Current revival of systems thinking and major challenges for systems analysis

Claudo Carere
StarFLAG EU FP6 project

Simon Levin

IIASA 2015

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GRAND
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CHALLENGES

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BRIDGING THE GAP
DARPA
POWERED BY IDEAS

THE ANDREW W. MELLON FOUNDATION

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The title of my talk is timely. Systems thinking is increasing in influence

- Ecological systems
- Financial systems
- International relations

The title of my talk is timely. Systems thinking is increasing in influence

- Ecological systems
- Financial systems
- International relations
- Food Security
- Energy
- Water

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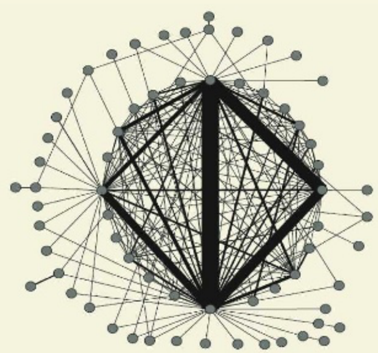
2008



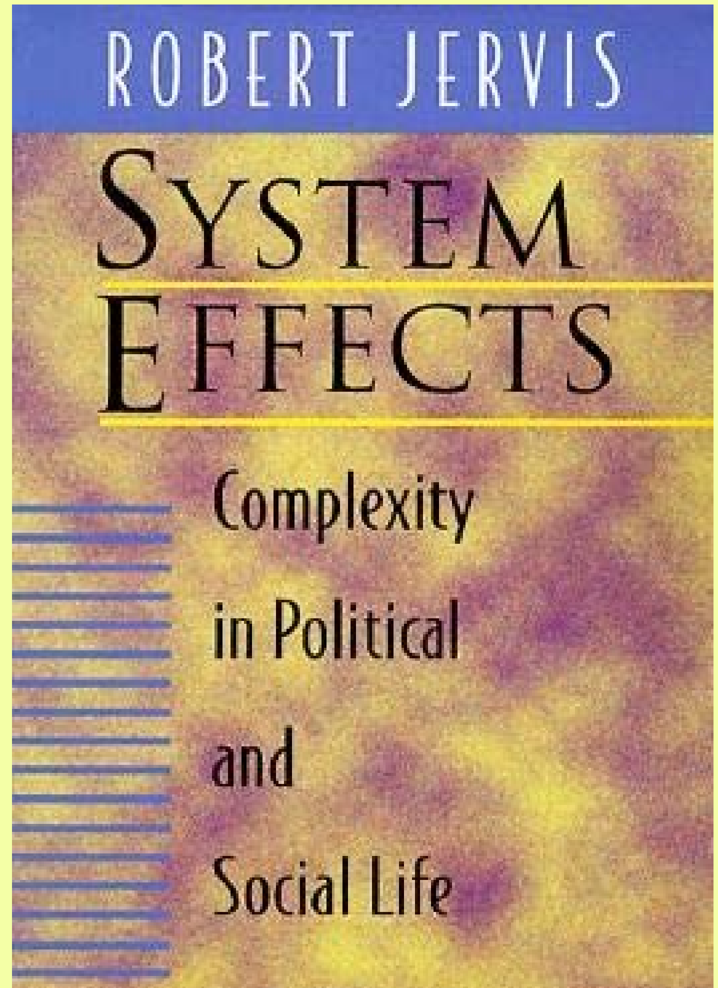
Financial regulation

OPINION

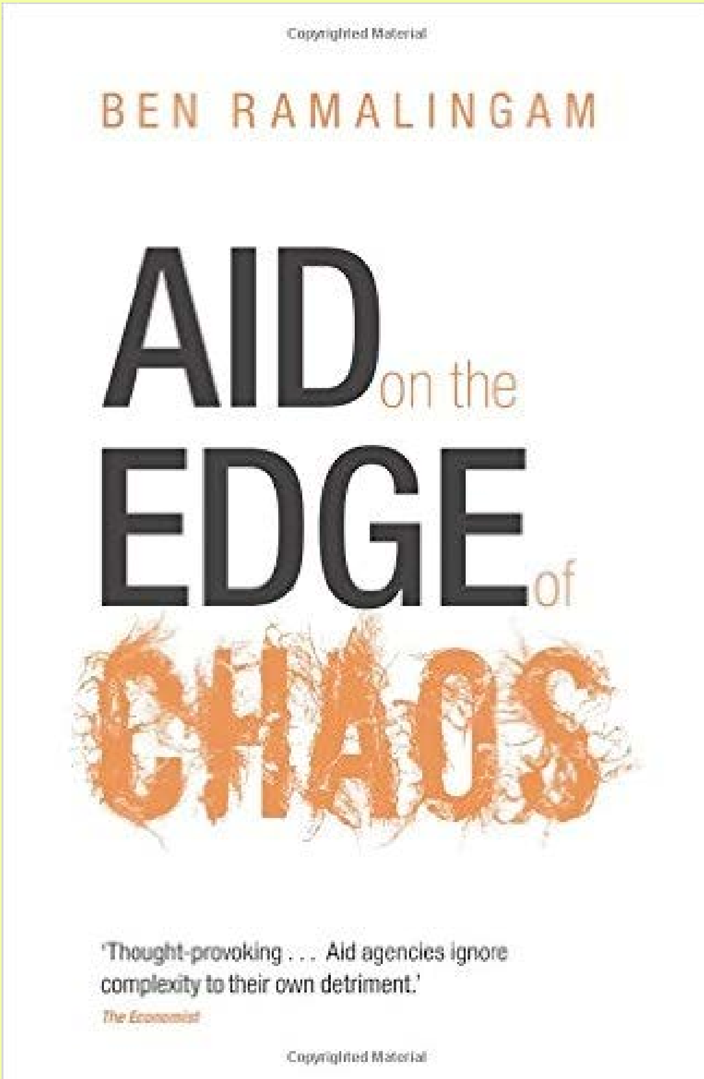
PNAS

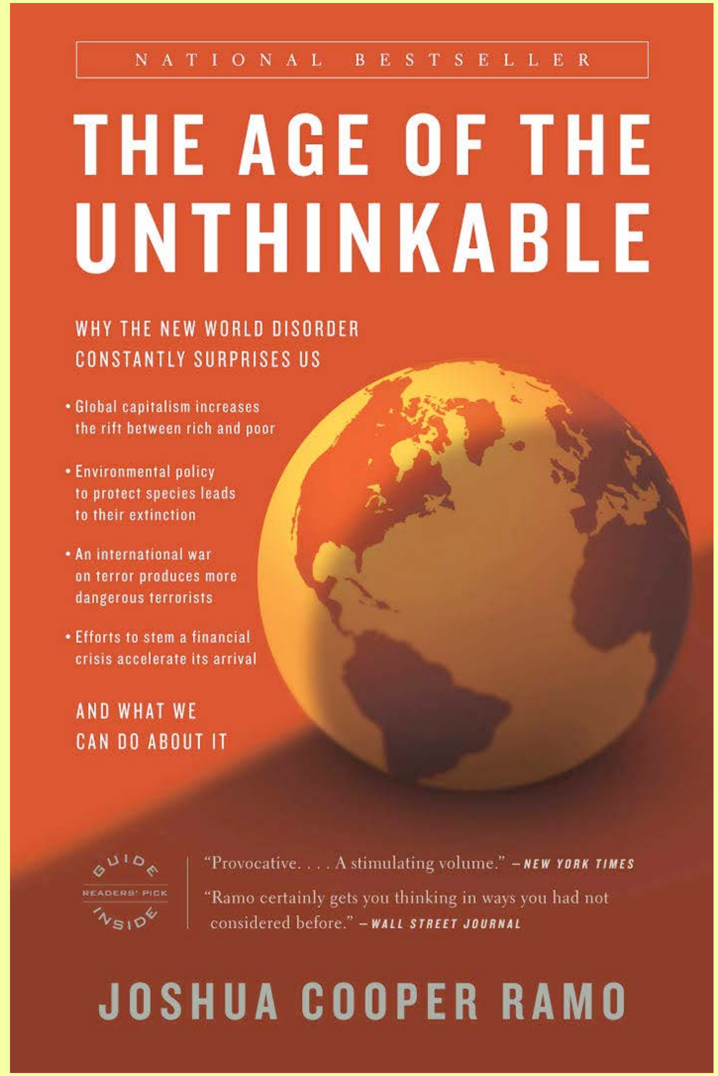
World politics

PERSPECTIVE



International relations





Outline of talk:
Grand challenges of systems theory

- Robustness and resilience to critical transitions
- Scaling from the microscopic to the macroscopic
- Dealing with problems of the Commons

The central problem facing societies is achieving a sustainable future

http://www.sustainablecherryhill.org/

Sustainability means many things to many people

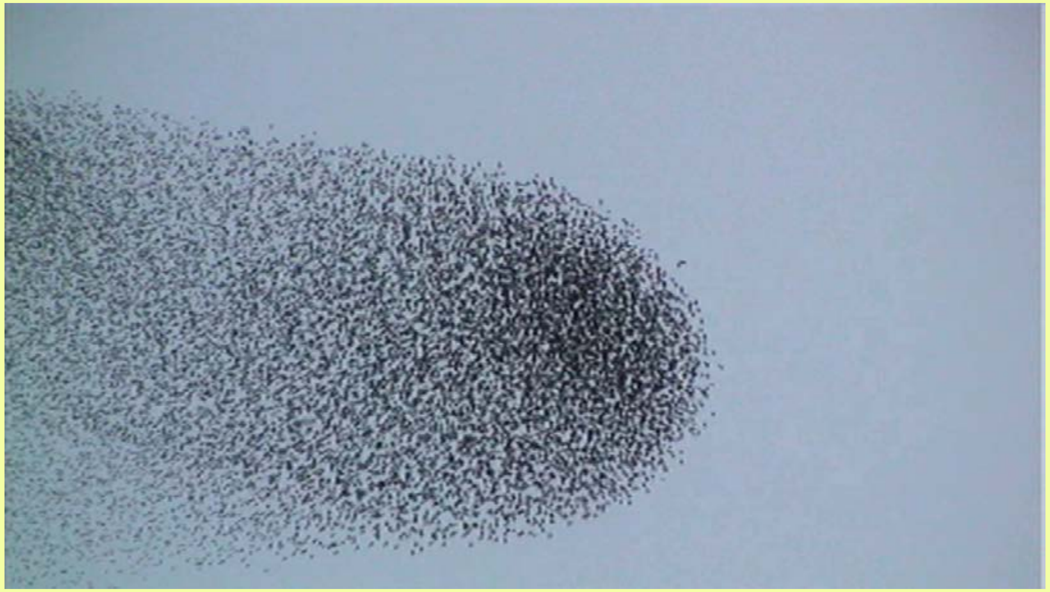
- Financial markets and economic security
- Energy and other natural resources
- Biological and cultural diversity
- Ecosystem services

- What sustains them?

www.serconline.org

Ecosystems and the Biosphere are Complex Adaptive Systems

Heterogeneous collections of individual units (agents) that interact locally, and evolve based on the outcomes of those interactions.



Courtesy of Claudio Carere / StarFLAG EU FP6 project

So too are the socio-economic systems with which they are interlinked

http://www.anunico.ec/anuncio-de/salud_y_belleza

Stock markets crash…as collective consequence of individual actions

There may be critical biosphere thresholds

REVIEW

doi:10.1038/nature11018

Approaching a state shift in Earth's biosphere

Anthony D. Barnosky[1,2,3], Elizabeth A. Hadly[4], Jordi Bascompte[5], Eric L. Berlow[6], James H. Brown[7], Mikael Fortelius[8], Wayne M. Getz[9], John Harte[9,10], Alan Hastings[11], Pablo A. Marquet[12,13,14,15], Neo D. Martinez[16], Arne Mooers[17], Peter Roopnarine[18], Geerat Vermeij[19], John W. Williams[20], Rosemary Gillespie[9], Justin Kitzes[9], Charles Marshall[1,2], Nicholas Matzke[1], David P. Mindell[21], Eloy Revilla[22] & Adam B. Smith[23]

Localized ecological systems are known to shift abruptly and irreversibly from one state to another when they are forced across critical thresholds. Here we review evidence that the global ecosystem as a whole can react in the same way and is approaching a planetary-scale critical transition as a result of human influence. The plausibility of a planetary-scale 'tipping point' highlights the need to improve biological forecasting by detecting early warning signs of critical transitions on global as well as local scales, and by detecting feedbacks that promote such transitions. It is also necessary to address root causes of how humans are forcing biological changes.

And we better do something about that

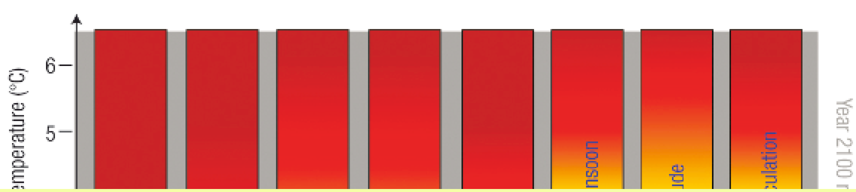
COMMENTARY

Tipping the scales

TIMOTHY M. LENTON[1] AND HANS JOACHIM SCHELLNHUBER[2]

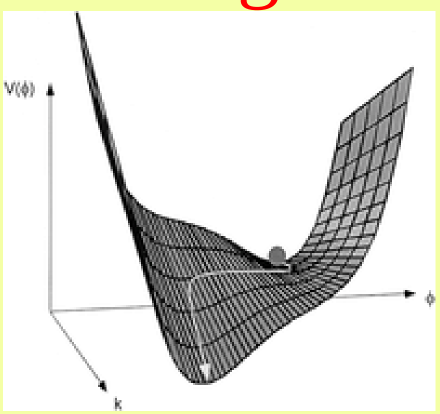
International climate policy needs to induce a socioeconomic tipping to a low or no-carbon economy if we are to avoid climate change tipping points.

The Intergovernmental Panel on Climate Change (IPCC) in its many excellent reports tends to portray climate change as a smooth transition. Although the projections are rarely straight lines, the underlying

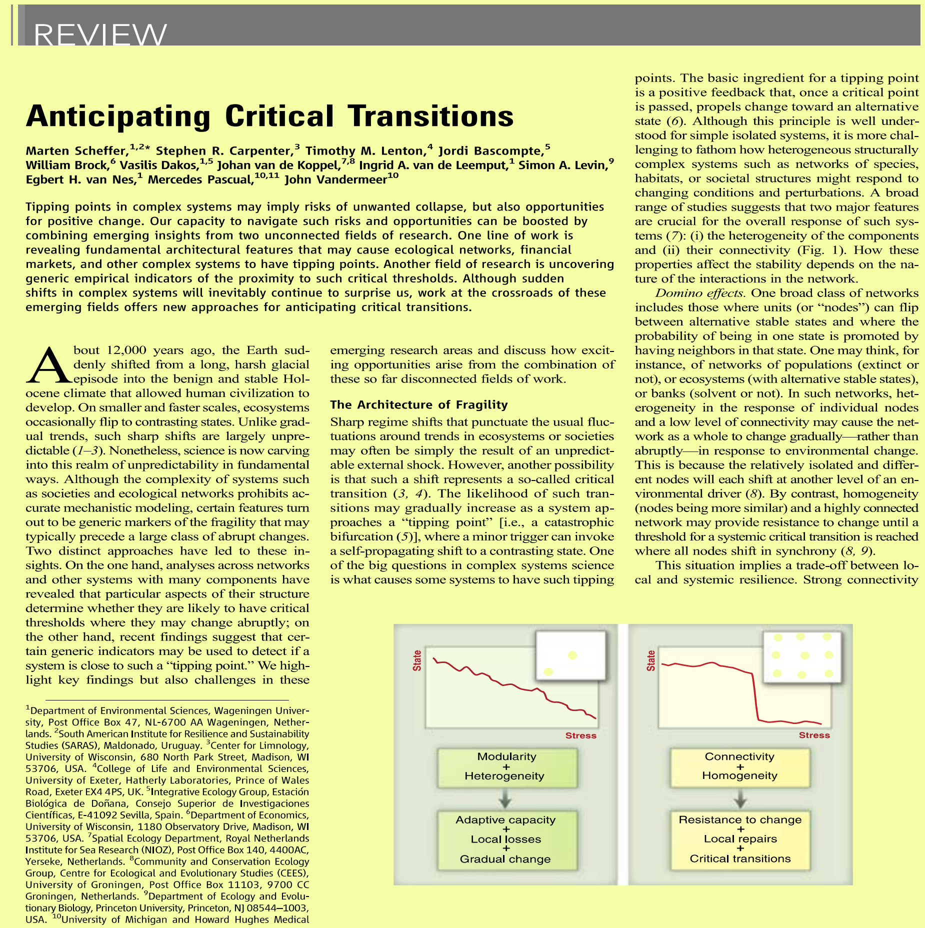


Many..but not all.. such transitions have characteristic early warning signals

- Critical slowing down
- Increasing variance
- Increasing autocorrelation
- Flickering between states



Bardy, B.; Oullier, O.; Bootsma, R. J.; Stoffregen, T. A.;J. Exp. Psych. Vol 28(3):499-514.



REVIEW

Anticipating Critical Transitions

Marten Scheffer,[1,2*] Stephen R. Carpenter,[3] Timothy M. Lenton,[4] Jordi Bascompte,[5] William Brock,[6] Vasilis Dakos,[1,5] Johan van de Koppel,[7,8] Ingrid A. van de Leemput,[1] Simon A. Levin,[9] Egbert H. van Nes,[1] Mercedes Pascual,[10,11] John Vandermeer[10]

Tipping points in complex systems may imply risks of unwanted collapse, but also opportunities for positive change. Our capacity to navigate such risks and opportunities can be boosted by combining emerging insights from two unconnected fields of research. One line of work is revealing fundamental architectural features that may cause ecological networks, financial markets, and other complex systems to have tipping points. Another field of research is uncovering generic empirical indicators of the proximity to such critical thresholds. Although sudden shifts in complex systems will inevitably continue to surprise us, work at the crossroads of these emerging fields offers new approaches for anticipating critical transitions.

About 12,000 years ago, the Earth suddenly shifted from a long, harsh glacial episode into the benign and stable Holocene climate that allowed human civilization to develop. On smaller and faster scales, ecosystems occasionally flip to contrasting states. Unlike gradual trends, such sharp shifts are largely unpredictable (*1–3*). Nonetheless, science is now carving into this realm of unpredictability in fundamental ways. Although the complexity of systems such as societies and ecological networks prohibits accurate mechanistic modeling, certain features turn out to be generic markers of the fragility that may typically precede a large class of abrupt changes. Two distinct approaches have led to these insights. On the one hand, analyses across networks and other systems with many components have revealed that particular aspects of their structure determine whether they are likely to have critical thresholds where they may change abruptly; on the other hand, recent findings suggest that certain generic indicators may be used to detect if a system is close to such a "tipping point." We highlight key findings but also challenges in these emerging research areas and discuss how exciting opportunities arise from the combination of these so far disconnected fields of work.

The Architecture of Fragility

Sharp regime shifts that punctuate the usual fluctuations around trends in ecosystems or societies may often be simply the result of an unpredictable external shock. However, another possibility is that such a shift represents a so-called critical transition (*3, 4*). The likelihood of such transitions may gradually increase as a system approaches a "tipping point" [i.e., a catastrophic bifurcation (*5*)], where a minor trigger can invoke a self-propagating shift to a contrasting state. One of the big questions in complex systems science is what causes some systems to have such tipping points. The basic ingredient for a tipping point is a positive feedback that, once a critical point is passed, propels change toward an alternative state (*6*). Although this principle is well understood for simple isolated systems, it is more challenging to fathom how heterogeneous structurally complex systems such as networks of species, habitats, or societal structures might respond to changing conditions and perturbations. A broad range of studies suggests that two major features are crucial for the overall response of such systems (*7*): (i) the heterogeneity of the components and (ii) their connectivity (Fig. 1). How these properties affect the stability depends on the nature of the interactions in the network.

Domino effects. One broad class of networks includes those where units (or "nodes") can flip between alternative stable states and where the probability of being in one state is promoted by having neighbors in that state. One may think, for instance, of networks of populations (extinct or not), or ecosystems (with alternative stable states), or banks (solvent or not). In such networks, heterogeneity in the response of individual nodes and a low level of connectivity may cause the network as a whole to change gradually—rather than abruptly—in response to environmental change. This is because the relatively isolated and different nodes will each shift at another level of an environmental driver (*8*). By contrast, homogeneity (nodes being more similar) and a highly connected network may provide resistance to change until a threshold for a systemic critical transition is reached where all nodes shift in synchrony (*8, 9*).

This situation implies a trade-off between local and systemic resilience. Strong connectivity

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rom

When do these work?
Avoid excessive claims

Theor Ecol (2013) 6:255–264
DOI 10.1007/s12080-013-0192-6

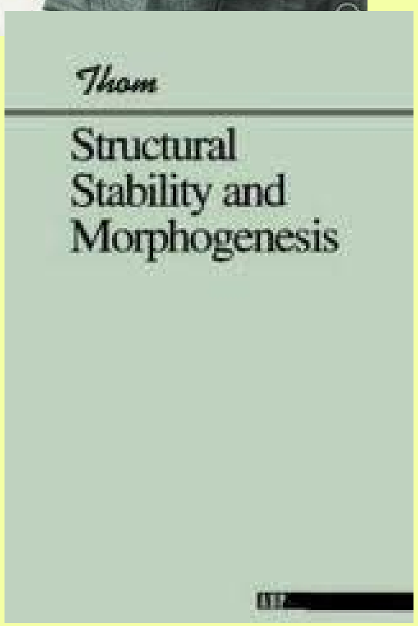
ORIGINAL PAPER

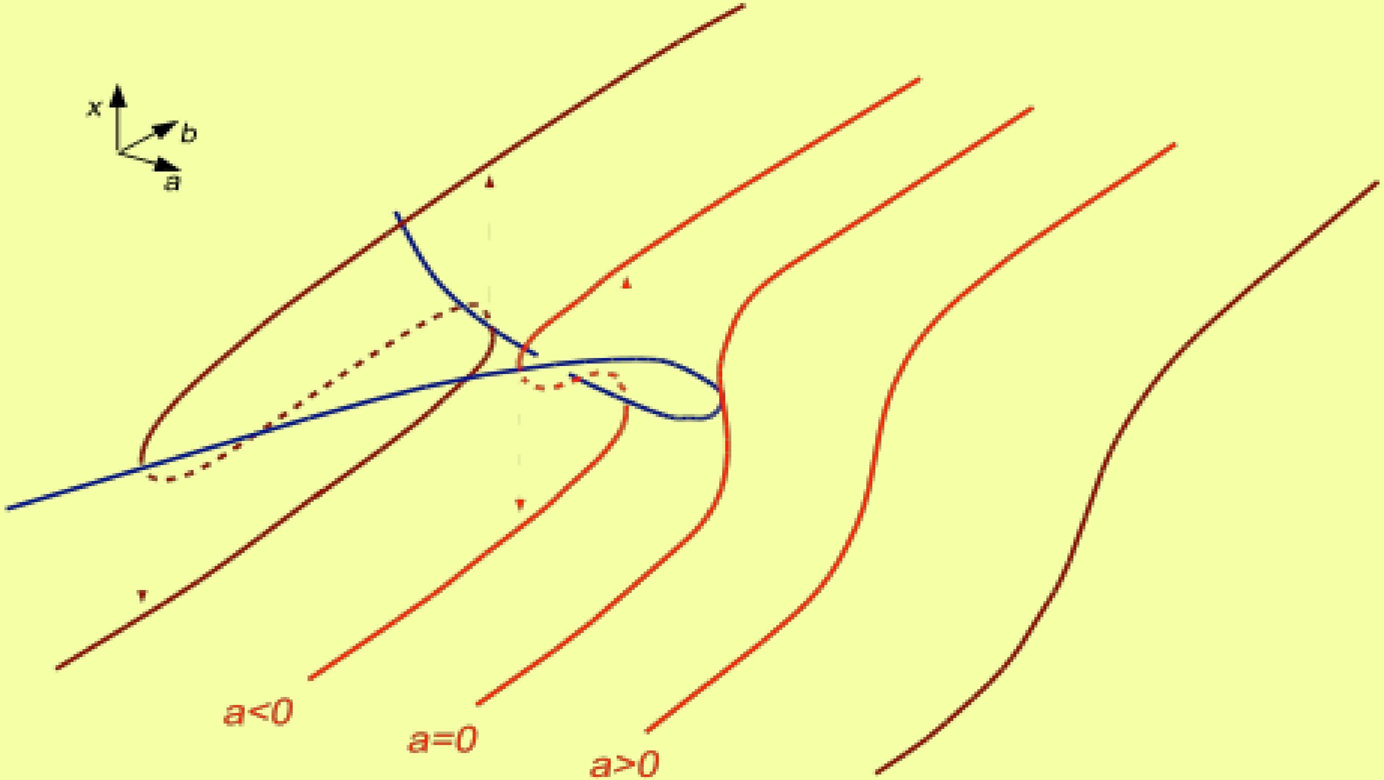
Early warning signals: the charted and uncharted territories

Carl Boettiger · Noam Ross · Alan Hastings

Received: 19 March 2013 / Accepted: 23 May 2013 / Published online: 21 June 2013

Caution is needed…mechanisms need to be identified



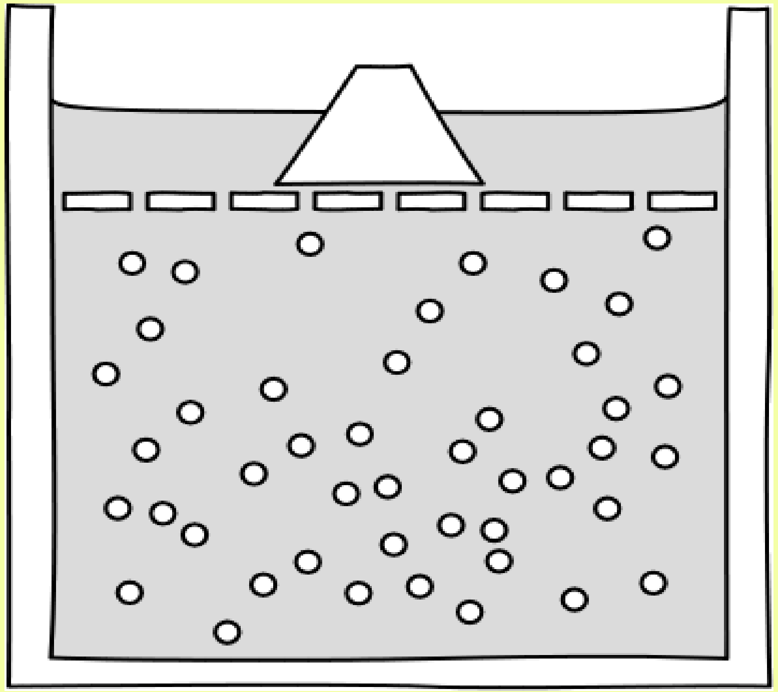


http://en.wikipedia.org/wiki/Catastrophe_theory
http://en.wikipedia.org/wiki/Ren%C3%A9_Thom

Challenges of systems theory

- Robustness and resilience to critical transitions
- Scaling from the microscopic to the macroscopic

Sustainability must focus on macroscopic features, while recognizing that control of those rests at lower levels of organization



Characteristic regularities in macroscopic patterns exist in all ecosystems

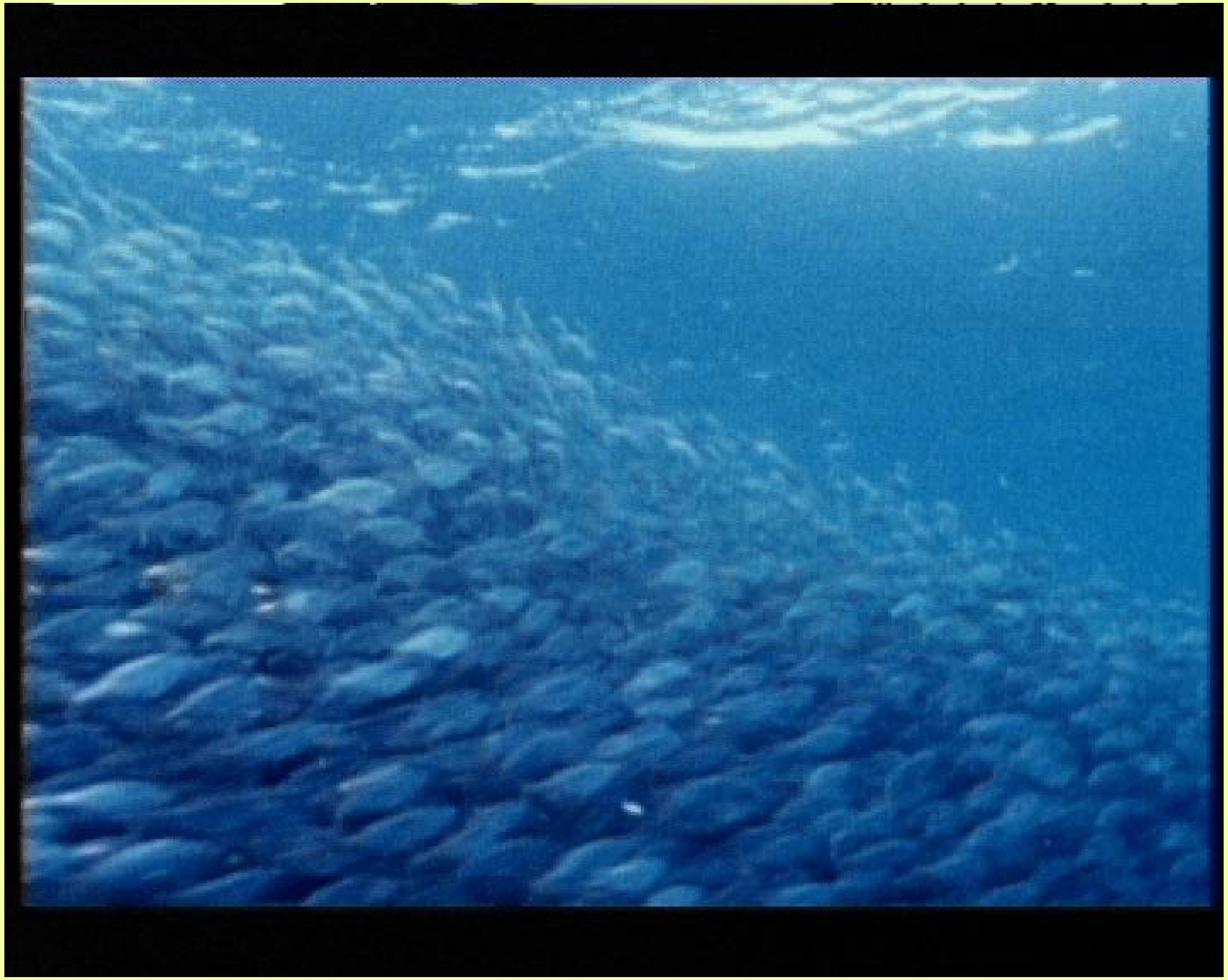
www.bio.unc.edu

www.yale.edu/yibs

www.csiro.au

These sustain ecosystem services

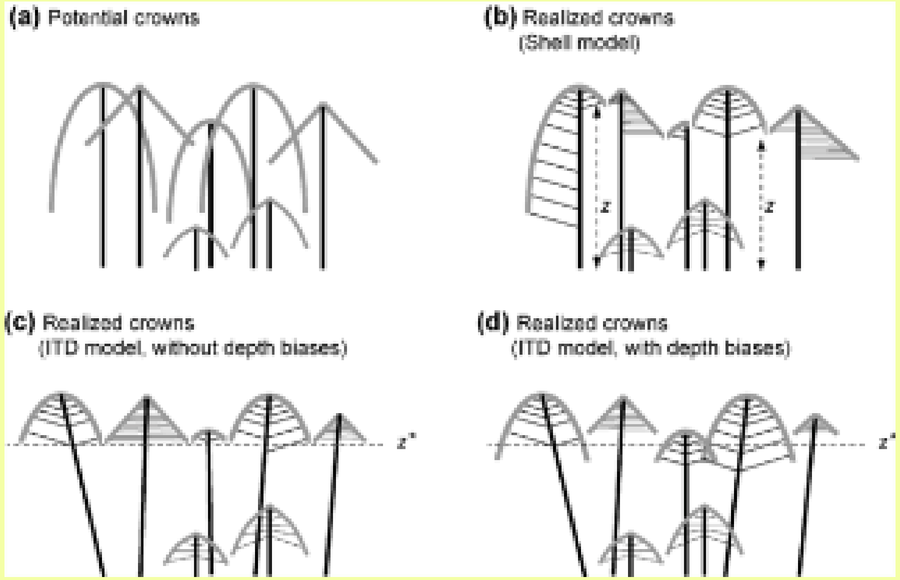
Individual-based models relate the small-scale to the large scale



Iain Couzin/BBC

Forest growth models can scale from individual to ecosystem

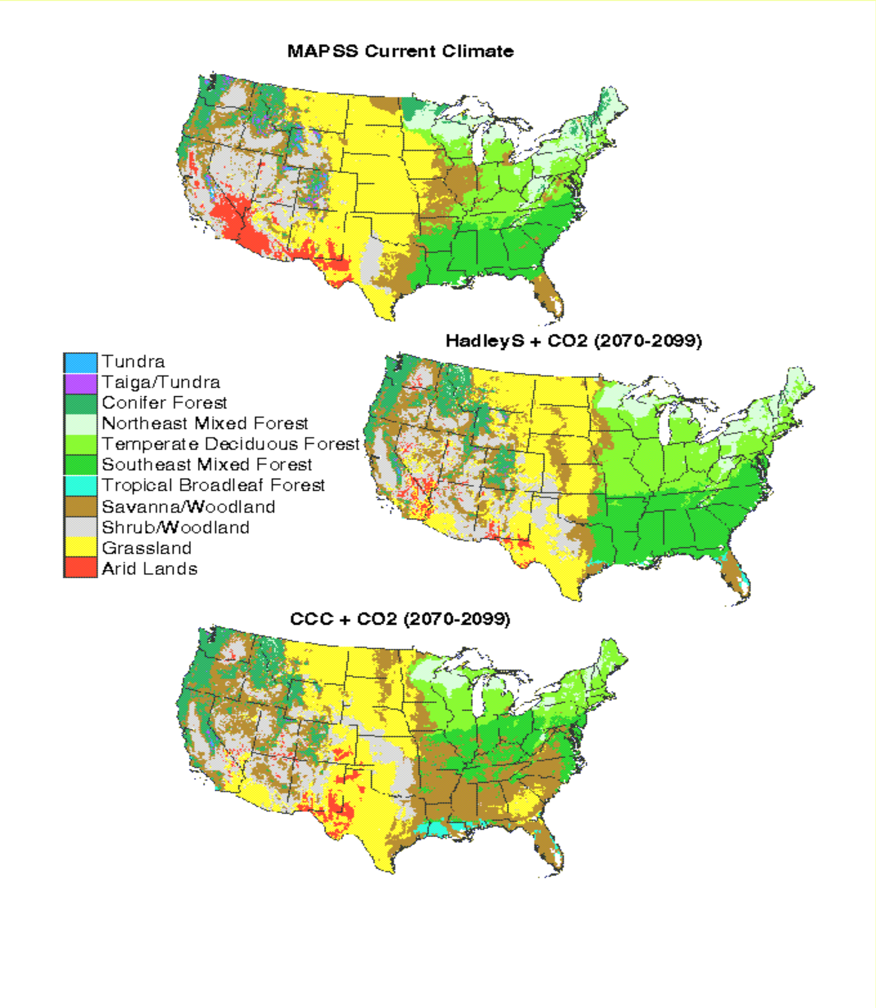
(Pacala, Botkin, Shugart, others)

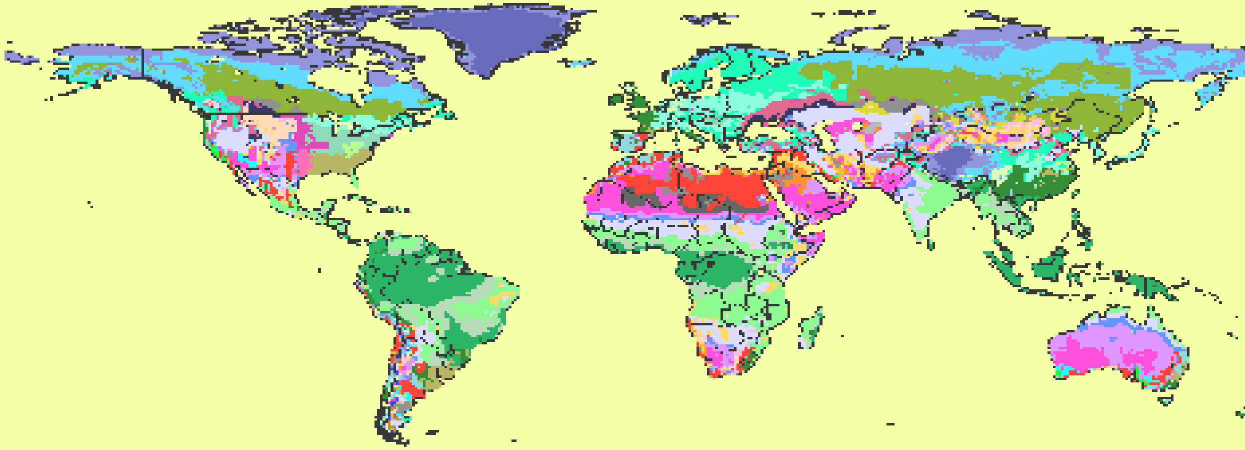


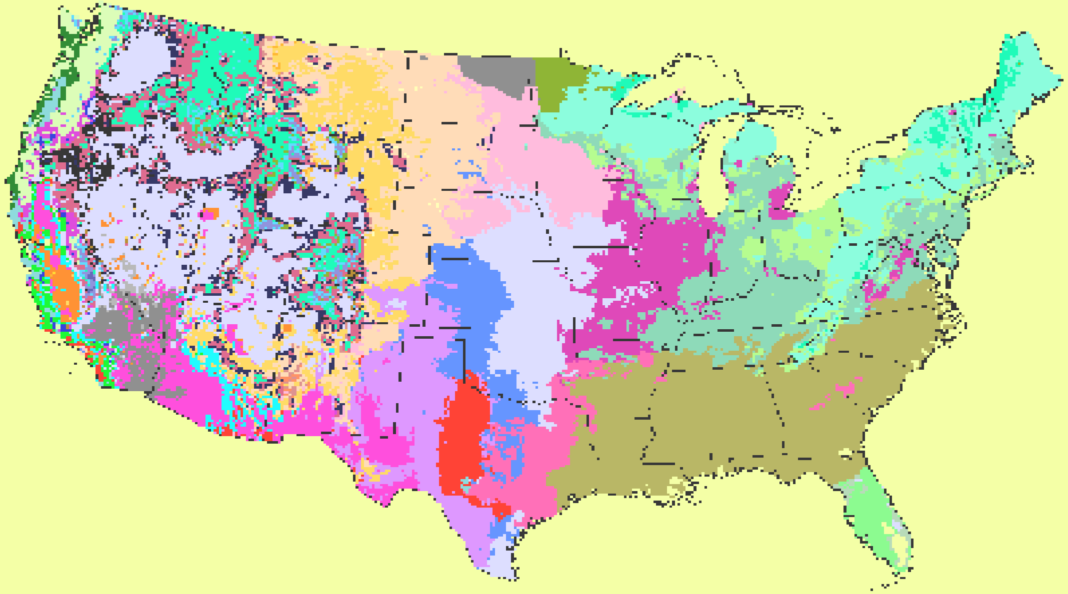
Drew W. Purves, Jeremy W. Lichstein, Stephen W. Pacala 2007 PLOSOne

Deutschman, DH, SA Levin, C Devine and LA Buttel. 1997. Science **277**:1688.

Vegetation models have been successful in explaining global patterns, though not individual species abundances







MAPSS

http://www.fs.fed.us/pnw/mdr/map

And similar approaches can examine collective decision-making

REPORTS

Uninformed Individuals Promote Democratic Consensus in Animal Groups

Iain D. Couzin,[1]* Christos C. Ioannou,[1]† Güven Demirel,[2] Thilo Gross,[2]‡ Colin J. Torney,[1] Andrew Hartnett,[1] Larissa Conradt,[3]§ Simon A. Levin,[1] Naomi E. Leonard[4]

Conflicting interests among group members are common when making collective decisions, yet failure to achieve consensus can be costly. Under these circumstances individuals may be susceptible to manipulation by a strongly opinionated, or extremist, minority. It has previously been argued, for humans and animals, that social groups containing individuals who are uninformed, or exhibit weak preferences, are particularly vulnerable to such manipulative agents. Here, we use theory and experiment to demonstrate that, for a wide range of conditions, a strongly opinionated minority can dictate group choice, but the presence of uninformed individuals spontaneously inhibits this process, returning control to the numerical majority. Our results emphasize the role of uninformed individuals in achieving democratic consensus amid internal group conflict and informational constraints.

Social organisms must often achieve a consensus to obtain the benefits of group living and to avoid the costs of indecision (*1–12*). In some societies, notably those of eu-

Consequently, for both human societies (*1*, *2*, *6*, *9*, *10*, *14*) and group-living animals (*6*, *13*), it has been argued that group decisions can be subject to manipulation by a self-interested

that uninformed individuals (defined as those who lack a preference or are uninformed about the features on which the collective decision is being made) play a central role in achieving democratic consensus.

We use a spatially explicit computational model of animal groups (*15*) that makes minimal assumptions regarding the capabilities of individual group members; they are assumed to avoid collisions with others and otherwise exhibit the capacity to be attracted toward, and to align direction of travel with, near neighbors (*5*, *16*). We investigate the case of consensus decision-making regarding a choice to move to one of two discrete targets in space (thus, the options are mutually exclusive).

The direction and strength of an individual's preference are encoded in a vector term $\vec{\boldsymbol{\omega}}$ (directed toward the individual's preferred target). Higher scalar values of $\boldsymbol{\omega}$ (equivalent to the length of the $\vec{\boldsymbol{\omega}}$ vector, $\boldsymbol{\omega} \equiv |\vec{\boldsymbol{\omega}}|$) represent a greater conviction in, or strength of, individual preference to move in the direction of the target and, thus, also represent greater intransigence to social in-

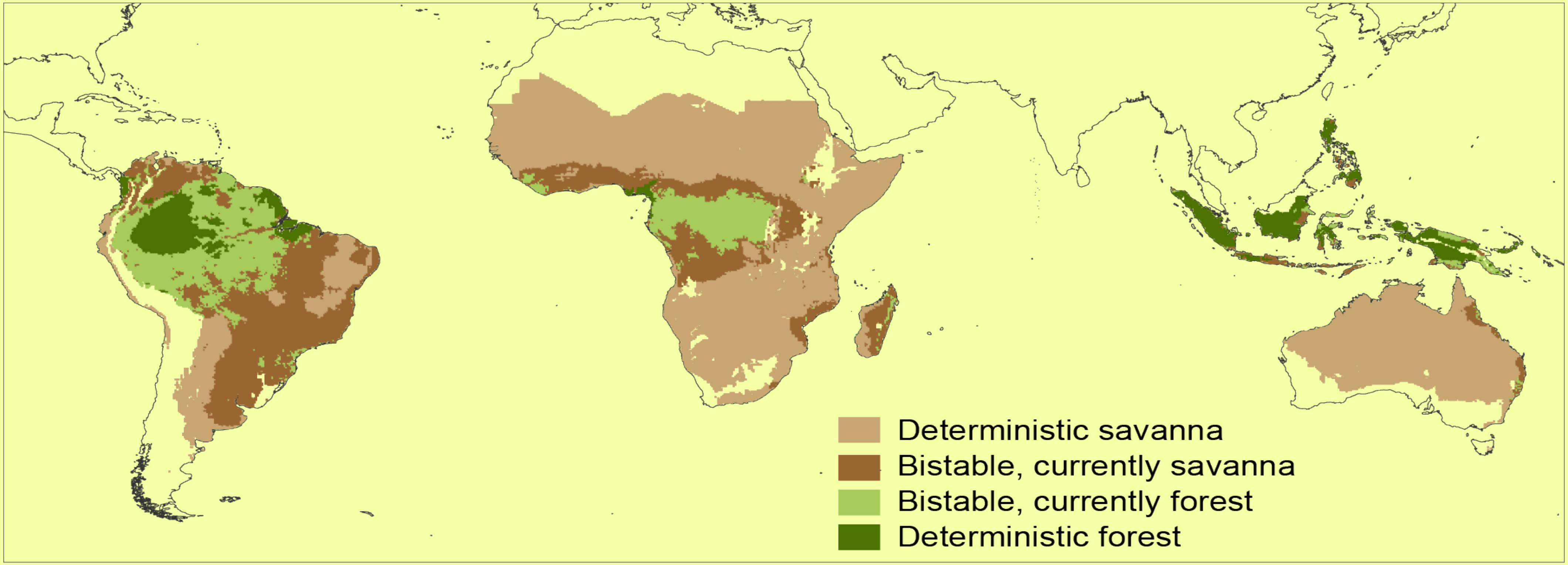
Science, 2011

Reduced dimensional descriptions will be essential for robustness of conclusions

- Hydrodynamic limits
- Moment closure
- Other approaches to aggregation

Systems models can inform the potential for critical transitions

There are limits to predictability:
Bistability characterizes global distributions



Staver *et al.* 2011 (*Ecology* and *Science*)

Global Resilience of Tropical Forest and Savanna to Critical Transitions

Marina Hirota,[1] Milena Holmgren,[2]* Egbert H. Van Nes,[1] Marten Scheffer[1]

It has been suggested that tropical forest and savanna could represent alternative stable states, implying critical transitions at tipping points in response to altered climate or other drivers. So far, evidence for this idea has remained elusive, and integrated climate models assume smooth vegetation responses. We analyzed data on the distribution of tree cover in Africa, Australia, and South America to reveal strong evidence for the existence of three distinct attractors: forest, savanna, and a treeless state. Empirical reconstruction of the basins of attraction indicates that the resilience of the states varies in a universal way with precipitation. These results allow the identification of regions where forest or savanna may most easily tip into an alternative state, and they pave the way to a new generation of coupled climate models.

Tree cover is one of the defining variables of landscapes, their ecological functioning, and their impact on climate. Despite insights into the effects of resource availability and disturbances on tree growth and survival (*1–4*), our understanding of the mechanisms determining global patterns of tree cover remains fragmented. A major question is whether tree cover will respond smoothly to climatic change and other stressors (*5*) or exhibit sharp transitions between contrasting stable states at tipping points (*6*). In some regions, forest, savanna, and treeless (barren or grassy) states have been suggested to represent alternative attractors (*7–9*). However, the case for multiple stable states of tree cover is largely based on models and on local observations of sharp transitions (*6–9*). Systematic studies of tree-cover distributions could help distinguish between hypotheses (*1*) but have been largely restricted to particular continents or biome types (*4–6*, *10*, *11*). To explore whether global patterns of tree abundance suggest gradual responses or, rather, alternative stable states, we

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*To whom correspondence should be addressed. E-mail: milena.holmgren@wur.nl

The Global Extent and Determinants of Savanna and Forest as Alternative Biome States

A. Carla Staver,[1]* Sally Archibald,[2] Simon A. Levin[1]

Theoretically, fire–tree cover feedbacks can maintain savanna and forest as alternative stable states. However, the global extent of fire-driven discontinuities in tree cover is unknown, especially accounting for seasonality and soils. We use tree cover, climate, fire, and soils data sets to show that tree cover is globally discontinuous. Climate influences tree cover globally but, at intermediate rainfall (1000 to 2500 millimeters) with mild seasonality (less than 7 months), tree cover is bimodal, and only fire differentiates between savanna and forest. These may be alternative states over large areas, including parts of Amazonia and the Congo. Changes in biome distributions, whether at the cost of savanna (due to fragmentation) or forest (due to climate), will be neither smooth nor easily reversible.

Fire is a strong predictor of the global distribution of the savanna biome (*1*, *2*) and of tree cover within savannas (*3–5*). Experimental work shows that fire can impact tree cover and can maintain savanna where climate can support forest (*6–8*). Meanwhile, fire spread de-

tree cover or on the potential distribution of fire effects. Locally, big differences in soil texture can have substantial effects on tree cover (*11*, *12*), whereas at the continental scale, soil texture and fertility have limited effects on tree cover (*2*, *3*, *5*). Marked rainfall seasonality is also associated

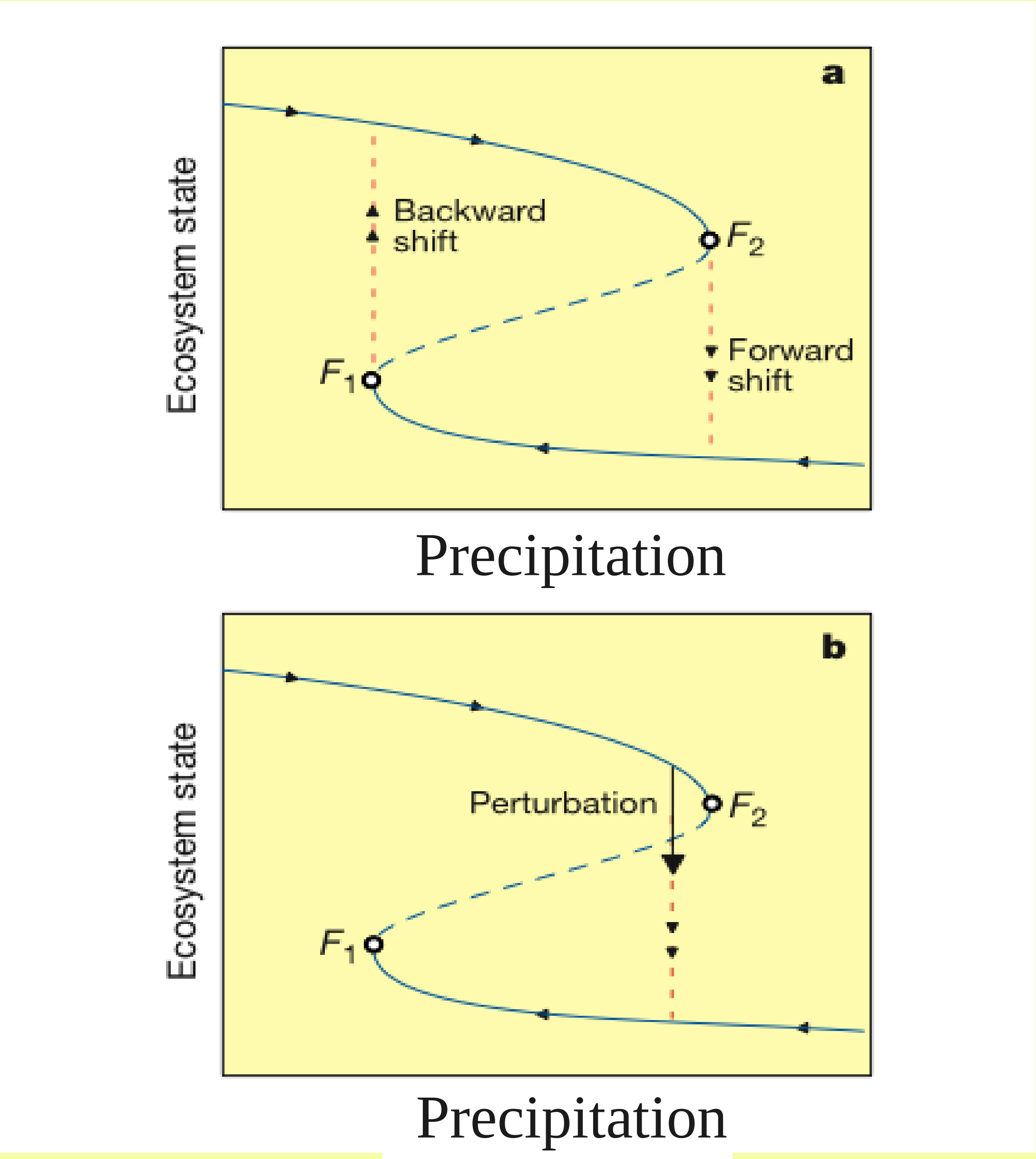
cover. Seasonality, although globally constrained by total rainfall, varies substantially, as exemplified in the extreme by the monsoon in Australia. If seasonality does affect tree cover, it may profoundly affect savanna and forest distributions. Mechanisms are largely unknown, but the effects of seasonality have been attributed to effects on tree physiology and/or fire spread (*2*). Direct physiological limitations to tree growth (*2*, *14*) might prevent forest establishment in seasonal environments, whereas indirect positive effects of long dry seasons on the likelihood of fire spread (*15*) could limit either savannas to seasonal environments (if seasonality is necessary for fire spread) or forests to aseasonal ones (if seasonality makes fire so likely that forest cannot persist).

A comprehensive understanding of tree-cover distributions and of the potential for fire feedbacks to maintain savanna and forest as distinct states requires more extensive, global evaluation. Incorporating not only tree cover, mean annual rainfall, and fire frequency, but also rainfall seasonality and soils into this analysis would provide additional insights into whether fire is a primary driver of biome distributions world-

Carla Staver

Fire is driving the flip

Staver et al. 2011 (Ecology) and Staver & Levin (Amer.Natur.)



Modified very slightly from Scheffer *et al.* 2003, Nature

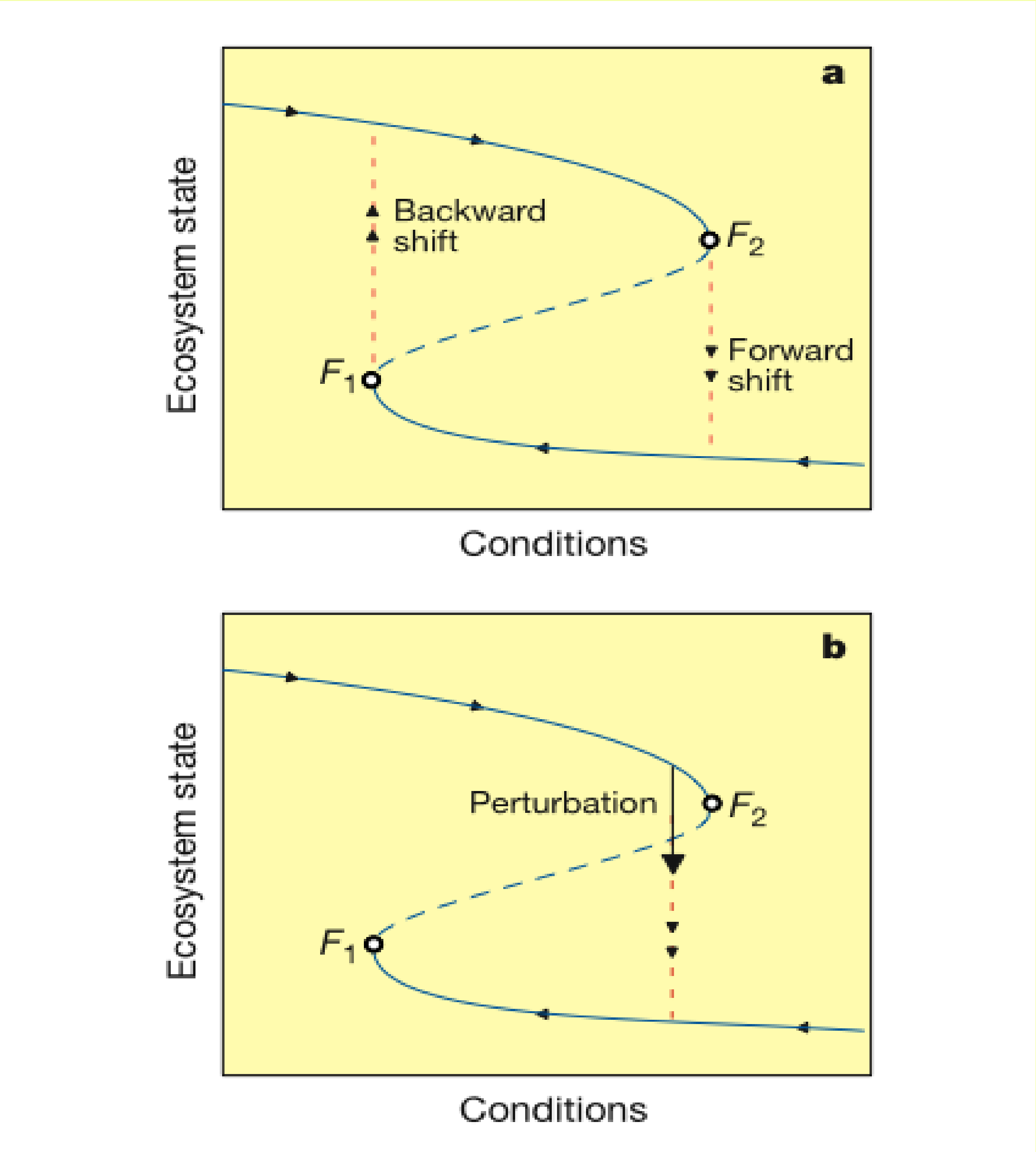
$$\frac{dG}{dt} = \mu S + \nu T - \beta G T$$

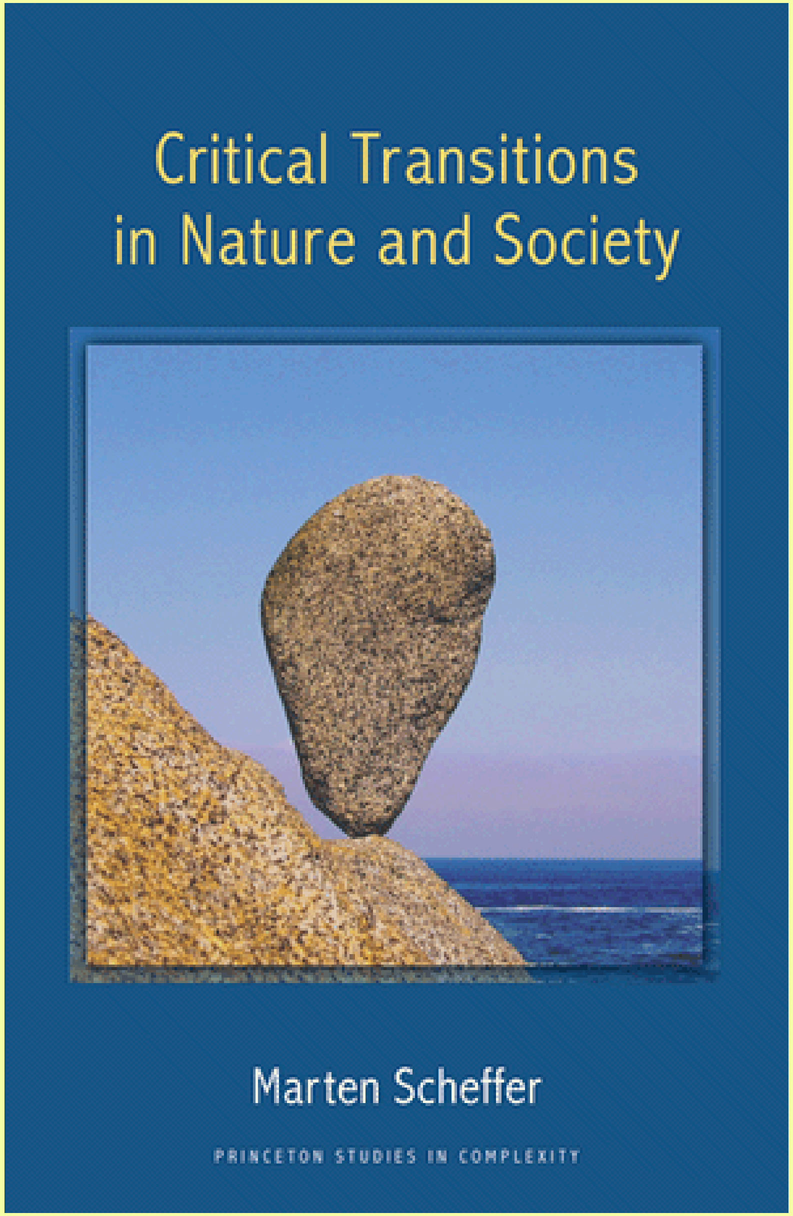
$$\frac{dS}{dt} = \beta G T - \omega(G) S - \mu S$$

$$\frac{dT}{dt} = \omega(G) S - \nu T$$

- Responses to changes in rainfall status will be rapid, threshold transitions
- Changes will not be linear or easy to reverse

Such phenomena are widespread





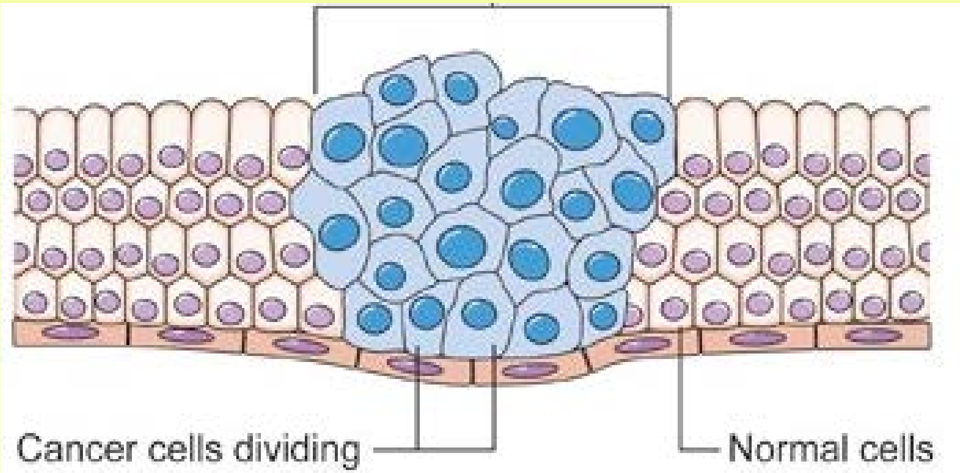
Scheffer et al. 2003

Challenges of systems theory

- Robustness and resilience to critical transitions
- Scaling from the microscopic to the macroscopic
- Dealing with problems of the Commons

Public goods problems are widespread in socio-economic and ecological contexts

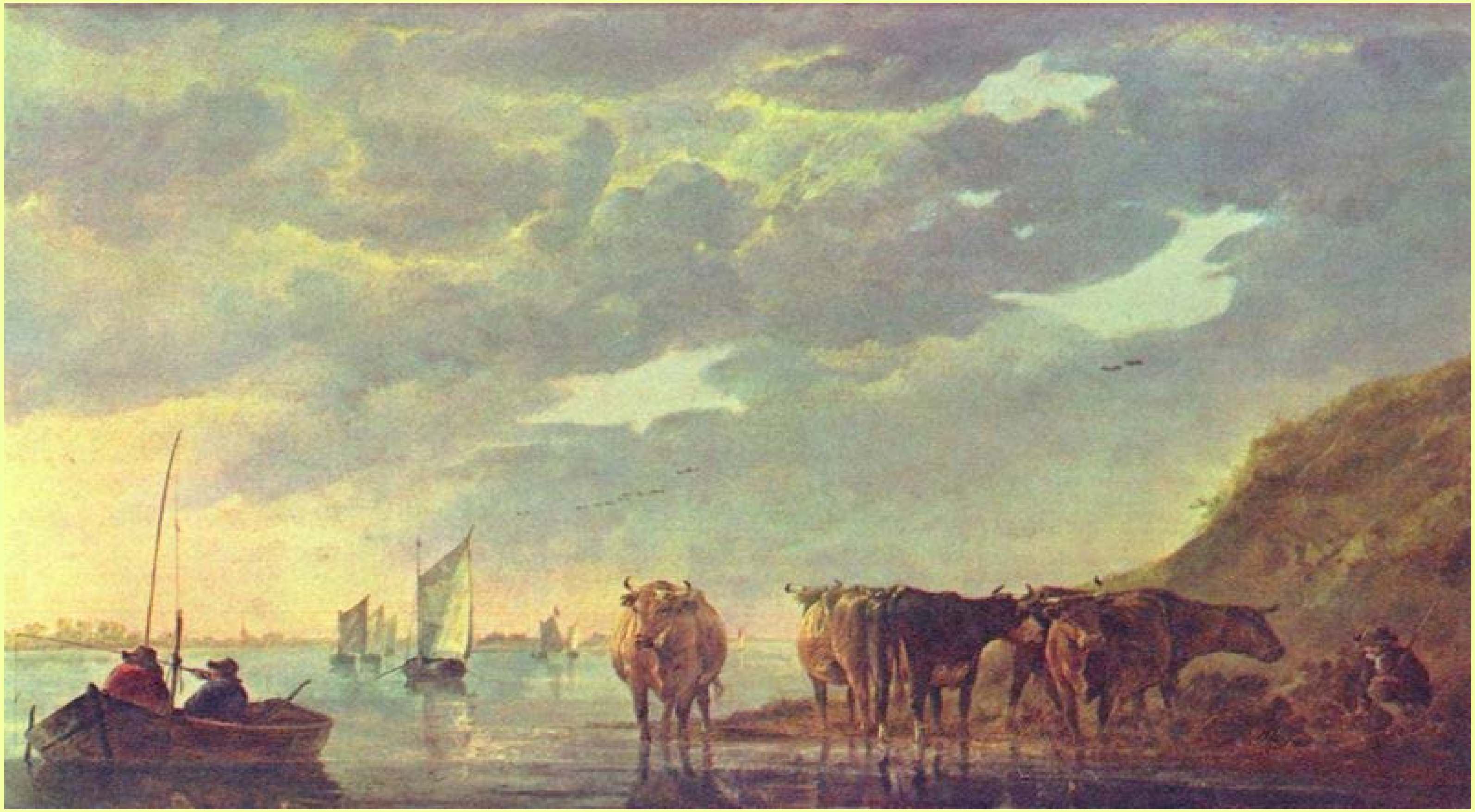
Patrick Semansky/AP



http://www.cancerresearchuk.org/

William Forster Lloyd (1832)

The Tragedy of the Commons



Aelbert_Cuyp

The Commons solution (Hardin, Ostrom)

"Mutual coercion, mutually agreed upon"

http://www.physics.ohio-state.edu/~wilkins

http://www.guardian.co.uk

Fairness norms can provide "mutual coercion, mutually agreed upon"

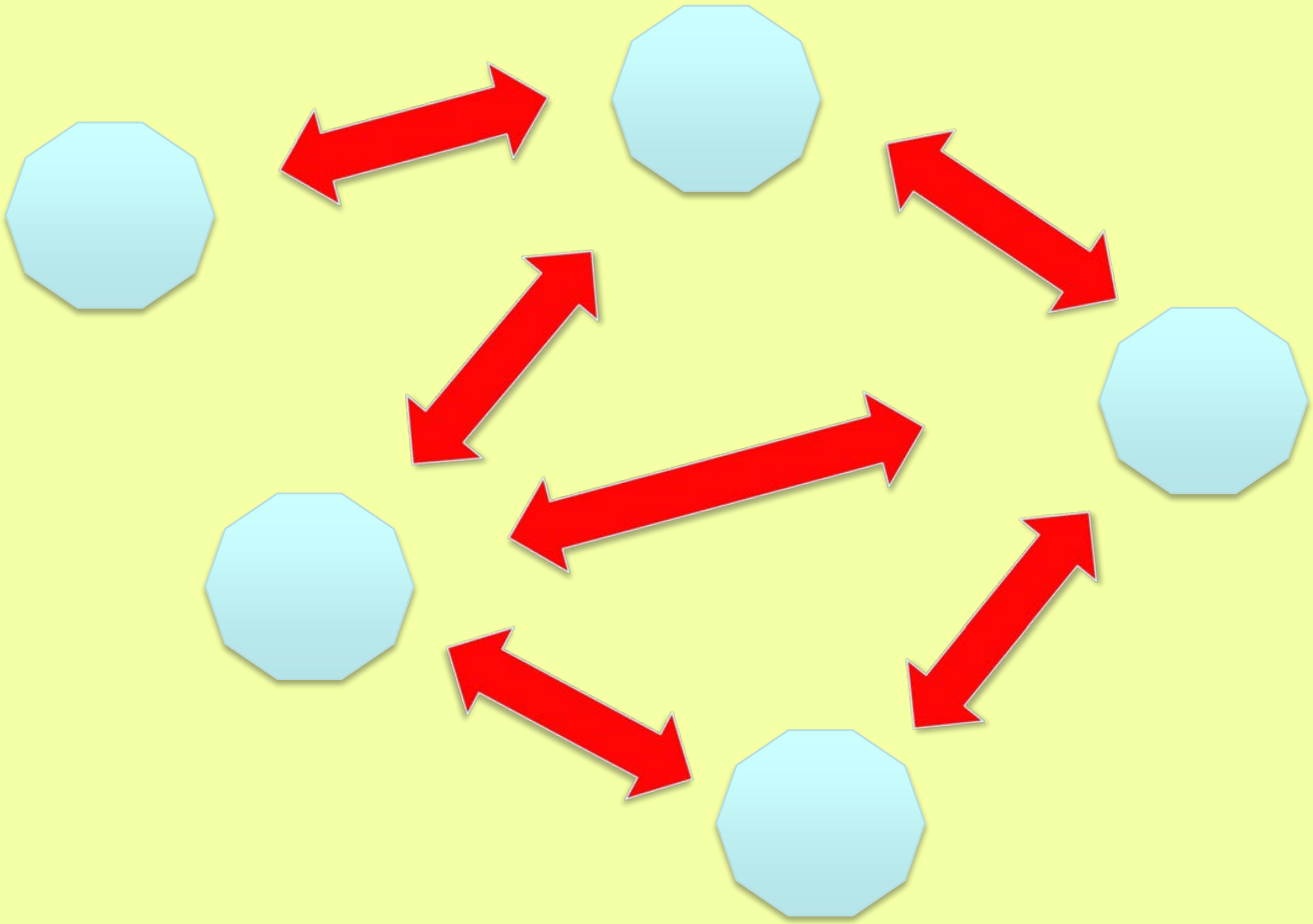
with Alessandro Tavoni and Maja Schlüter

http://geo.coop/node/654

Lessons learned

- Such challenges involve ***coordination*** games
- Achieving cooperation may depend upon getting above a threshold number of cooperators
- Modular structure can provide building blocks for broader agreements, especially at the international scale

Avinash Dixit-Simon Levin
Prosociality and multiple groups



ANNALS OF ECONOMICS AND FINANCE **15-1**, 97–134 (2014)

Ostrom: Climate change

A Polycentric Approach for Coping with Climate Change

Elinor Ostrom

Indiana University

This paper proposes an alternative approach to addressing the complex problems of climate change caused by greenhouse gas emissions. The author, who won the 2009 Nobel Prize in Economic Sciences, argues that single policies adopted only at a global scale are unlikely to generate sufficient trust among citizens and firms so that collective action can take place in a comprehensive and transparent manner that will effectively reduce global warming. Furthermore, simply recommending a single governmental unit to solve global collective action problems is inherently weak because of free-rider problems. For example, the Carbon Development Mechanism (CDM) can be 'gamed' in

American Economic Review 2015, 105(4): 1339–1370
http://dx.doi.org/10.1257/aer.15000001

Climate Clubs: Overcoming Free-riding in International Climate Policy†

By William Nordhaus*

Notwithstanding great progress in scientific and economic understanding of climate change, it has proven difficult to forge international agreements because of free-riding, as seen in the defunct Kyoto Protocol. This study examines the club as a model for international climate policy. Based on economic theory and empirical modeling, it finds that without sanctions against non-participants there are no stable coalitions other than those with minimal abatement. By contrast, a regime with small trade penalties on non-participants, a Climate Club, can induce a large stable coalition with high levels of

Incomplete cooperation and co-benefits:
Deepening climate cooperation with a proliferation of small agreements

Phillip M. Hannam[a,1], Vítor V. Vasconcelos[b,c,d], Simon A. Levin[d,e,f], Jorge M. Pacheco[g,b,h]

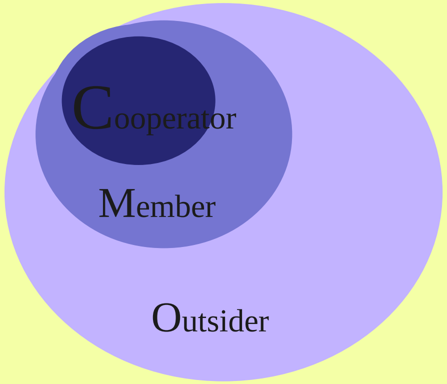
Climatic Change


www.princeton.edu

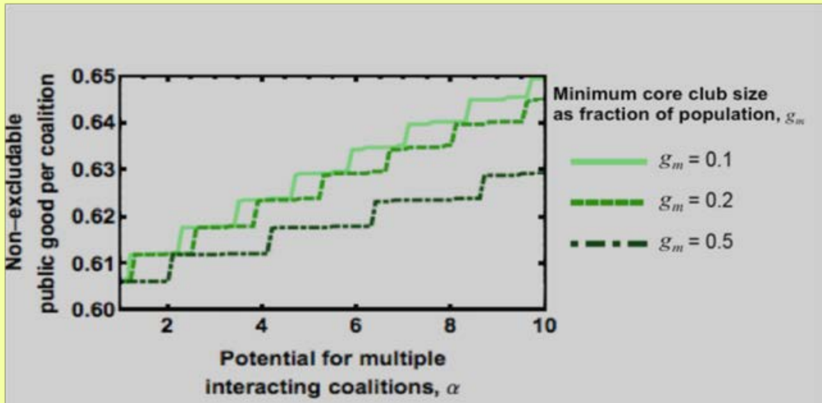

https://pt.linkedin.com


http://www.cienciahoje.pt

Club approach



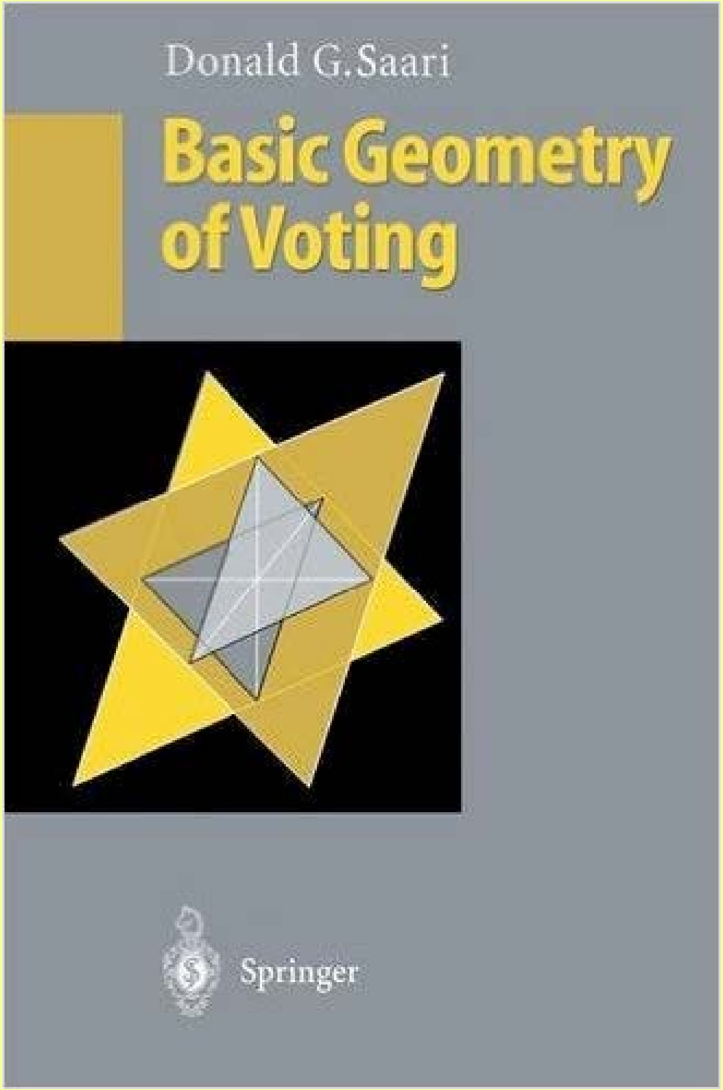
- Cooperators C (pay base +mitigation)
- Members M (pay base)
- Outsiders O (pay nothing)
- Nations can belong to multiple consortia
- This increases the collective public good



Summary so far:

- Collective action can be effective if it includes enforcement
- Prosociality is an important contributor to the maintenance of public goods and common pool resources
- How are collective decisions made?

Voting theory and models of collective action



REPORTS

Uninformed Individuals Promote Democratic Consensus in Animal Groups

Iain D. Couzin,[1]* Christos C. Ioannou,[1]† Güven Demirel,[2] Thilo Gross,[2]‡ Colin J. Torney,[1] Andrew Hartnett,[1] Larissa Conradt,[3]§ Simon A. Levin,[1] Naomi E. Leonard[4]

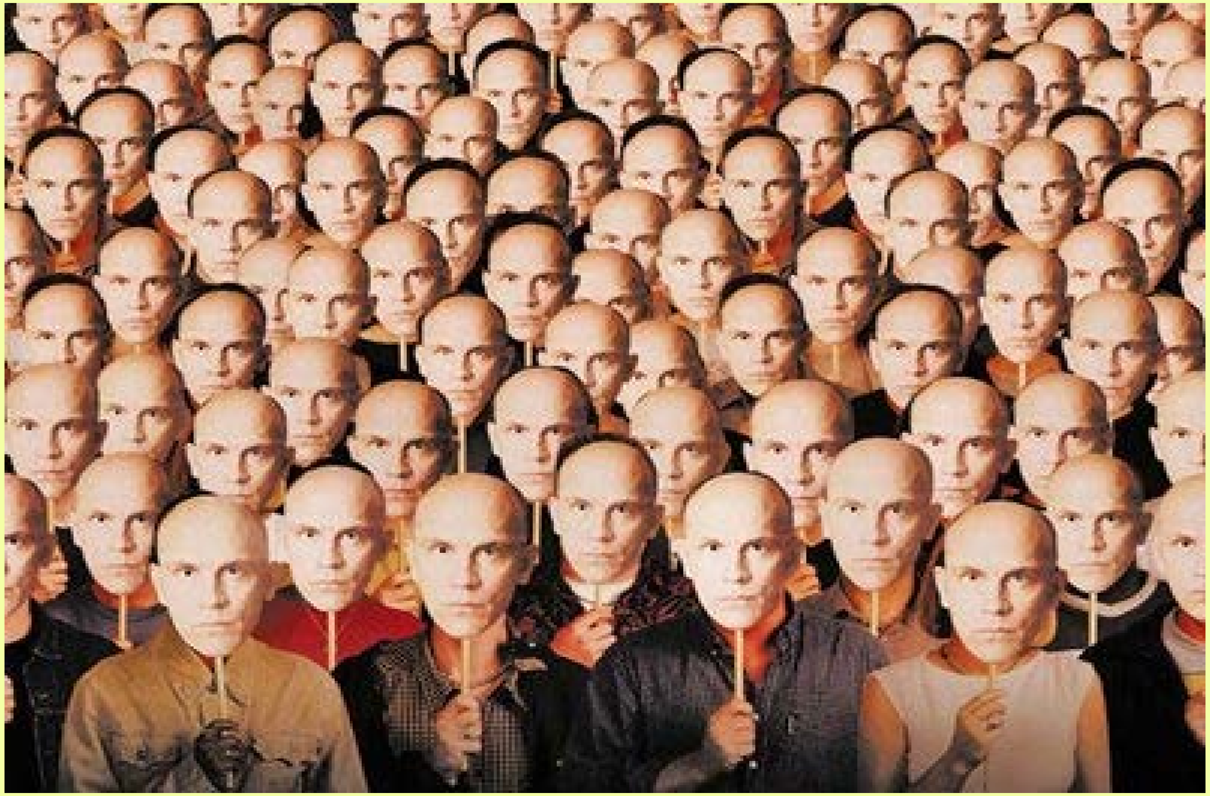
Conflicting interests among group members are common when making collective decisions, yet failure to achieve consensus can be costly. Under these circumstances individuals may be susceptible to manipulation by a strongly opinionated, or extremist, minority. It has previously been argued, for humans and animals, that social groups containing individuals who are uninformed, or exhibit weak preferences, are particularly vulnerable to such manipulative agents. Here, we use theory and experiment to demonstrate that, for a wide range of conditions, a strongly opinionated minority can dictate group choice, but the presence of uninformed individuals spontaneously inhibits this process, returning control to the numerical majority. Our results emphasize the role of uninformed individuals in achieving democratic consensus amid internal group conflict and informational constraints.

Social organisms must often achieve a consensus to obtain the benefits of group living and to avoid the costs of indecision (*1–12*). In some societies, notably those of eu-

Consequently, for both human societies (*1*, *2*, *6*, *9*, *10*, *14*) and group-living animals (*6*, *13*), it has been argued that group decisions can be subject to manipulation by a self-interested

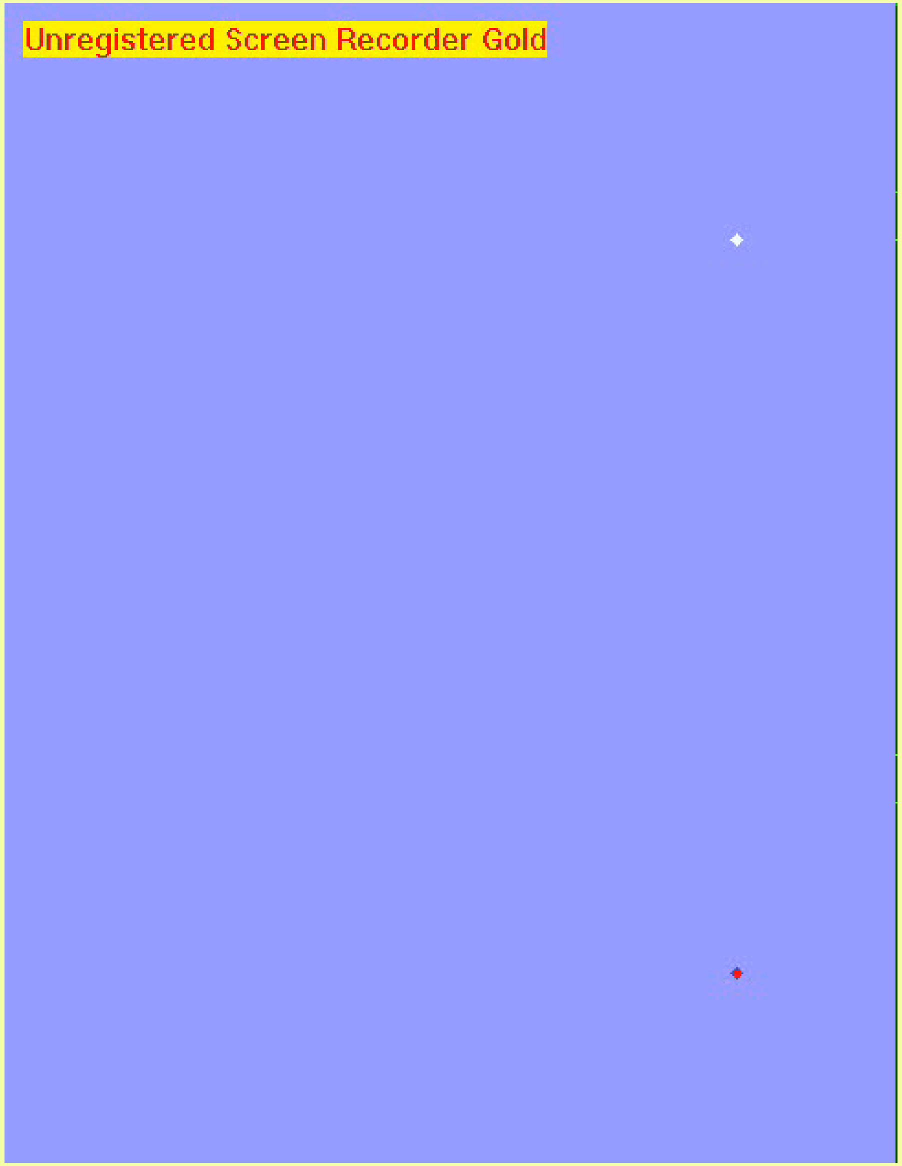
Science 2011

Theoretically and empirically, unopinionated individuals are crucial to nature of consensus



http://motherjones.com/kevin-drum

Without them, groups may split apart

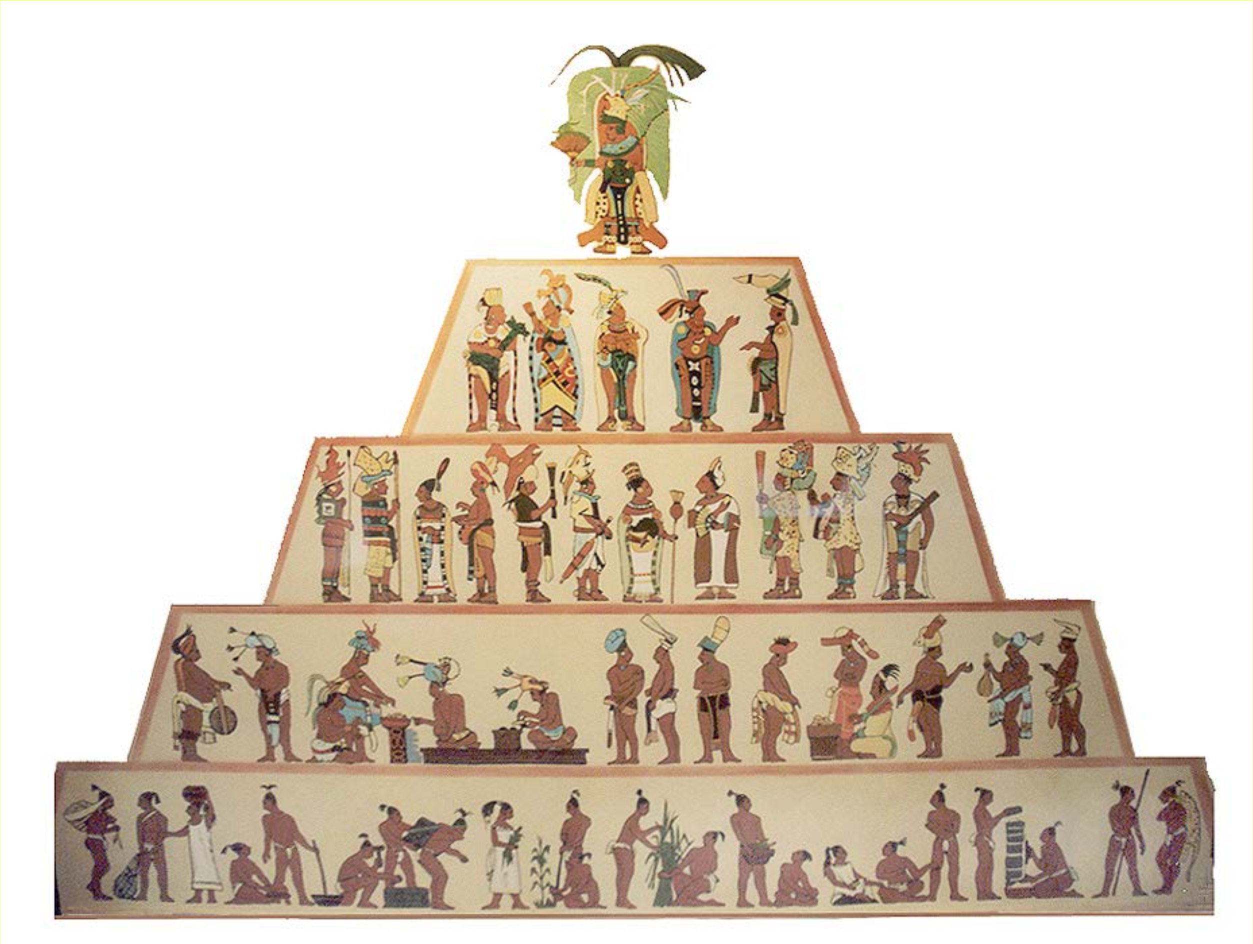


Couzin et al.

Attitudinal shifts affect action on issues like climate change

- In human societies as in animal groups, there may be few leaders and many followers
- Sudden shifts in attitudes given momentum by large numbers of followers
- Environmental action must take such potential volatility into account

Conclusion:
Ecological systems and socio-economic systems alike are complex adaptive systems



http://www.latinamericanstudies.org/maya

Systems Challenges

- Develop a *statistical mechanics* of ecological communities, socio-economic systems and of the biosphere and its coupling with human systems.
- Model the *emergence* of pattern, on multiple scales
- Develop indicators of impending *critical transitions* between states.
- Find pathways to *governance* in multi-scale Commons.

Where better than IIASA to address these challenges?

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