especially phosphorus

Consequences:

Blooms of toxic algae, associated diseases

the ONION

WALL STREET

Species Of Blue-Green Algae Announces IPO

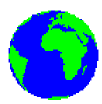
Consequences of eutrophication, continued:

Fish kills

Increased costs of water purification for domestic, agricultural or industrial use

Water supply involves quality as well as quantity.

Fresh Water Problems are Global



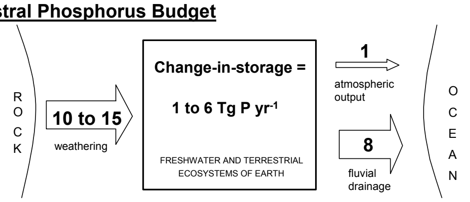
One third of the world's people live under water stress (1.3 billion lack adequate supply of safe water; 2 billion lack access to sanitation). By 2025, two thirds of people, mainly in developing nations, will live under moderate to severe water stress.

Half of world's available fresh water is used by people; all of it will be needed by 2035. 70% of this water is used for irrigation.

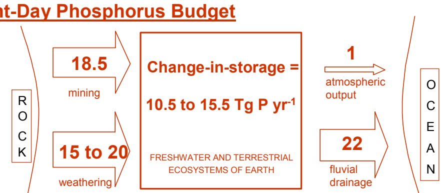
Poor land use is a major cause of water resource degradation.

Source: UNEP 1998

Ancestral Phosphorus Budget



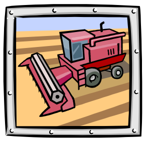
Present-Day Phosphorus Budget



Source: Bennett, Carpenter & Caraco, BioScience 2002

Where does the phosphorus come from?

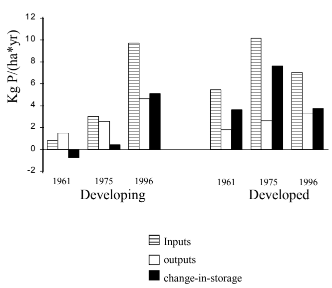
Mining has doubled the flow of phosphorus from rocks (where it is not available) to soils. Fertilizer can be taken up by plants or run off to streams, lakes and oceans.



The accumulation rate of phosphorus in the world's agricultural soils has doubled in the past century.

Discharge of phosphorus to the world's oceans has tripled.

Fertilizer Application is Declining in Developed Nations But Accelerating in Developing Nations

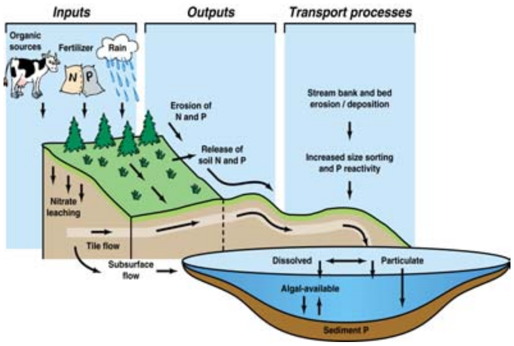


Source: Bennett, Carpenter & Caraco, BioScience 2002

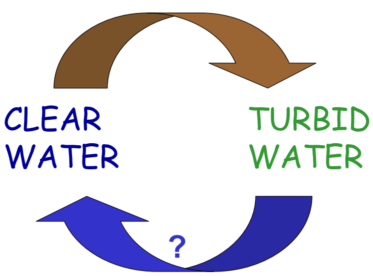
Moderate amounts of phosphorus in soils increase agricultural production.

Excessive amounts of phosphorus in soils increase water pollution and decrease water quality.

Nonpoint Nutrient Runoff to Freshwater Depends on Land Use, Livestock Density, and Fertilizer Use



Reversibility is the key question:
Can eutrophication be reversed at the same rate it is created?



Some experiences with reversing eutrophication:

Success is likely in certain types of lakes
(e.g. deep, fast flushing, low sediment P)

Recovery is delayed, or requires extreme P reduction
(or additional measures) in many lakes

Recycling of phosphorus can impede recovery

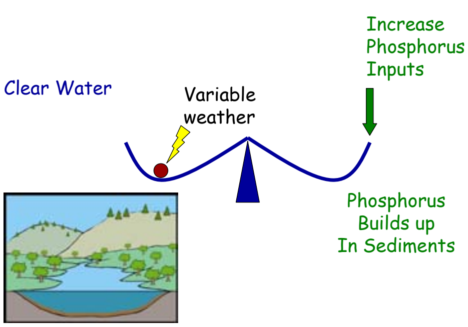
In some lakes, reversal has failed (so far)
(e.g. anoxic hypolimnia, slow flushing, high sediment P)

Some sources: Sas 1989, National Research Council 1992, Cooke et al. 1993

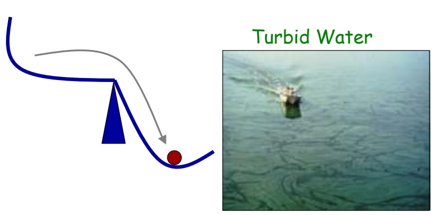
Conclusion: Reversibility is not guaranteed.

Reversal of eutrophication may be delayed, may require massive manipulation, or may sometimes be impossible.

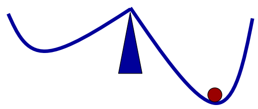
Toxic Algae Bloom



Buildup of Phosphorus in sediments, plus ongoing input, shifts the lake to the turbid state:



Phosphorus buildup in sediments makes the turbid state permanent



Accumulation of phosphorus in lake sediment (mud)
*Decreases resilience of clear-water state
* Increases resilience of turbid-water state

Accumulation of phosphorus in farmland soil increases mean and variance of phosphorus input

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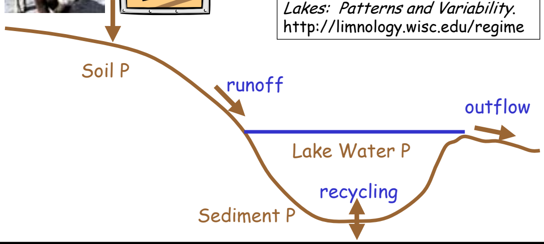
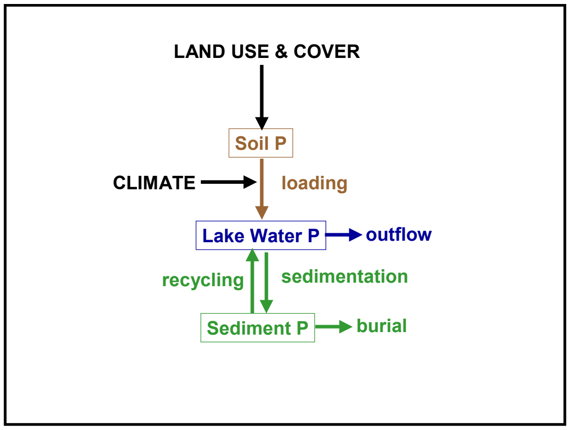
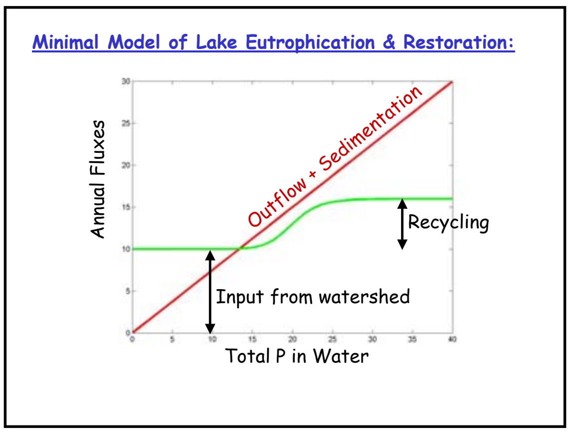
Minimal Model of Lake Eutrophication & Restoration: Pools and Fluxes

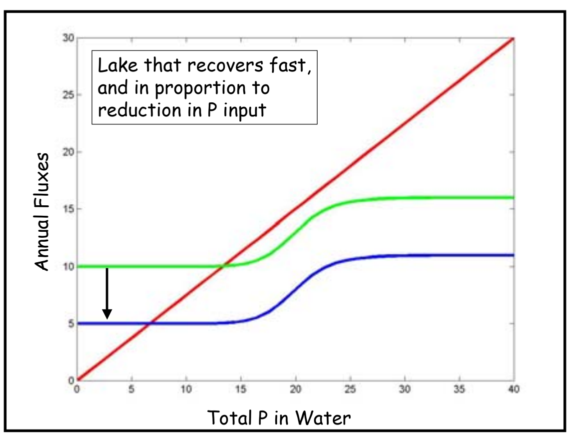
Carpenter, Ludwig & Brock, Ecological Applications 9: 751-771

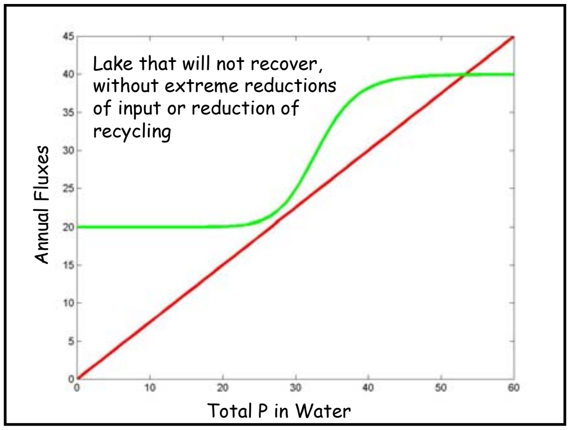
Carpenter, 2003, *Regime Shifts in Lakes: Patterns and Variability.* http://limnology.wisc.edu/regime



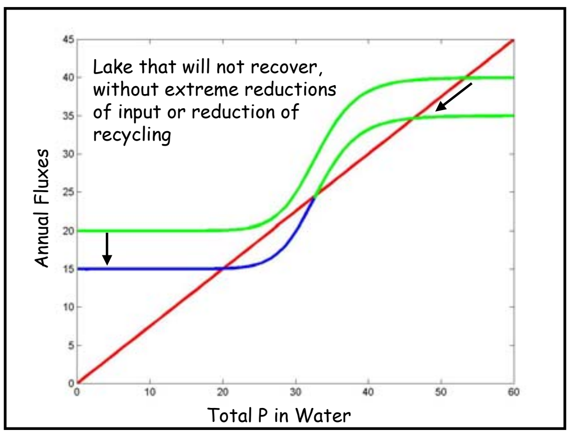

LAND USE & COVER
Soil P
CLIMATE
loading
Lake Water P
outflow
recycling
sedimentation
Sediment P
burial


Minimal Model of Lake Eutrophication & Restoration:
Annual Fluxes
Outflow + Sedimentation
Recycling
Input from watershed
Total P in Water


Lake that recovers fast,
and in proportion to
reduction in P input
Annual Fluxes
Total P in Water



Lake that will not recover,
without extreme reductions
of input or reduction of
recycling
Annual Fluxes
Total P in Water



Lake that will not recover,
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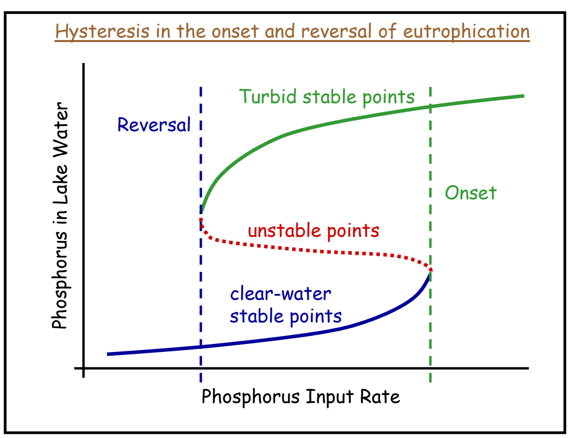
of input or reduction of
recycling
Annual Fluxes
Total P in Water



Hysteresis in the onset and reversal of eutrophication
Turbid stable points
Reversal
Onset
unstable points
clear-water
stable points
Phosphorus in Lake Water
Phosphorus Input Rate

Minimal Model – Key Features:

Mass balance for P cycle of soil-water-sediment system

Principal methods for mitigating eutrophication (Cooke et al. 1993) can be built in by adjusting parameters.

Accounts for management case studies, including the delays and failures, with appropriate parameters.

Accounts for stochasticity of inputs and variance of parameter estimates

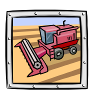
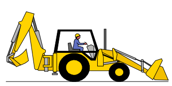
Designed for use in decision analyses, using economic costs and benefits

Carpenter, Ludwig & Brock, 1999, Ecological Applications 9: 751-771

Decision Analysis of Eutrophication:


Balance two economic flows:

Economic benefits of activities that create P pollution

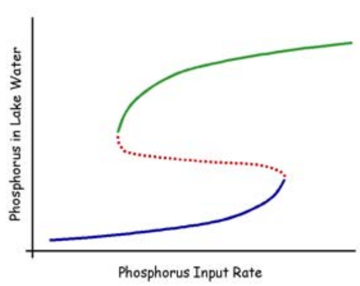





Economic benefits of water quality




Water for: * drinking * health * irrigation * industry

General outcome for the eutrophication problem:



High P Input can be optimal*

Decreasing P input is optimal

* Analysis does not include downstream impacts

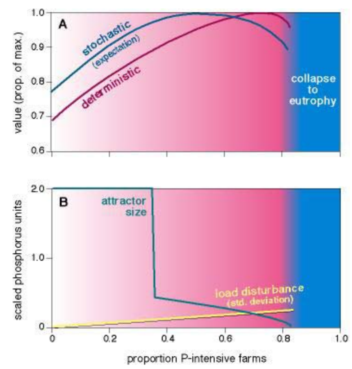
Consequences of slow reversibility / irreversibility:

Economically optimal P input rates are lower than if rapid reversibility is assumed.

Because of P buildup in soils and sediments, the system can be "an accident waiting to happen"

Should decision analyses focus on soil and sediment phosphorus (the "slow variables"), instead of water chemistry ("fast variable")?

Optimal Inputs are Lower if Variability is Considered



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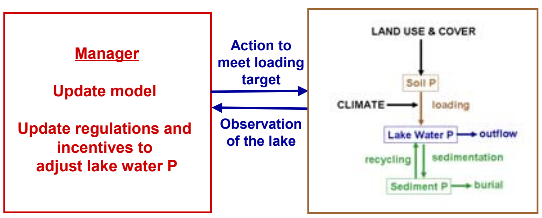
Uncertainty and Learning

For most ecosystems, the appropriate model is unknown, the parameters are uncertain, the data are observed with error, and inputs are subject to large random shocks.

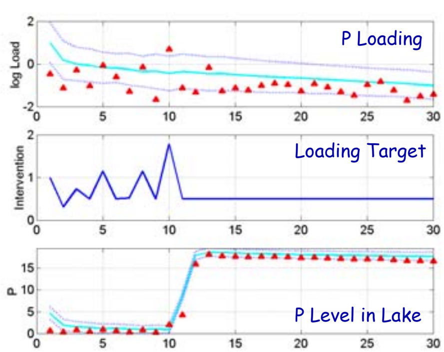
Therefore, learning could significantly improve management.

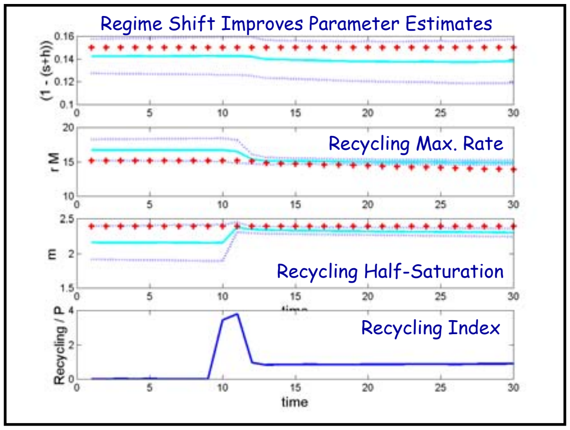
Is it possible to “learn by doing”, i.e. reduce uncertainty while we manage?

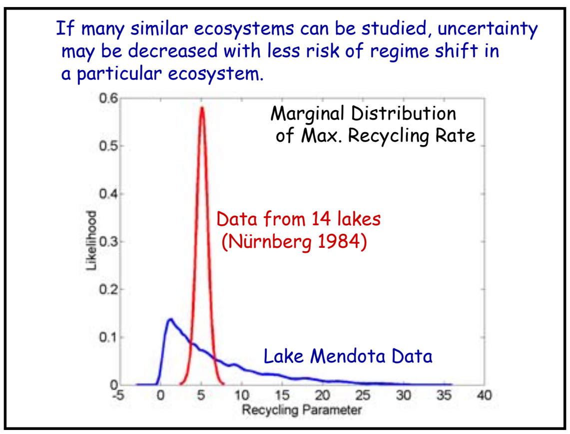
Simulation Exercise

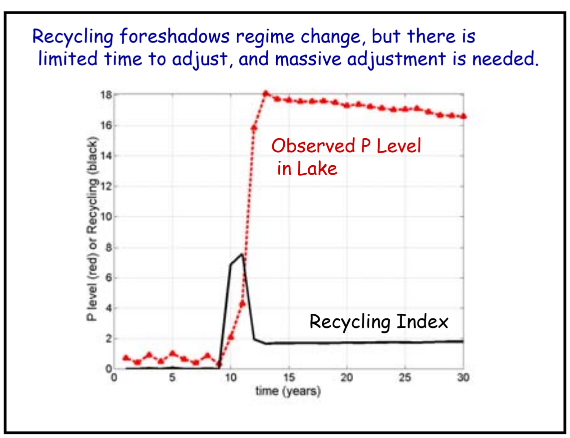


Experiments Can Lead to Regime Shifts




Regime Shift Improves Parameter Estimates
(1 - (s+h))
Recycling Max. Rate
r M
m
Recycling Half-Saturation
Recycling / P
Recycling Index
time


If many similar ecosystems can be studied, uncertainty may be decreased with less risk of regime shift in a particular ecosystem.
Marginal Distribution of Max. Recycling Rate
Likelihood
Data from 14 lakes (Nürnberg 1984)
Lake Mendota Data
Recycling Parameter


Recycling foreshadows regime change, but there is limited time to adjust, and massive adjustment is needed.
P level (red) or Recycling (black)
Observed P Level in Lake
Recycling Index
time (years)

Recycling is a "leading indicator" of shift to the turbid-water state.

Other indicators related to the second derivative of P level in the water also provide advance warning.

In other systems, research shows that variance spectrum "reddens" prior to a regime shift. (e.g. Kleinen, Held & Petschel-Held, PIK)

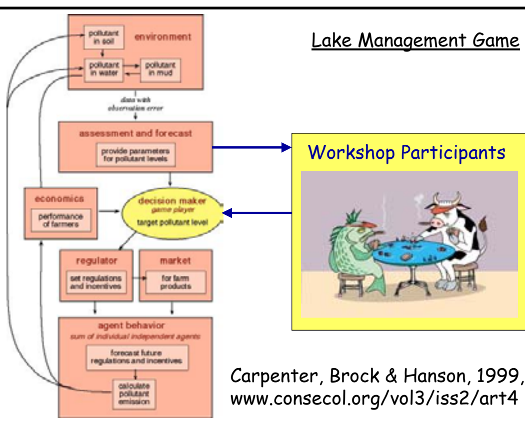
Can management institutions respond to these signals rapidly enough?
Lakes: 1-2 years
Thermohaline circulation: decades?

In singular (unique) ecosystems, lessons about regime shifts may come "the hard way".

Surprises are not rare in ecosystem management.

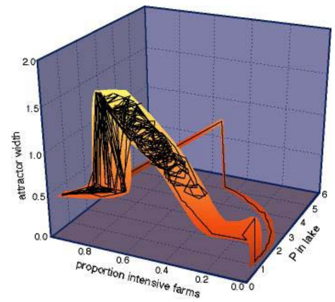

the ONION
God Promises 'Big Surprises' In Store For Hurricane Season

Lake Management Game

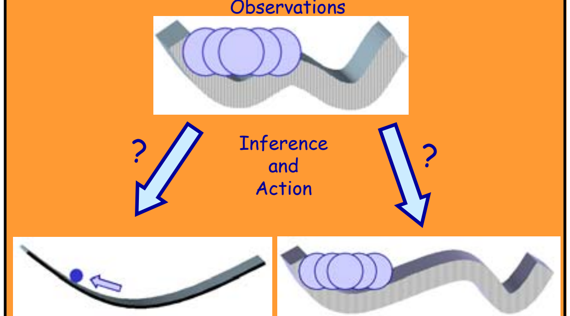


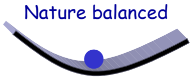
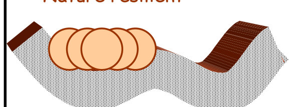
Carpenter, Brock & Hanson, 1999, www.consecol.org/vol3/iss2/art4

Experimental management can sustain agriculture and clear water for extended periods of time.



This takes flexibility, monitoring, fast responses.



Belief	Implications
Nature balanced 	•Changes are predictable •Variability can be squashed •Resilience is infinite •Control the fast variables
Nature resilient 	•Prediction is limited •Embrace variability •Build resilience •Tend the slow variables

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Regime shifts and the precautionary principle:

Precautionary Principle (Rio Declaration, 1992, Article 15):

". . . where there are threats of serious and irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

Difficulties:

Which threat? And how probable?
Serious and irreversible damage to what?
Cost-effective to whom?

Heal & Kriström, 2002, Environment & Resource Economics 22: 3-39

Could regime shifts provide a scientific basis for the precautionary principle?

Yes, in cases where there are substantial data.

This is most feasible for regime shifts we have seen often, like lake eutrophication and fisheries collapse.

* Ironically, these continue to occur, over and over; lessons never learned?

But completely novel regime shifts have occurred in the past, and there is no reason to think they will not occur in the future.

Summary

Regime shifts are infrequent, but important, events in ecosystems. Regime shifts have thresholds that may change over time. Resilience of a regime is measured by distance to the threshold.

Humans can increase the frequency and intensity of regime shifts, or build resilience of desired regimes.

Eutrophication is a type of regime shift with well-known mechanisms and big implications for human well-being.

Optimal policies for clear lakes call for low phosphorus input near the threshold.

Stochasticity and uncertainty imply even lower optimal levels of phosphorus input.

Summary, continued

Near the threshold, inclusive value is directly related to resilience. The direction of change needed to build resilience is known even when parameters are uncertain.

In general, ecological resilience depends on slowly-changing variables. Variability is sometimes crucial for resilience.

For most ecosystems, the appropriate model is unknown, the parameters are uncertain, the data are observed with error, and inputs are subject to large random shocks.

Uncertainty can be reduced by experimentation, especially when multiple similar ecosystems exist.

Economic analysis of ecological regime shifts may yield a scientific form of the precautionary principle.

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