Complex systems theory applied to ecosystem management

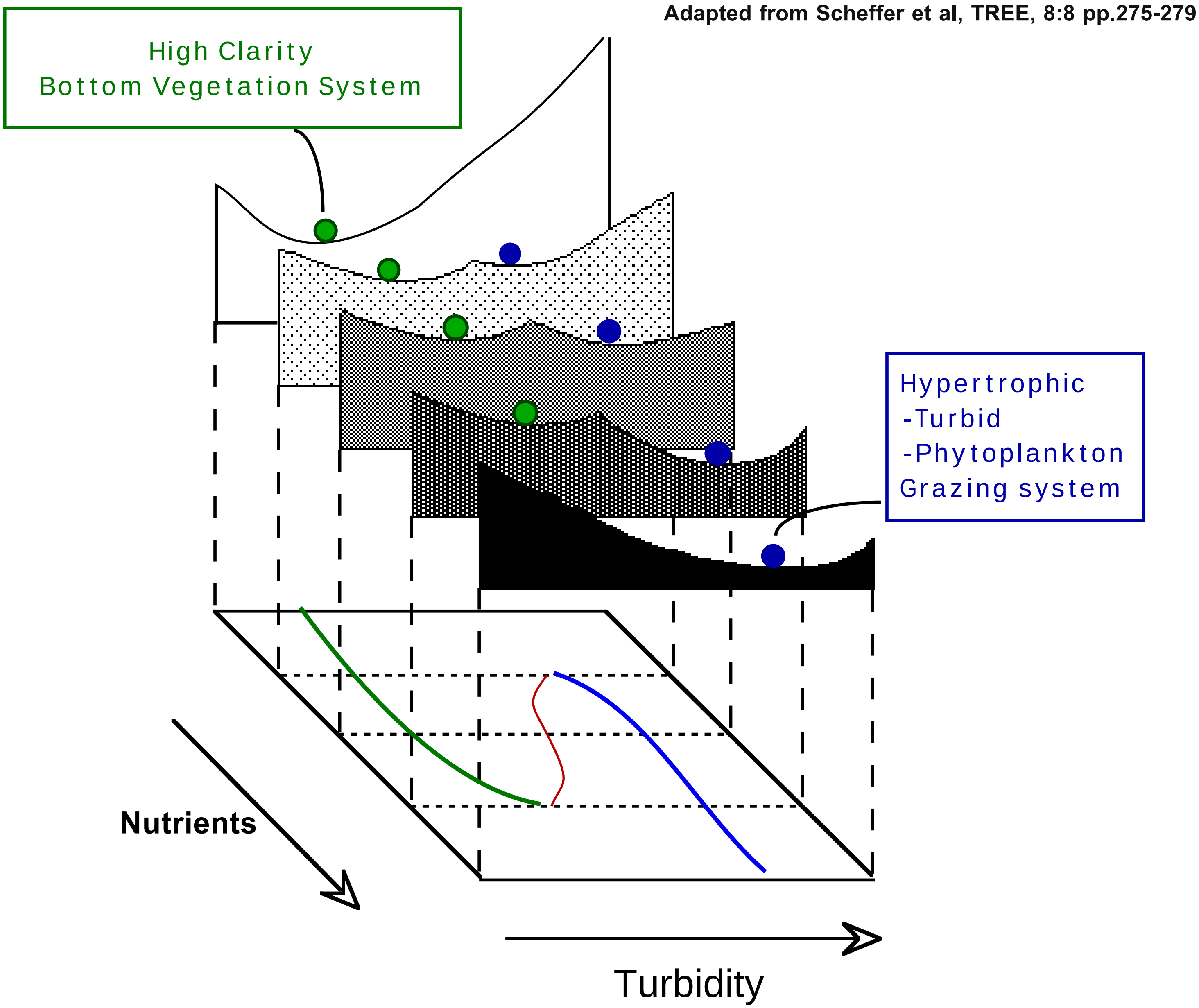
James J. Kay

in collaboration with:

Henry Regier, George Francis, David Waltner-Toews, Nina-Marie Lister, Martin Bunch….

Complex Systems Behaviour

- **The dynamics of complex systems involve:**
  - non-linear behaviour,
  - attractors and flips between attractors,
  - feedbacks,
  - emergence,
  - self-organization
  - chaos.
- **Generally these behaviours are not intuitive to people. They do not conform to the Newtonian linear causality mode of reasoning that is a cornerstone of our culture.**


Adapted from Scheffer et al, TREE, 8:8 pp.275-279
High Clarity
Bottom Vegetation System
Hypertrophic
-Turbid
-Phytoplankton
Grazing system
Nutrients
Turbidity

Linear Amp

Sound Out

Volume Control

Non-Linear Amp

Sound Out

Volume Control

Two state Amp (up)

Sound Out

Volume Control

Two state Amp (up)

Sound Out

Volume Control

Two state Amp (down)

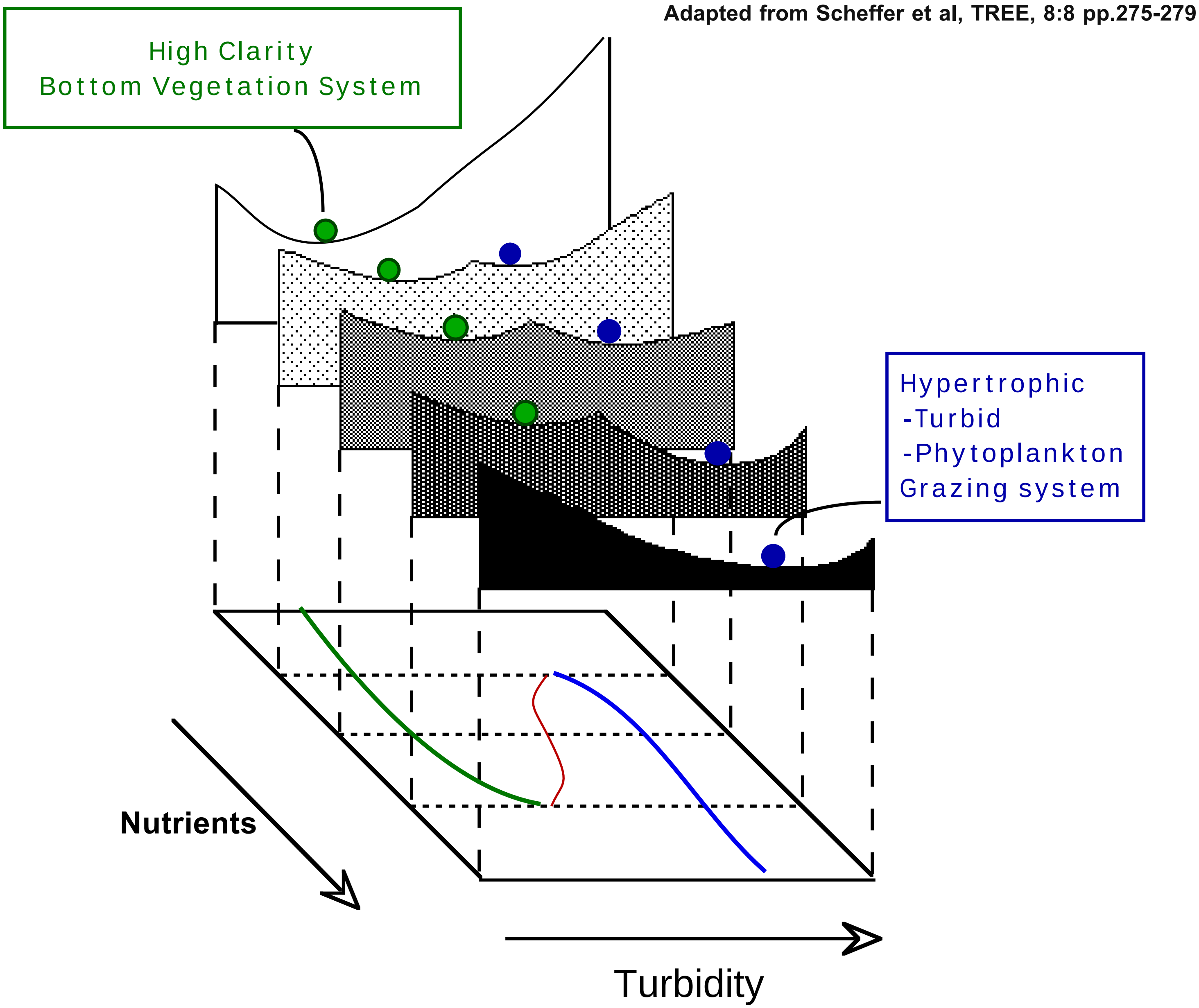
Sound Out

Volume Control

Two state Amp (down)

Sound Out

Volume Control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THE RECORD, Kitchener, Ontario

NEWS

TUESDAY, March 3, 1998

Erie's fish would benefit from pollution, anglers say

Could Lake Erie, long given up for dead, be too clean and need a little more pollution?

Yes, says the Ontario Federation of Anglers and Hunters, which believes fish populations are suffering because the lake is too clean.

The federation believes controls on sewage-treatment plants should be loosened to help boost flagging fish stocks — an approach many scientists warn is ecologically dangerous.

Anglers and scientists are at odds over phosphorus, the principal chemical controlling the productivity of freshwater ecosystems.

Phosphorus is critical in small concentrations for plant growth, but it was so abundant in the 1960s from sources such as detergents and sewage that it worked like a fertilizer, prompting out-of-control growth of seaweed and algae.

The decay of these plants took oxygen out of the water, suffocating fish and giving rise to suggestions that Lake Erie was dead.

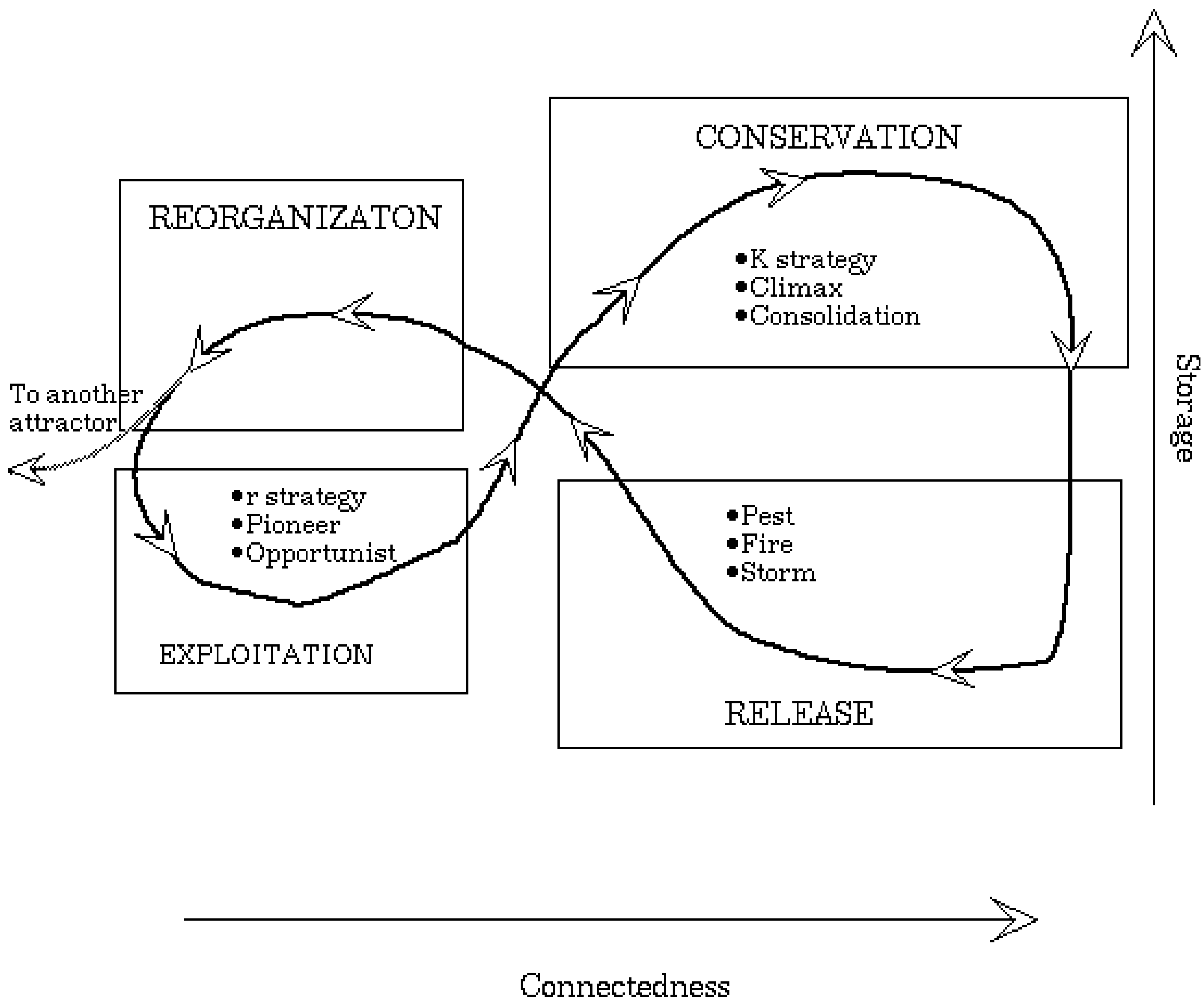
"We had too much of a good thing, too much of a critical nutrient," said Terry Quinney, a wildlife biologist at the federation.

"But gosh, have we reached a point where there is too little of this good thing to the detriment of healthy fish and wildlife?"

The phosphorus debate prompted research experts at the Lake Erie committee of the Great Lakes Fishery Commission to recommend last week that authorities hold the line on levels pending more study.

Phosphorus loadings have fallen in recent years, largely through better controls at sewage plants. The drop has contributed to an 80 per cent cut in algae levels, although the arrival in the late 1980s of zebra mussels, an exotic invader from Europe, is also a major factor in this decline.

Holling four box (∞)



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Implications of attractors

- **It now appears that flips, as versus slow continuous change, are quite normal in nature. It seems that the global climate system behaves this way as well. There is evidence of 8 flips, changes of mean temperature of 10°C in less than a decade. It appears that 15,000 years ago there was an increase of 16°C in a couple of decades.** (J. P. Severinghaus, E. J. Brook, Abrupt Climate Change at the End of the Last Glacial Period Inferred from Trapped Air in Polar Ice, Science, Volume 286, Number 5441 Issue of 29 Oct 1999, pp. 930 - 934).

Implications of attractors

- Incremental external change (pollution etc.) may not result in incremental change in an ecosystem. In fact it may appear that there has been no effect on the ecosystem. So no problem may be perceived. However if a threshold is reached, a small external change may cause dramatic ecosystem change. And then it is too late.

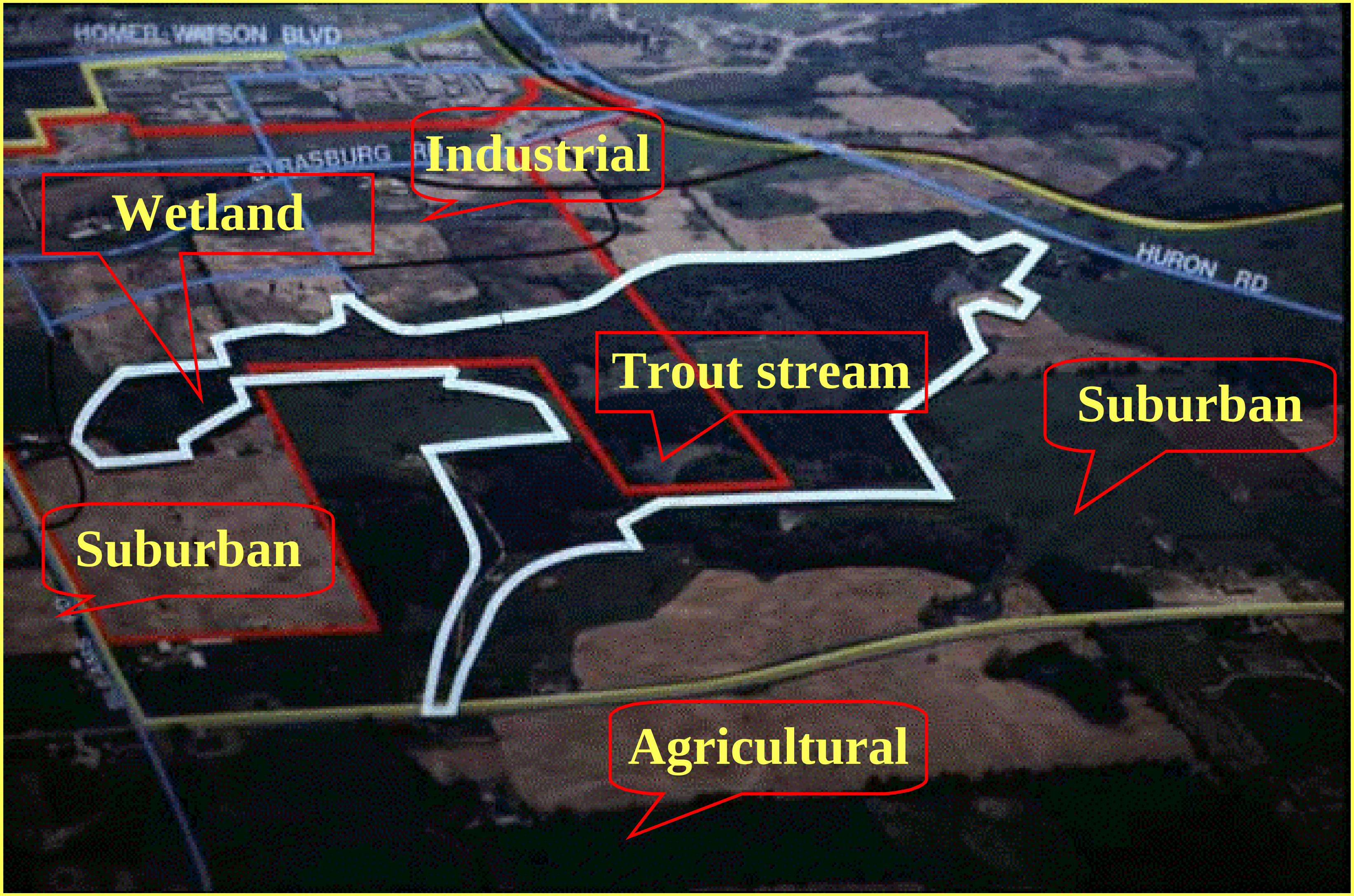
Implications of attractors

- **Ecosystems are organized about attractors. There are maintained at attractors by feedback loops. Feedback loops cannot be explained by linear cause and effect relationships, that is the traditional mechanical explanations that we use. This is because in a feedback loop the effect is part of the cause.**
- **The existence of more than one possible attractor in a given situation means that there may not be an ecologically preferred state for the system.**

Implications for modelling

- Models which incorporate feedback loops are needed. Linear models, except in special circumstances, will not suffice.
- Generally each attractor will have its own set of species, communities, interrelationships and canon (rule sets, emergent properties) associated with it. Thus each attractor will require a very different model to describe it. (How do we connect the models?)
- The ability to model and predict flips is problematic. Yet this is what decision makers need to know about.
- Modelling cannot tell us which is the “right” ecosystem in a given situation.

Huron Natural Area



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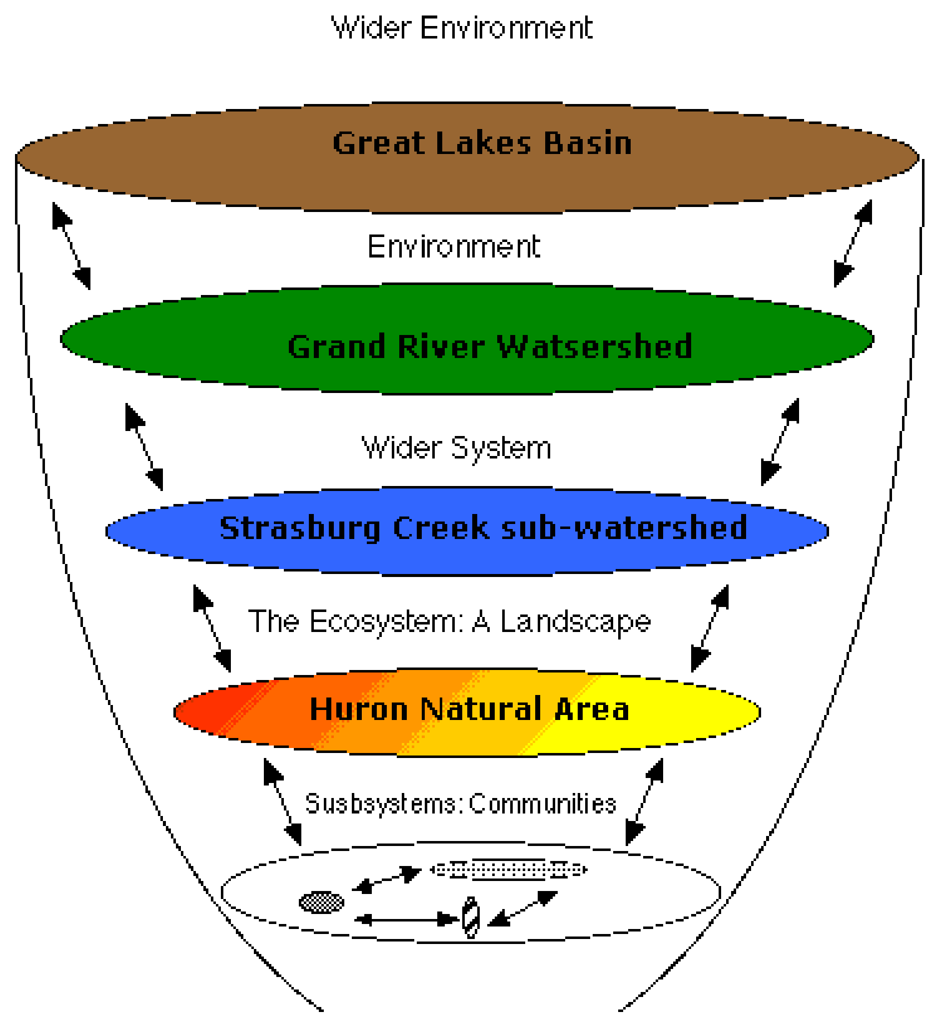
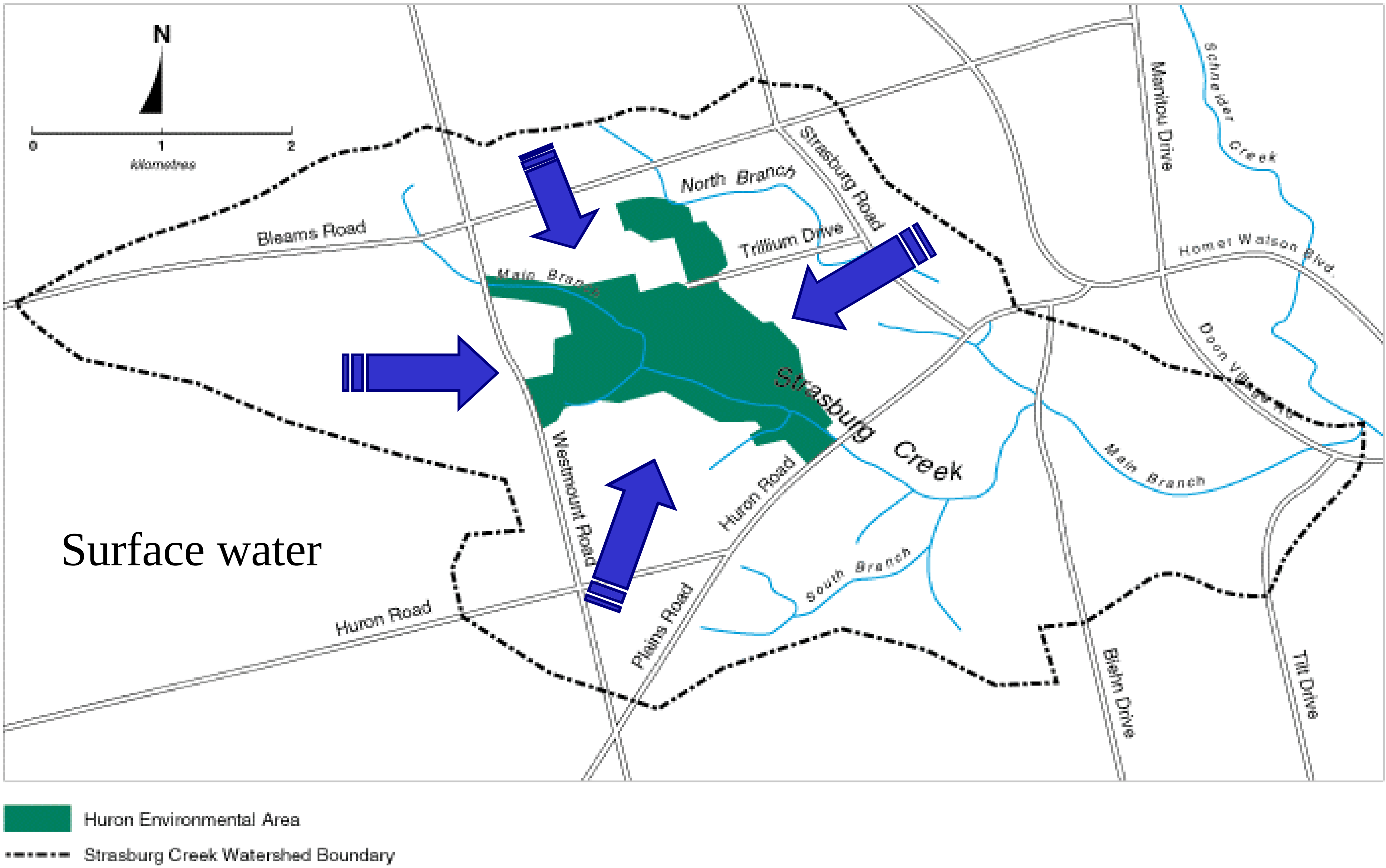
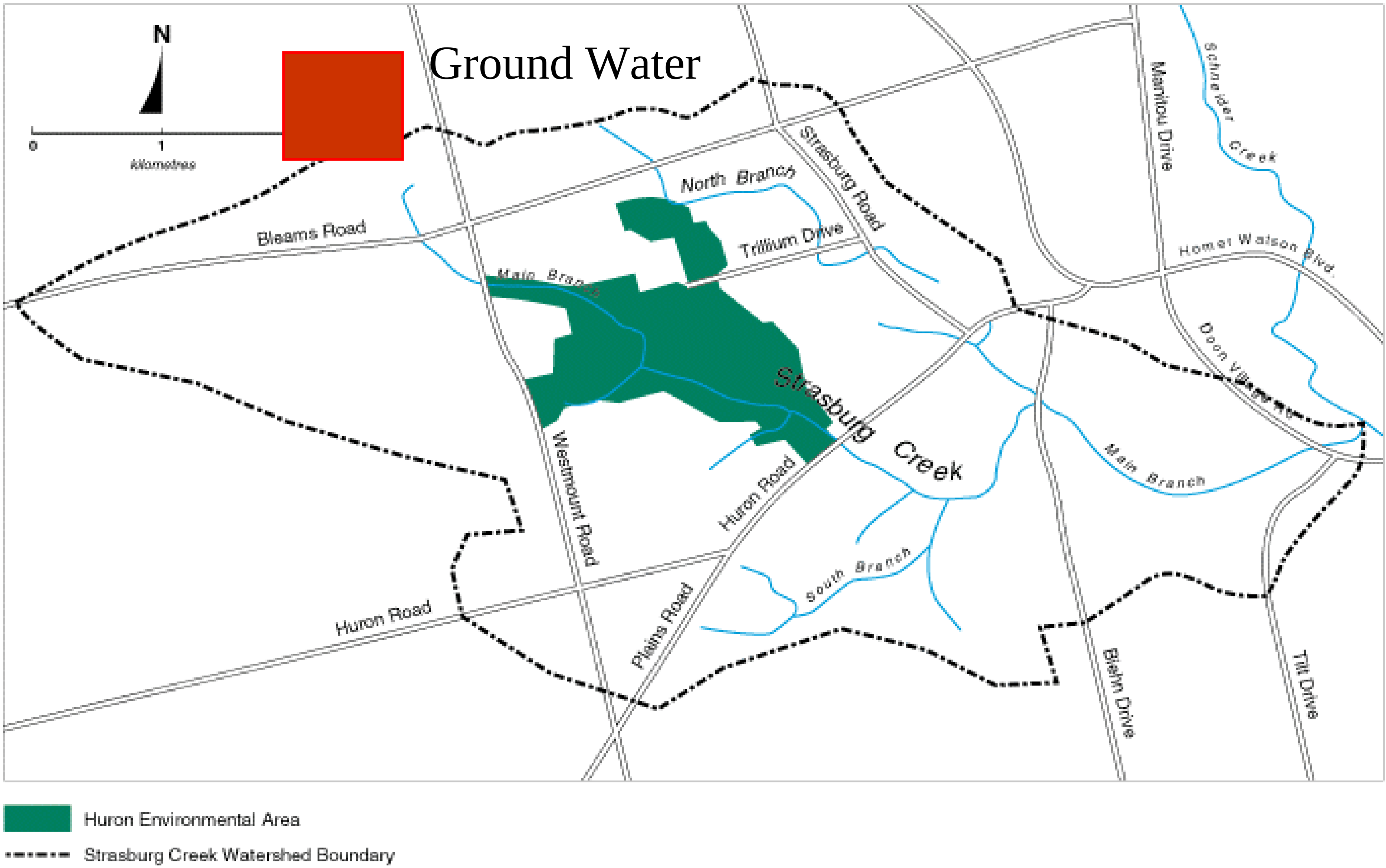
Nested Holons



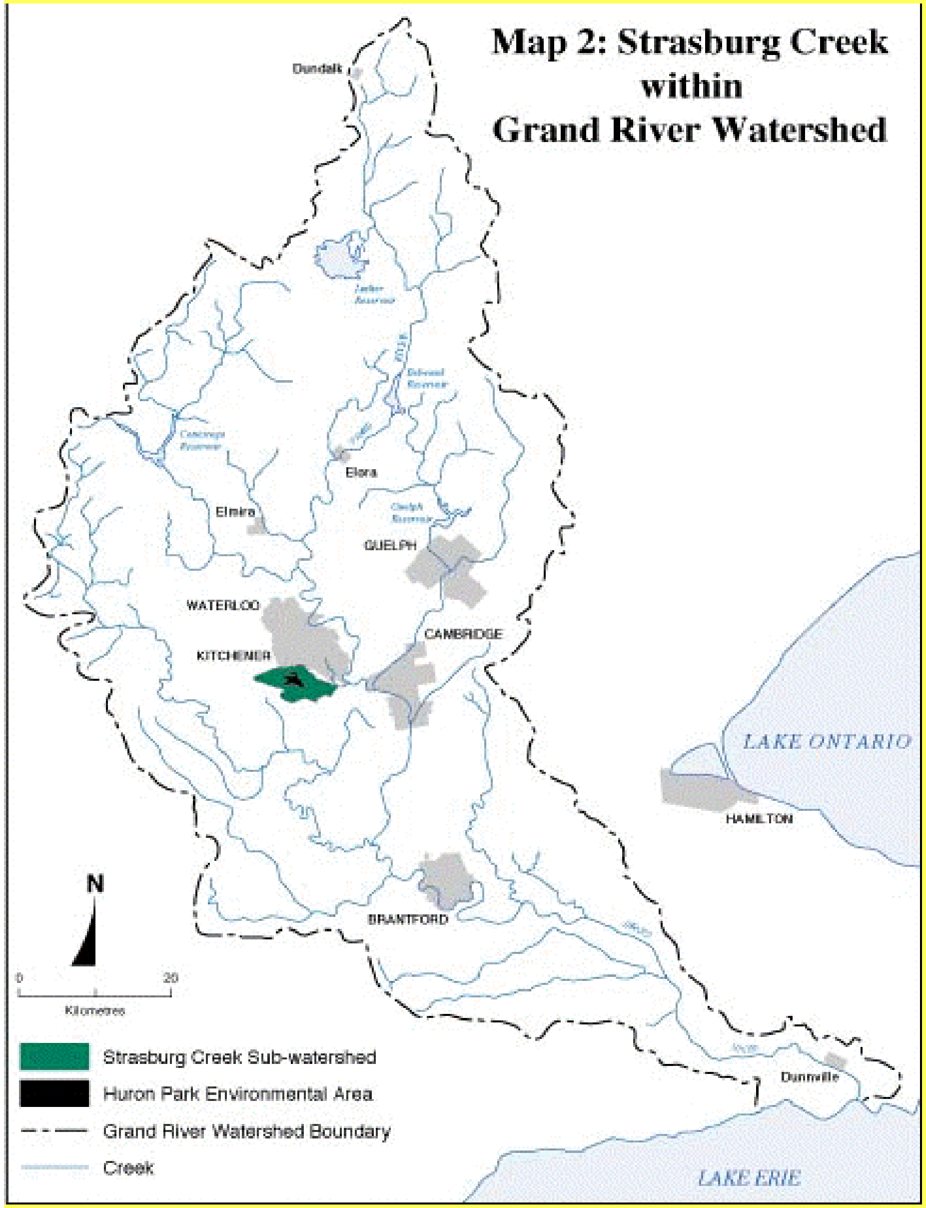
Subwatershed holon



Subwatershed holon

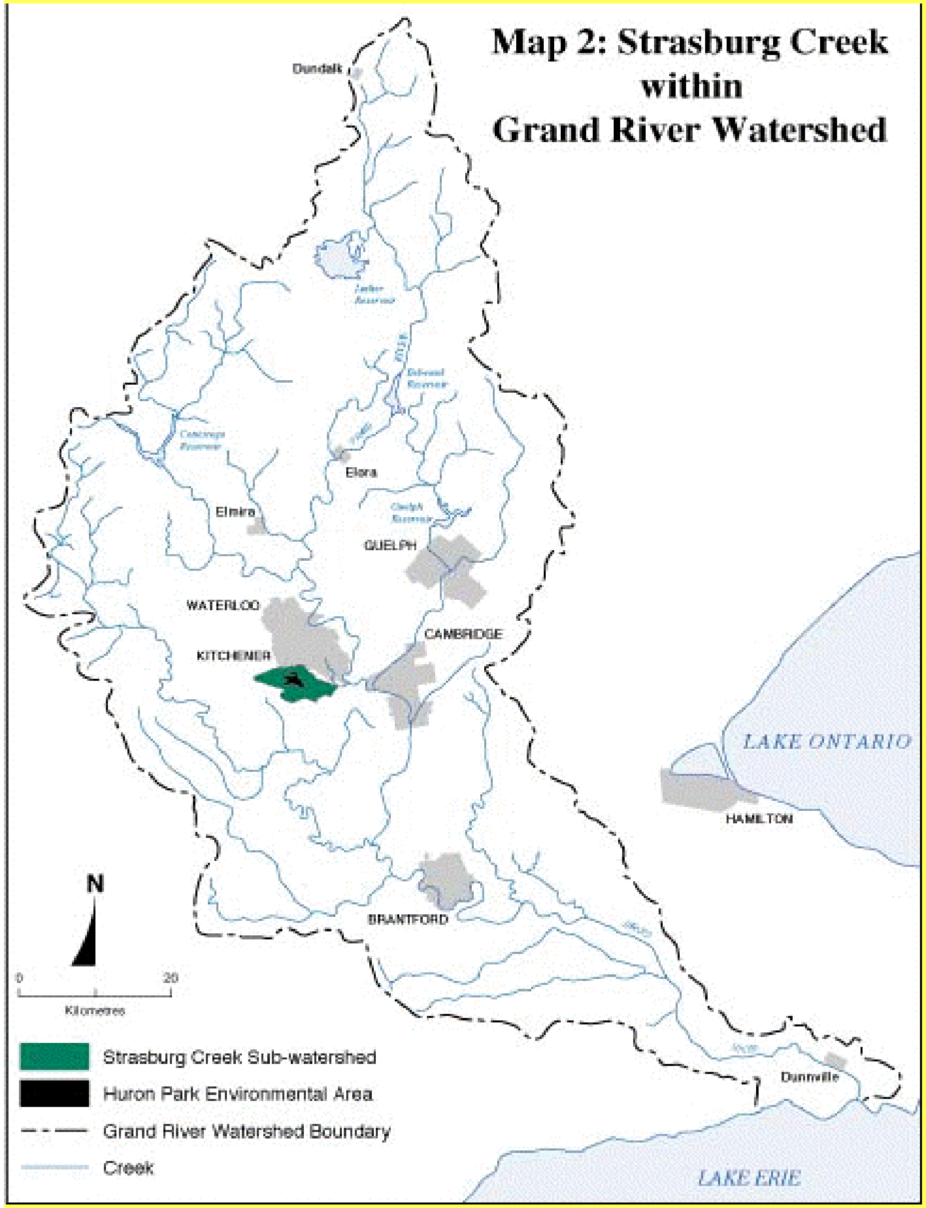


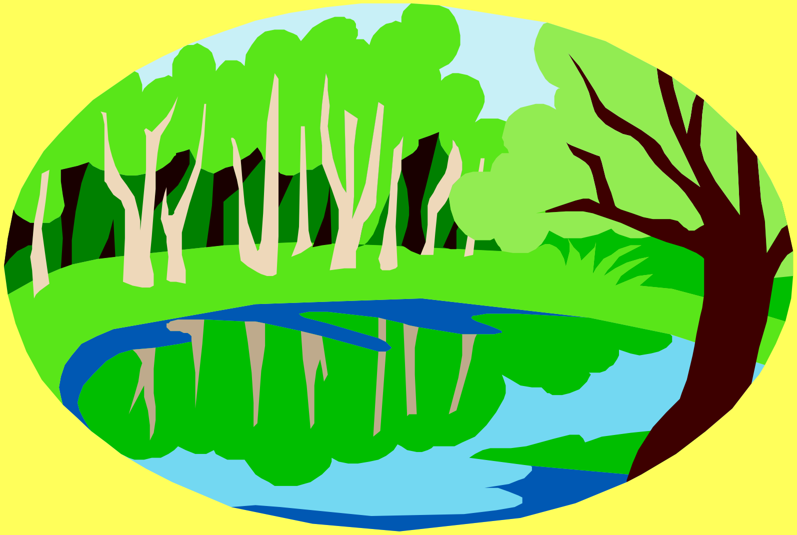
Watershed holon



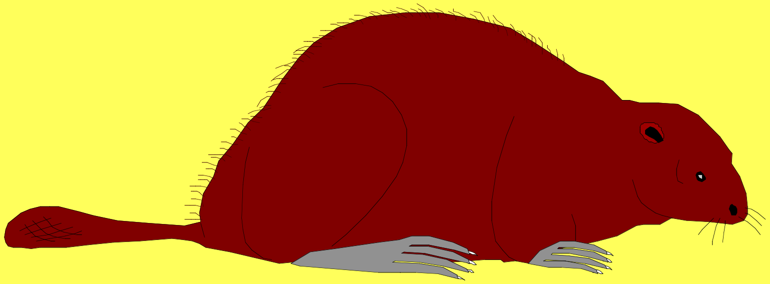
Trout Stream Attractor

Watershed holon



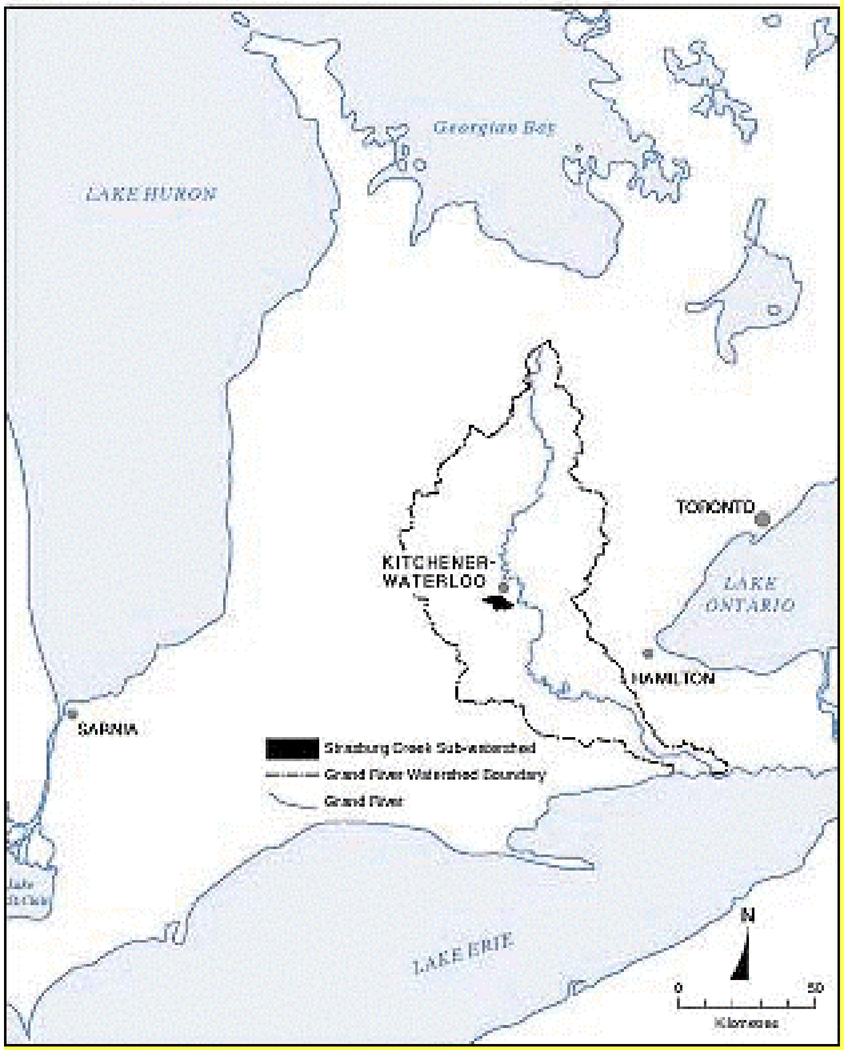


Beaver Pond Attractor



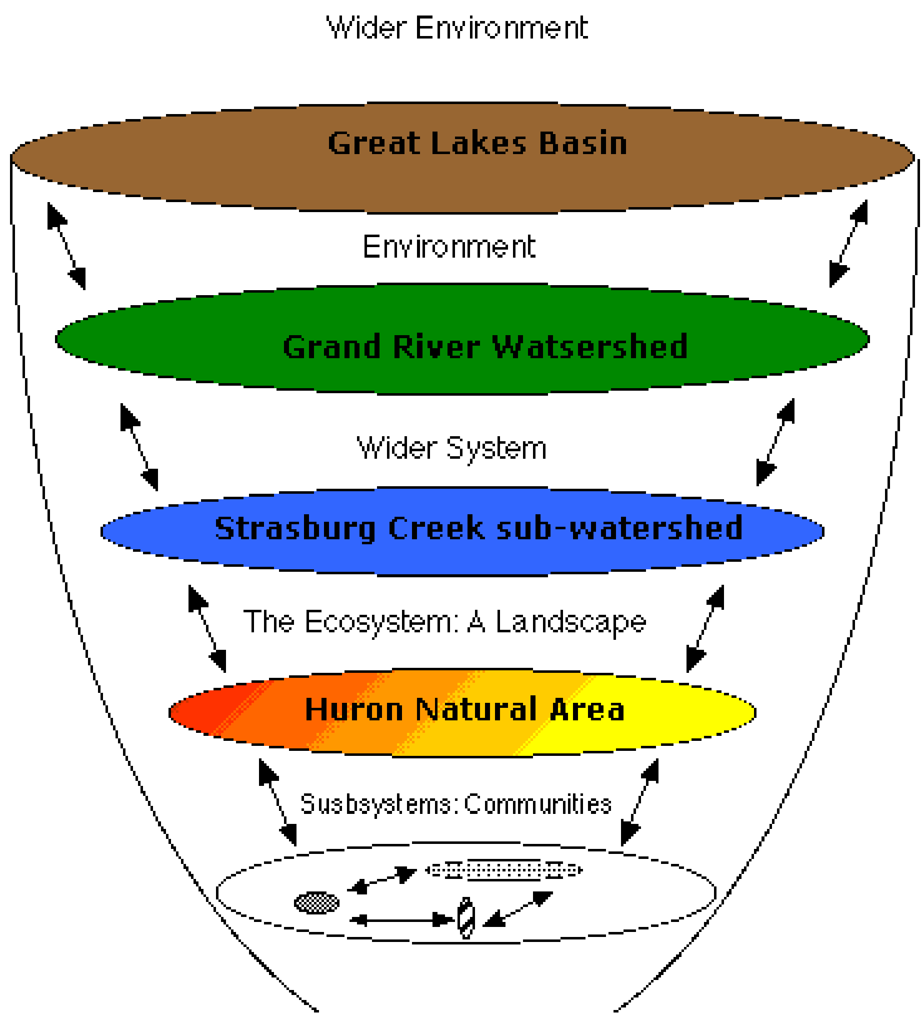
Wider environment

Map 1: Grand River Watershed within Central Southwestern Ontario

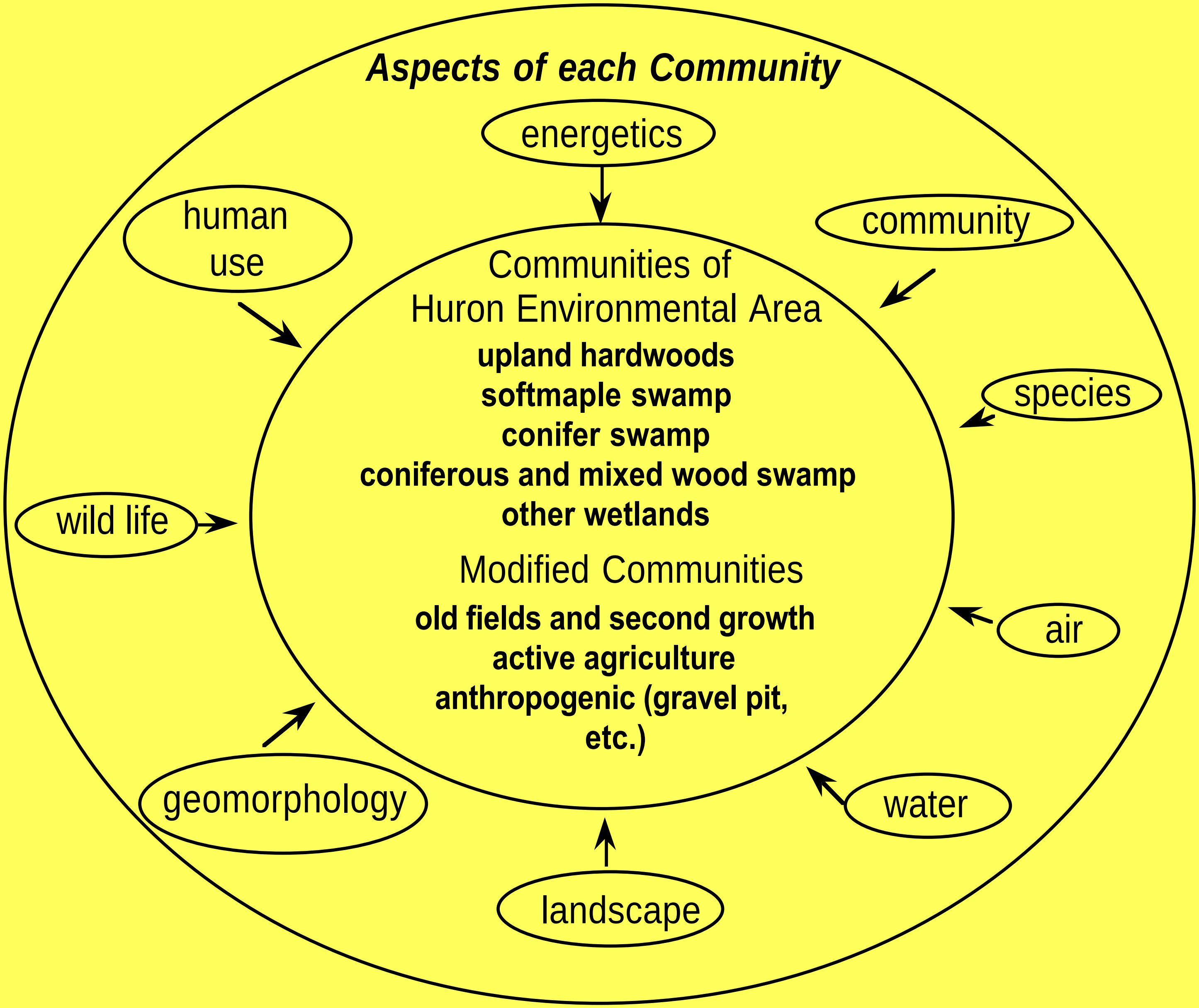


- **Air Quality**
- **Invasive species**
- **Climate Change**

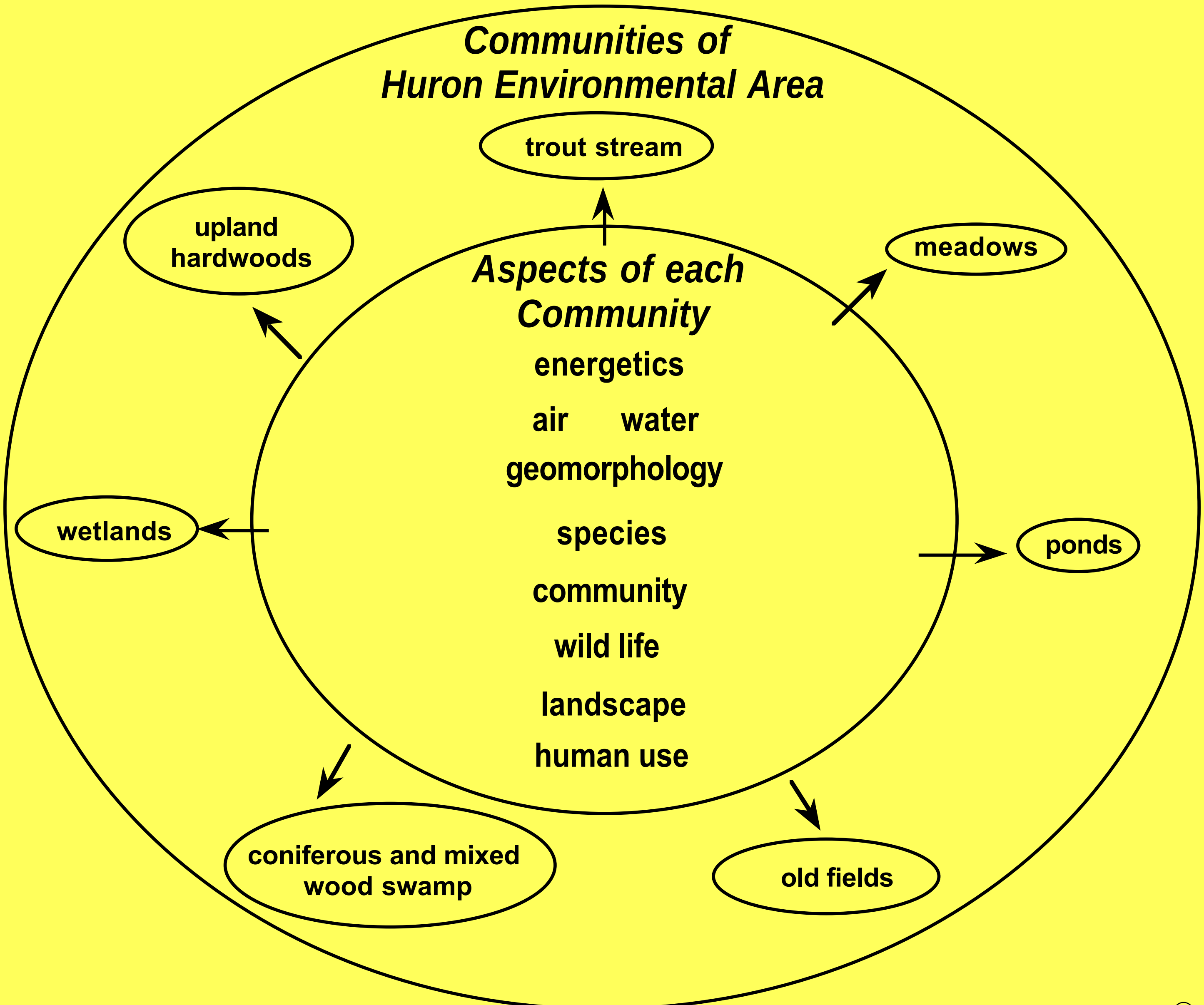
Nested Holons



Analysis (multiple models)



Synthesis of models



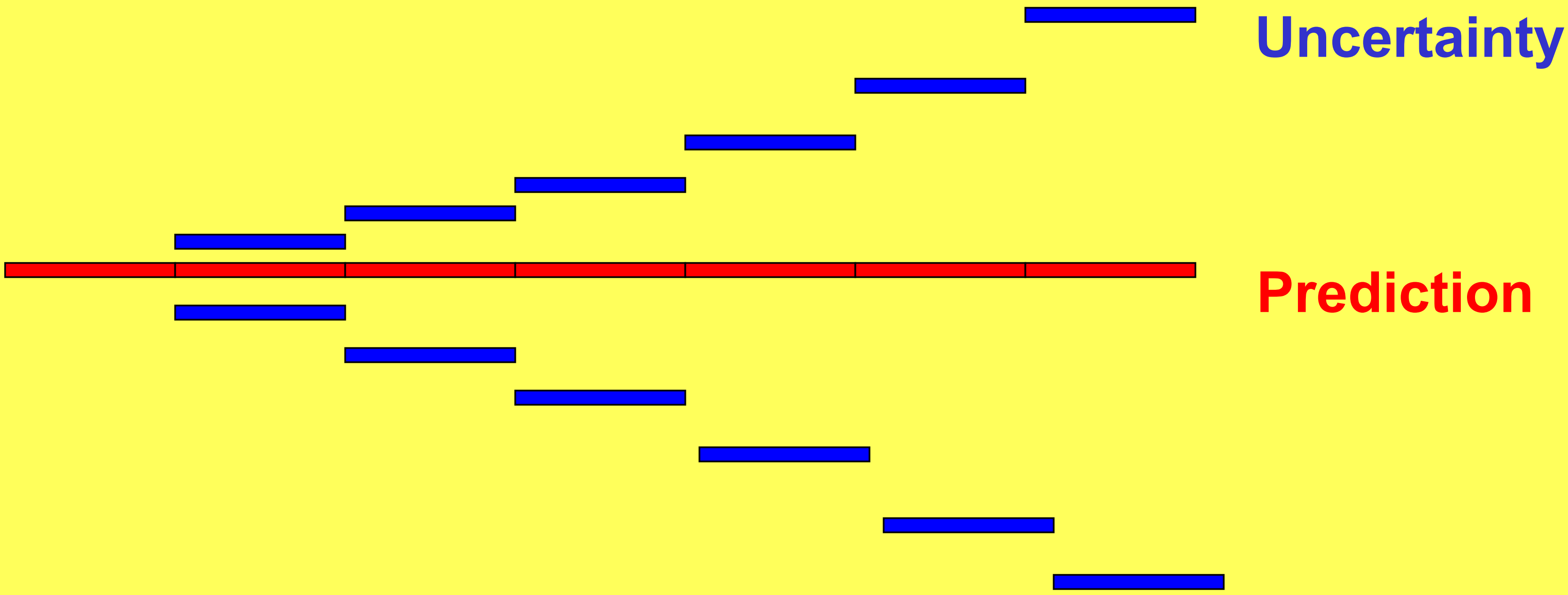
Implications for modelling

- Need models which deal with nesting (holarchies)
- Need different types of models at each scale.
- Need cross scale models
- Need a means of synthesising the outcomes of the different types of models at different scales into an overall understanding and appreciation of the situation and how it might unfold.

Chaos theory

- **Double Pendulum**
- **scruffy.phast.umass.edu/a114/DP2.html**

Chaos theory



- **Our ability to forecast and predict is always limited, regardless of how big our computers and how much information we have. For example, for weather forecasts, five to ten days is the outer limit.**

Complex systems

- **Non-Linear:** **Behave as a whole, a system. Cannot be understood by decomposing into pieces which are simply added together.**
- **Self-organizing (Internal Causality):** **are Non-Newtonian, not a mechanism, but rather self-organizing. Characterized by: goals, positive and negative feedback, autocatalysis (self-reinforcing processes), emergent properties and surprise.**
- **Window of Vitality:** **Must have enough complexity but not too much. Complex systems strive for optimum, not minimum or maximum.**

Complex systems

- **Hierarchical:** **The system is nested within a system and is made up of systems. Such nestings cannot be understood by focusing on one hierarchical level (holon) alone. Understanding comes from the multiple perspective of different types and scale.**
- **Multiple steady states:** **There is not necessarily a unique preferred system state in a given situation. Multiple attractors can be possible in a given situation and the current system state may be as much a function of historical accidents as anything else**.

Complex systems

- **Dynamically Stable?: equilibrium points may not exist for the system.**
- **Catastrophic Behaviour: The norm**
  - **Bifurcations**: moments of unpredictable behaviour
  - **Flips:** sudden discontinuities, rapid change
  - **Holling four box ∞:** Shifting steady state mosaic
- **Chaos Theory: our ability to forecast and predict is always limited regardless of how sophisticated our computers are and how much information we have.**

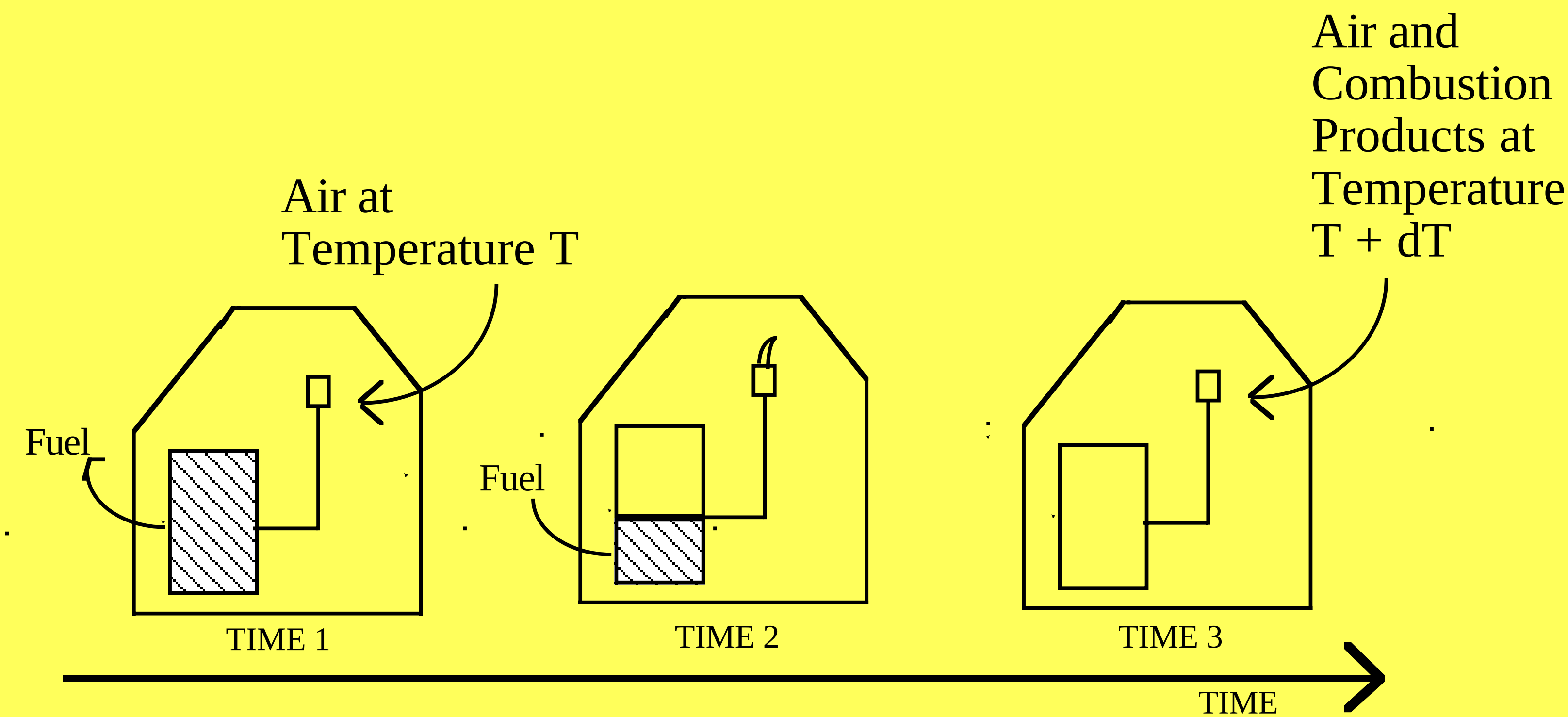
Complexity

- We must deal with irreducible uncertainty, emergence and surprise, the lack of a preferential perspective, and the reality that life is a tradeoff.
- We no longer have the luxury of dealing with problems for which reductionist “scientific method” approaches are sufficient, and predictability and the ability to anticipate are the hallmark of success.

The challenge

- Bring together all the players (scientist and non-scientist alike).
- Deal with irreducible uncertainty and unavoidable surprise.
- Synthesize different viewpoints and types of understanding at different scales.
- Produce narratives about how the future ought and might unfold.
- There is no right answer, no solution, just resolution of tradeoffs through negotiation…adaptive management…….

Exergy: The quality of energy

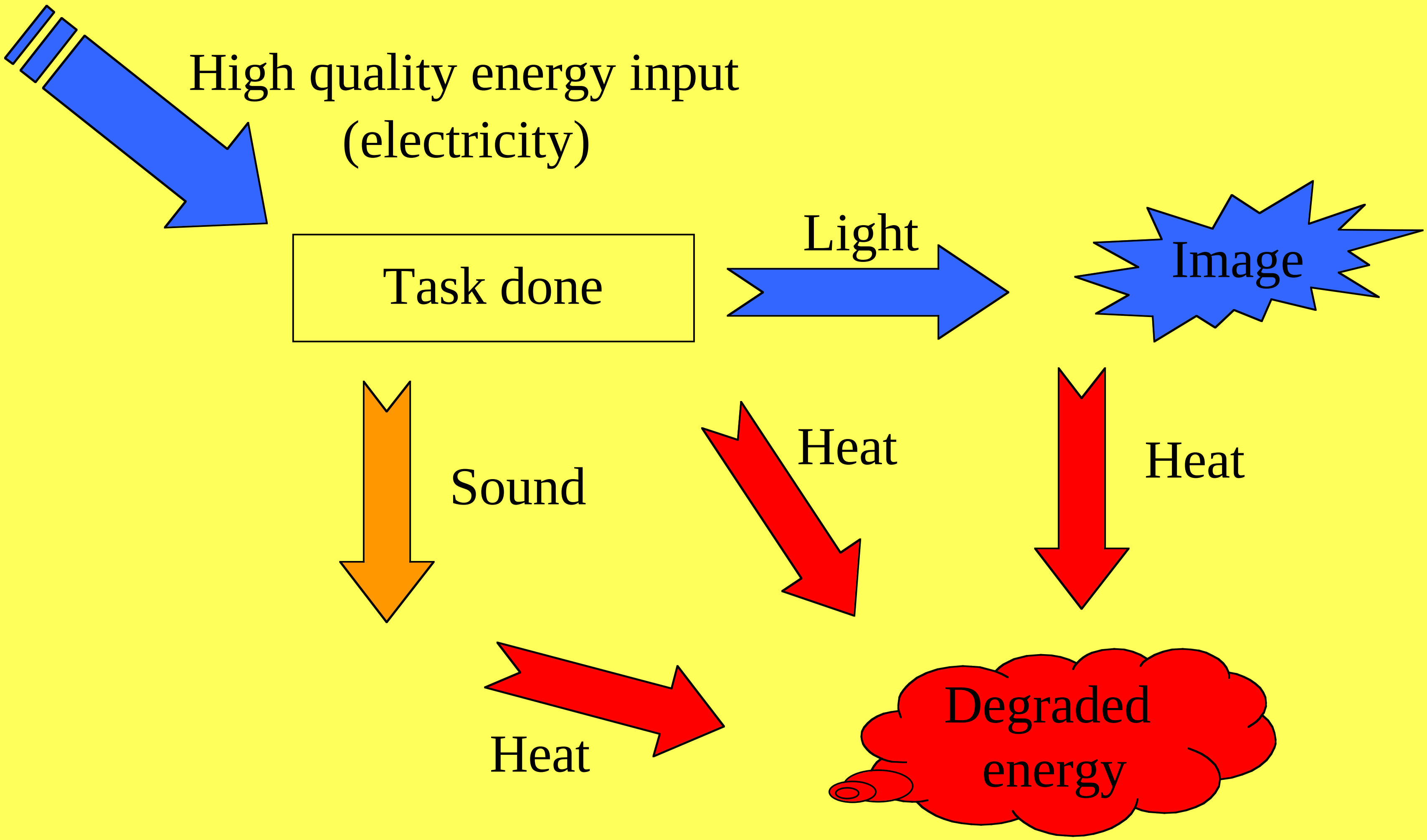


Energy Quantity in the container is constant.
Energy Quality (Exergy) in the container decreases.

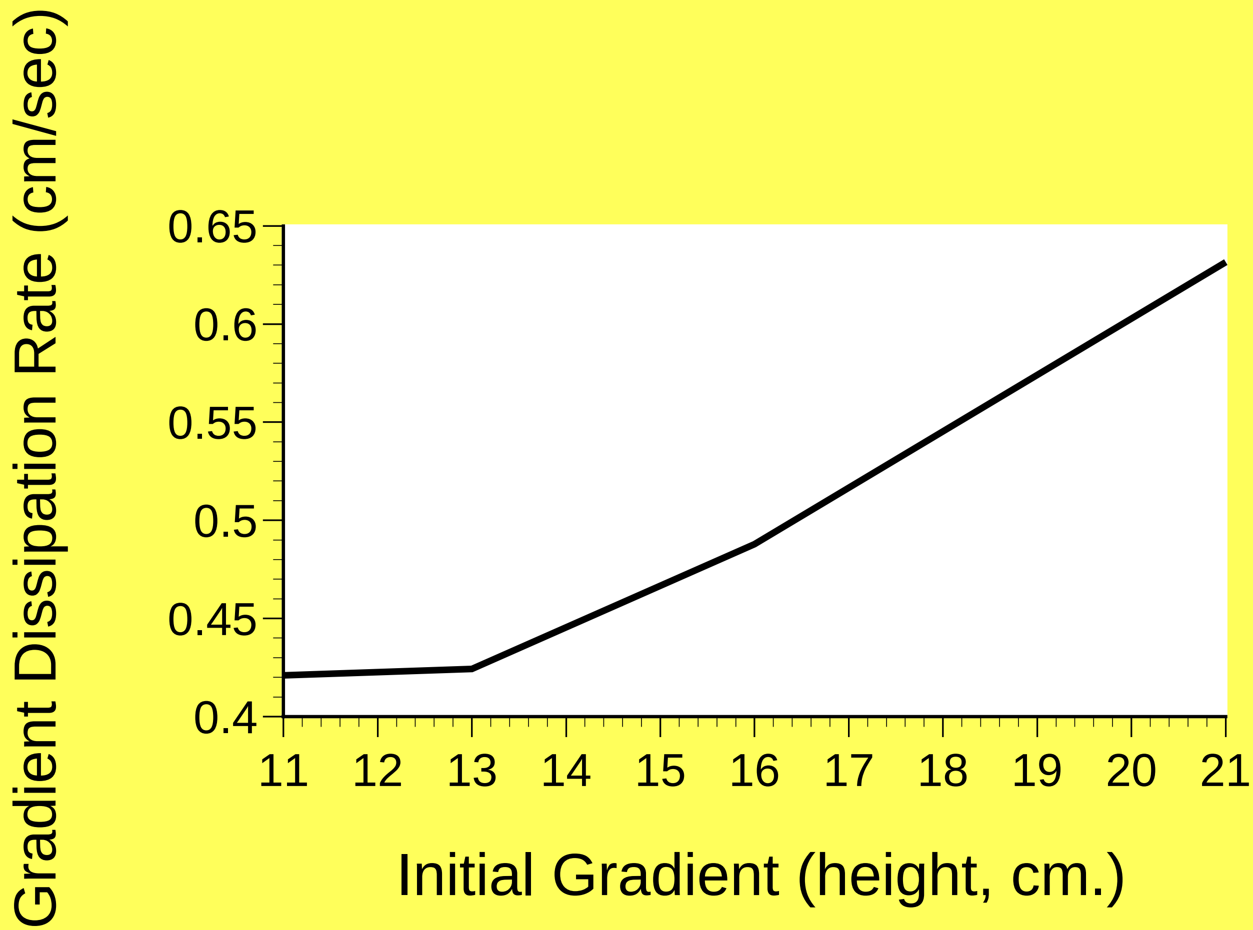
(after Moran)

Energy **IN** = Energy **OUT**

Exergy **IN** »» Exergy **OUT**



Tornado in the bottle



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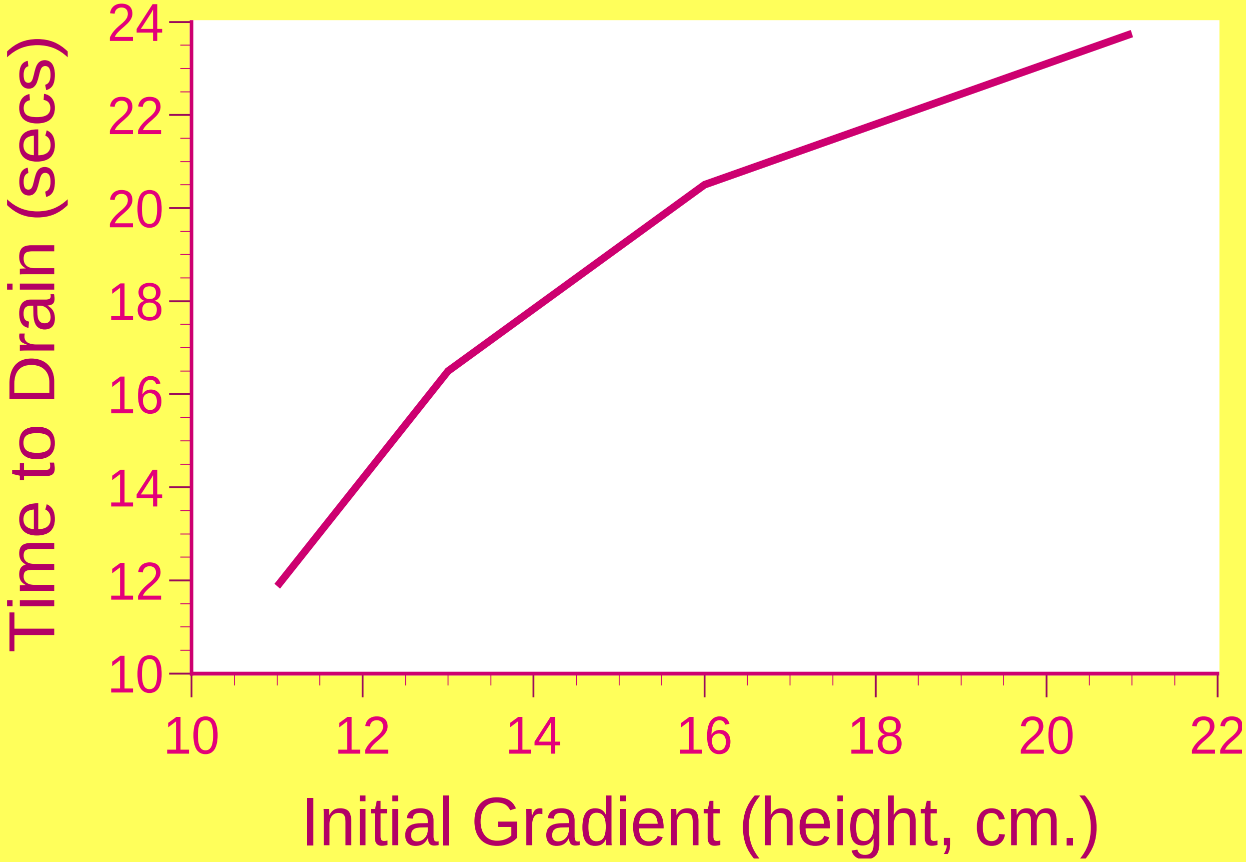
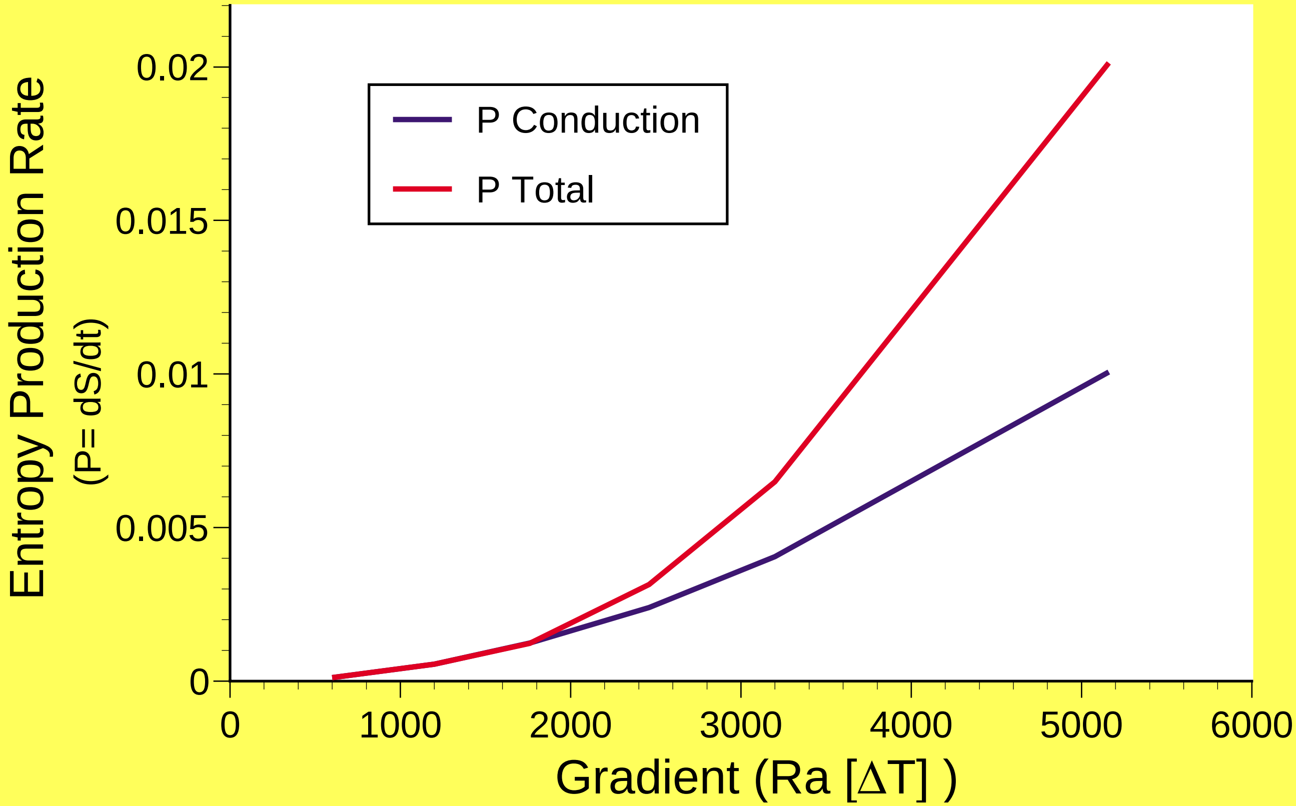
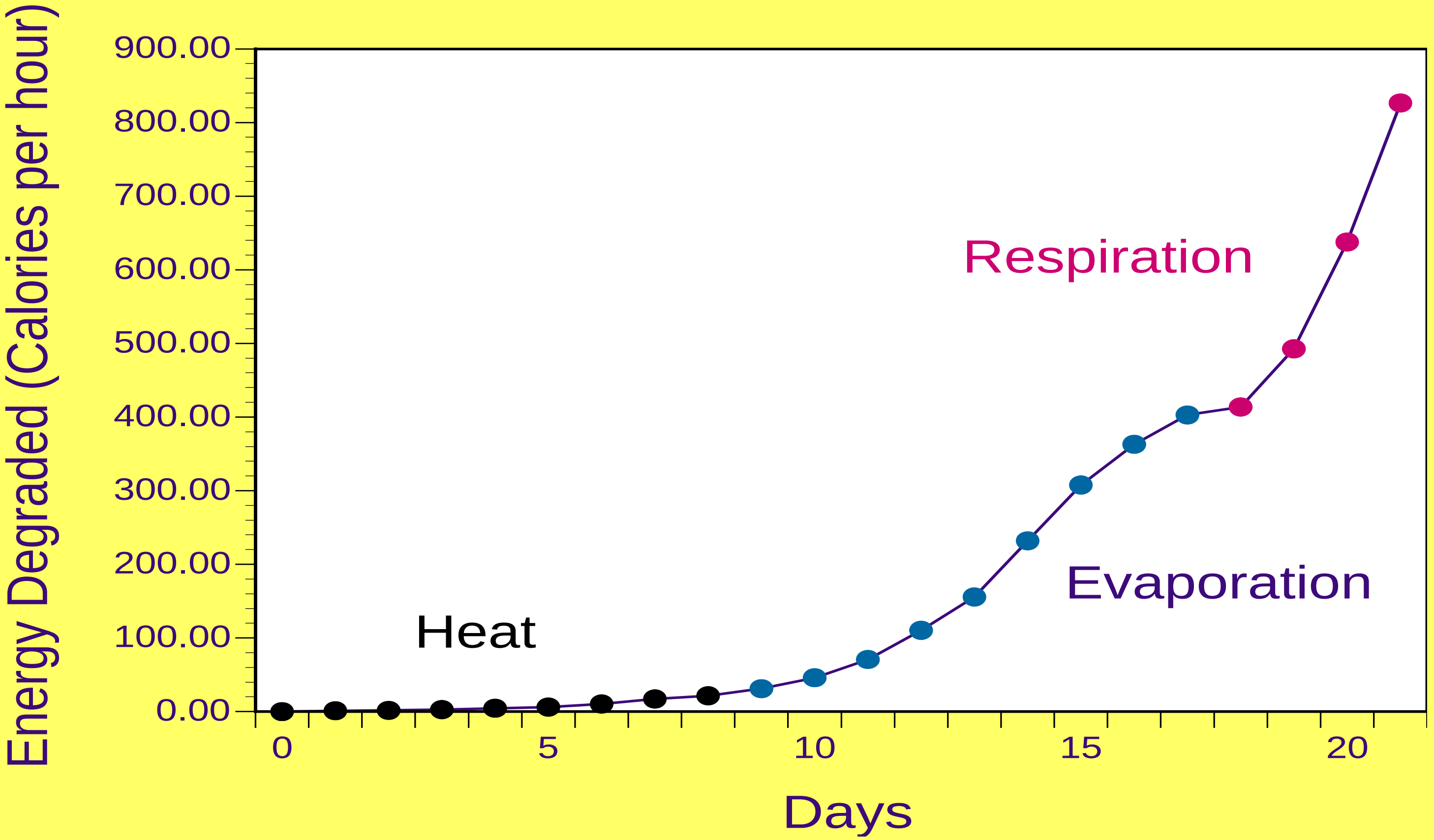


Bénard Cells



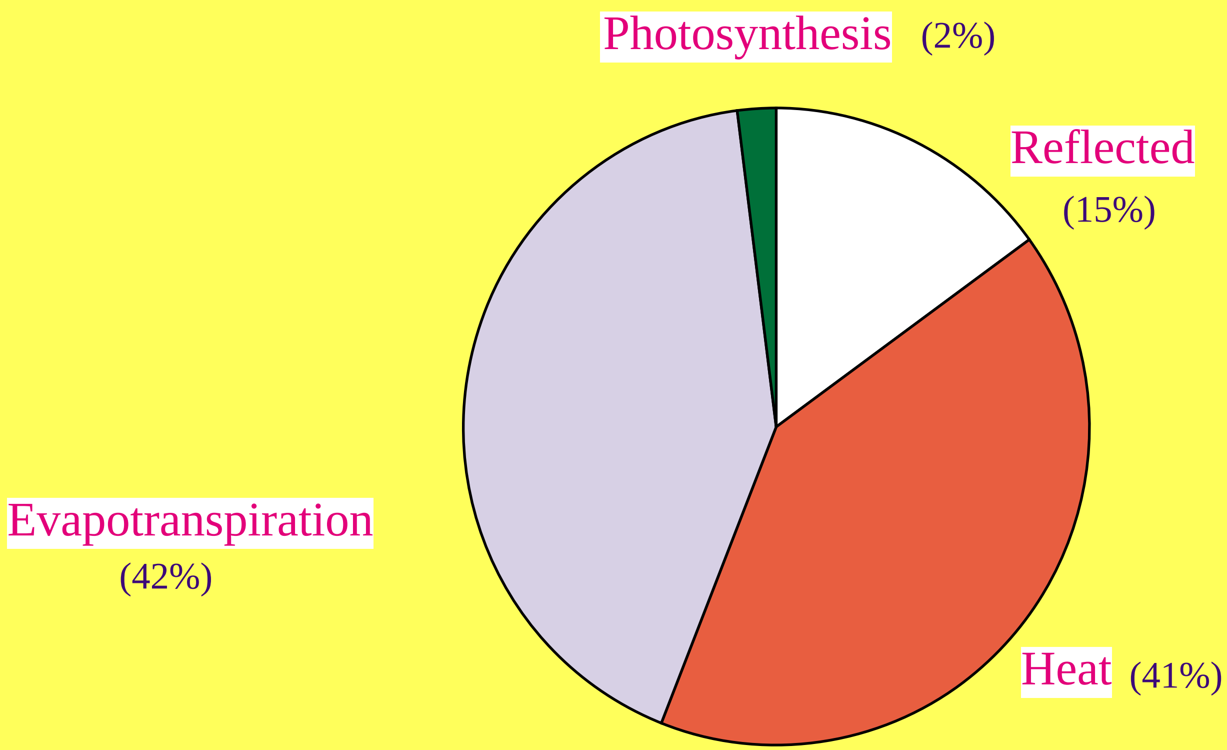
Dissipation rate for a chicken embryo



- **(Data from Briedis and Seagrave, 1984)**

The distribution of solar energy during the growing season in the Hubbard Brook Forested Ecosystem

(From Bormann and Likens, 1978)



	Quarry	Clearcut	Douglas Fir Plantation	Natural Regrowth	400 year old Douglas Fir Forest
K* (w/m^2)	718	799	854	895	1005
L* (w/m^2)	273	281	124	124	95
R_n (w/m^2)	445	517	730	771	830
T (^oC)	50.7	51.8	29.9	29.4	24.7
R_n/K* (%)	62	65	85	86	90

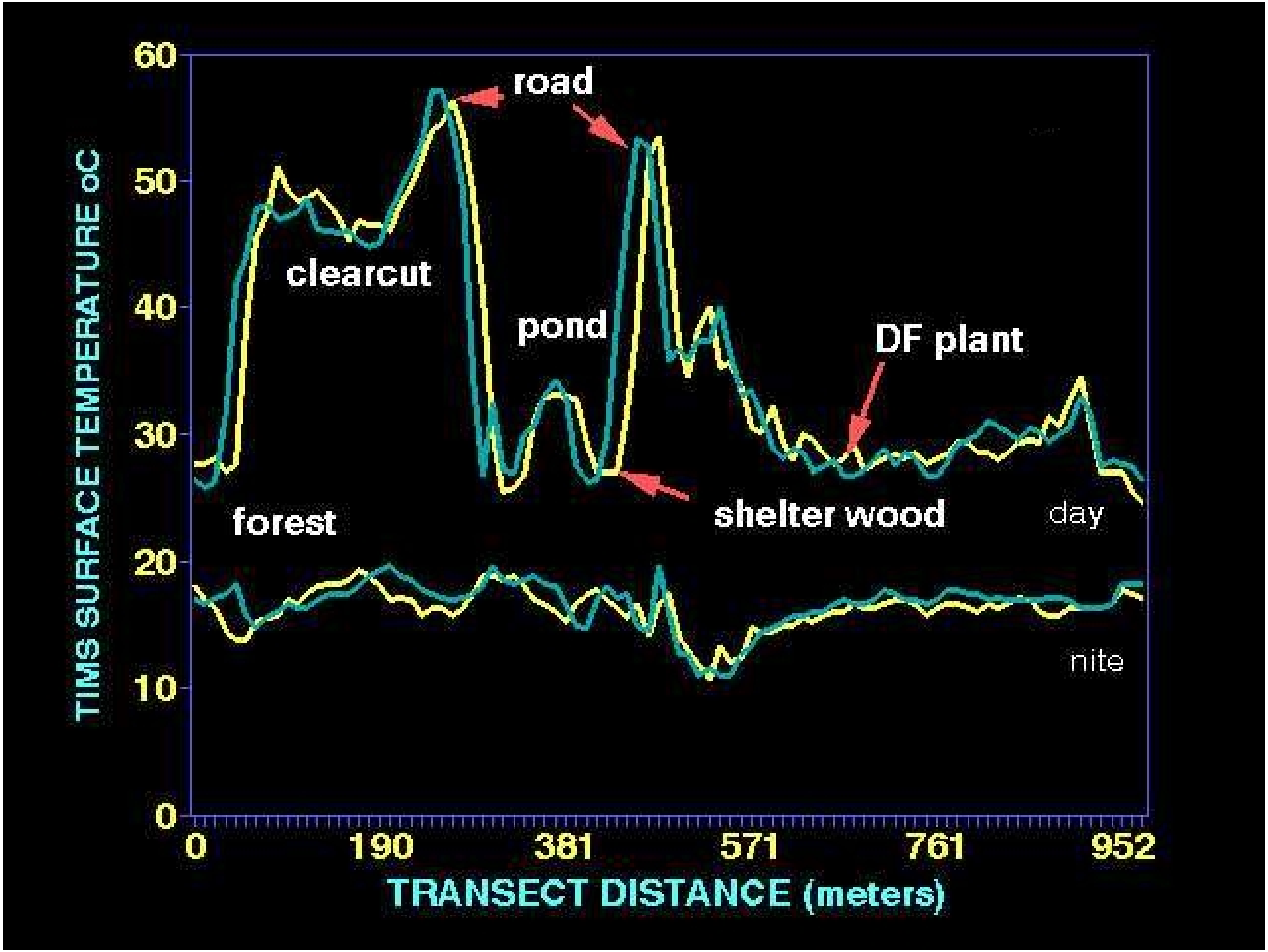
where

$$R_n = K^* - L^* \quad \text{and} \quad R_n = H + L_e + G$$

$$L^* = \varepsilon\, [\sigma\, (T)^4]$$

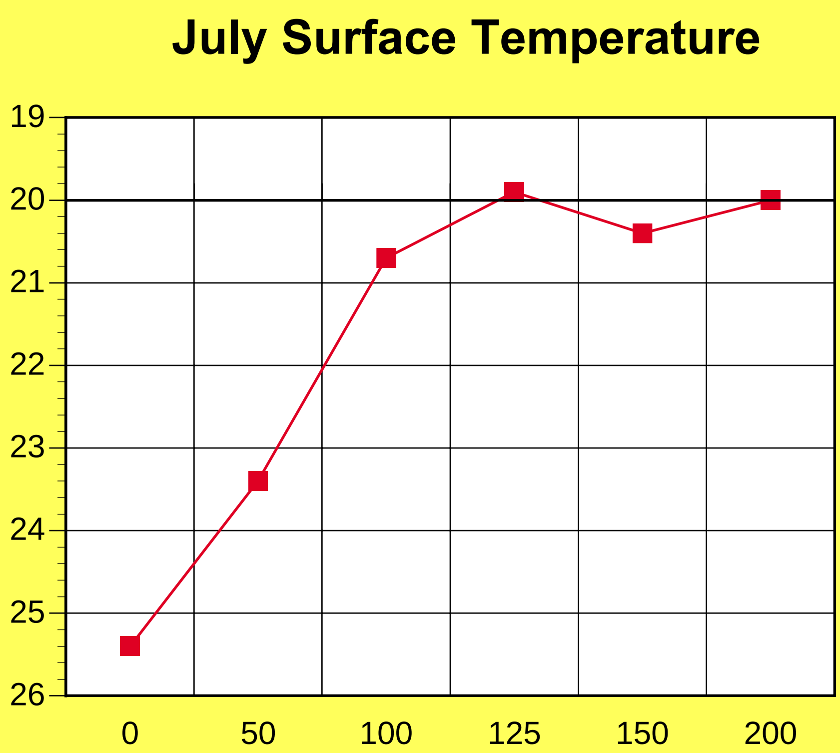
R_n is the energy which is degraded from radiation into molecular motion, that is captured by the ecosystem and utilized.

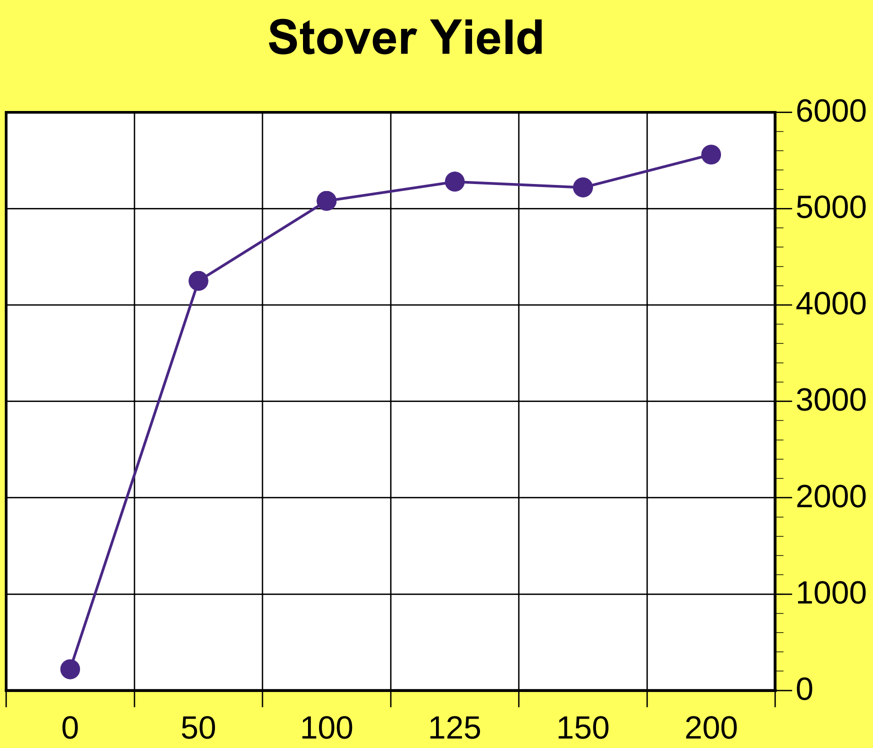
R_n/K* = percent of net incoming solar radiation degraded into nonradiative processes, that is used by the ecosystem. This is a measure of second law effectiveness of the processes, a measure of the organizational state of an ecosystem.



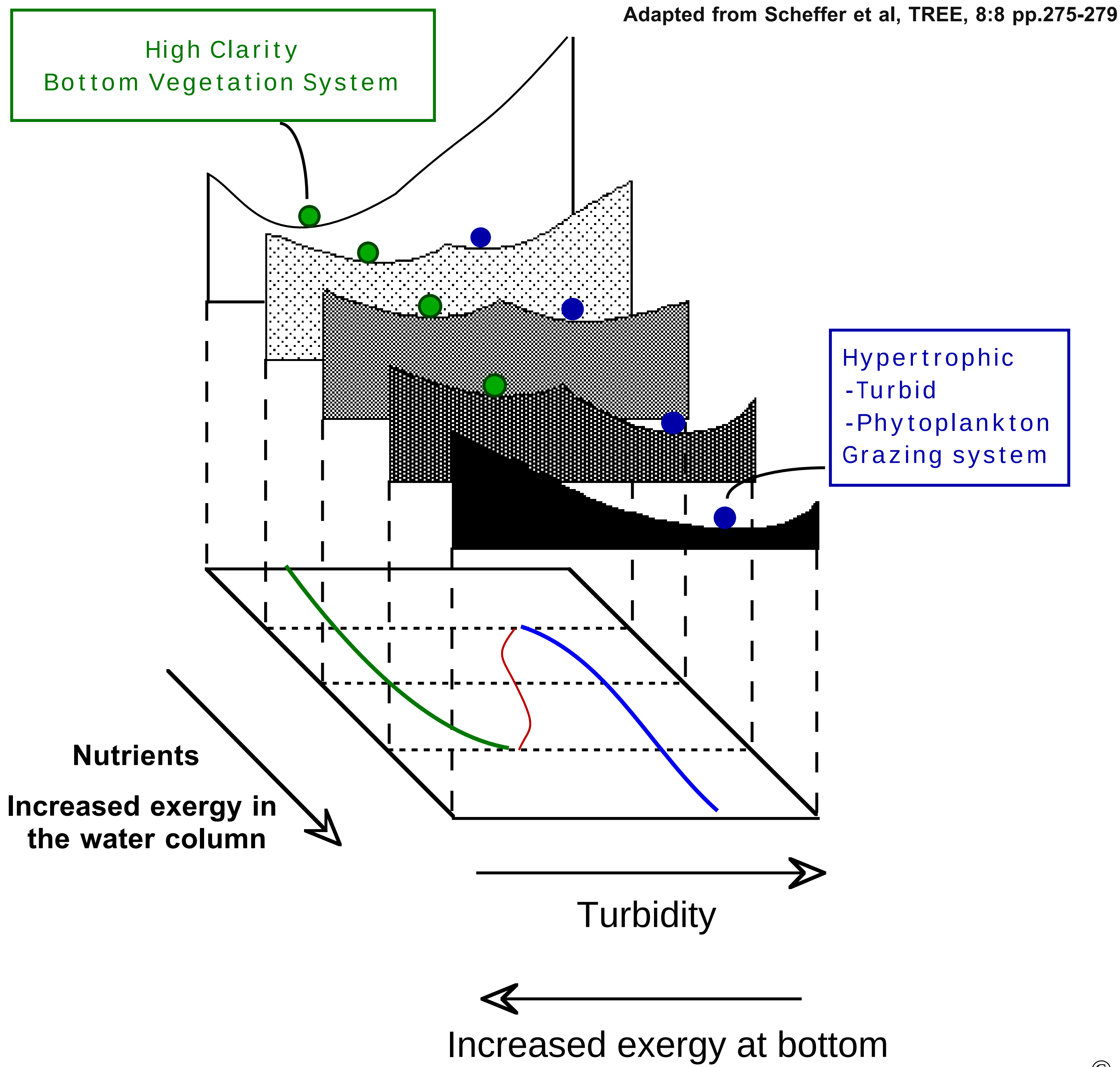
road
clearcut
pond
DF plant
shelter wood
forest
day
nite
TIMS SURFACE TEMPERATURE oC
60
50
40
30
20
10
0
0
190
381
571
761
952
TRANSECT DISTANCE (meters)

Surface temperature vs fertilizer application (Akbari et al)



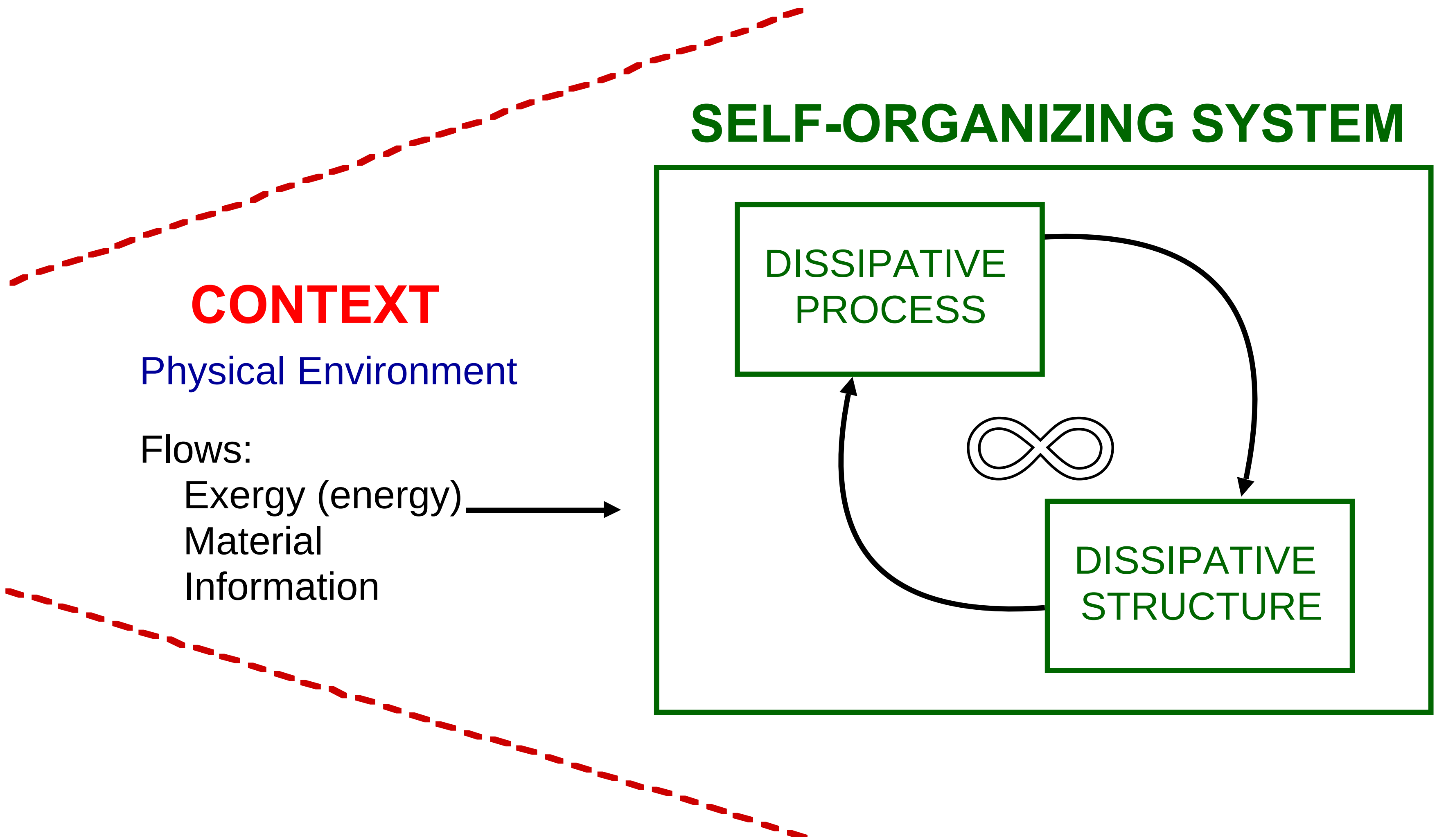


Nitrogen applied kg/ha



Adapted from Scheffer et al, TREE, 8:8 pp.275-279
High Clarity
Bottom Vegetation System
Hypertrophic
-Turbid
-Phytoplankton
Grazing system
Nutrients
Increased exergy in the water column
Turbidity
Increased exergy at bottom

Self-organizing holarchic open (SOHO) conceptual model



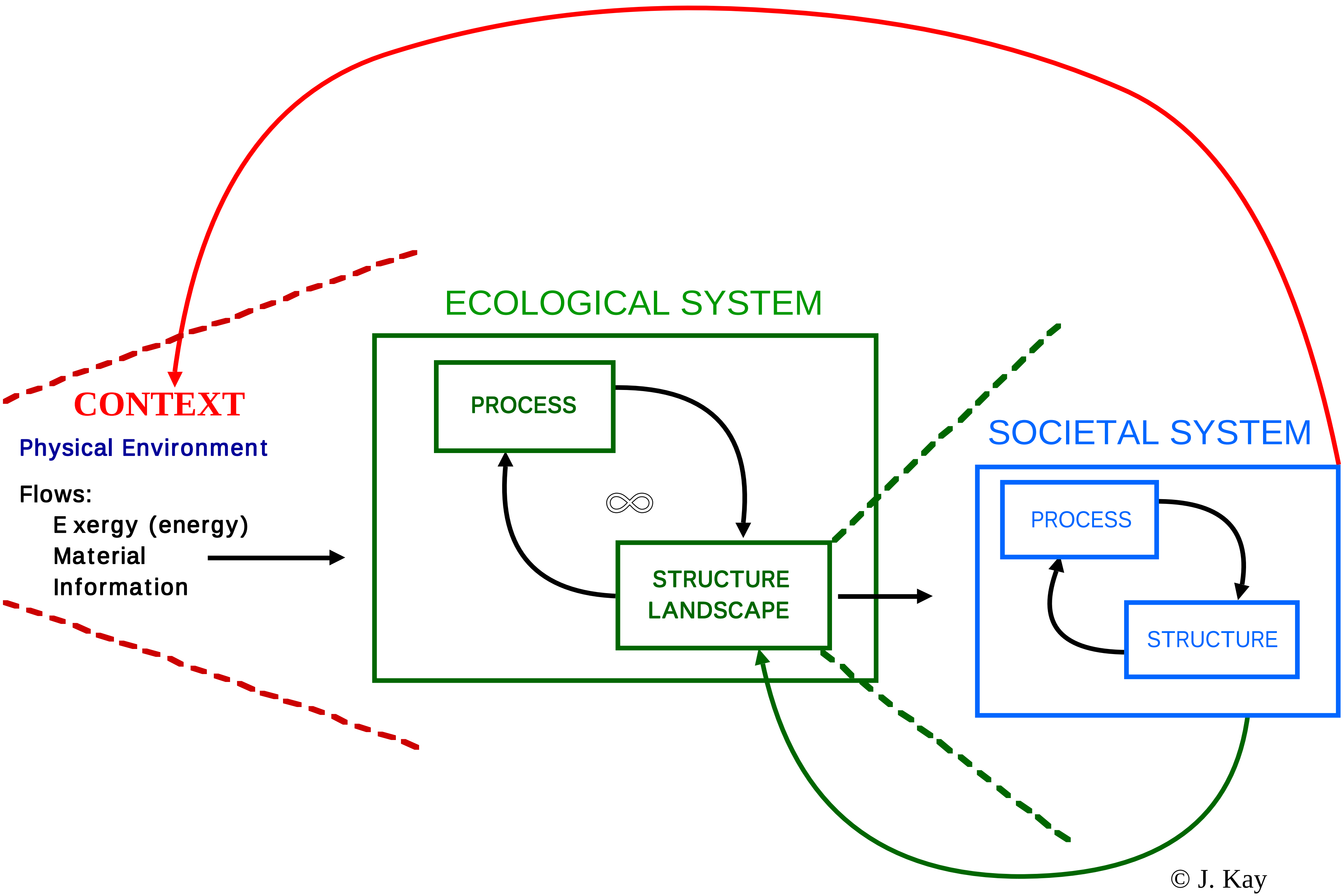
Properties of SOHO Systems

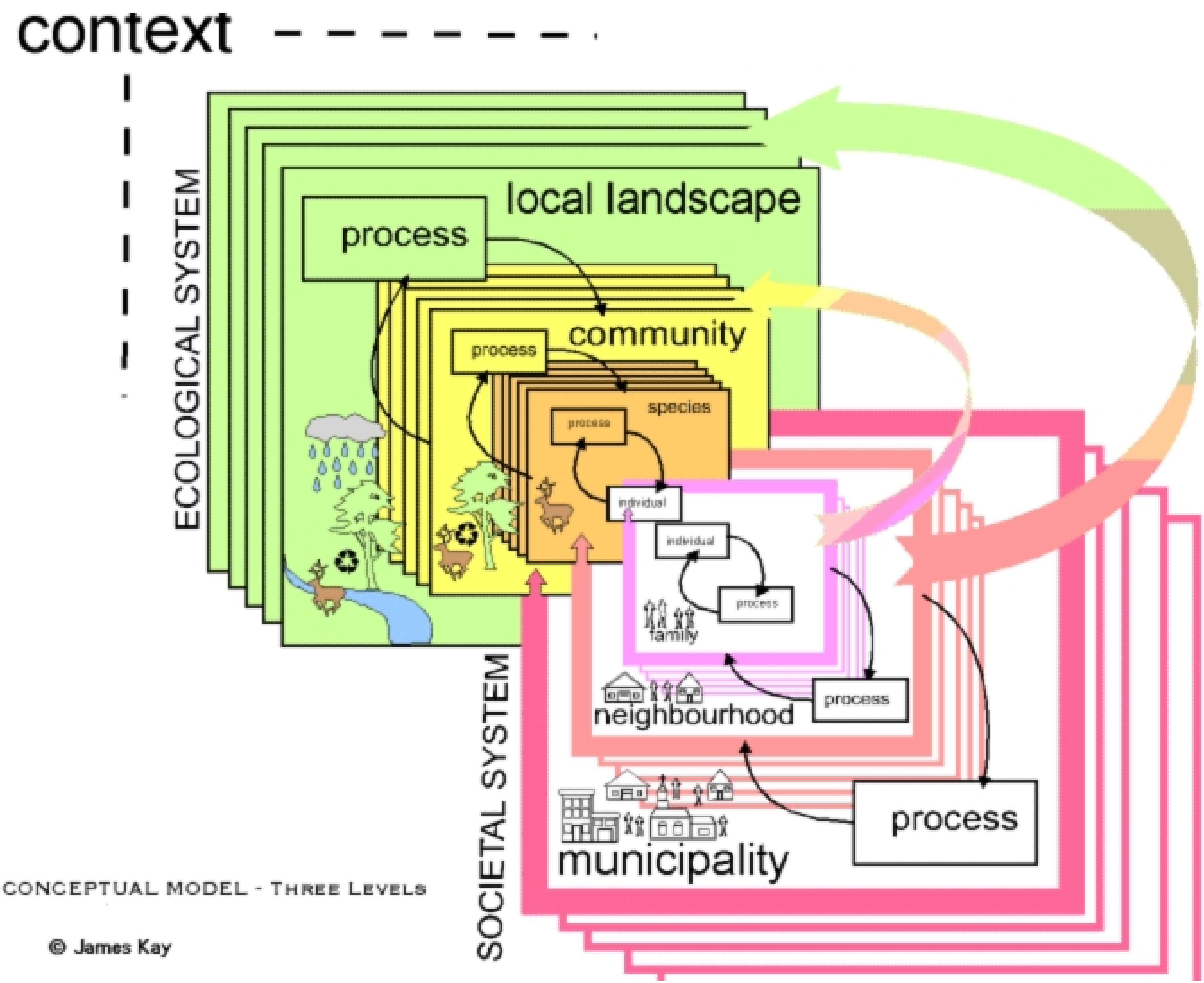
- **Open to material and energy flows.**
- **Nonequilibrium: Exist in quasi-steady states some distance from equilibrium.**
- **Thermodynamic: Maintained by energy gradients (exergy) across their boundaries. The gradients are irreversibly degraded (the exergy is used up) in order to build and maintain organization. These systems maintain their organized state by exporting entropy to other hierarchical levels.**

Properties of SOHO Systems……..

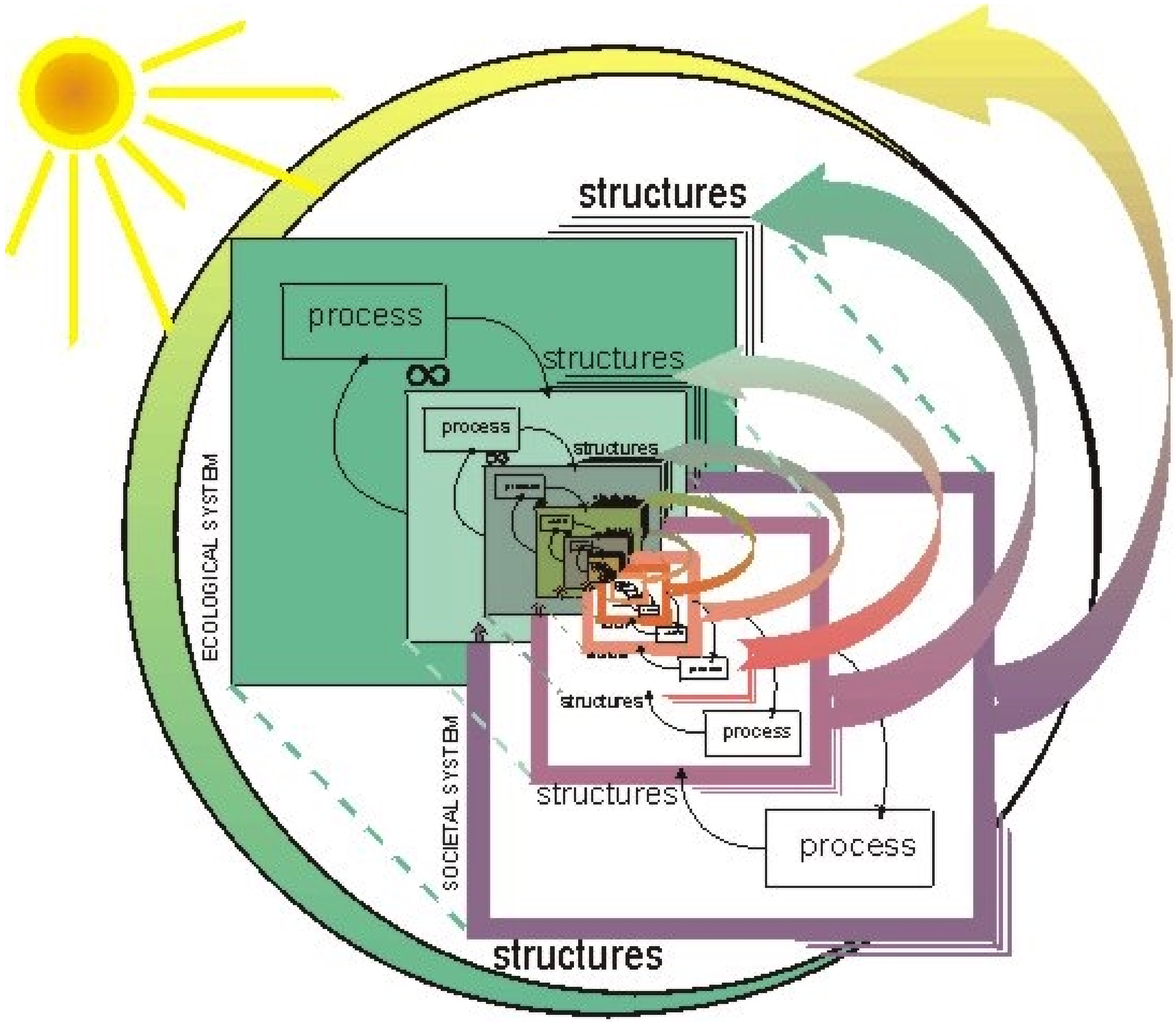
- **Propensities: As dissipative systems are moved away from equilibrium they become organized:**
  - **they use more exergy**
  - **they build more structure**
  - **this happens in spurts as new attractors become accessible.**
  - **it becomes harder to move them further away from equilibrium**

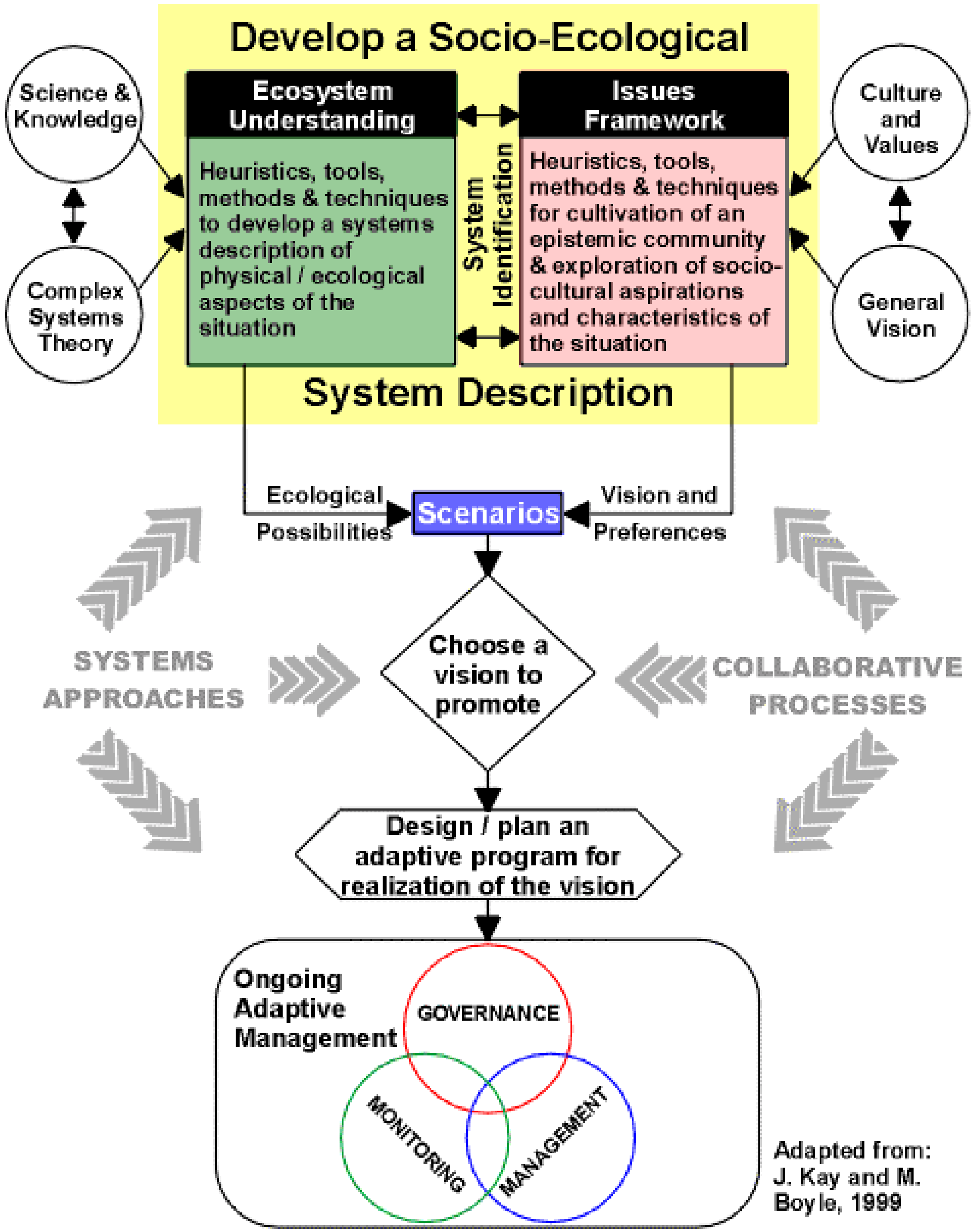
ECO-ECO Model



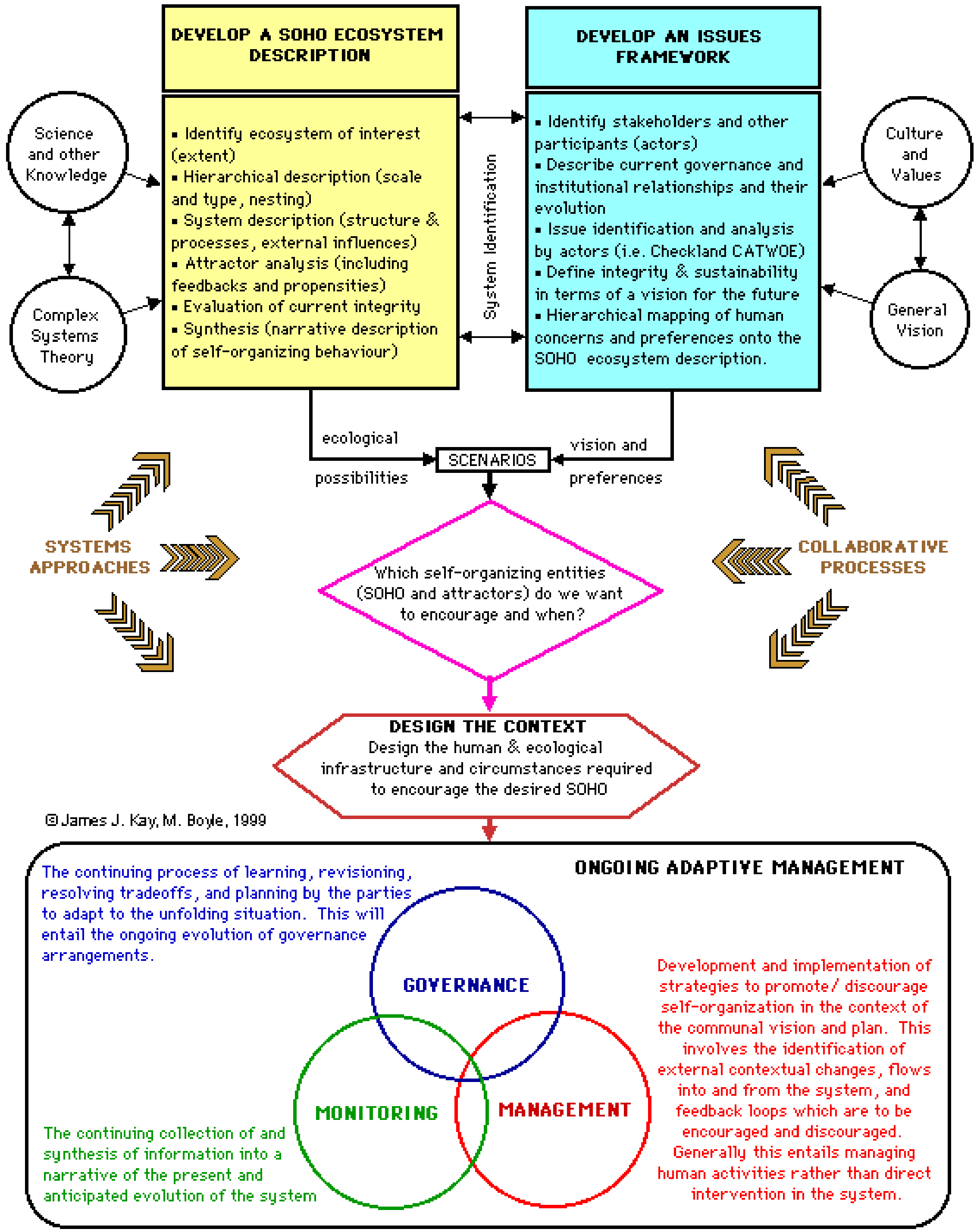


CONCEPTUAL MODEL - Three Levels

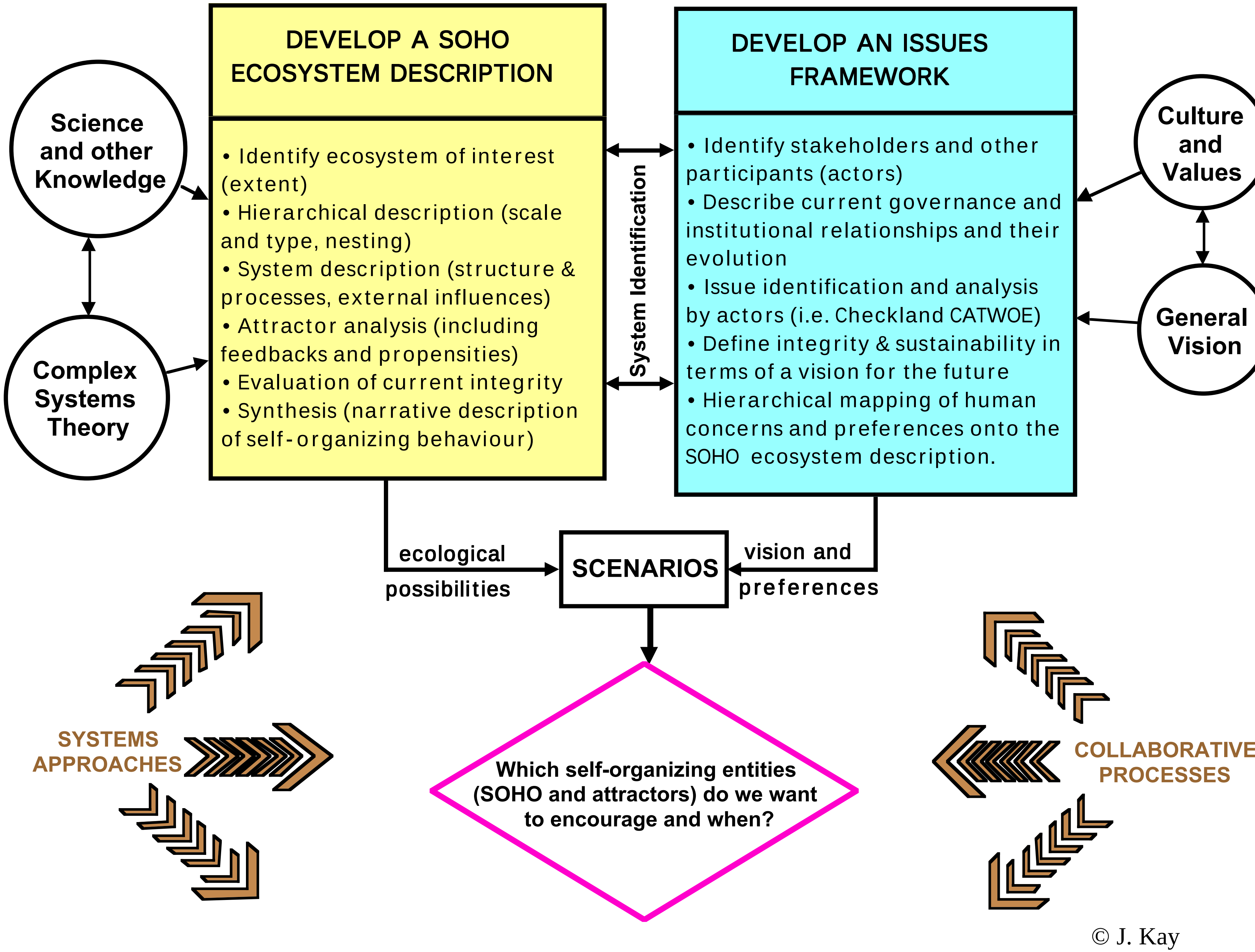

structures
process
structures
process
structures
ECOLOGICAL SYSTEM
SOCIETAL SYSTEM
structures
process
structures
process
structures



Develop a Socio-Ecological
Ecosystem Understanding
Heuristics, tools, methods & techniques to develop a systems description of physical / ecological aspects of the situation
Issues Framework
Heuristics, tools, methods & techniques for cultivation of an epistemic community & exploration of socio-cultural aspirations and characteristics of the situation
System Identification
System Description
Science & Knowledge
Complex Systems Theory
Culture and Values
General Vision
Ecological Possibilities
Scenarios
Vision and Preferences
SYSTEMS APPROACHES
COLLABORATIVE PROCESSES
Choose a vision to promote
Design / plan an adaptive program for realization of the vision
Ongoing Adaptive Management
GOVERNANCE
MONITORING
MANAGEMENT
Adapted from: J. Kay and M. Boyle, 1999



DEVELOP A SOHO ECOSYSTEM DESCRIPTION
▪ Identify ecosystem of interest (extent)
▪ Hierarchical description (scale and type, nesting)
▪ System description (structure & processes, external influences)
▪ Attractor analysis (including feedbacks and propensities)
▪ Evaluation of current integrity
▪ Synthesis (narrative description of self-organizing behaviour)
DEVELOP AN ISSUES FRAMEWORK
▪ Identify stakeholders and other participants (actors)
▪ Describe current governance and institutional relationships and their evolution
▪ Issue identification and analysis by actors (i.e. Checkland CATWOE)
▪ Define integrity & sustainability in terms of a vision for the future
▪ Hierarchical mapping of human concerns and preferences onto the SOHO ecosystem description.
System Identification
Science and other Knowledge
Complex Systems Theory
Culture and Values
General Vision
ecological possibilities
SCENARIOS
vision and preferences
SYSTEMS APPROACHES
COLLABORATIVE PROCESSES
Which self-organizing entities (SOHO and attractors) do we want to encourage and when?
DESIGN THE CONTEXT
Design the human & ecological infrastructure and circumstances required to encourage the desired SOHO
© James J. Kay, M. Boyle, 1999
ONGOING ADAPTIVE MANAGEMENT
The continuing process of learning, revisioning, resolving tradeoffs, and planning by the parties to adapt to the unfolding situation. This will entail the ongoing evolution of governance arrangements.
GOVERNANCE
MONITORING
MANAGEMENT
Development and implementation of strategies to promote/ discourage self-organization in the context of the communal vision and plan. This involves the identification of external contextual changes, flows into and from the system, and feedback loops which are to be encouraged and discouraged. Generally this entails managing human activities rather than direct intervention in the system.
The continuing collection of and synthesis of information into a narrative of the present and anticipated evolution of the system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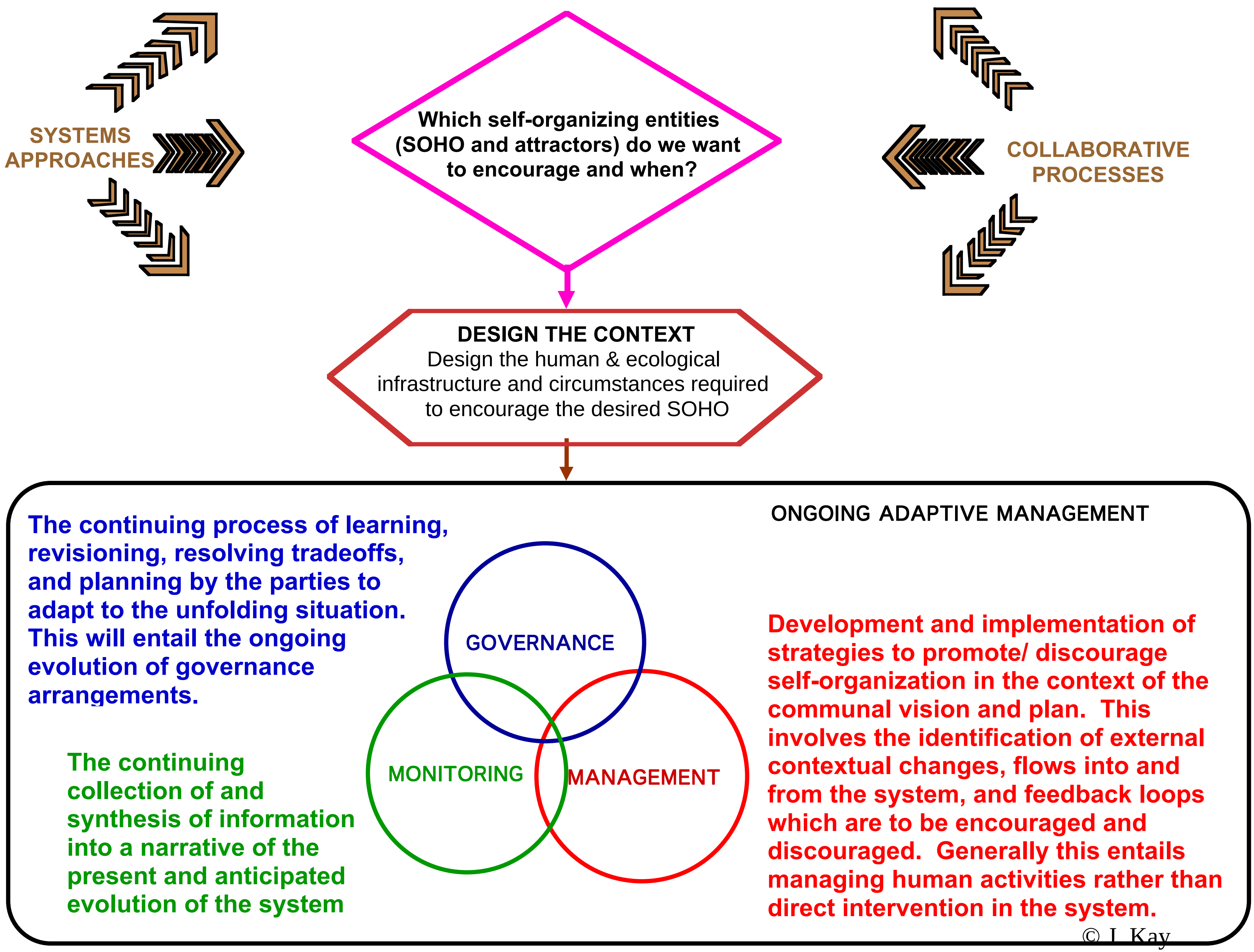
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The role of scientists

In post normal science, the scientist's role in decision making shifts from inferring what will happen, that is making predictions which are the basis of decisions, to providing decision makers and the community with an appreciation, through narrative descriptions, of how the future might unfold. These narratives consist of several scenarios of how the ecological systems in question might evolve.

The role of scientists

These narratives focus on a qualitative/quantitative understanding that describes:

- the human context for the narrative
- the hierarchical nature of the system;
- the attractors which may be accessible to the system;
- how the system behaves in the neighbourhood of each attractor, potentially in terms of a quantitative simulation model;
- the positive and negative feedbacks and autocatalytic loops and associated gradients which organize the system about an attractor;
- what might enable and disable these loops and hence might promote or discourage the system from being in the neighbourhood of an attractor; and
- what might be likely to precipitate flips between attractors.

The role of scientists

These narratives are in the service of informing decision makers and the community about:

- **possible future states of organization of the system;**
- **understanding of conditions under which these states might occur;**
- **understanding of the tradeoffs which the different states represent;**
- **appropriate schemes for ensuring the ability to adapt to different situations;**
- **and perhaps most importantly the appropriate level of confidence that the narrative deserves, this is our degree of uncertainty.**

The role of scientists

Having painted a picture of the possibilities in the future, it remains for scientists to suggest ways of mitigating and adapting to the inevitable surprises, both surprises in the form of unexpected flips to known attractors and those that involve flips to new attractors which correspond to heretofore unknown manifestations of system organization. Only through learning to do this will science be able to contribute to humanities quest of learning how to live sustainably.

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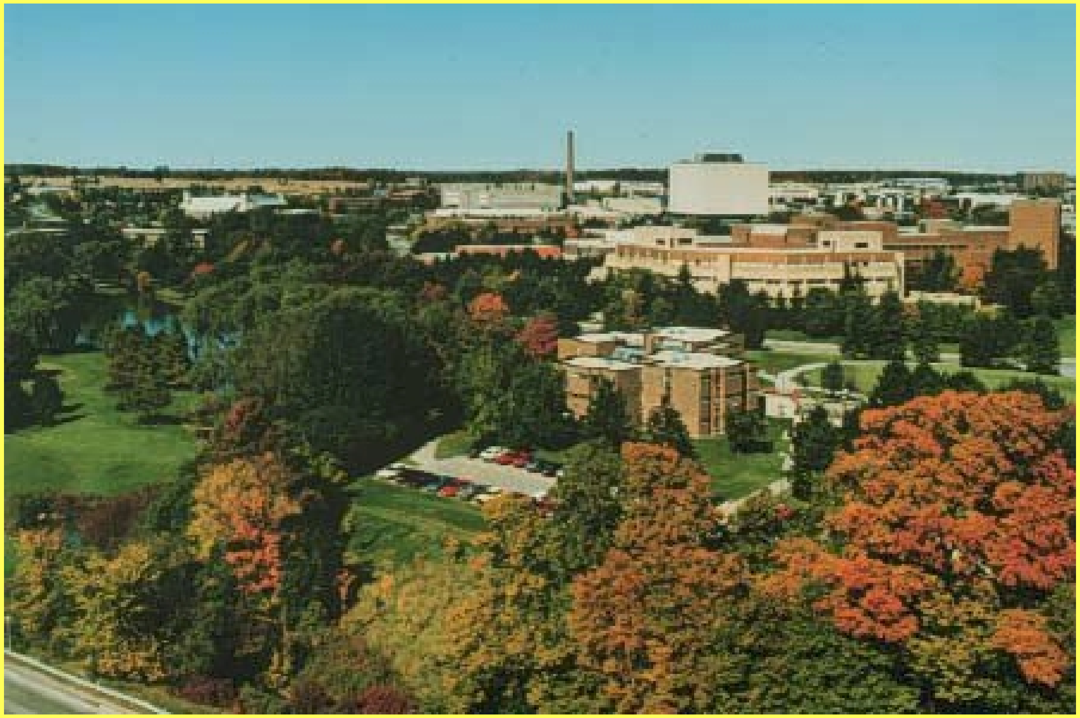
Faculty of Environmental Studies
University of Waterloo



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