The trophic coherence of food webs and its effects on stability, feedback loops and motifs

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Stability
Diversity vs. Stability

R. H. MacArthur (1955); C. S. Elton (1958)

“simple communities are more easily upset than […] richer ones; that is, more subject to destructive oscillations in populations, and more vulnerable to invasions.”

R. May (1972): Diversity destabilises community dynamics!

“That stability may usually go with complexity in the natural world, but not usually in general mathematical models, is not really paradoxical. In nature we deal not with arbitrary complex systems, but rather with ones selected by a long and intricate process.”
Linear stability

\[
x(t) = x^* + \zeta(t)
\]

\[
\frac{d}{dt}\zeta(t) = Df(x^*)\zeta(t)
\]

\[
R = Re(\lambda_{max})
\]

\[
R = \text{Degree of self-regulation required for system to be stable.}
\]

\[
R \sim \sqrt{SC} \quad \quad SC = K
\]

*Will a Large Complex System be Stable?*

*Robert M. May*
Long debate

Stability and Diversity of Ecosystems
Anthony R. Ives, et al.
Science 317, 58 (2007);
DOI: 10.1126/science.1133258

The diversity–stability debate
Kevin Shea McCann

Reconciling complexity with stability in naturally assembling food webs
Anje-Margriet Neutel, Johan A. P. Heesterbeek, Johan van de Koppel, Guido Hoenderbroek, An Vos, Coen Kaldeeway, Frank Berendse & Peter C. de Ruiter
www.foodwebs.org
Dynamics

\[
\frac{d}{dt} x_i = \eta \sum_j a_{ij} F(x_i, x_j) - \sum_j a_{ji} F(x_j, x_i) + G(x_i)
\]

\[
W = \eta A - A^T
\]

\[
R = Re(\lambda_{max})
\]
No complexity-stability relationship in natural communities

Claire Jacquet¹, Charlotte Moritz¹,², Lyne Morissette², Pierre Legagneux¹, François Massol³, Phillippe Archambault², and Dominique Gravel¹
Structural food-web models

Cohen & Newman (1985)  
**Cascade Model**

Williams & Martinez (2000)  
**Niche Model**

Stouffer et al. (2005)  
**Generalised Niche Model**

The probabilistic niche model reveals substantial variation in the niche structure of empirical food webs

Richard J. Williams¹ and Drew W. Purves

Microsoft Research, 7 J J Thomson Avenue, Cambridge CB30FB United Kingdom
Structural food-web models

More niche-based models...

Minimum Potential Niche Model

Nested Hierarchy Model
Structural food-web models
Structural food-web models

Chesapeake Bay
Minimum Potential Niche Model
Trophic coherence

\[ s_i = 1 + \frac{1}{k_{in}^i} \sum_j a_{i,j} s_j \]

\[ x_{i,j} = s_i - s_j \]

\[ p(x) \begin{cases} \\ \langle x \rangle = 1 \\ \sigma = q \end{cases} \]
Trophic coherence

\[ r^2 = 0.596 \]

\[ r^2 = 0.804 \]
Preferential Preying Model

\[ P_{il} \propto \exp\left(-\frac{|s_j - s_l|}{T}\right) \]
Preferential Preying Model

Chesapeake Bay

Minimum Potential Niche Model

Preferential Preying Model
Preferential Preying Model
Preferential Preying Model
May's Paradox

\[ K = S^\alpha \]
May's Paradox

\[ W = \eta A - A^T \]
May's Paradox
May's Paradox
May's Paradox
May's Paradox
May's Paradox

[Diagram showing plots for Lotka-Volterra, Type II, and Type III models with different values of $a$ and $\sigma_x$.]
Tipping points

Scaling in a network model of a multispecies ecosystem

Ricard V. Solé\textsuperscript{a,b,*}, David Alonso\textsuperscript{a,c}, Alan McKane\textsuperscript{d}
Spreading
Cycles and spectra

\[ \langle \lambda^\nu \rangle = \frac{1}{N} \text{Tr}(A^\nu) \]

\[ \tilde{q} = \sqrt{\frac{N}{B}} - 1 \]

Coherence ensemble: \{\mathbf{k}^{\text{in}}, \mathbf{k}^{\text{out}}, q\}
Cycles and spectra
Cycles and spectra
Cycles and spectra
Cycles and spectra

\[ m_\nu = \frac{\tilde{q}}{q} \exp^{\tau_\nu} \]

\[ \tau = \ln \alpha + \frac{1}{2\tilde{q}^2} - \frac{1}{2q^2} \]

\[ \alpha \equiv \frac{\langle k^{in} k^{out} \rangle}{\langle k \rangle} \]
Cycles and spectra

\[ \langle \lambda^\nu \rangle = \frac{1}{N} \frac{\tilde{q}}{q} e^{\tau \nu} \]

\[ \lambda_1 = e^\tau \]
Cycles and spectra
Cycles and spectra

\[ P_{DAG} \simeq \exp \left[ -\frac{\tilde{q}}{q} \frac{1}{e^{-\tau} - 1} \right] \]

\[ P_{OSC} \simeq \exp \left[ -\frac{\tilde{q}}{q} \frac{e^{\tau}}{e^{-\tau} - 1} \right] - P_{DAG} \]
Cycles and spectra
Buffered Qualitative Stability explains the robustness and evolvability of transcriptional networks

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Selection against instability: stable subgraphs are most frequent in empirical food webs

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No natural selection
Why are networks coherent?
Motifs

Feed-forward loop

Food web

Coherence $q$
Motifs

Feed-forward loop
Conclusions

Preferential Preying Model better than niche-based models.

Trophic coherence key to:
- May's paradox, tipping points?, spreading phenomena?
- Cycle structure, eigenspectra, and motif signature of directed networks. Loopless and loopful regimes.
- Ubiquity of “qualitatively stable” systems

What mechanisms lead to trophic coherence?
More refined food-web model?

SJ, V Domínguez-García, L Donetti, MA Muñoz (2014) PNAS.
Thank you for your attention!!