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Modeling Ecological Complexity

Challenges and Opportunities

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COMPLEXITY IS WHAT YOU DON'T UNDERSTAND !
YOU DON'T UNDERSTAND COMPLEXITY!
A Scientific Discussion

Generally scientists apply logic, experience, and quantitative analysis to explain a pattern in terms of the processes believed to underlie it. But to what extent do these patterns mirror the processes that created them?

- For long time, physicists were convinced that the best science was reductionist and that all other sciences, at least in principle, could eventually be predicated on, if not reduced to, physical laws.
- Even though, in practice, it would be impossible to accomplish such a vast reduction, there was comfort and pride in believing that our science was fundamental.
- Recent development of emergent phenomena has made many of us no longer blindly buy into the idea that reductionism is superior to other science.

Shifting Paradigms of Systems Thinking in Complex Ecology

- Reductionism —› Holism
- Realism —› Constructivism
- Single perspective —› Multiple perspectives
- Disciplinary boundaries —› Isomorphisms among disciplines
- Disciplinary problems —› Cross-disciplinary problems
- Simple systems —› Complex systems/Simplification

Cont.

- Closed systems ⟶ Open systems
- Observer and systems ⟶ Observer in system
- Invariance ⟶ Variability/higher level invariance
- Reversibility ⟶ Irreversibility
- Regularities ⟶ Singularities
- Linearities ⟶ Nonlinearities
- Predictability ⟶ Randomness and chaos
- Additivity ⟶ Nonadditivity
- Causality ⟶ Constraints and possibilities
- Certainty ⟶ Uncertainty

Mathematical, statistical and computational challenges from complex ecology

- How do we incorporate variation among individual units in nonlinear systems?
- How do we treat the interactions among phenomena that occur on a wide range of scales, of space, time, and organizational complexity?
- What is the relation between pattern (or structure) and process (or function)?
- How do we quantify emergent property of ecological (landscape) system?

Ecological Complexity

- refers to the complex interplay between all living systems and their environment, and emergent properties from such an intricate interplay.
- The concept of ecological complexity stresses the richness of ecological systems and their capacity for adaptation and self-organization.
- The science of ecological complexity seeks a truly quantitative and integrative approach towards a better understanding of the complex, nonlinear interactions (behavioral, biological, chemical, ecological, environmental, physical, social, cultural) that affect, sustain, or are influenced by all living systems, including humans.
- It deals with questions at the interfaces of traditional disciplines and its goal is to enable us to explain and ultimately predict the outcome of such interactions.
- The field is based on a complexity theoretical framework for solving real world environmental problems

What are complex systems?

- Complex systems are characterized by strong (usually nonlinear) interactions between the parts, complex feedback loops that make it difficult to distinguish cause from effect, significant time and space lags, discontinuities, thresholds, and limits.

Complex systems self-organize themselves into states of greater complexity.

That behavior is not predictable from knowledge of the individual elements, no matter how much we know about them.

But it can be discovered by studying how these elements interact and how the system adapts and changes throughout time.

This new, emergent behavior of the system is important for understanding how nature operates on the macroscopic level.

The Types of Complexity

- Structural complexity
- Functional complexity

or

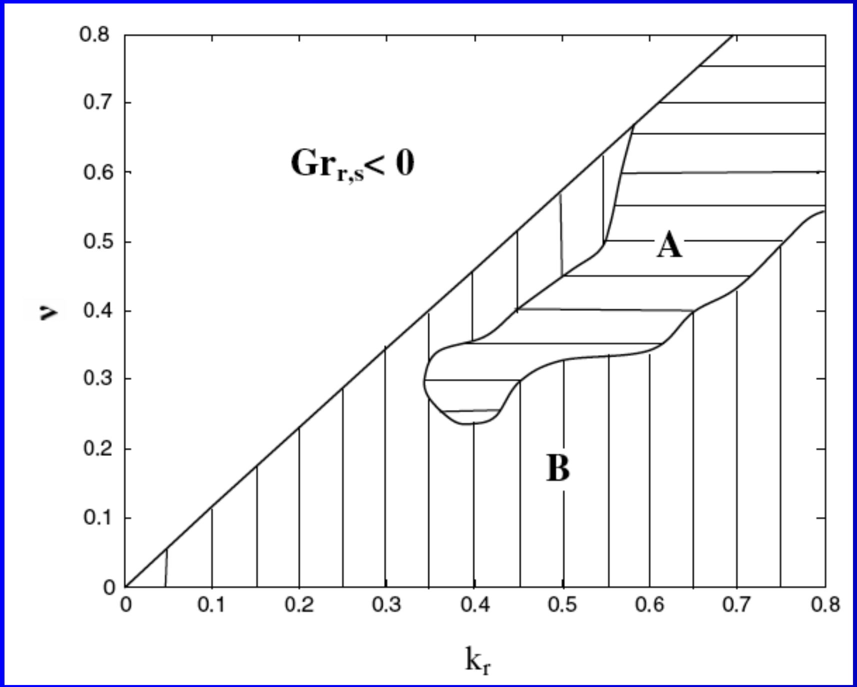
- Static complexity
- Dynamic complexity
- Self-organizing and evolving complexity

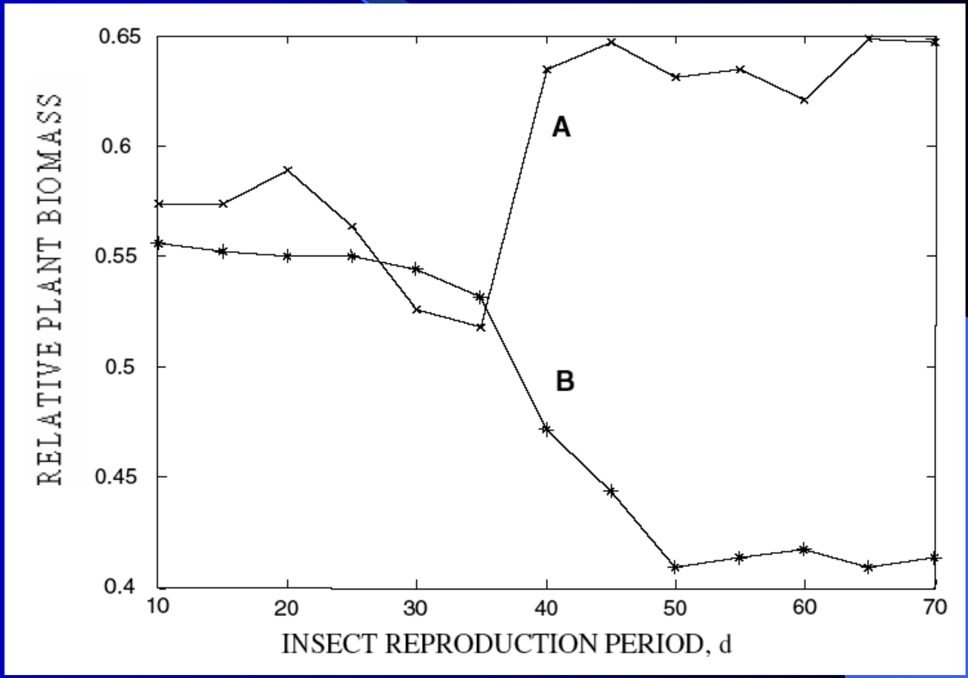
Main Research Focuses of Current Ecological complexity Studies

- **Nonlinearity:** bifurcation, chaos …
- **Self-organized hierarchy and emergent properties**
- **Threshold, criticality and phase transition**
- **Scaling issue:** scale invariance, scale covariance and scale or across-scale dynamics

- **Complex Systems Theory** states that critically interacting components self-organize to form potentially evolving structures exhibiting a hierarchy of emergent system properties.
- **Nonlinear Dynamics Theory:** Bifurcations, cellular automata, chaos, fractals, percolation theory, wavelets …
- **Nonlinear Nonequilibrium Thermodynamics** (I. Prigogine)
- **Complex Adaptive Systems Theory:** Adaptability theory (Conrad), self-organized criticality (Bak et al.), highly optimized tolerance (Carlson and Doyle), synergetics (H. Haken) …
- **Information Theory**
- **Fuzzy Systems Theory** (Zadeh)

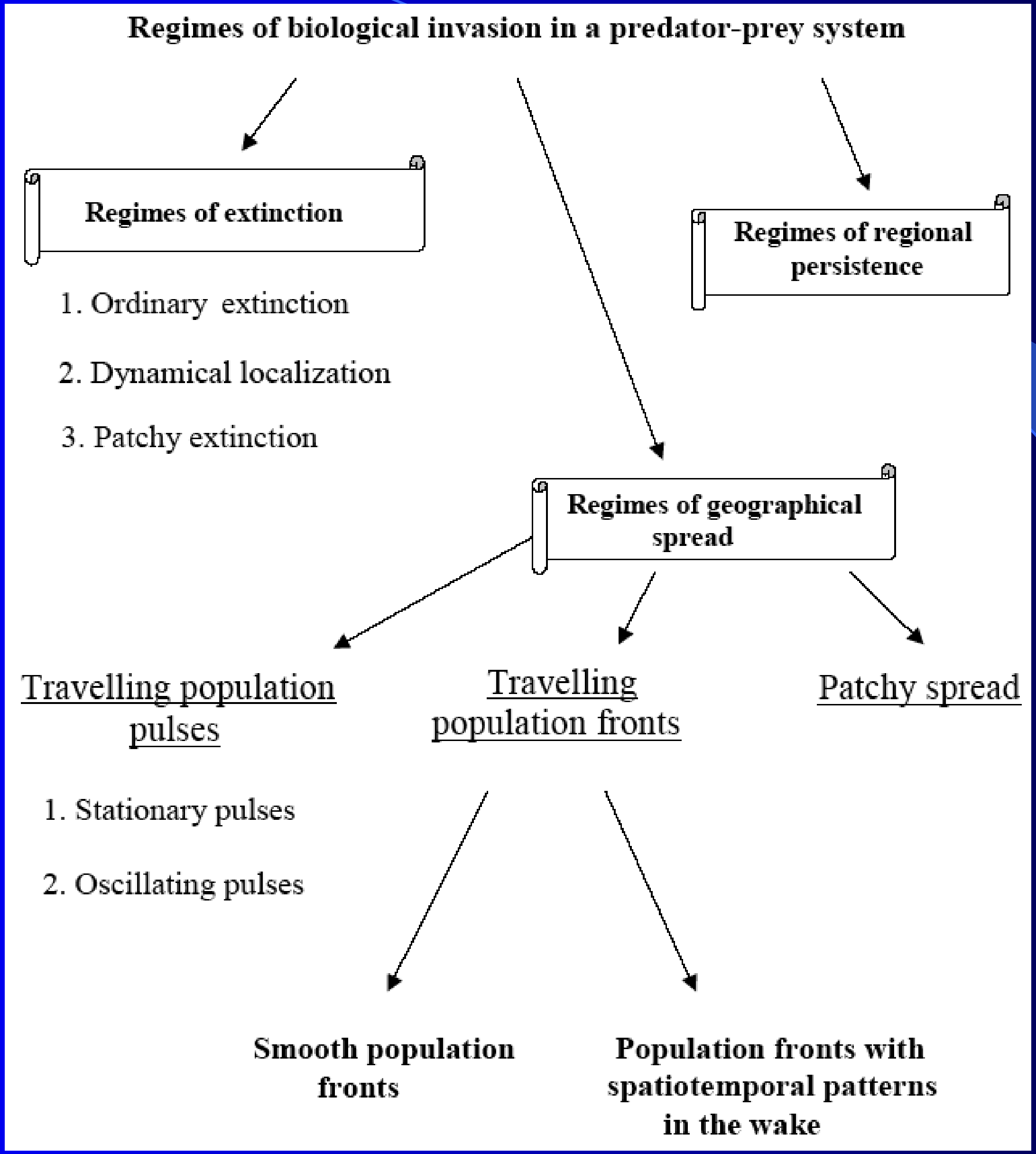
Modeling invasion of recessive Bt-resistant insects:
An impact on transgenic plants





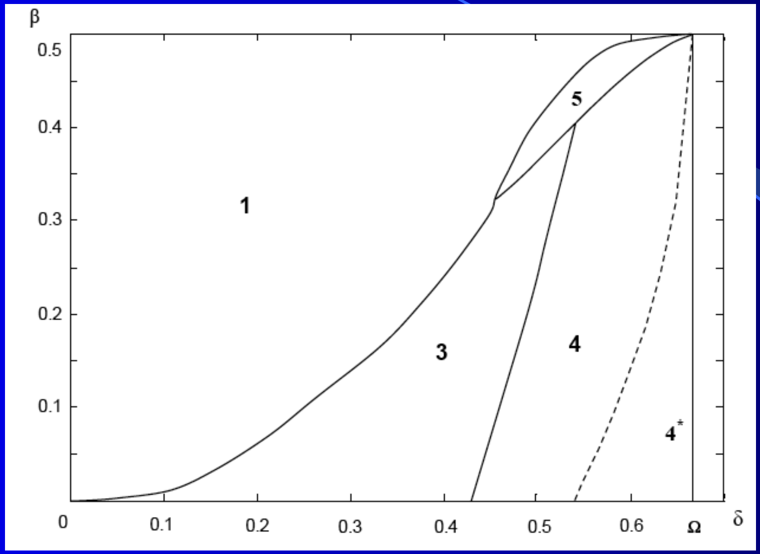
(Medvinsky et al. 2004. J. Theor. Biology, 231: 121-127)

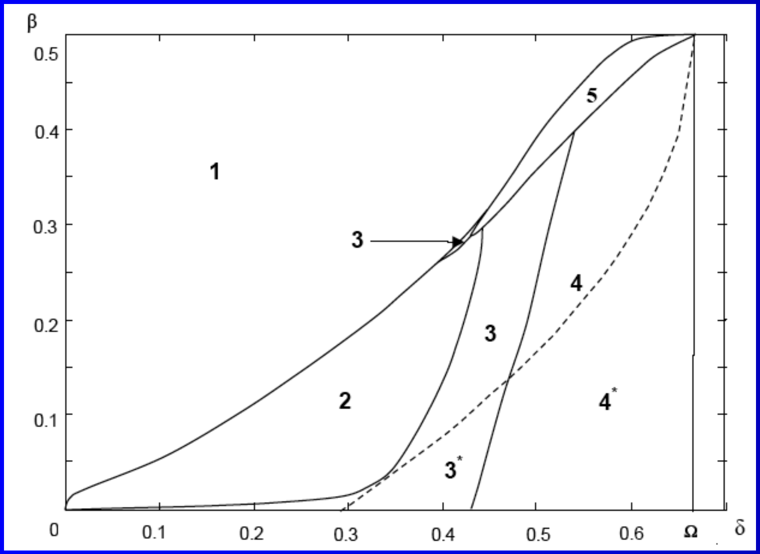
Dynamic Regimes of Biological Invasion

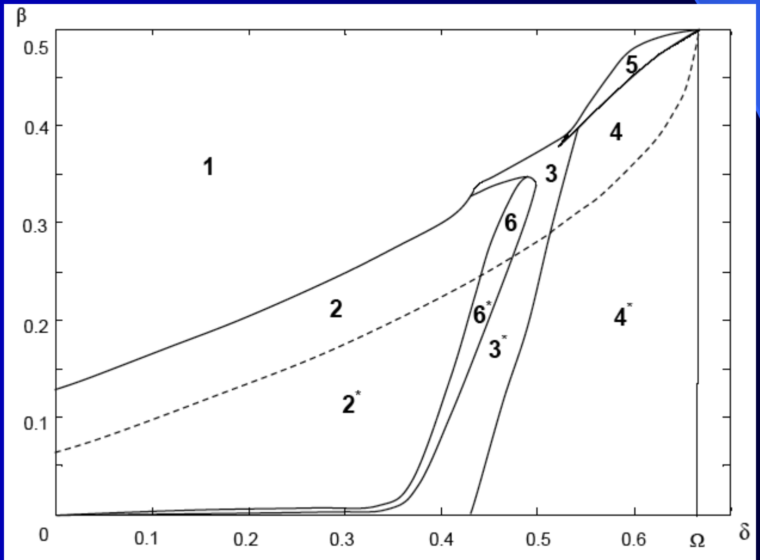


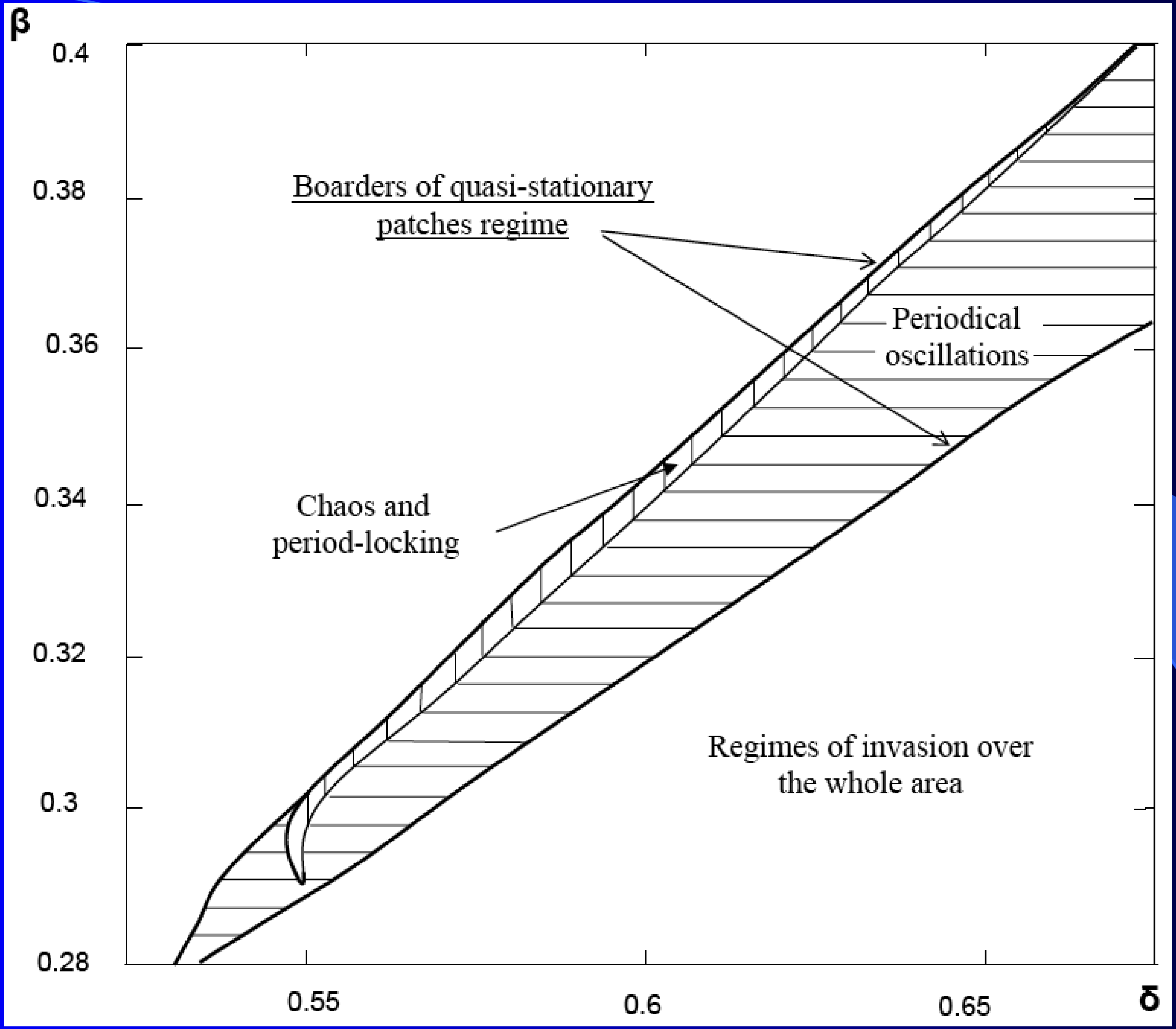
Dynamic Regimes of Biological Invasion (cont.)

(Petrovsky, Morozov, & Li, Bull. Math. Biol., in press)



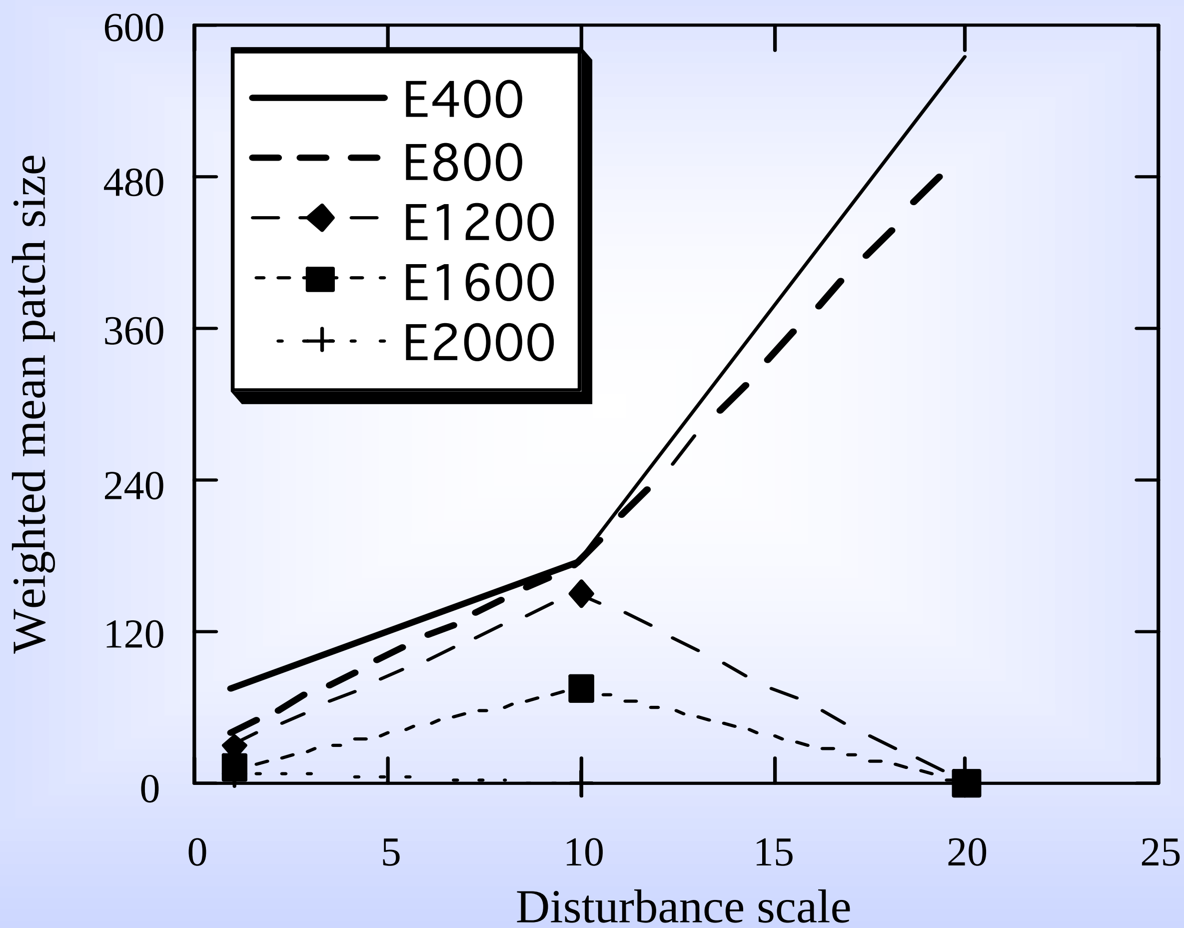






(Morozov, Petrovskii & Li, 2004. *Proc. R. Soc. Lond. B*, 271: 1407-1414)

Landscape responses to disturbances



(Li & Archer, 1997)

Self-Organization

- The essence of self-organization is that system structure often appears without explicit pressure or involvement from outside the system. In other words, the constraints on form (i.e. organization) of interest to us are internal to the system, resulting from the interactions among the components and usually independent of the physical nature of those components.
- The organization can evolve in either time or space, maintain a stable form or show transient phenomena.
- General resource flows within self-organized systems are expected (dissipation), although not critical to the concept itself.

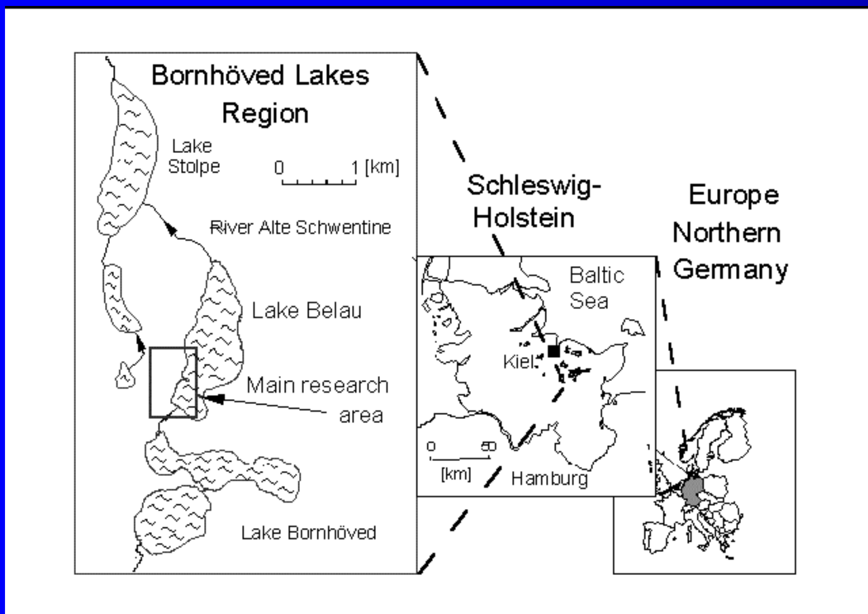
Typical features include

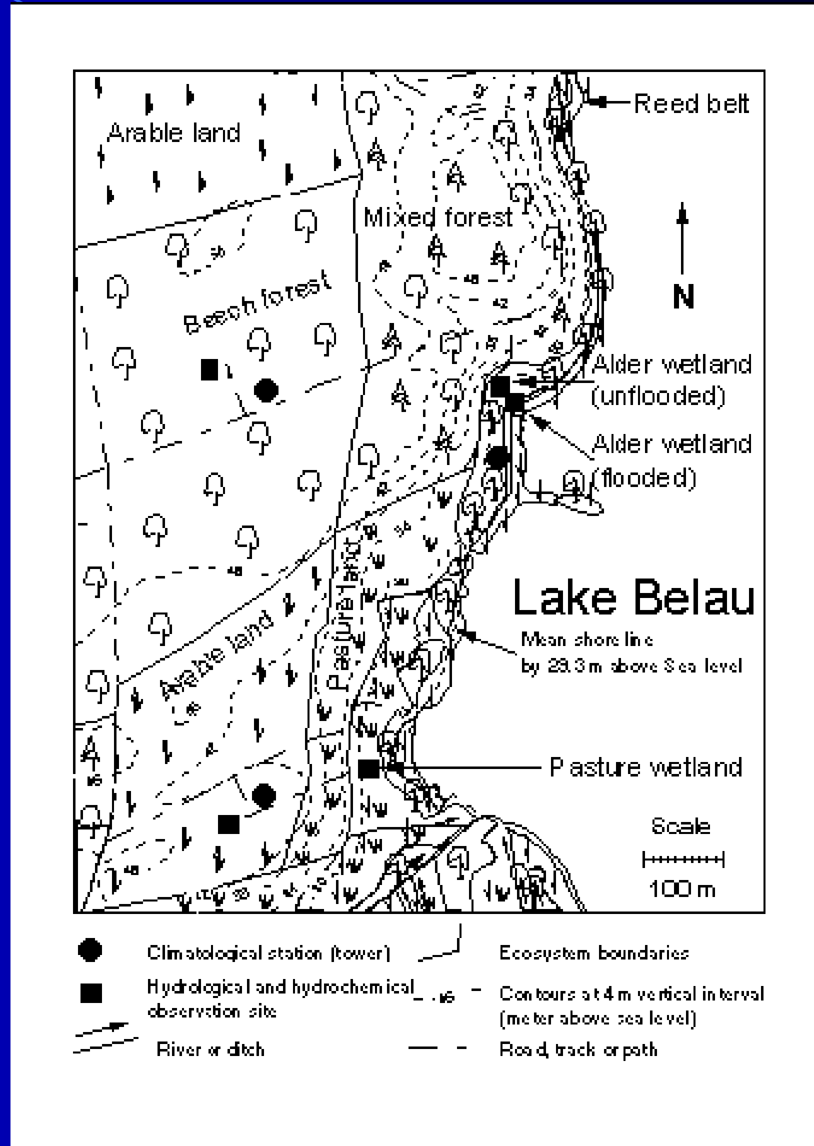
- Absence of centralized control (competition)
- Dynamic operation (time evolution)
- Fluctuations (searches through options)
- Symmetry breaking (loss of freedom)
- Instability (self-reinforcing choices)
- Multiple equilibria (possible attractors)
- Criticality (threshold effect phase changes)
- Global order (emergence from local interactions)
- Dissipation (energy usage and export)
- Redundancy (insensitive to damage)
- Self-maintenance (repair & part replacement)
- Adaptation (stability to external variation)
- Complexity (multiple parameters)
- Hierarchies (multiple self-organized levels)

Criteria of Order in Open Systems

- Boltzmann's H-theorem
- Prigogine's dissipative structures
- The Glansdorff-Prigogine criterion
- Klimontovich's S-theorem
- K-entropy
- Spectral entropy

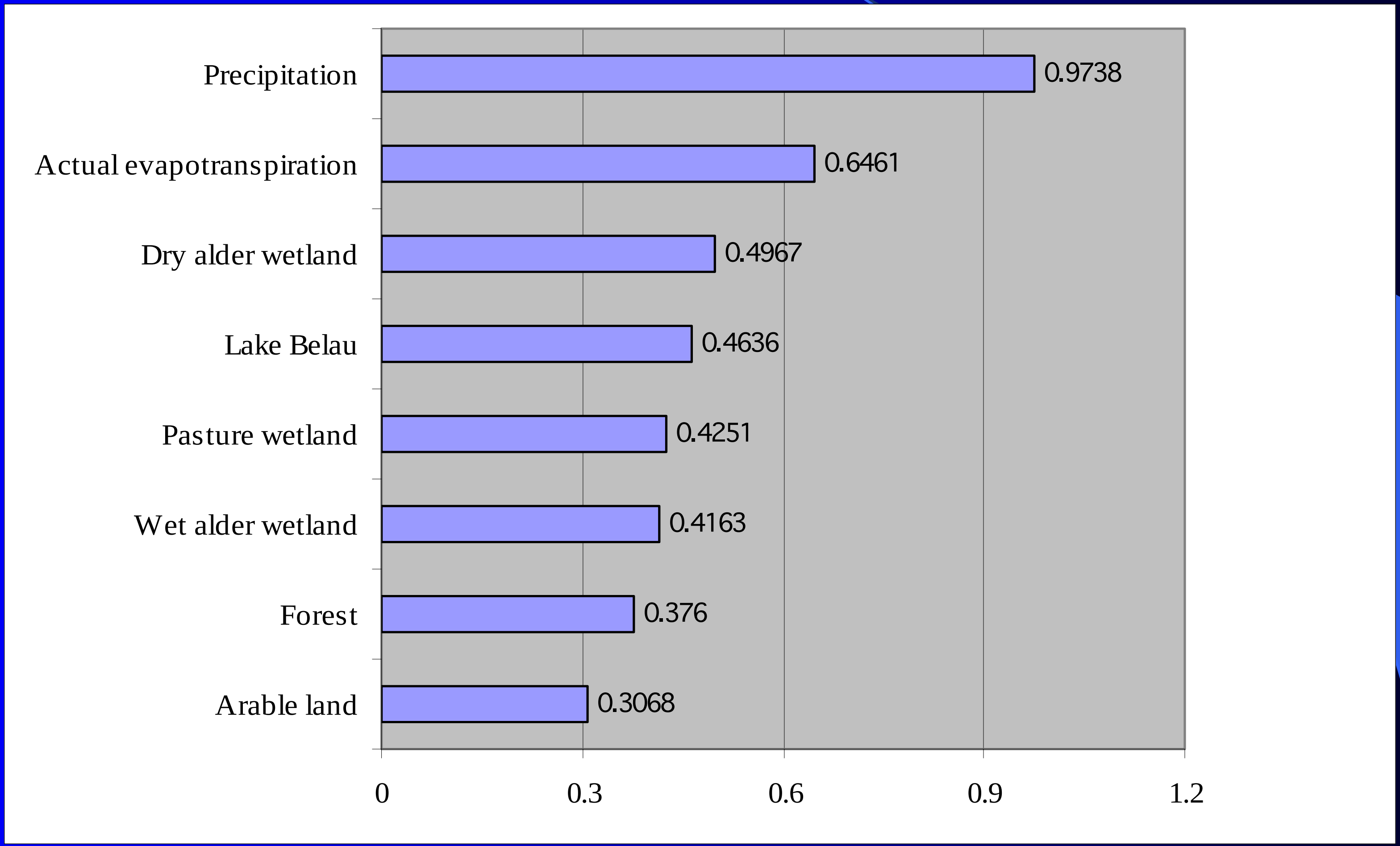
German Long-Term Ecological Monitoring Site



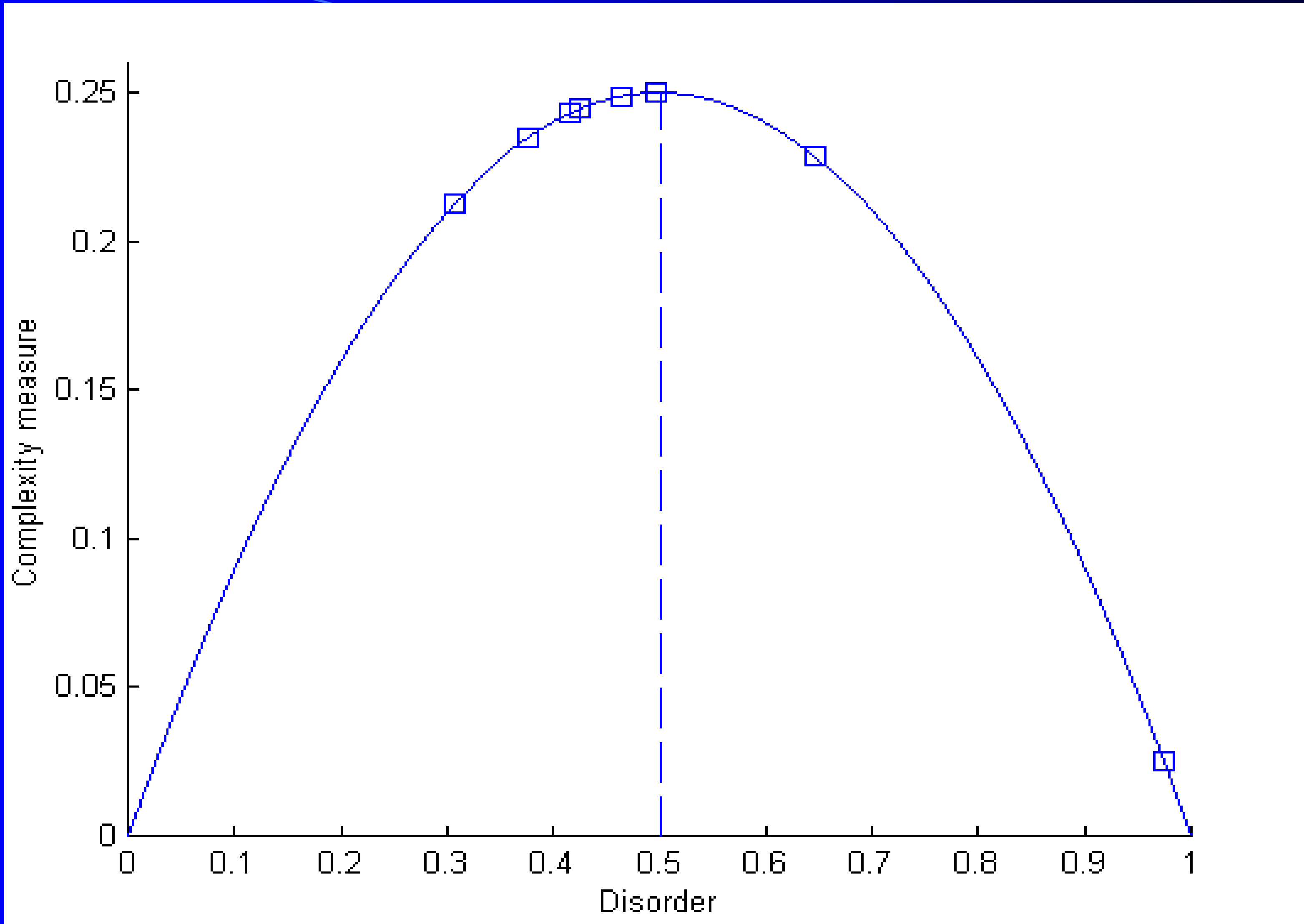


Self-organization, entropy, order and complexity

The normalized spectral entropy measure



Li, 2000



Biotic Abiotic

Chaos theory's contributions include the following discoveries:

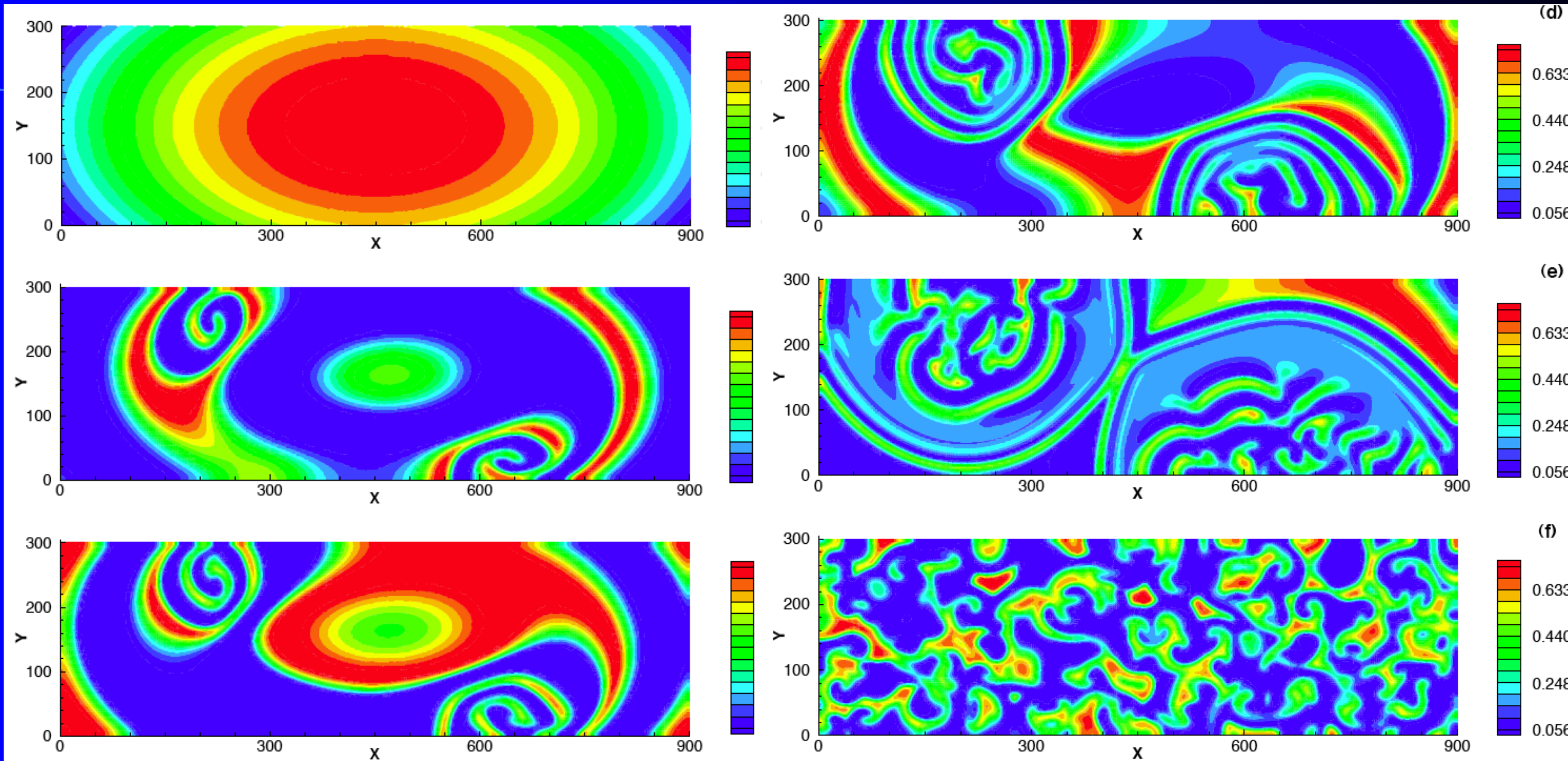
- Change isn't necessarily linear; that is, small causes can have larger effects. Determinism and predictability are not synonymous – deterministic equations can lead to unpredictable results – chaos- when there is feedback within a system.
- In systems that are "far-from-equilibrium" (i.e., chaotic), change does not have to be related to external causes. Such systems can self-organize at a higher level of organization.

More specifically, chaos may provide the foundation of ecological complexity with a few rather simple lessons, as follows:

- Order is hidden in chaos
- The order in chaos is holistic order and results from mutual effects
- The order in chaos provides a mechanical explanation for “mysterious” hidden global ordering (an “invisible hand”)
- Nonlinear interdependent dynamics have a penchant for creating whole out of parts
- Nonlinear systems may exhibit qualitative transformations of behavior (bifurcations)
- Chaotic dynamical systems may be permanently in a ‘critical’ state

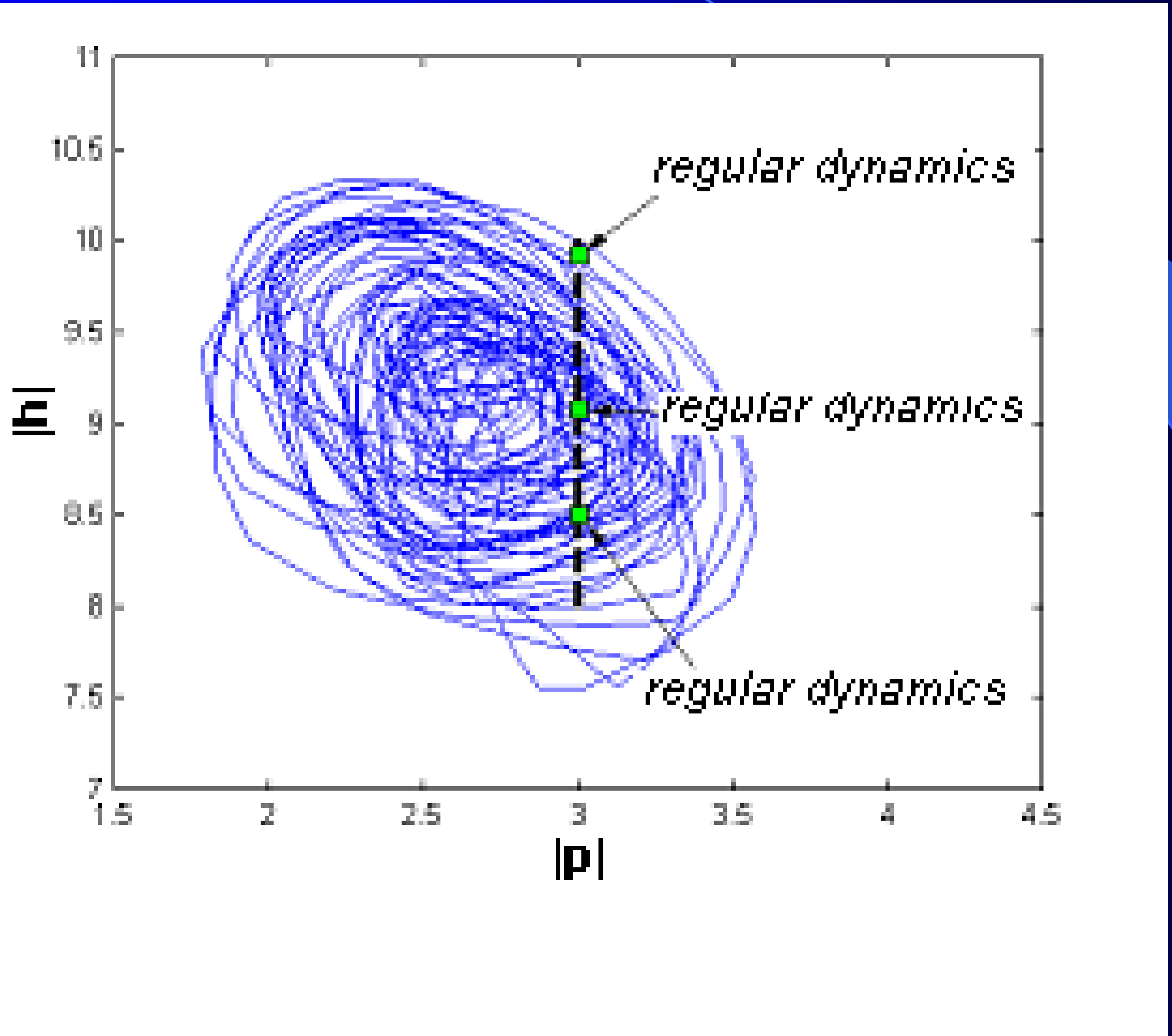
Spatio-temporal chaos

- Complex phenomena in space and time are common in nature, although no standard theory has been developed. Spatially extended systems possess an infinite number of degrees of freedom.
- Large classes of spatially extended systems may undergo a sequence of transitions leading to regimes displaying aperiodic dependence in both space and time, which we referred to rather loosely as *spatio-temporal chaos*.

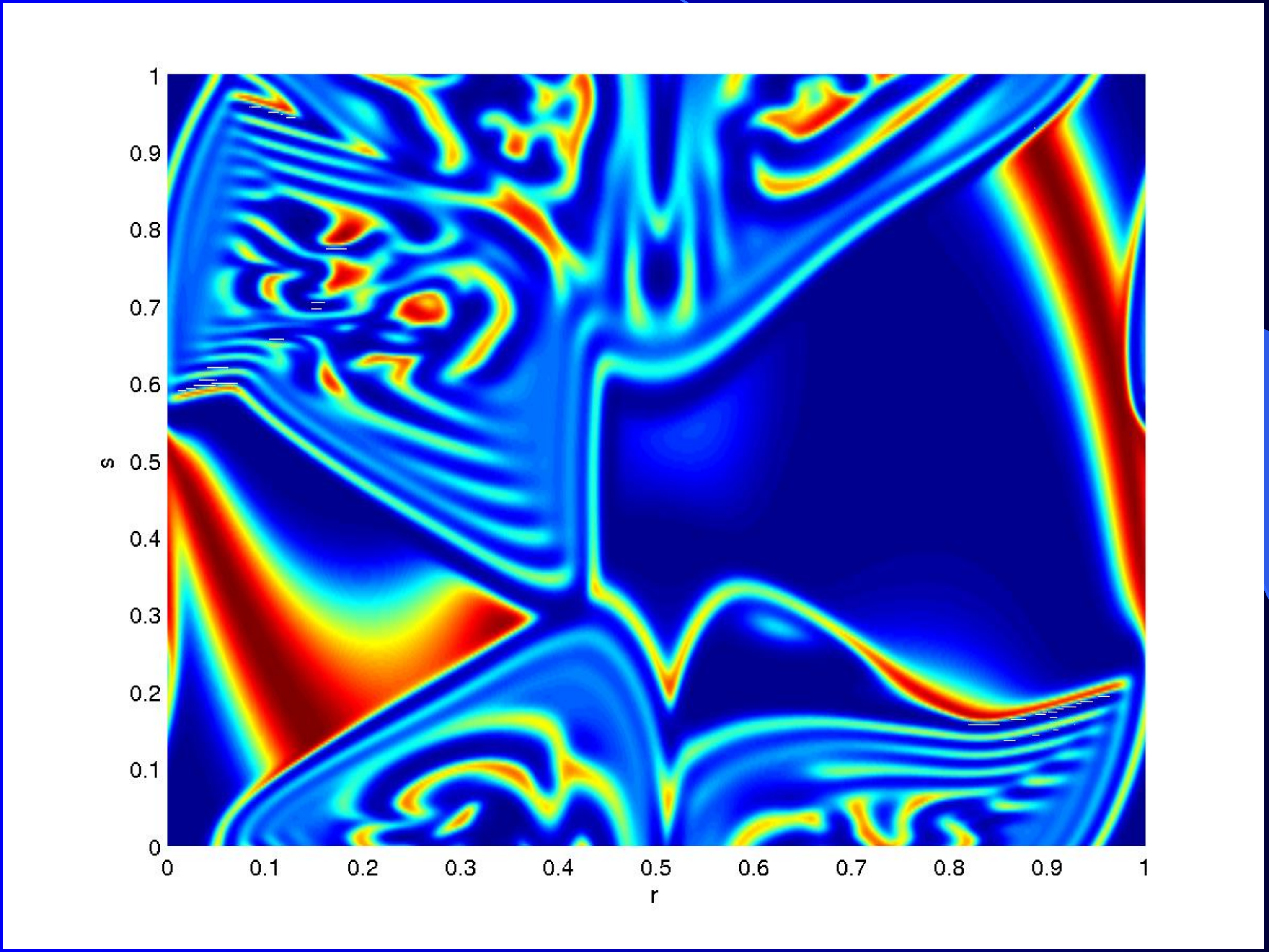


(SIAM Review, 44(3): 311-370, 2002)

Coexistence of multiple attractors



rs-space



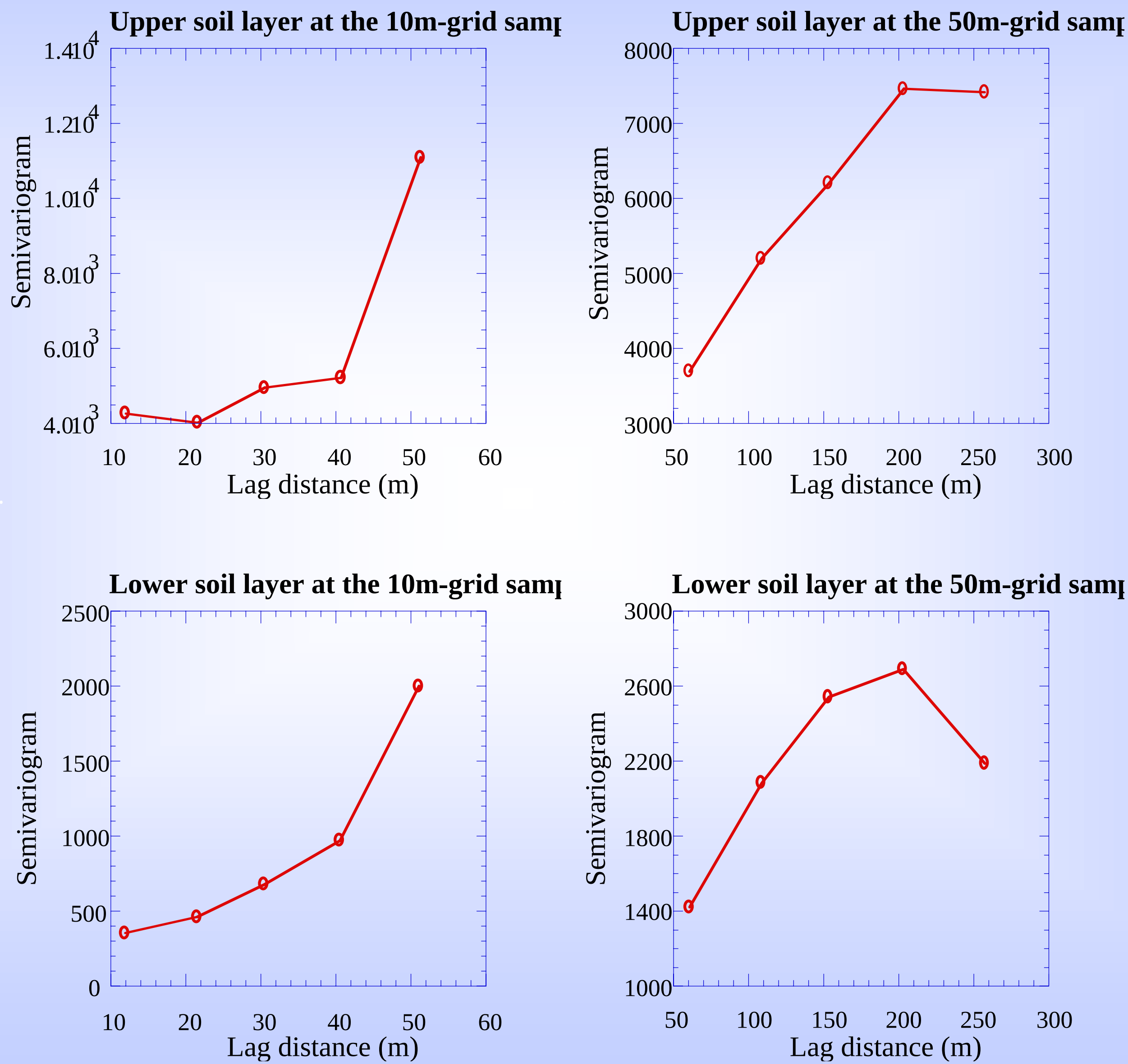
- Heterogeneity is a fundamental characteristic of nature, which is present in most variables representing natural phenomena. Heterogeneity appears at any scale of ecological systems.
- Ecological systems are organized hierarchically over a broad range of interrelated space-time scales.

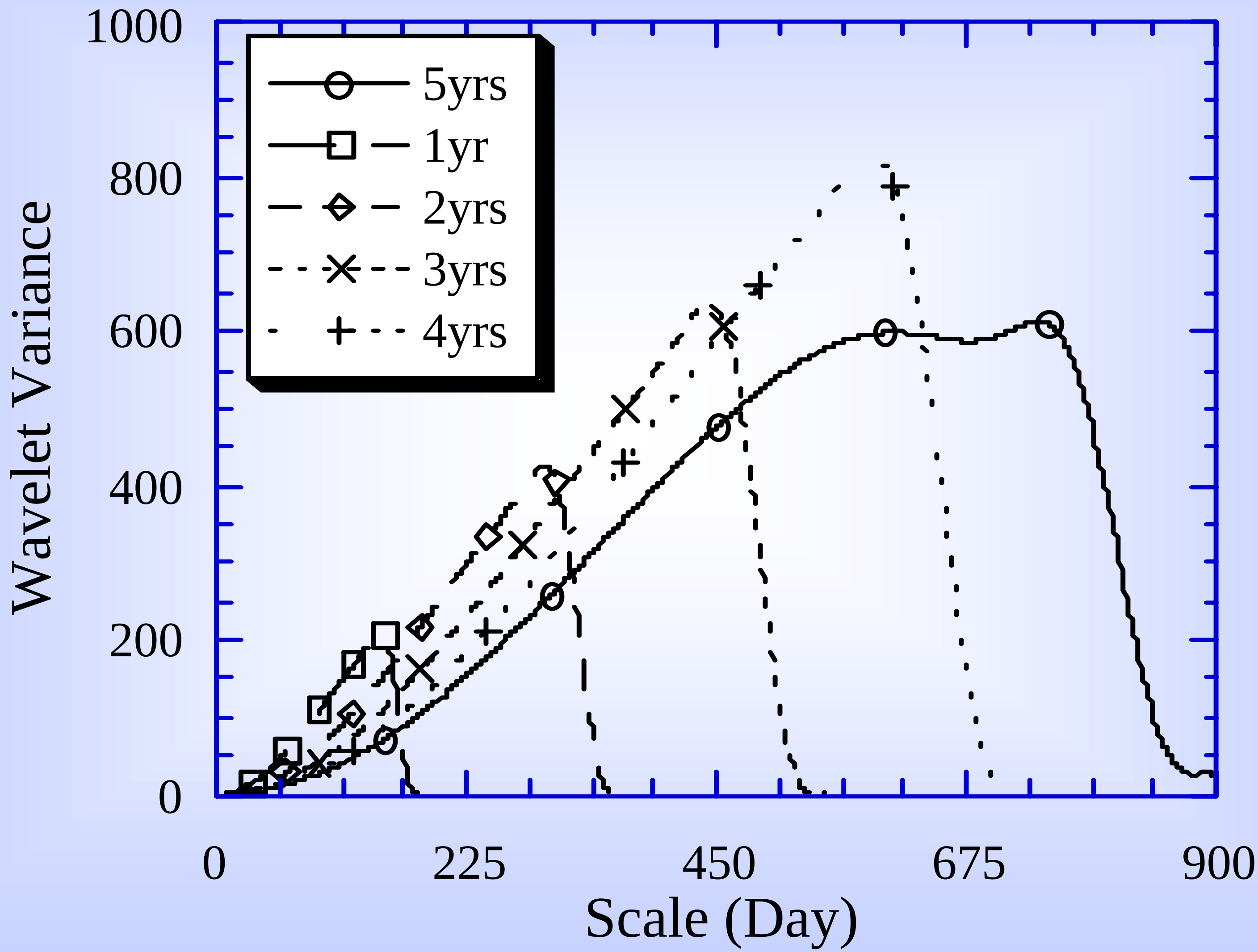
In general, we need to consider the following scales:

- ***Temporal scale*****:** (a) the lifetime/duration; (b) the period/cycle; and (c) the correlation length/integral scale;
- ***Spatial scale***: (a) spatial extent; (b) space period; and (c) the correlation length/integral scale;
- ***"Organism" scale***: (a) body size/mass; (b) species-specific growth rate; (c) species extinction rate; (d) the life span; (e) the home range; (f) niche, and so on.

In practice, we have to identify:

- *Process scale*
- *Observation scale*
- *Modeling/working scale*
- *Management scale*

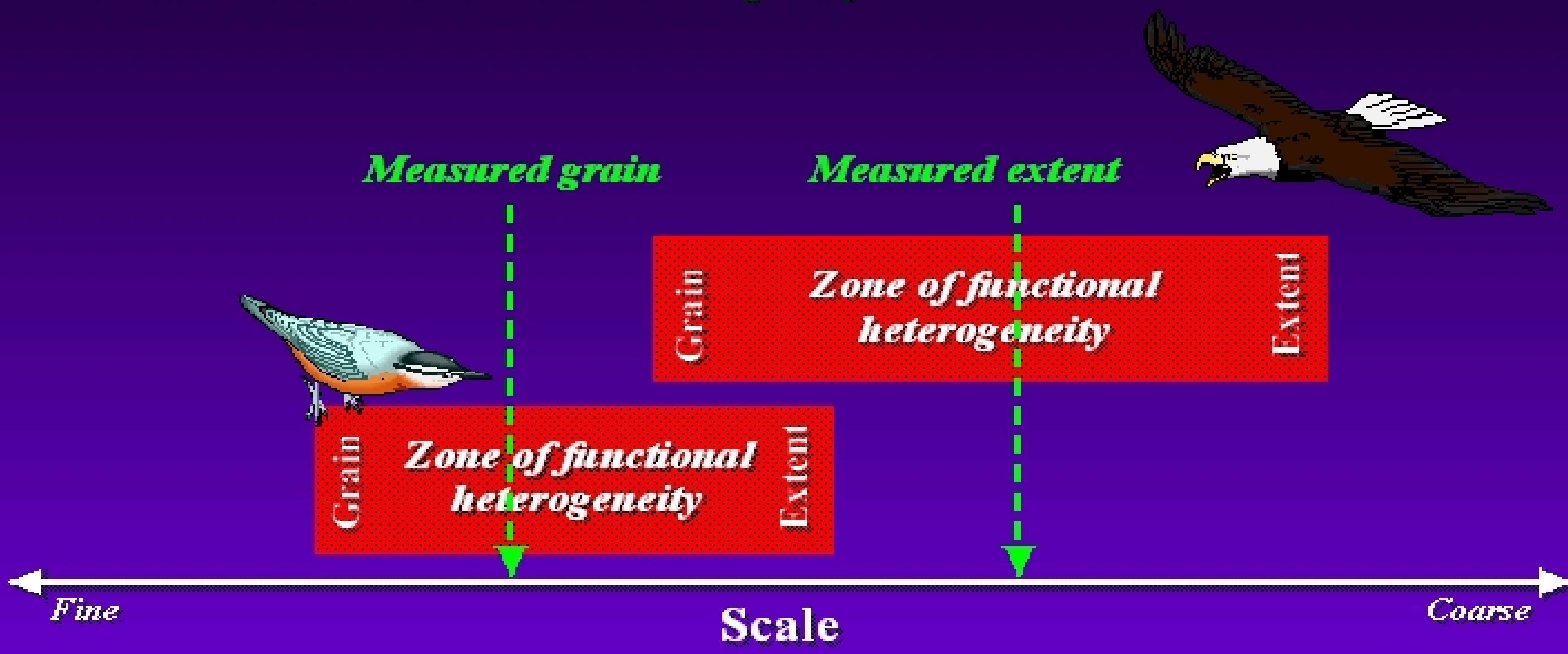

Upper soil layer at the 10m-grid samp
$1.4\,10^4$
$1.2\,10^4$
$1.0\,10^4$
$8.0\,10^3$
$6.0\,10^3$
$4.0\,10^3$
Semivariogram
10 20 30 40 50 60
Lag distance (m)
Upper soil layer at the 50m-grid samp
8000 7000 6000 5000 4000 3000
Semivariogram
50 100 150 200 250 300
Lag distance (m)
Lower soil layer at the 10m-grid samp
2500 2000 1500 1000 500 0
Semivariogram
10 20 30 40 50 60
Lag distance (m)
Lower soil layer at the 50m-grid samp
3000 2600 2200 1800 1400 1000
Semivariogram
50 100 150 200 250 300
Lag distance (m)



1000
800
600
400
200
0
0
225
450
675
900
Wavelet Variance
Scale (Day)
5yrs
1yr
2yrs
3yrs
4yrs

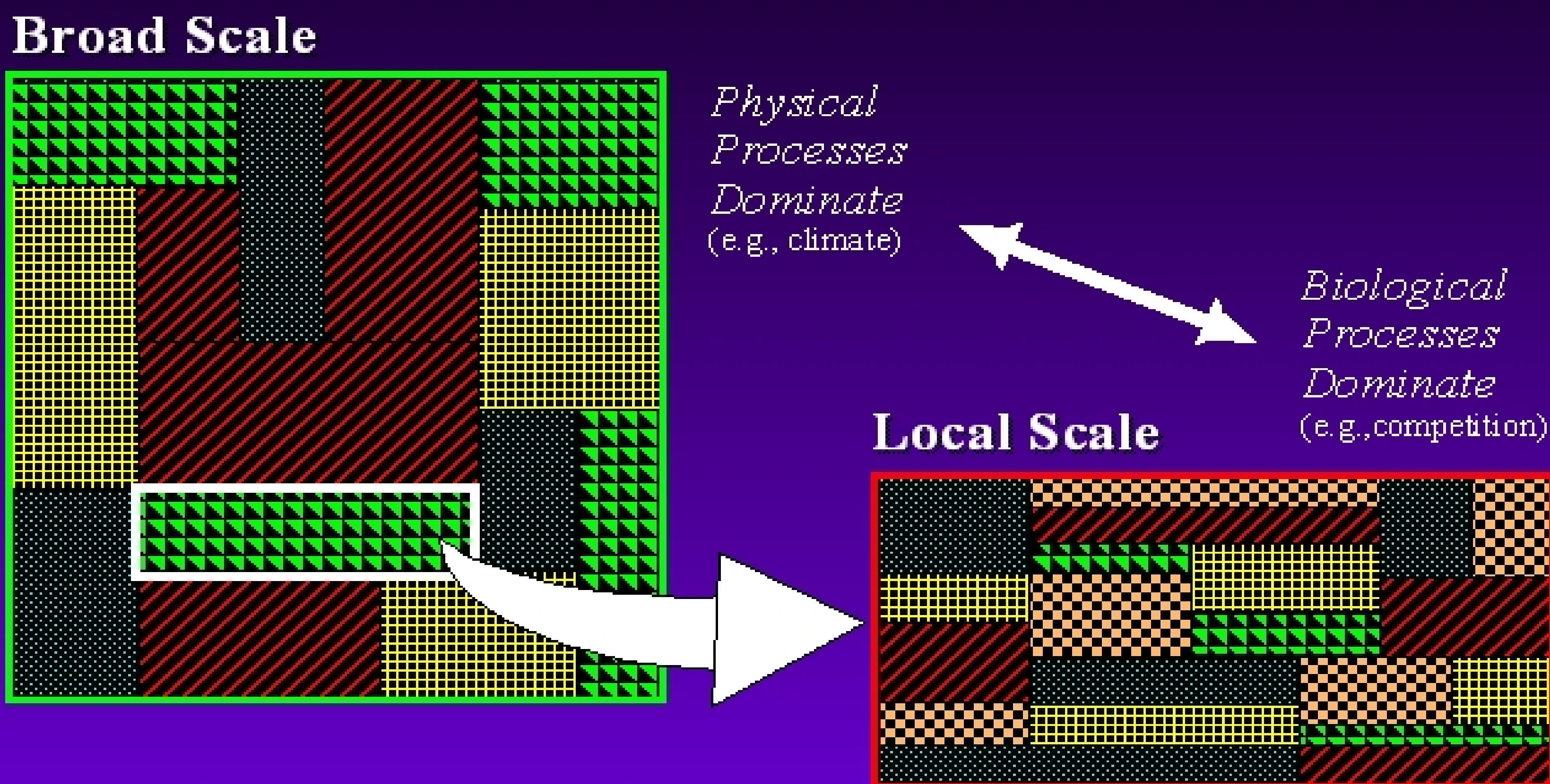
Ecological Scaling: Components of Scale

- In is critical that grain and extent be defined for a particular study and represent the ecological phenomenon or organism under study, otherwise the patterns detected will have little meaning and there is a good chance of reaching erroneous conclusions.
  - Measured versus functional heterogeneity.



Ecological Scaling: Consequences of Scale

- **Local biological interactions (e.g., competition) have the effect of decoupling systems from direct physical determination of patterns by introducing temporal and spatial lags in system dynamics or creating webs of indirect effects. At broader scales, physical processes my dominate or dissipate these biological effects.**



Scale invariance or symmetry
= Self-similarity = Criticality
= Scale independence

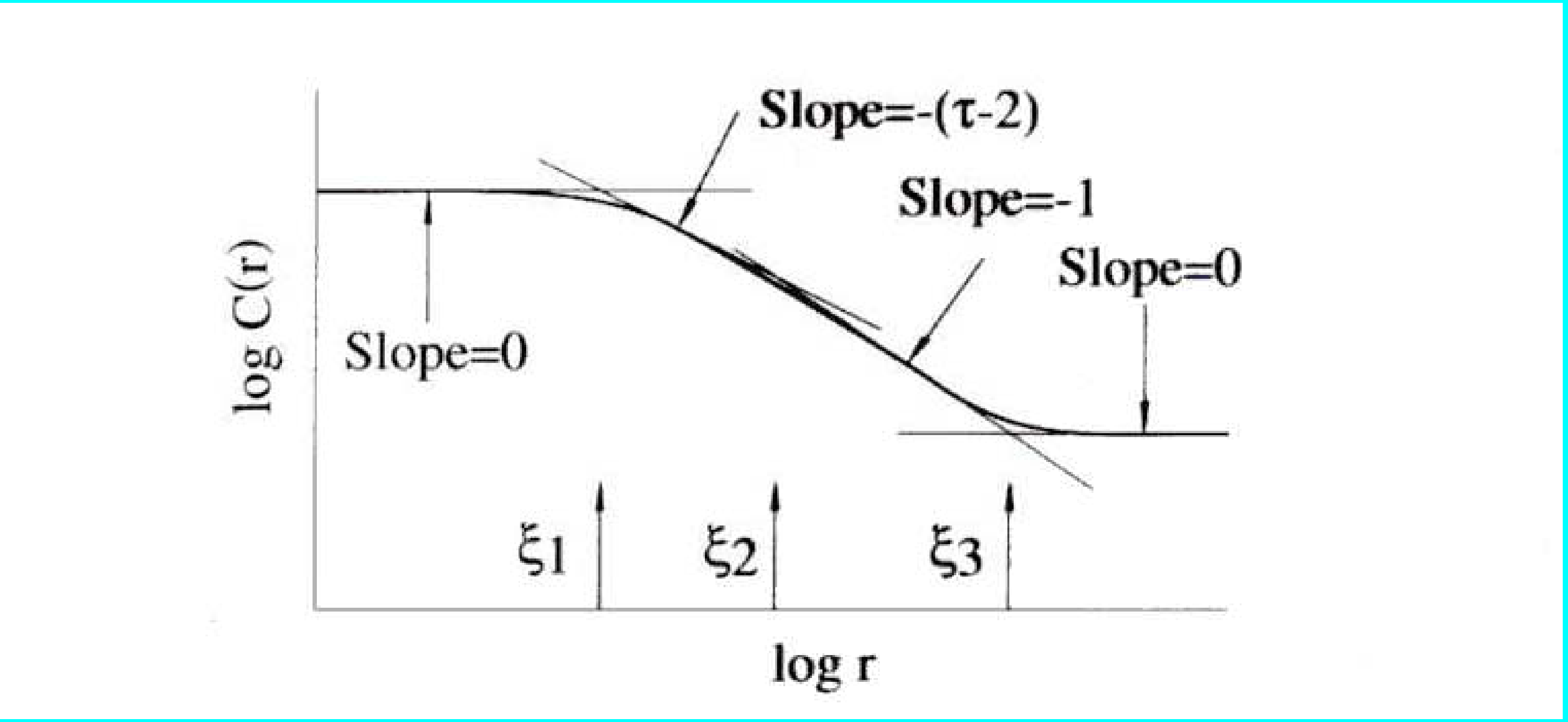
$$X(t) \overset{d}{\equiv} X(at) \overset{d}{\equiv} a^{H} X(t)$$

Ecological scale invariance →
Ecological equivalence of all lengths

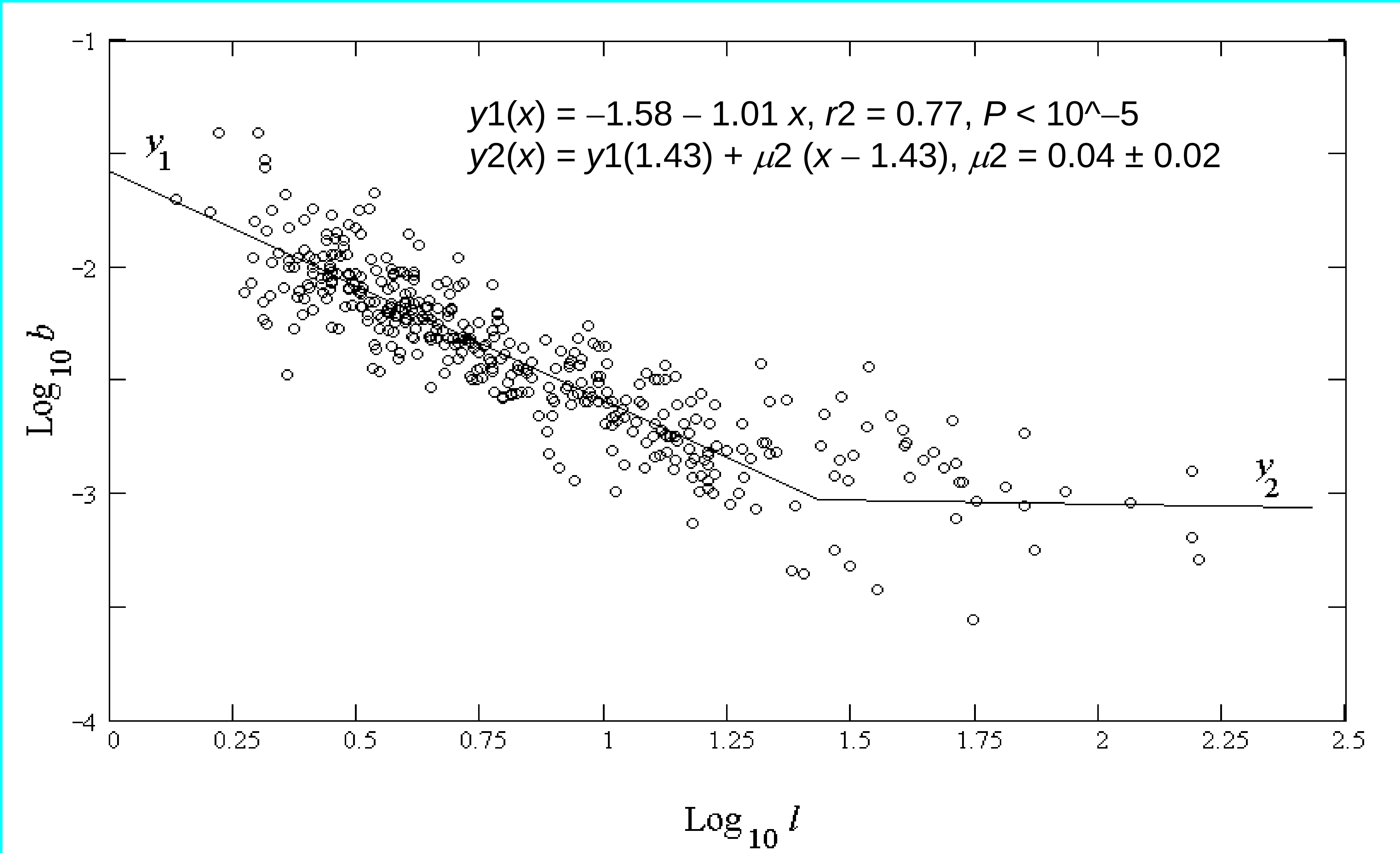
From scale invariance to scale covariance

- The scale dependence (covariance) is a spontaneously broken scale symmetry.

- That means that we have to take non-linearity in scale into account.



(**Hierarchy theory**: characteristic scales or rates.)



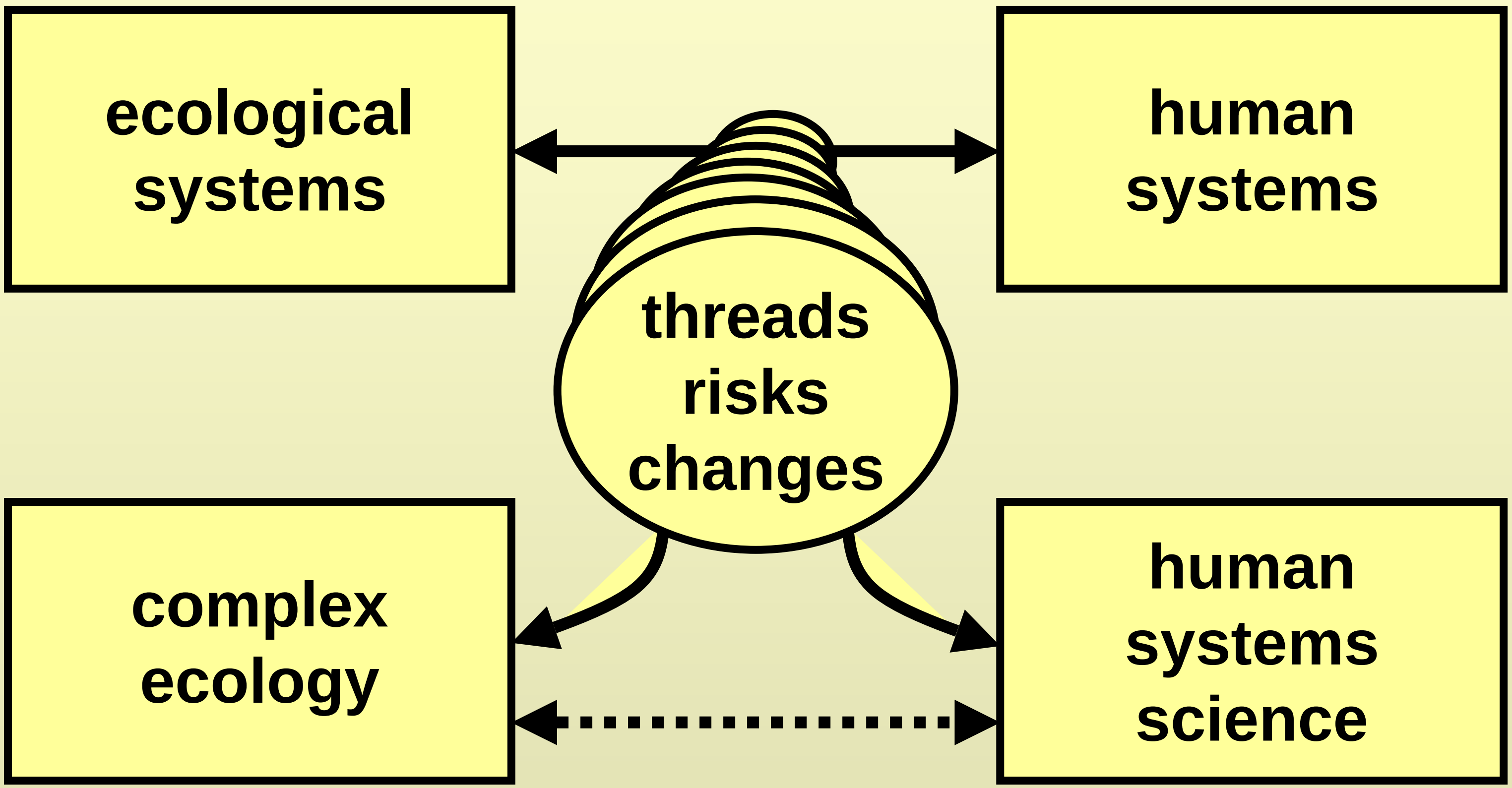
(Modified after Makarieva, Gorshkov & Li, 2003. J. Theor. Biol., 221: 301-307)

In general, boundary conditions, finite size effects, forcing or dissipation spoil this scale invariance, and the solution is not power-law anymore. The concept of scale covariance is then very useful to study the breaking of scale symmetry.

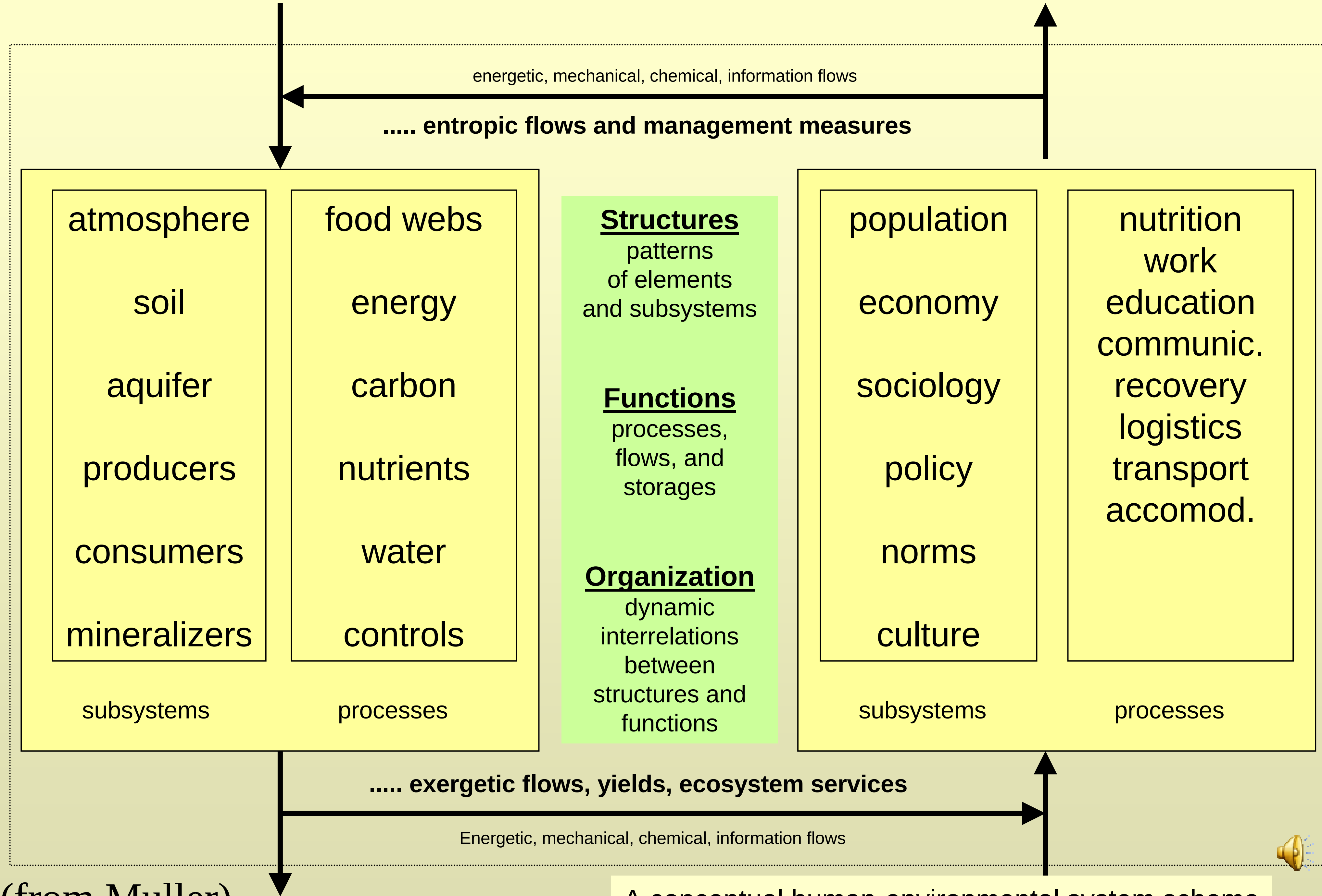
Scale (or across-scale) dynamics

- To identify and study the scale-force responsible for the scale distortion (i.e., for the deviation to standard scaling, mono- or multi-fractals).
- The methodology includes, such as, scale relativity, scale-acceleration, the Lagrange scale-equation, discrete scale invariance, etc.

COMPLEX SYSTEMS APPROACHES TO STUDY HUMAN - ENVIRONMENT ***INTERACTIONS***

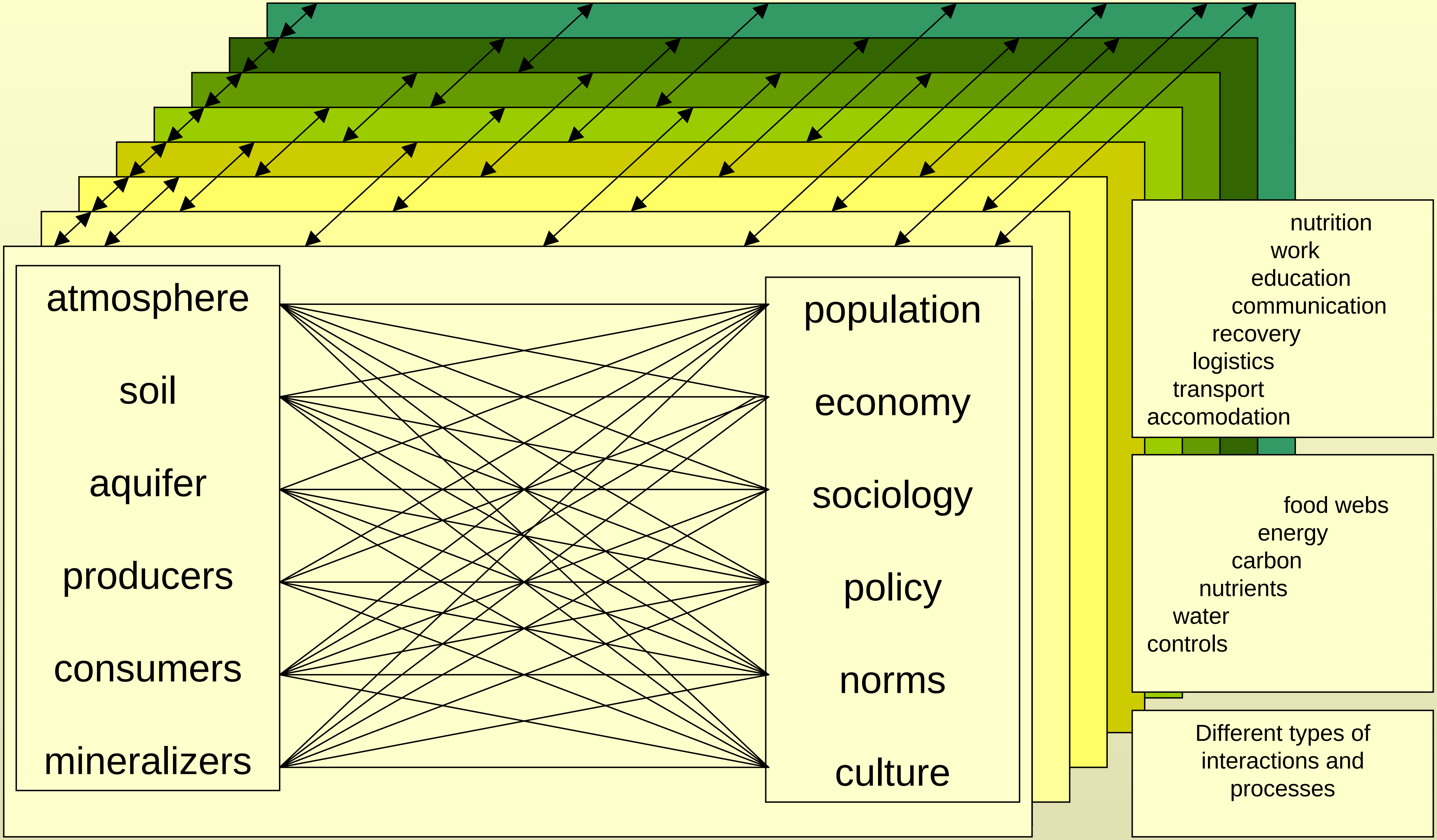


How to understand the complex interactions, and how to use that understanding?



(from Muller)

A conceptual human-environmental system scheme



How to cope with that complexity?

Table 2. The SDI ranks and trends of sustainability for different countries in the world

Rank	Country Name	SDI	Rank	Country Name	SDI	Rank	Country Name	SDI
1	Canada	0.73997 +	59	St. Lucia	0.53403 -	117	Viet Nam	0.37344 -
2	Sweden	0.71060 -	60	Cyprus	0.53003 -	118	Maldives	0.37168 +
3	Norway	0.70813	61	Belize	0.52923 +	119	Iran	0.36102 +
4	Denmark	0.69121 +	62	Singapore	0.52865 +	120	Jordan	0.35862 +
5	Finland	0.68686 +	63	Moldova	0.52712 -	121	Algeria	0.35344 +
6	New Zealand	0.68659 +	64	Greece	0.52330 +	122	Guatemala	0.35325
7	Iceland	0.68570 +	65	Armenia	0.52138 -	123	Morocco	0.35267 +
8	Japan	0.65698 -	66	Guyana	0.52124 +	124	Iraq	0.35001 -
9	Barbados	0.64472 -	67	Korea Dem.	0.51768 +	125	Equatorial Guinea	0.34479 +
10	USA	0.64037 -	68	Kuwait	0.51514 -	126	Lesotho	0.34037 +
11	Latvia	0.63758 -	69	St. Vincent	0.51307 +	127	El Salvador	0.33994
12	Hong Kong	0.63471 -	70	Anti. & Barb.	0.50830 +	128	Liberia	0.33969 +
13	Ukraine	0.63136 -	71	Romania	0.50795	129	Bhutan	0.33700 +
14	Australia	0.62930 -	72	St. Kitts & Nevis	0.50455 +	130	Zaire	0.33582 +
15	Germany	0.62581	73	Thailand	0.50308 +	131	India	0.33565 +
16	Czech Rep.	0.62433 +	74	Mauritius	0.50286 +	132	Swaziland	0.33264 -
17	Bahamas	0.62053 -	75	Bahrain	0.50259	133	San Tom & Prin.	0.32508 -
18	Luxembourg	0.61834 -	76	Mexico	0.49365 +	134	Comoros	0.31698
19	Malta	0.61813	77	Ecuador	0.49038 +	135	Togo	0.31284 +
20	Suriname	0.61683 +	78	Kazakhstan	0.49023 -	136	Egypt	0.31228 +
21	Bulgaria	0.61637 +	79	Jamaica	0.48368 -	137	Bangladesh	0.31071 +
22	France	0.61622	80	Congo	0.48125 +	138	Tanzania	0.30987
23	Belgium	0.61535 -	81	United Arab	0.47798	139	Zambia	0.30485
24	Russian	0.61509	82	Albania	0.47650 -	140	Ghana	0.30049 +
25	Panama	0.61232 +	83	Solomon Islands	0.47485 +	141	Cambodia	0.30017 +
26	Venezuela	0.61229 +	84	Turkey	0.47075 +	142	Oman	0.29926 +
27	Hungary	0.60584	85	Nicaragua	0.46792 -	143	Guinea	0.29766 +
28	Estonia	0.60496	86	Turkmenistan	0.46198 +	144	Cape Verde	0.29711 +
29	UK	0.60278	87	Samoa	0.45762 +	145	Senegal	0.29502 +
30	Belarus	0.59923 -	88	Georgia	0.45578 -	146	Kenya	0.29303 +
31	Netherlands	0.59838	89	Uzbekistan	0.45551	147	Cote dIvoire	0.28873 -

32	Lithuania	0.59617	-	90	Azerbaijan	0.45541	-	148	Namibia	0.28422	+
33	Austria	0.59549	-	91	Paraguay	0.45416	-	149	Angola	0.27480	+
34	Brunei	0.59530	-	92	Peru	0.44875	+	150	Madagascar	0.27063	+
35	Slovakia	0.59389	+	93	Bolivia	0.44447	+	151	Burundi	0.27057	-
36	Switzerland	0.59162	+	94	Papua New Guinea	0.43779	+	152	Mozambique	0.26256	+
37	Brazil	0.58814		95	Kyrgyzstan	0.43432	-	153	Rwanda	0.26055	+
38	Poland	0.58380	+	96	Libyan	0.43244	+	154	Nigeria	0.25690	+
39	Korea Rep.	0.58310	+	97	Vanuatu	0.42552	+	155	Malawi	0.25379	
40	Spain	0.58225	+	98	Saudi Arabia	0.42141	+	156	Uganda	0.24923	+
41	Grenada	0.57753		99	Philippines	0.41932	+	157	Pakistan	0.24857	+
42	Malaysia	0.57124	-	100	Botswana	0.41160	+	158	Djibouti	0.24736	+
43	Seychelles	0.56916	-	101	Tajikistan	0.41044	-	159	Benin	0.24463	+
44	Italy	0.56902	+	102	Indonesia	0.41010	+	160	Sierra Leone	0.24438	
45	Colombia	0.56811	+	103	Mongolia	0.40905	+	161	Guinea-Bissau	0.24147	+
46	Chile	0.56118	+	104	Tunisia	0.40178	+	162	Nepal	0.24103	+
47	Israel	0.56037		105	South Africa	0.40086	+	163	Haiti	0.23265	+
48	Qatar	0.55381		106	Zimbabwe	0.40052	-	164	Gambia	0.21746	+
49	Dominica	0.55308	+	107	Syrian	0.39554		165	Ethiopia	0.21706	
50	Trinidad & Tobago	0.55216	-	108	Central Africa	0.39468	+	166	Mauritania	0.21433	+
51	Uruguay	0.55043	+	109	China	0.39398		167	Yemen	0.20869	+
52	Costa Rica	0.54727		110	Lebanon	0.39289	+	168	Burkina Faso	0.20824	+
53	Portugal	0.54597	+	111	Lao	0.39110	+	169	Sudan	0.20660	+
54	Gabon	0.54569	+	112	Honduras	0.38954	-	170	Chad	0.18174	+
55	Fiji	0.54446	+	113	Sri Lanka	0.38594	+	171	Niger	0.17033	-
56	Ireland	0.54102		114	Dominican	0.38025	+	172	Mali	0.15175	+
57	Argentina	0.54037	+	115	Myanmar	0.37998	+	173	Somalia	0.12820	-
58	Cuba	0.53682	-	116	Cameroon	0.37763	+	174	Afghanistan	0.11661	+

Notes: The sign +, - and vacancy after the SDI value indicate that its trend for sustainable development is rising, declining or stabilizing from 1988-1994.

Table 3. Classification of countries according to our sustainability indicator

	SDI Value	Number	Increasing	%	Stabling	%	Decreasing	%
Stronger	.55-.74	51	20	11.5%	12	6.9%	19	10.9%
Above average	.45-.55	40	21	12.1%	6	3.4%	13	7.5%
Below average	.35-.45	33	25	14.4%	3	1.7%	5	2.9%
Weaker	.11-.35	50	37	21.3%	7	4.0%	6	3.4%
Total	.11-.74	174	103	59.2%	28	16.1%	43	24.7%

(Wang, Wang & Li, 2001. *Int. J. Sustainable Development and World Ecology*, 8: 119-126)

- The highest SDI value is for North America (0.6274), and the lowest is for Africa (0.3007) (less than half of the North America). In descending order, mean regional SDI ranks were: North America, West Europe, East Europe, South America, Middle America, Pacific and Oceanic countries, East Asia, West Asia, South Asia and Africa.
- The mean SDI value for the world is 0.45 (1988-1994). The strongest country has a SDI value 5 times greater than the weakest country.
- SDI values in 29% of the world's countries are strong. The three strongest are Canada, Sweden and Norway with SDI values of 0.740, 0.711 and 0.708, respectively. All of these countries are industrialized and have rich resource potential.

- SDI values in 42% of the world’s countries have middle values. In these countries 52% are above average and 48% are below average.
- SDI values in 29% of the world’s countries are weak. Of these, 82% are located in Africa. The three weakest countries are Afghanistan, Somalia and Mali, with SDI values of 0.117, 0.128 and 0.152, respectively. These are all less developed countries with poor resource potential and turbulent social and environmental states.
- Over the past eight years, SDI values in 58.6% of the world’s countries show a positive trend; 16.1% are relatively stable, and 25.3% show a negative trend. SDI values for all former USSR countries are declining.

- In countries whose SDI values are below average, 75% are increasing, 12% are stable and only 13% are decreasing. Generally speaking, these results suggest most of the less sustainable developing countries are improving their situation. Only 13% of these countries show a decreasing trend.

Conclusions

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