Ecological Complexity and Sustainability
challenges and opportunities for 21st-century's ecology

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We have been looking more at this ...
... and this
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 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
- Expandable Sets Theory
Risk Assessment of Agricultural Biotechnology:
Modeling invasion of Bt-resistant insects into transgenic crop fields
δ-Endotoxin from *B. thuringiensis*
Resistance to Bt Toxins

Target insects are perpetually exposed to toxins and this creates a strong selection pressure for the development of resistance to the toxins.

*The Example*

Resistant roundwarms fed Bt by toxin show no damage to internal structures, unlike the susceptible form.
Biological Background

- **Two major concerns on Bt crops:**
  1. Spread of Bt gene of crops to crops and wild relatives
  2. Human-directed evolution of Bt resistance genes

- **Genetics of Bt resistance genes (natural):**
  1. Dominance (RR, Rs, ss)
  2. Recessive (rr, rS, SS)
  3. Co-dominance (RR, RS, SS)
Wild population (on non-Bt plants)
(1) Dominance (Rs, ss)
(2) Recessive (rS, SS)
(3) Co-dominance (RS, SS)

Treated population (on Bt plants)
(1) Dominance (RR, Rs)
(2) Recessive (rr)
(3) Co-dominance (RR, pRS)
High-dose/refuge strategy to slow down the increase of R allele

(1) Dose of Bt toxin 25 times more than that required to kill 99% SS (RS cannot survive 25 times more toxin than that required by SS).

(2) Refuge (grow non-Bt at least 4% plants in the neighbor) to provide mating so that all the progeny RRxSS=RS will be killed.

Three requirements for the success of high-dose/refuge strategy

(1) RS must be killed in treated area (high-dose)

(2) R is rare (estimate frequency)

(3) Mating between RR from the treated area with SS from the refuge (gene flow)
The Mathematical Model - 1

$P$ - plant biomass

$I_r$ - resistant insect biomass

$I_s$ - susceptible insect biomass

The assumption
The resistance to Bt toxins in insects is coded by recessive genes. This implies that offsprings of susceptible male (female) and resistant female (male) are Bt susceptible.

\[
\frac{\partial P}{\partial \tau} = \tau P \left(1 - \frac{P}{K}\right) - \frac{C_1 P}{C_2 + P} (I_s + I_r)
- \left[ \frac{1}{4} \eta_s(P) I_s^2 + \frac{1}{4} \eta_r(P) I_r^2 + \frac{1}{2} \eta_s(P) I_s I_r \right]_{\tau \in [nT, nT+\varepsilon_T]},
\]

(1)

\[
\frac{\partial I_s}{\partial \tau} = \frac{k_s C_1 P}{C_2 + P} I_s - \mu I_s + \delta_s \left[ \frac{1}{4} \eta_s(P) I_s^2 + \frac{1}{2} \eta_s(P) I_s I_r \right]_{\tau \in [nT, nT+\varepsilon_T]} + D \frac{\partial^2 I_s}{\partial X^2},
\]

(2)

\[
\frac{\partial I_r}{\partial \tau} = \frac{k_r C_1 P}{C_2 + P} I_r - \mu I_r + \delta_r \left[ \frac{1}{4} \eta_r(P) I_r^2 \right]_{\tau \in [nT, nT+\varepsilon_T]} + D \frac{\partial^2 I_r}{\partial X^2},
\]

(3)

\[
\eta_s(P) = \eta_s^0 P \exp \left( - \frac{\lambda P}{K} \right),
\]

(4)

\[
\eta_r(P) = \eta_r^0 P,
\]

(5)

\[
P = P_0 \text{ at } \tau = nT, \text{ where } n = 0, 1, 2, \ldots.
\]

(6)
The Mathematical Model - 2

Dimensionless variables

\[
p = \frac{P}{K}; i_s = \frac{I_s}{K}; i_r = \frac{I_r}{K}; t = \frac{A\tau}{T}; x = X\sqrt{\frac{A}{DT}}.
\]

Dimensionless parameters and functions

\[
\begin{align*}
\frac{\partial p}{\partial t} &= \alpha p(1 - p) - \frac{\beta p}{\gamma + p}(i_s + i_r) \\
&\quad - \left[\omega_s(p)i_s^2 + \omega_r(p)i_r^2 + 2\omega_s(p)i_s i_r\right]_{x=[nA, nA+eA]}, \\
\frac{\partial i_s}{\partial t} &= \frac{k_s \beta p}{\gamma + p} i_s - \nu i_s + \delta_s \left[\omega_s(p)i_s^2 + 2\omega_s(p)i_s i_r\right]_{x=[nA, nA+eA]} + \frac{\partial^2 i_s}{\partial x^2}, \\
\frac{\partial i_r}{\partial t} &= \frac{k_r \beta p}{\gamma + p} i_r - \nu i_r + \delta_r \left[\omega_r(p)i_r^2\right]_{x=[nA, nA+eA]} + \frac{\partial^2 i_r}{\partial x^2}, \\
\omega_s(p) &= \omega_s^0 p \exp(-\lambda p), \\
\omega_r(p) &= \omega_r^0 p, \\
p &= p_0 \text{ at } t = nA, \text{ where } n = 0, 1, 2, 
\end{align*}
\]

\[
\alpha = r \frac{T}{A}, \beta = C_1 \frac{T}{A}, \gamma = C_2 \frac{T}{K}, \nu = \mu \frac{T}{A}, \omega_s = \frac{T}{4A} \eta_s K, \omega_r = \frac{T}{4A} \eta_r K, \omega_s^0 = \eta_s^0 K, \omega_r^0 = \eta_r^0 K.
\]
A Key Parameter of the Insect Fitness

Growth number

\[ Gr = \frac{k\beta}{\gamma + 1} - \nu. \]

Resistant insects win their competition with susceptible insects and can invade **only** if the values of their \( Gr \) are positive, and when \( Gr_r > Gr_s \)
Modeling invasion of recessive Bt-resistant insects: An impact on transgenic plants

The Dependence of the Averaged Plant Biomass on the Duration of the Insect Reproduction Period. Non-unique Plant - Insect Dynamics

Averaged plant biomass

\[ \langle p \rangle = \frac{1}{L} \int_0^L \int_0^t p(x, t') dx dt', \quad t = nA \]

CURVE 1: \( \omega_x^0 = \omega_r^0 = 60 \)
Chaos coexists with regular oscillations

CURVE 2: \( \omega_x^0 = \omega_r^0 = 5 \)
Regular oscillations

CURVE 3: \( \omega_x^0 = \omega_r^0 = 1 \)
Equilibrium

(O) - regular oscillations
(*) - chaotic oscillations
(•) - equilibrium
Correspondence between Spatial Distributions and Temporal Dynamics

\[ \varepsilon A = 20 \]

\[ \varepsilon A = 10 \]
The Regions of Chaos and Order in the Rugosity Space

\[ R_p = \frac{k}{N_p} \left( \frac{\partial p}{\partial x} \right) \sum_{j=1}^{N_p} (p_j^{\text{max}} - p_j^{\text{min}}), \]

\[ R_r = \frac{k}{N_i} \left( \frac{\partial i_r}{\partial x} \right) \sum_{j=1}^{N_i} (i_r^{\text{max}} - i_r^{\text{min}}), \]

where:

\( p_j^{\text{max}}, i_r^{\text{max}}, p_j^{\text{min}}, i_r^{\text{min}} \) - maxima and minima in the spatial biomass distributions

\( N_p \) and \( N_i \) - the number of maxima in the plant and insect distributions, correspondingly,

\[ \left\langle \frac{\partial p}{\partial x} \right\rangle = \frac{1}{L} \int_0^L \left| \frac{\partial p}{\partial x} \right| dx, \]

\[ \left\langle \frac{\partial i_r}{\partial x} \right\rangle = \frac{1}{L} \int_0^L \left| \frac{\partial i_r}{\partial x} \right| dx, \]

\( k \) is the scale coefficient.

(•) - regular oscillations

(*) - chaotic oscillations
The dependence of the Bt Plant Biomass on the Duration of the Insect Reproduction Period Under Decreased Germination of Seeds

(○) - regular oscillations
(•) - chaotic oscillations
Regimes of biological invasion in a predator–prey system with the Allee effect

Sergei Petrovskii\textsuperscript{a,b,*}, Andrew Morozov\textsuperscript{a,b}, Bai-Lian Li\textsuperscript{b}
Stages of biological invasion

1. Introduction of an alien species:

2. Establishment of the introduced species in the new environment:

3. Spread of the introduced species over space, invasion of new areas:

where $U$ is the population density.
Main equations

\[
\frac{\partial P(X,T)}{\partial T} = D_1 \frac{\partial^2 P}{\partial X^2} + F(P) - f(P, Z)
\]

\[
\frac{\partial Z(X,T)}{\partial T} = D_2 \frac{\partial^2 Z}{\partial X^2} + k f(P, Z) - m Z
\]

- \( T \) – time,
- \( X \) – location in space,
- \( Z, P \) – predator and prey densities;
- \( D_1, D_2 \) – diffusion coefficients;
- \( F(P) \) – prey growth (multiplication);
- \( mZ \) – predator mortality,
- \( k \) – food utilization coefficient;
- \( f(P, Z) \) – predation

\[
f(P, Z) = A \frac{Z}{1 + R_P}
\]
Parameterization of the prey growth influenced by the Allee effect:

Logistic prey growth:

Prey growth influenced by the Allee effect:

Parameterization of the prey growth influenced by the Allee effect:

\[ F(P) = \left( \frac{4}{K - P_0} \right)^2 P \left( P - P_0 \right)(K - P) \]

\[ 0 < P_0 < K \quad \text{-Allee effect is strong} \]
Dimensionless form of the main equations:

\[
\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial x^2} + \gamma u (u - \beta)(1 - u) - \frac{uv}{1 + \alpha u} \\
\frac{\partial v}{\partial t} = \epsilon \frac{\partial^2 v}{\partial x^2} + \frac{uv}{1 + \alpha u} - \delta v
\]

variables: \( u = \frac{P}{K}, \ v = \frac{Z}{(kK)},\ t = aT,\ x = X(a/D_1)^{1/2},\ a = AkK.\)

where: \( \alpha = K R,\ \beta = \frac{P_0}{K},\ \gamma = \frac{4\omega K}{A(K - P_0)^2},\ \delta = M/a,\ \epsilon = \frac{D_2}{D_1}.\)

\( \alpha, \beta, \gamma, \delta, \epsilon > 0 \)

Initial conditions:

\[
\begin{align*}
\Delta_v & \quad \Delta_u & \quad 0 & \quad \Delta_u & \quad \Delta_v \\
-\frac{L}{2} & \quad & \quad & \quad & \frac{L}{2}
\end{align*}
\]

- Population size of prey.

Integral description: population sizes:

\[
U(t) = \int_{-\frac{L}{2}}^{\frac{L}{2}} u(x,t) \, dx \\
V(t) = \int_{-\frac{L}{2}}^{\frac{L}{2}} v(x,t) \, dx
\]

- Population size of predator.
Dynamic Regimes of Biological Invasion

Regimes of biological invasion in a predator-prey system

- Regimes of extinction
  1. Ordinary extinction
  2. Dynamical localization
  3. Patchy extinction

- Regimes of geographical spread
  - Travelling population pulses
    1. Stationary pulses
    2. Oscillating pulses
  - Travelling population fronts
  - Patchy spread
    Population fronts with spatiotemporal patterns in the wake

- Regimes of regional persistence
Dynamic Regimes of Biological Invasion (cont.)

Critical threshold: \( \beta = 0.22 \)
FIG. 1: (Color online) Field observation of the plankton ecosystem in the Gulf of Maine. (a) Reprinted from the Ref. [1]; (b) The color red is a false color, indicating high concentrations of chlorophyll. Note the strong concentration over Georges Bank (GB), one of the most productive fishing grounds in the world [Data collected by E. Feldman].
FIG. 1: The sketch map for the bistability and the Hopf bifurcation in the system (2) with $r = 5.0$, $a = 5.0$, $b = 5.0$, $m = 0.6$, and $n = 0.4$. The black curve is the $g_1(p, h)$. The colored curves are $g_2(p, h)$ with different values of $f$. The red curve: $f = 0.3$, the blue: $f = 0.445$, the green: $f = 0.5$ and the cyan: $f = 0.658$.

FIG. 2: The sketch map of parameter space $(f, \nu)$ bifurcation diagrams of the system (1) with $r = 5.0$, $a = 5.0$, $b = 5.0$, $m = 0.6$, $d_p = 0.05$, and $n = 0.4$. 
Chaos and Regularity in Plankton Dynamics

Bifurcation diagrams for (a) the fish-populated habitat, and (b) the fish-free habitat.

The dependencies of the Lyapunov exponent value on the fish predation rate for (c) the fish-populated habitat, and (d) the fish-free habitat.
Two Types of Sensitivity to Initial Conditions

The time series correspond to two initial zooplankton densities, which differ by 0.001.

This type of sensitivity implies chaos.

The stable limit cycle (a) and chaotic attractor (b) in the phase space are obtained at initial zooplankton densities differing only by 0.0001.

This type of sensitivity implies coexistence of the chaotic attractor and the limit cycle.
THE BIFURCATION DIAGRAM (Lake Syamozero) (THE JUVENILE INVADER, INTERMEDIATE PREDATOR)

The stationary fish density before the invasion. Chaos occurs if the initial invader density > 8500 км². The windows of regularity: [9150,9450], [10700,11000], [15900,16200].

We found the coexistence of
(1) chaos and regular oscillations;
(2) chaos, regular oscillations and stationary regimes;
(3) regular oscillations and stationary regimes.

The oscillatory fish density before the invasion. Here the irregular dynamics is chaotic.
Coexistence of multiple attractors
Reaction-diffusion on a torus (Jon Jacobsen and his students)
rs-space
(Hierarchy theory: characteristic scales or rates.)
$y_1(x) = -1.58 - 1.01x, r^2 = 0.77, P < 10^{-5}$

$y_2(x) = y_1(1.43) + \mu_2 (x - 1.43), \mu_2 = 0.04 \pm 0.02$

Figure 1. Limits and scopes of mass-specific metabolic rate in the living organisms. Solid and open circles: endogenous and growth mass-specific metabolic rates of prokaryotes. Boxes, diamonds and triangles (MIN): metabolic rates of eukaryotes in various energy-saving regimes. Dotted circles (MAX): record mass-specific metabolic rates per unit working tissue mass during peak activities in various organisms. Asterisks: basal metabolic rates of whales and elephants. Solid lines: fitted equations for endogenous/standard/basal metabolic rate in, U, unicellular eukaryotes at 20°C (Vladimirova & Zotin 1985), A, terrestrial arthropods at 25°C (Lighton et al. 2001) and, M, mammals (Peters 1983), respectively. P, prokaryotes. Crossed circles: standard metabolic rate corresponding to body size class with maximum species numbers in terrestrial arthropods and mammals; mean endogenous respiration of the studied prokaryotes and unicellular eukaryotes (Vladimirova & Zotin 1985). Dashed lines: the uniform minimum, maximum and hypothesized optimum values of mass-specific metabolic rate of the living matter. Numeric values and literature sources for all points shown in the figure are given in the Electronic Appendix.
Fig. 1. Model examples for the origin of various scaling exponents $\mu$ for mass-specific metabolic rate $q$ across 15 orders of magnitude range in body mass. Circles denote model points for which regressions are made. (a) The proposed size-invariance ($\mu = 0$) of mean $q = q_{opt}$ in unicells (U), invertebrates (I) and endotherms (E) when $q$ is measured in comparable physiological states at natural temperatures. (b) $\mu = -0.15$ results from comparison of standard metabolic rates of invertebrates and endotherms to growth metabolic rates of unicells assuming that the latter are about 20 times higher than ‘standard’ metabolic rates of unicells. (c) $\mu = -0.21$ results from pattern (b) when basal metabolic rates of endotherms are corrected to 20 °C, a temperature incompatible with viability in most mammals.

(Functional Ecology, 19: 547-557, 2005)
COMPLEX SYSTEMS APPROACHES TO STUDY HUMAN - ENVIRONMENT INTERACTIONS

How to understand the complex interactions, and how to use that understanding?
The concept of sustainable development

… “a development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

…”acting in a way that is economically profitable, socially acceptable and environmentally compatible.”

(Agenda 21, Rio Declaration)

Recent challenges of environmental management
The ambitious demands of sustainability

- long-term strategies ..... think in generations
- multi-scale strategies ..... human vs. ecological time scales
- interdisciplinary strategies ..... ecology is only a part
- holistic strategies ..... structures and functions
- realistic strategies ..... include uncertainties
- nature oriented strategies ..... take nature as a model
- theory-based strategies ..... make sure correctness
- hierarchical strategies ..... realise constraints and scales
- goal oriented strategies ..... joint definition of the targets
Ecological science has changed

- mono-scale analysis
- neglecting complexity
- reductionistic analysis
- reversible reactions
- continuity
- linearity
- chains
- stability
- closed systems
- equilibrium
- predictability
- strong causality

- multi-scale analysis
- exploring complexity
- holistic synthesis
- irreversible reactions
- bifurcations and transitions
- non-linearity
- webs and networks
- steady state and development
- open systems
- non-equilibrium
- non-predictability
- weak causality and possibility
Ecological science has changed

..... systems arguments have taken over

- look for **indirect effects and feedbacks in networks**
- find **chronical effects**
- investigate **de-localized effects**
- consider **systems relations and processes**
- link **structures and functions**
- realize **complexity and reduce it correctly**
- understand **and include self-organization**
Environmental management is changing

• instrumental orientation
  • single-problem-view
  • disciplinary structures
  • reductions to sectors
  • focus on compartments
  • maximum load
  • constraints of ressorts
  • weak information base
  • ecology vs. economy
  • top-down regulation
  • national limitation

• policy mix
• sustainability
• interdisciplinary structures
• coupling different sectors
• focus on ecosystems
• disturbance reduction
• integrating ressorts
• communication
• ecology and economy
• participation
• international cooperation
**Indicandum:**

Complex (Eco)Systems

- Complex Interactions
- Hardly Determinable Variables
  - Expensive
  - Complicated
  - Complex

Reduced Complexity

Variables can be easily
- Measured
- Modelled
- Aggregated
- Justified
- Understood

Variables are Relevant for the Management Problem

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Science

Policy
..."Meet the needs of future generations"....

=  

Keep available the functions/services of nature
Ecological systems providing natural resources

Ecological structures providing space and suitable substrates

Production Functions
- e.g. Oxygen
- e.g. Food
- e.g. Fuel

Carrier Functions
- e.g. Habitation
- e.g. Cultivation
- e.g. Tourism

Regulation Functions
- e.g. Energy
- e.g. Climate
- e.g. Erosion

Information Functions
- e.g. Aesthetics
- e.g. History
- e.g. Education

Ecological interactions regulating human life support demands

"Functions of Nature" „Ecosystem Services“

Functions of nature after de Groot (1992)
- Protection cosmic influences
- Regulation energy balance
- Regulation chemistry atmosphere
- Regulation chemistry ocean
- Regulation climate
- Regulation runoff & flood prevention
- Regulation groundater recharge
- Regulation waterbalance catchments
- Regulation erosion and sedimentation
- Regulation soil fertility
- Regulation biomass production
- Regulation organic matter
- Regulation nutrient budgets
- Regulation waste storage
- Regulation biological control
- Regulation habitat maintenance
- Regulation diversity maintenance
The „functions of nature“ provide the framework for the ecological focus of sustainable development.

Providing the functions of nature results in an appropriate performance of the regulation functions.

The „functions of nature“ are based upon self-organizing processes.

To maintain the „functions of nature“ the ability for future self-organization of ecosystems must be supported.

Eco-target „ecological integrity“: preservation against non-specific ecological risks.
Exergy Capture

Biodiversity

Abiotic Heterogeneity

Storage

Biotic Water Flows

Nutrient Loss $-1$

Metabolic Efficiency $-1$

Entropy Export

Capacity for Self-Organization

50% 100% 150%

Beech Forest

Maize Field
Main collaborators:
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Thank you!

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