What is resilience? Review, critical assessment, and outlook

Volker Grimm, Department of Ecological Modelling

HELMHOLTZ
CENTRE FOR
ENVIRONMENTAL
RESEARCH – UFZ

CONTENTS

HELMHOLTZ
CENTRE FOR
ENVIRONMENTAL
RESEARCH – UFZ

PRELUDE: DEFINITIONS

- The ability to recover quickly from depression or discouragement
- The ability to recover quickly from illness, change, or misfortune
- Strength of character
- An act of springing back
- The property of a material that enables it to resume its original shape or position after being bent, stretched, or compressed

PRELUDE: DEFINITIONS

http://publicaffairs.uth.tmc.edu/hleader/gfx/2004art/resilience.jpg

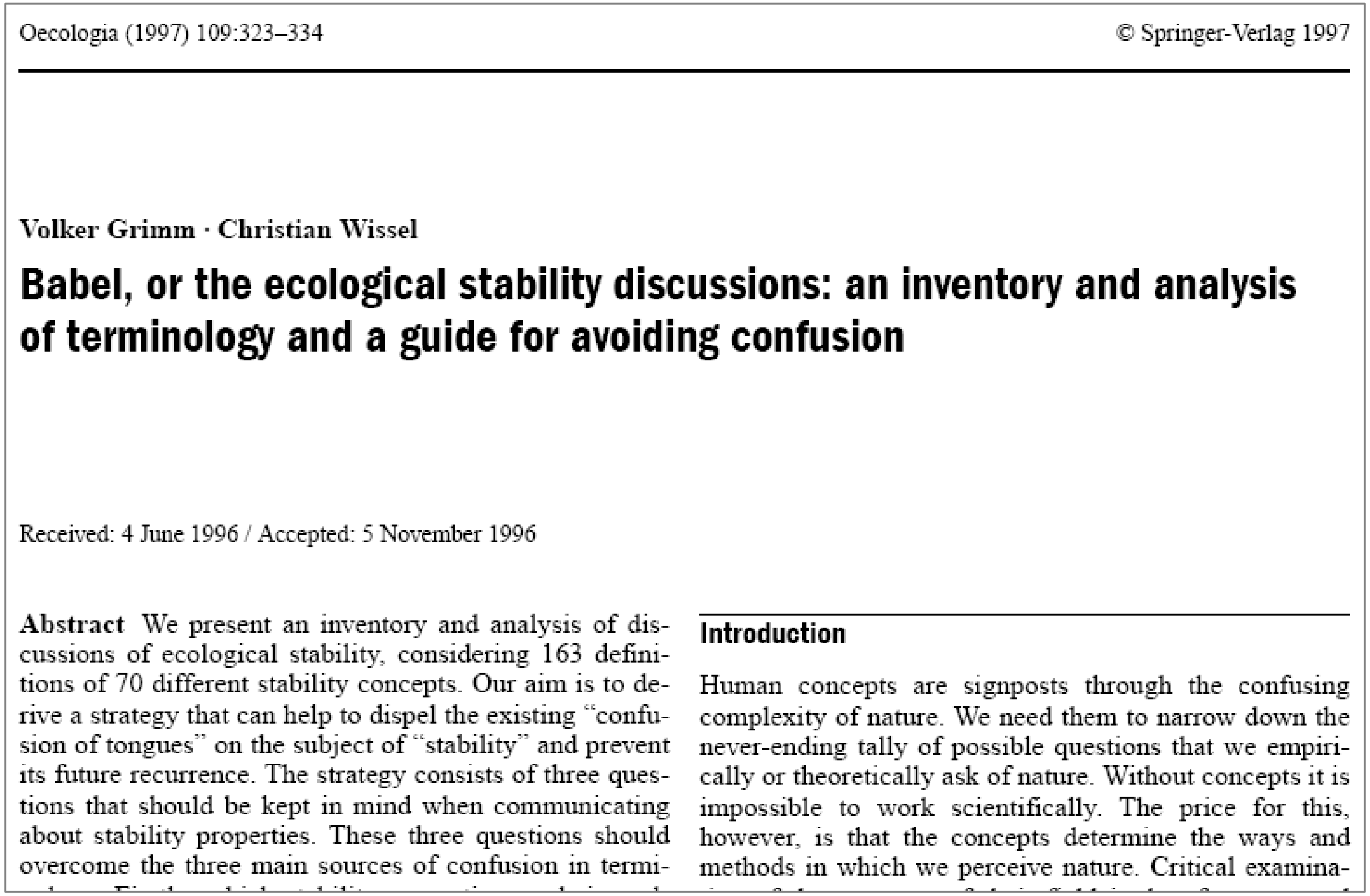
Prelude: Definitions

- What „is“ resilience: Wrong question!
- What, exactly, do we mean by „resilience“?
- Who, we?
- Me, a theoretical ecologist!

- Complex systems including adaptive agents, self-organized, self-similar over time
- Resilience is one of myriads of stability concepts in ecology

STABILITY CONCEPTS IN ECOLOGY

A terminological morass:



Oecologia (1997) 109:323–334

Volker Grimm · Christian Wissel

Babel, or the ecological stability discussions: an inventory and analysis of terminology and a guide for avoiding confusion

Received: 4 June 1996 / Accepted: 5 November 1996

Abstract We present an inventory and analysis of discussions of ecological stability, considering 163 definitions of 70 different stability concepts. Our aim is to derive a strategy that can help to dispel the existing "confusion of tongues" on the subject of "stability" and prevent its future recurrence. The strategy consists of three questions that should be kept in mind when communicating about stability properties. These three questions should overcome the three main sources of confusion in termi-

Introduction

Human concepts are signposts through the confusing complexity of nature. We need them to narrow down the never-ending tally of possible questions that we empirically or theoretically ask of nature. Without concepts it is impossible to work scientifically. The price for this, however, is that the concepts determine the ways and methods in which we perceive nature. Critical examina-

STABILITY CONCEPTS IN ECOLOGY

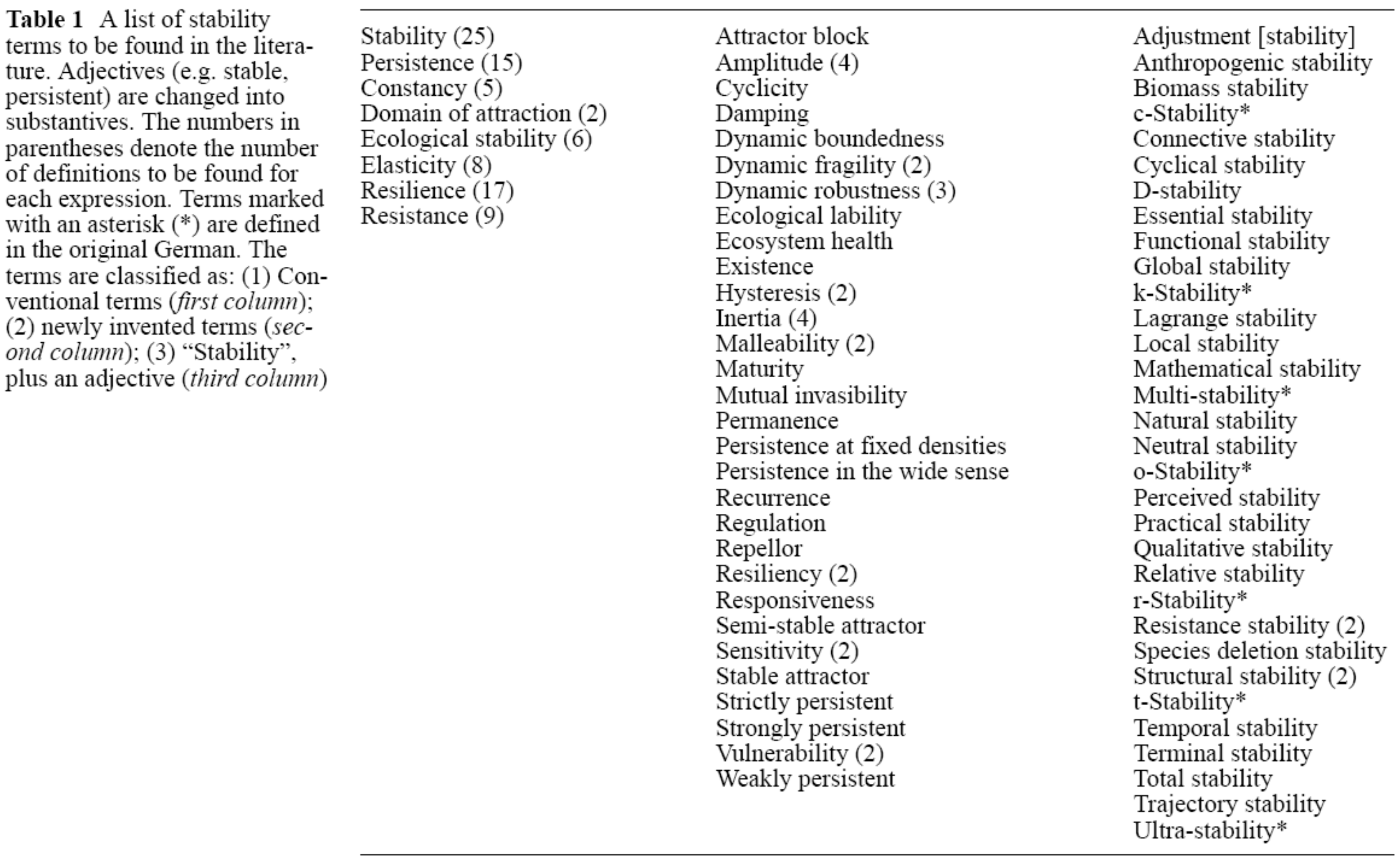


Table 1 A list of stability terms to be found in the literature. Adjectives (e.g. stable, persistent) are changed into substantives. The numbers in parentheses denote the number of definitions to be found for each expression. Terms marked with an asterisk (*) are defined in the original German. The terms are classified as: (1) Conventional terms (*first column*); (2) newly invented terms (*second column*); (3) "Stability", plus an adjective (*third column*)

- Stability (25)
- Persistence (15)
- Constancy (5)
- Domain of attraction (2)
- Ecological stability (6)
- Elasticity (8)
- Resilience (17)
- Resistance (9)

- Attractor block
- Amplitude (4)
- Cyclicity
- Damping
- Dynamic boundedness
- Dynamic fragility (2)
- Dynamic robustness (3)
- Ecological lability
- Ecosystem health
- Existence
- Hysteresis (2)
- Inertia (4)
- Malleability (2)
- Maturity
- Mutual invasibility
- Permanence
- Persistence at fixed densities
- Persistence in the wide sense
- Recurrence
- Regulation
- Repellor
- Resiliency (2)
- Responsiveness
- Semi-stable attractor
- Sensitivity (2)
- Stable attractor
- Strictly persistent
- Strongly persistent
- Vulnerability (2)
- Weakly persistent

- Adjustment [stability]
- Anthropogenic stability
- Biomass stability
- c-Stability*
- Connective stability
- Cyclical stability
- D-stability
- Essential stability
- Functional stability
- Global stability
- k-Stability*
- Lagrange stability
- Local stability
- Mathematical stability
- Multi-stability*
- Natural stability
- Neutral stability
- o-Stability*
- Perceived stability
- Practical stability
- Qualitative stability
- Relative stability
- r-Stability*
- Resistance stability (2)
- Species deletion stability
- Structural stability (2)
- t-Stability*
- Temporal stability
- Terminal stability
- Total stability
- Trajectory stability
- Ultra-stability*

Stability term and definition	Authors who use the term in the first column in more or less the same way	Terms with definitions mainly the same as in the first column
(1) **Constancy:** Staying essentially unchanged	Connell and Sousa 83:97 Gigon 83:97 Harrison 79:661 Lewontin 69:21 Orians 75:141 Remmert 89:286	Biomass stability – King and Pimm 1983:329 Ecological stability* – Zwölfer 78:15 Functional stability – Rejmánek 92:455 Perceived stability – Begon et al. 90:802 Persistence – Rahel 90:328 Stability* – Haber 79:24 Stability – Murdoch 70:497 Stability – Putman and Wratten 85:338 Temporal stability – Preston 69:9
(2) **Resilience:** Returning to the reference state (or dynamic) after a temporary disturbance	Harrison 79:660 Leps et al. 82:54 Putman and Wratten 85:339 Ulrich 92:181 Westman 78:705	Stability – Hallet 91:383 Stability – Holling 73:17 Stability – Pimm 84:322 Stability – Steele 74:180 Adjustment – Connell and Sousa 83:790 Connective stability – Siljak 74:280 Elasticity – Gigon 83:98 Elasticity* – Remmert 84:286 [Global, local] stability – Begon et al. 90:792 Mathematical stability – Danielson and Stenseth 92:83 Regulation – Murdoch 70:497 Resiliency – Kuss and Hall 91:715 Species deletion stability – Pimm 80:142
(3) **Persistence:** Persistence through time of an ecological system	Allen 83:4 Armstrong and McGhee 76:320 Botkin and Sobel 75:629 Connell and Sousa 83:791 DeAngelis and Waterhouse 87:7 Estberg and Patten 76:151 Harrison 79:660 Hastings 88:1666 Strong 90:421 Warner and Chesson 85:772 Yodzis 89:128	Stability – Begon et al. 90:792 Stability – Chesson and Huntly 89:293 Stability – Connell and Slatyer 77:1129 Stability – Crowley 92:246 Stability – Preston 69:7 Stability – Roff 74:246 Stability – Wu 76:156 Ecological stability – Nisbet and Gurney 82:10 Ecological stability – Wu 77:347 Essential stability – Wu 77:352 Existence – Bossel 92:267 Lagrange stability – Thornton and Mulholland 74:479 Mutual invasibility – Yodzis 89:128 Persistence at fixed densities – Armstrong and McGhee 76:319 Persistence in the wide sense – Royama 77:3 Permanence – Law and Blackford 92:568 Practical stability – Thornton and Mulholland 74:483 Strictly persistent – Royama 77:2 Strongly persistent – Li 88:353 Terminal stability – Wu 76:159 Total stability – Wu 76:159 Weakly persistent – Li 88:353

(4) **Resistance:** Staying essentially unchanged despite the presence of disturbances	Begon et al. 90:792 Boesch 74:109 Connell and Sousa 83:790 Gigon 83:98 Harrison 79:660 Harwell et al. 81:108 Kuss and Hall 91:715 Leps et al. 82:54 Steinman et al. 90:80	Stability – Hurd and Wolf 74:465 Stability – MacArthur 55:534 Stability – Margalef 68:12 Stability* – Remmert 89:286 Ecological stability – Mulholland 76:167 Ecological stability – Rutledge et al. 76:356 Inertia – Murdoch 70:500 Inertia – Orians 74:64 Inertia – Orians 75:141 Inertia – Westman 78:705 Malleability – Westman 91:213 Resilience – Holling 73:17 Resistance stability – Sutherland 90 Responsivness – Roughgarden 75:6 Sensitivity – Estberg and Patten 76:152 Sensitivity* – Remmert 84:286 Vulnerability – Vincent and Anderson 79:218
(5) **Elasticity:** Speed of return to the reference state (or dynamic) after a temporary disturbance	Connell and Sousa 83:790 Orians 74:64 Orians 75:141 Westman 78:706 Westman 91:213	Ecological stability – Danielson and Stenseth 92:38 Resilience – Begon et al. 90:792 Resilience – Carpenter et al. 92:784 Resilience – Crowley 92:247 Resilience – DeAngelis 80:764 Resilience – Hallet 91:384 Resilience – Harwell et al. 81:108 Resilience – Nakajima and DeAngelis 89:502 Resilience – Pimm 84:322 Resilience – Steinman et al. 90:80 Resilience – Steinman et al. 91:1299 Resiliency – Boesch 74:109
(6) **Domain of attraction:** The whole of states from which the reference state (or dynamic) can be reached again after a temporary disturbance	Holling 73:3 Pimm 84:322	Amplitude – Connell and Sousa 83:790 Amplitude – Orians 75:141 Amplitude – Westman 78:706 Amplitude – Westman 91:213 Attractor block – Armstrong and McGhee 76:320 Dynamic fragility – Begon et al. 90:792 Dynamic fragility – May 75:163 Dynamic robustness – Begon et al. 90:792 Dynamic robustness – Danielson and Stenseth 92:38 Dynamically bounded – Lewontin 69:18 Dynamical robustness – May 75:163 Elasticity – Ulrich 92:181 Repellor – Byers et al. 92:26 Semi-stable attractor – Byers et al. 92:25 Stable attractor – Byers et al. 92:10

STABILITY CONCEPTS IN ECOLOGY

Essentially, there are only six (three) different stability properties

1. **Constancy: Staying essentially unchanged**
2. **Resistance: Staying essentially unchanged despite the presence of disturbances**
3. **Persistence: Persistence through time of an ecological system**

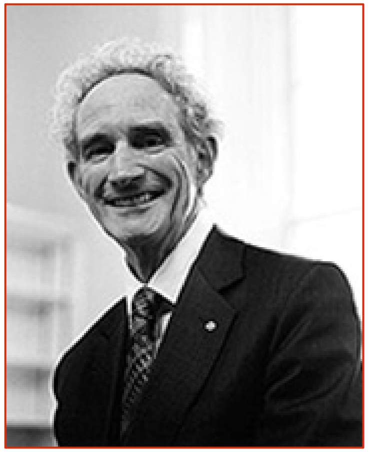
STABILITY CONCEPTS IN ECOLOGY

4. Resilience: Returning to the reference state (or dynamics) after a temporary disturbance
5. Elasticity: Speed of return to the reference state (or dynamics) after a temporary disturbance
6. Domain of attraction: The whole of states from which the reference state (or dynamics) can be reached again after a temporary disturbance

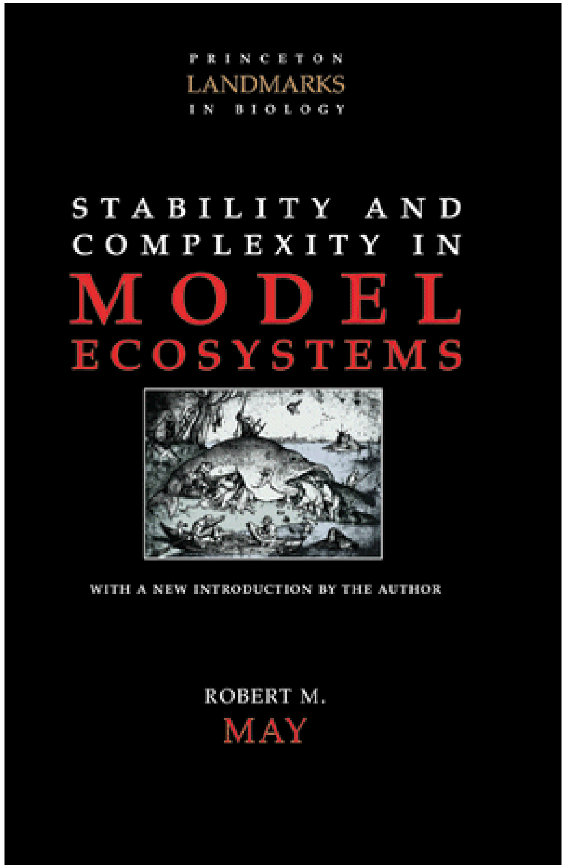
ENGINEERS’ RESILIENCE

- Resilience: Returning to the reference state (or dynamics) after a temporary disturbance
- Very often also referred to just as „stability“
- Until about 2000, the most frequently used stability concept in Theoretical Ecology
- Why? Linear Stability Analysis (calculating eigenvalues of linearized Lotka-Volterra models)

EXAMPLE: LORD ROBERT MAY'S BOOK



- 1973 – Reprinted in 2001
- Cited more than 1600 times
- Lotka-Volterra plus linear stability analysis (plus brilliant mind)
- Why so successful?



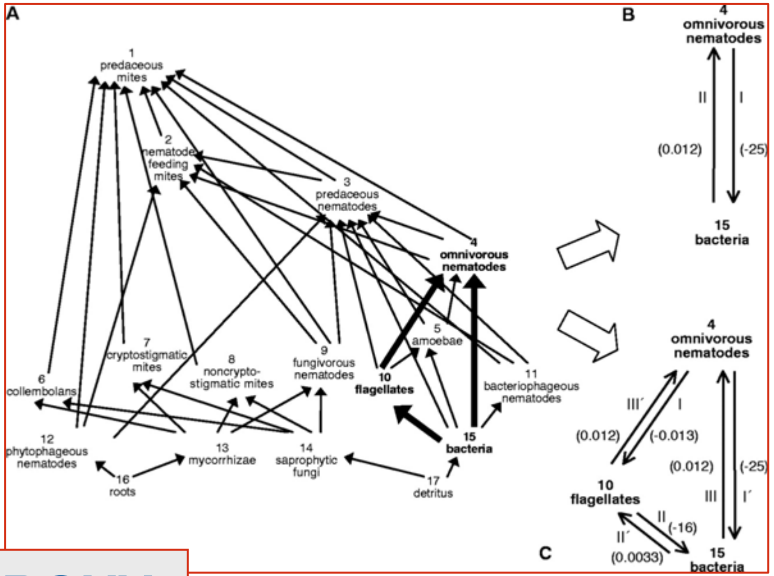
PRINCETON
LANDMARKS
IN BIOLOGY

STABILITY AND
COMPLEXITY IN
MODEL
ECOSYSTEMS

WITH A NEW INTRODUCTION BY THE AUTHOR

ROBERT M.
MAY

EXAMPLE: LORD ROBERT MAY’S BOOK



PROXY

Neutel et al. 2002

Eigenvalue

PROXY

Stability

PROXY

- PROXY science
- Intellectually appealing and thought-provoking
- „Success“ in terms of capturing key features of real systems depends on quality of those proxies

ECOLOGICAL RESILIENCE

- Not all ecologists were happy with the „engineers‘“ notion of resilience
- Holling‘s review from 1973 introduced a different notion of resilience, that intrigued generations of ecologists, but never took ground in Theoretical Ecology:
- **"Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist. In this definition resilience is the property of the system and persistence or probability of extinction is the result."**

ECOLOGICAL RESILIENCE

„There are two resilience measures : Since resilience is concerned with probabilities of extinction,

Firstly, the overall area of the domain of attraction will in part determine whether chance shifts in state variable will move trajectories outside the domain.

Secondly, the height of the lowest point of the basin of attraction (e.g. the bottom of the slice described above) above equilibrium will be a measure of how much the forces have to be changed before all trajectories move to extinction of one or more of the state variables."

ECOLOGICAL RESILIENCE

Main difference to engineers‘ notion of resilience:

1. **Shift from equilibrium to domain of attraction**
2. **Shift from focus on numerical values of certain state variables to „persistence of relationships“, i.e. some sort of „functioning“ and self similarity**
3. **Introduction of the idea that ecosystems have the „ability“ to „absorb“ changes**

RESILIENCE ALLIANCE

In 1999, Holling and a small group of other scientists founded the „Resilience Alliance“ (www.resalliance.org):

„*The Resilience Alliance* is a research organization comprised of scientists and practitioners from many disciplines who collaborate to explore the dynamics of social-ecological systems. The body of knowledge developed by the RA, encompasses key concepts of resilience, adaptability and transformability and provides a <u>foundation for sustainable development policy and practice</u>.“

RESILIENCE ALLIANCE

Ecological resilience

> **„Magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behavior“**

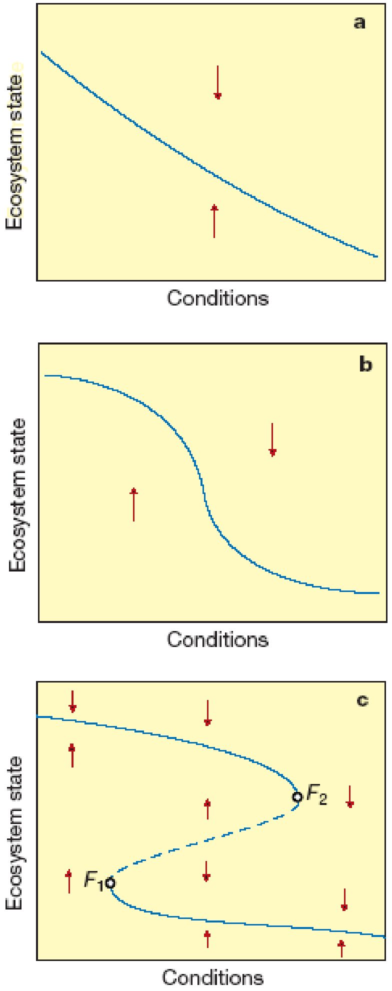
Holling und Gunderson (2002)

REGIME SHIFTS AND ALTERNATIVE STATES

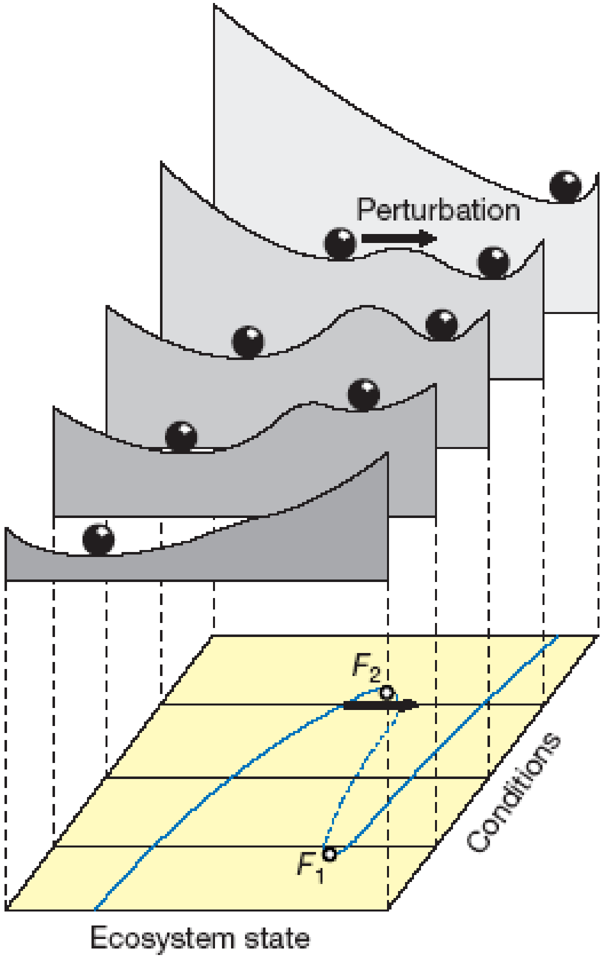
linear

threshold

multi-stable



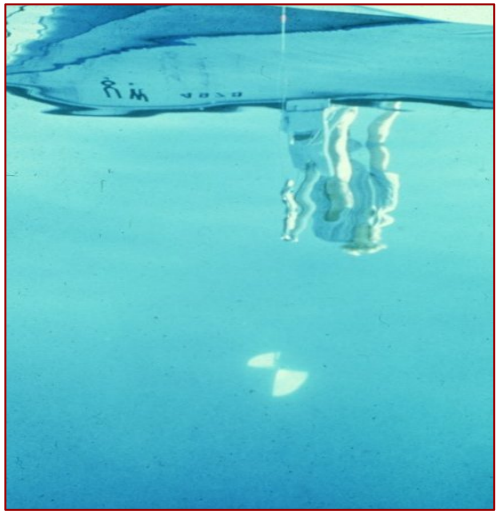
Reaction to external trends

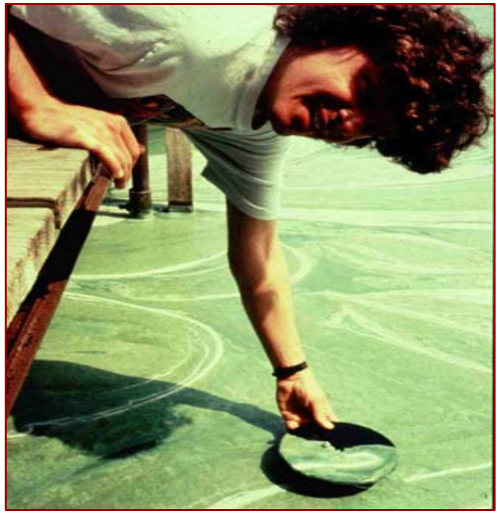


Reaction to disturbance

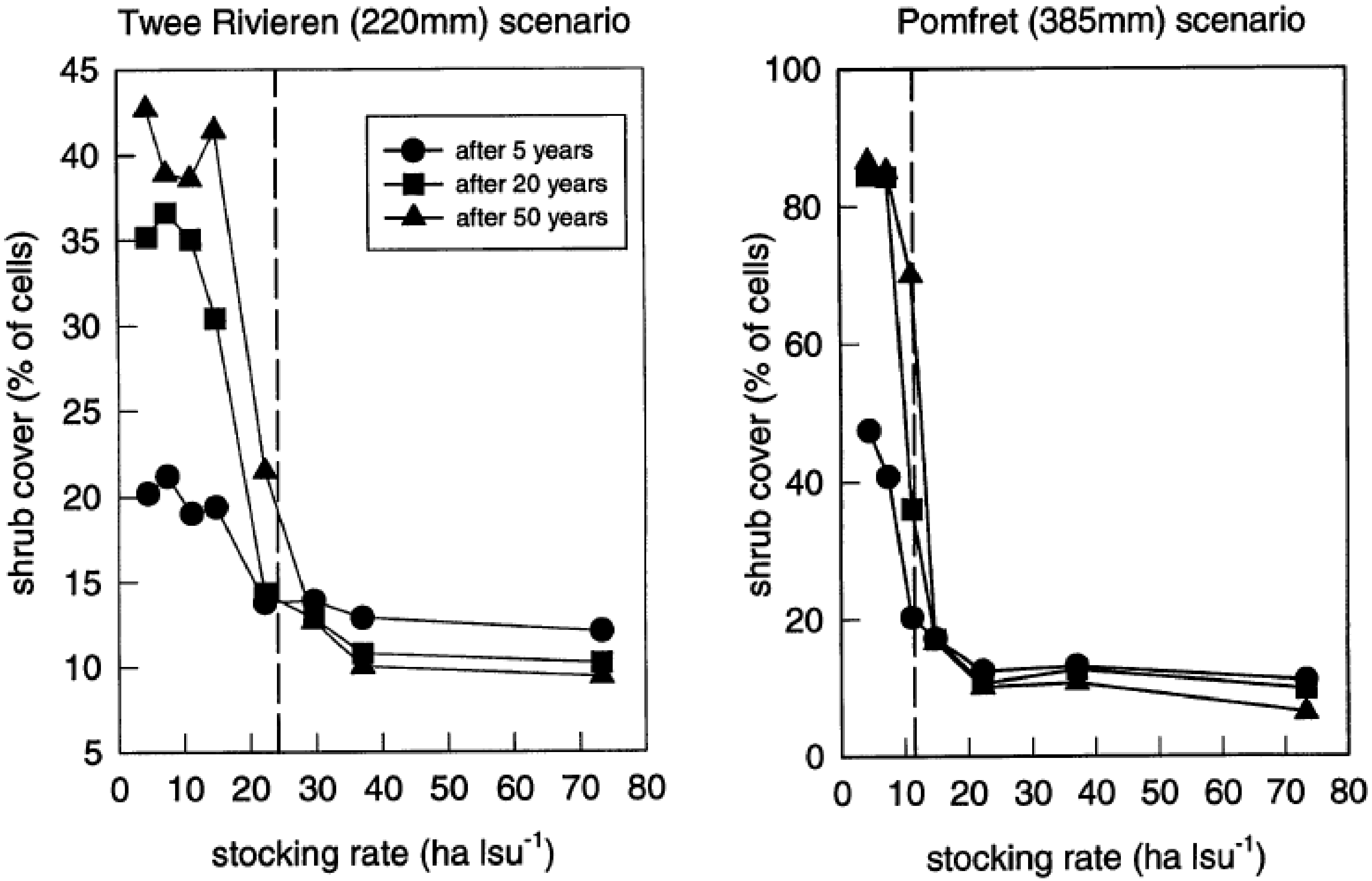
(Scheffer et al. 2001)

REGIME SHIFTS AND ALTERNATIVE STATES





REGIME SHIFTS IN SAVANNAS



(Jeltsch et al.1997)

SO FAR, SO GOOD

- Ecological resilience (Holling 1973)

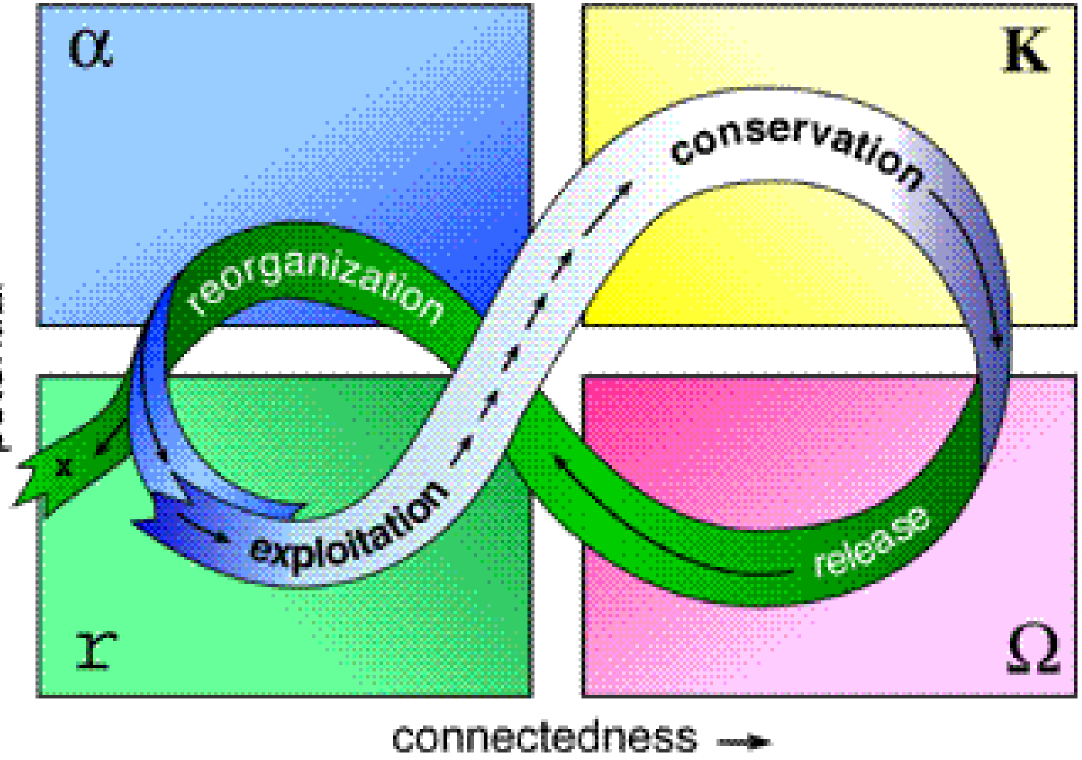
But then:

- Notions of internal cyclical dynamics („adaptive cycle“, Holling 1986)
- Cross-scale morphology („panarchy“, Holling 1992)
- Notion of systems being „adaptive“?
- Consequences for management
- Socio-ecological systems

ADAPTIVE CYCLE

Potential: e.g. accumulated resources of biomass and nutrients

Connectedness: e.g. degree of connectedness among controlling variables



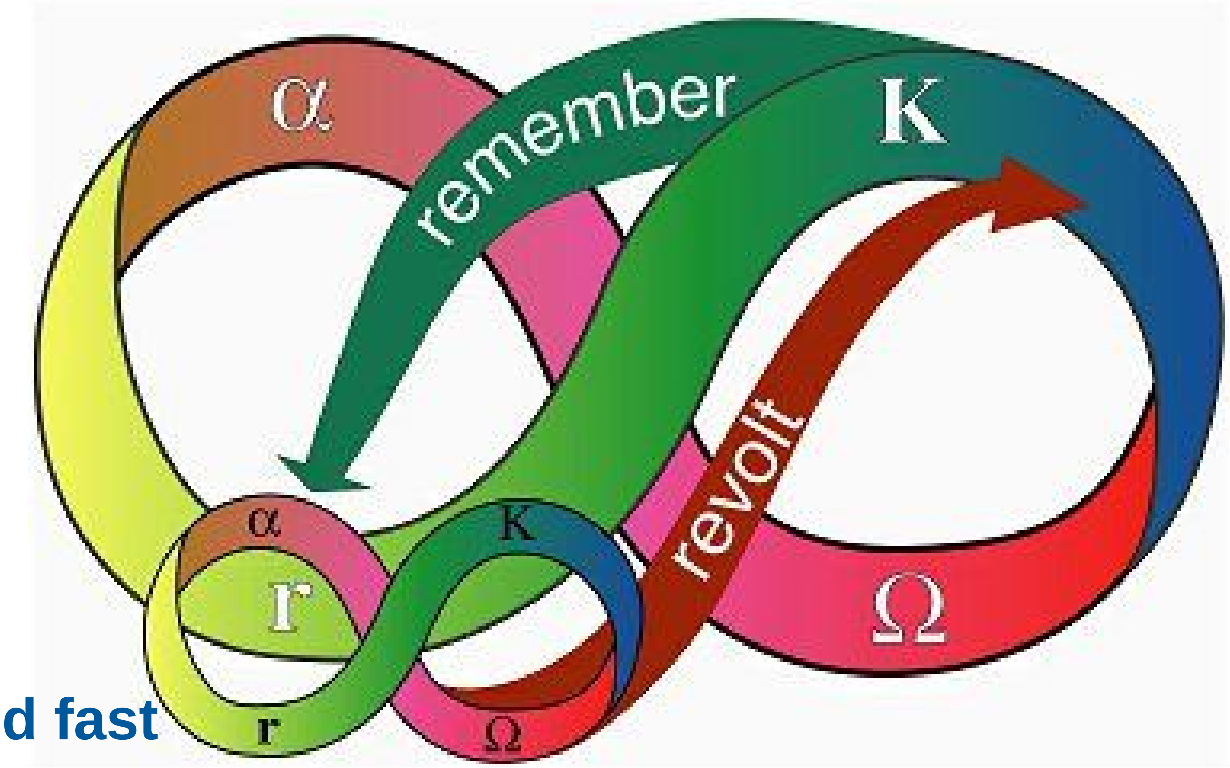
ADAPTIVE CYCLE

“Potential sets limits to what is possible – it determines the number of alternative options for the future.

Connectedness determines the degree to which a system can control its own destiny (...).

Resilience determines how vulnerable the system is to unexpected disturbances and surprises that can exceed or break that control” (Holling and Gunderson 2002, p. 51).

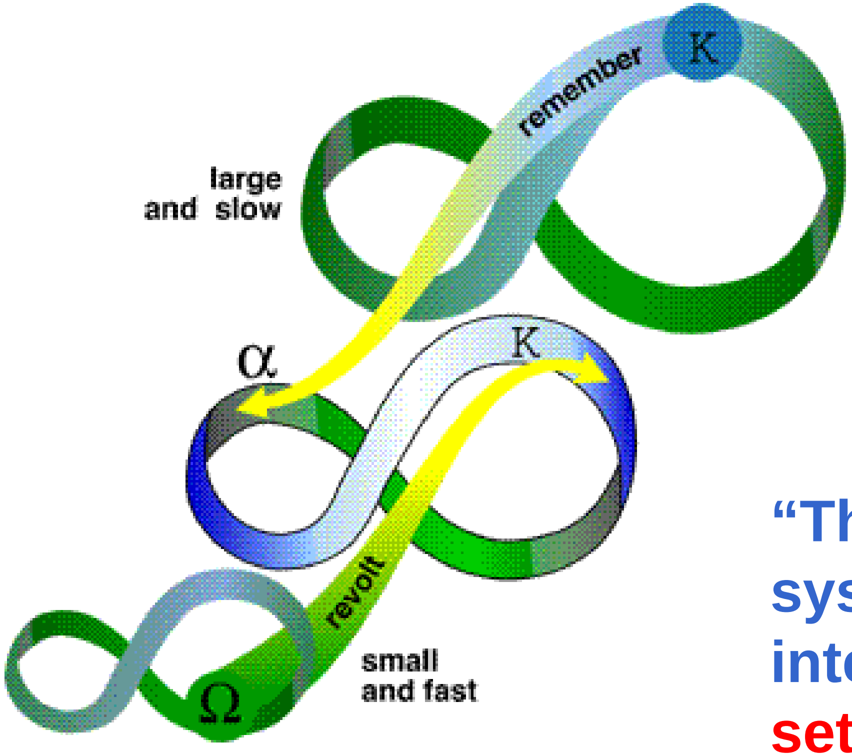
PANARCHY



Large and slow

Small and fast

PANARCHY



“The complexity of adaptive systems can be traced to interactions among three to five sets of variables, each operating at a qualitatively distinct speed and scale.” (Frido Brand, UFZ Report)

STATE OF THE ART: RESILIENCE ALLIANCE

- RA has ist own journal(s)
- Started with (and still maintains) a „brotherhood“ kind of behavior and communication
- „RA talk“ (reminding me sometimes of psychoanalysis and marxism)

BUT:

- Ideas made it into high profile journals
- Quite a few highly respected ecologists are involved
- Highly active, prolific, and influential
- Pressure group
- General perception: Important concepts and idea, but…

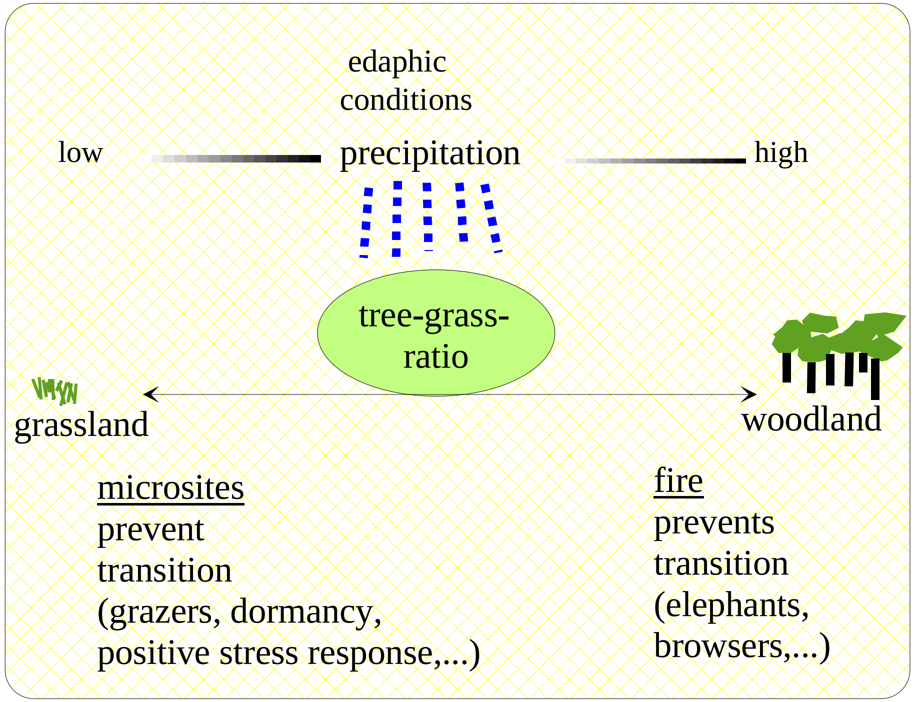
CRITIQUE IN RESILIENCE ALLIANCE

1. **Understanding of system‘s dynamics is imposed, rather than emerging from mechanistic approaches**
2. **Based more on intuition than on rigorous evidence (is that good or bad?)**
3. **Missing distinction between normative vs. descriptive definitions of resilience**
4. **Economic parts of framework not up-to-date?**
5. **Adaptive Cycle and Panarchy are quite strange**
6. **Entire framework might rather prevent, than foster, research that would develop mechanistic understanding and, in turn, better management**
7. **Organismic notion of ecosystems (again)**

WE NEED

- Mechanistic models (e.g., savannas: Jeltsch vs. Calabrese model: tension between simple and complex is productive!)
- Concepts need to be formulated as working hypothesis
- If „aborbing change“ is decisive, we need to focus on buffer(ing) mechanisms!

BUFFER MECHANISMS



edaphic conditions

low precipitation high

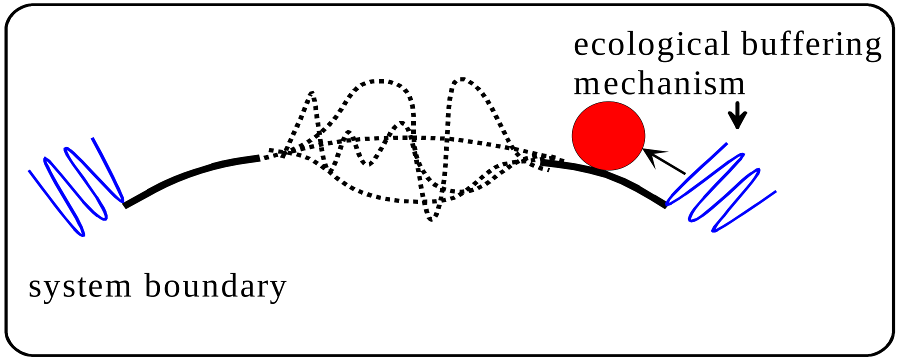
tree-grass-ratio

grassland

woodland

microsites prevent transition (grazers, dormancy, positive stress response,...)

fire prevents transition (elephants, browsers,...)



ecological buffering mechanism

system boundary

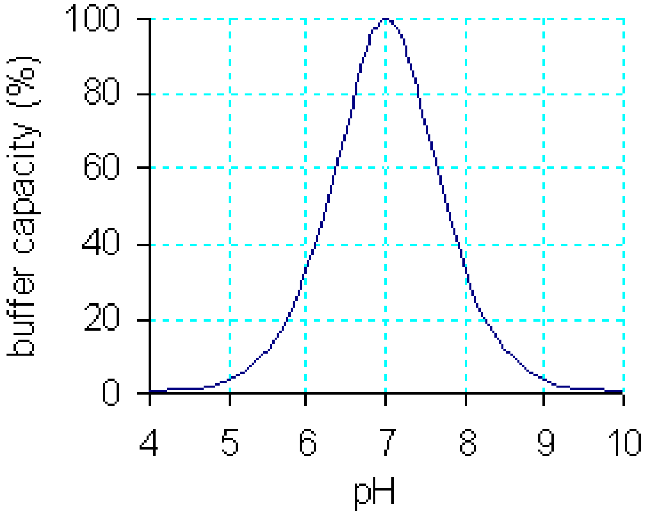
Theory: Buffer mechanisms prevent savannas from transition to grassland or woodland.

These mechanisms may be different in different savannas

(Jeltsch, Weber & Grimm 2000)

To be because of not not to be

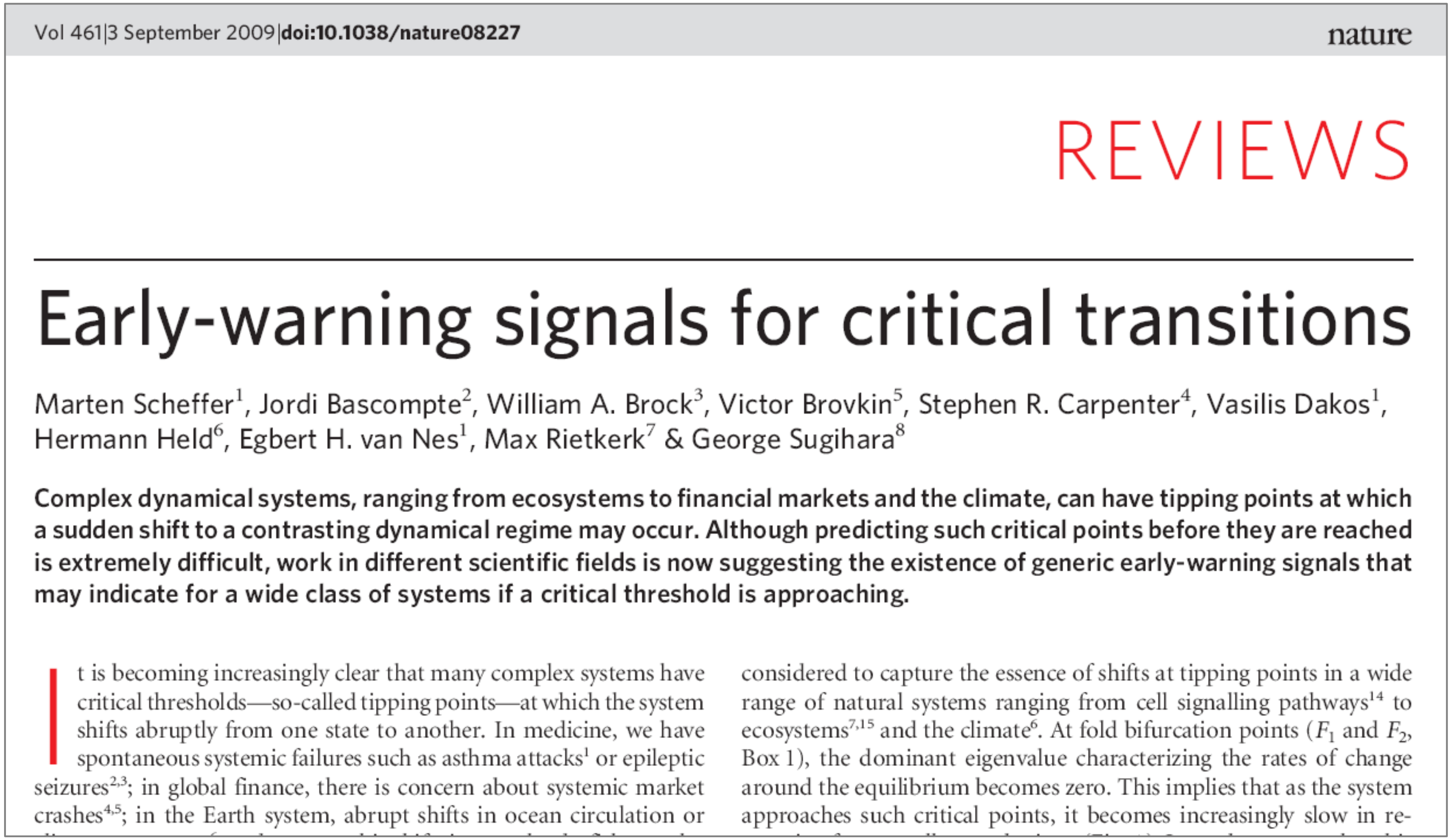
BUFFER CAPACITY



Buffer solution: has the property that the pH of the solution changes very little when a small amount of acid or base is added to it.

Buffer capacity is a quantitative measure of the resistance of a buffer solution to pH change on addition of hydroxide ions.

REGIME SHIFTS: INDICATORS?



Vol 461|3 September 2009|**doi:10.1038/nature08227**

nature

REVIEWS

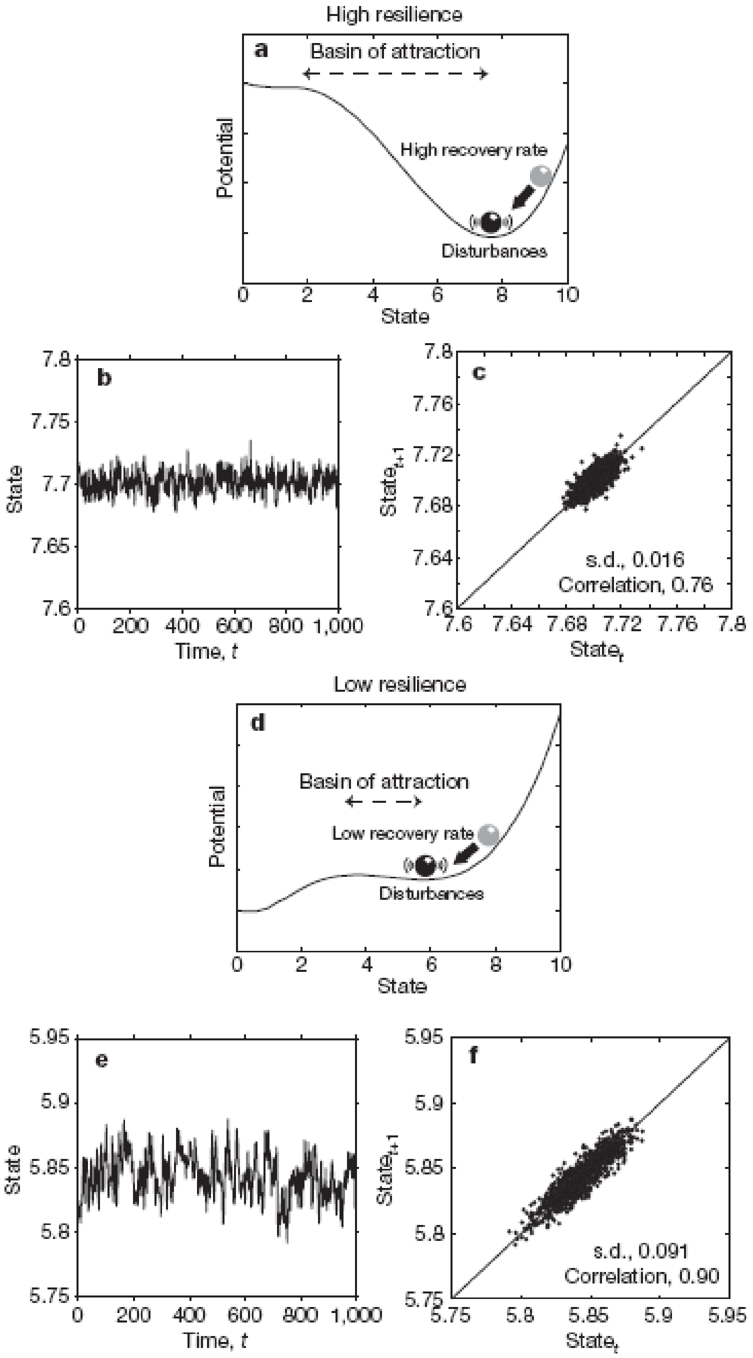
Early-warning signals for critical transitions

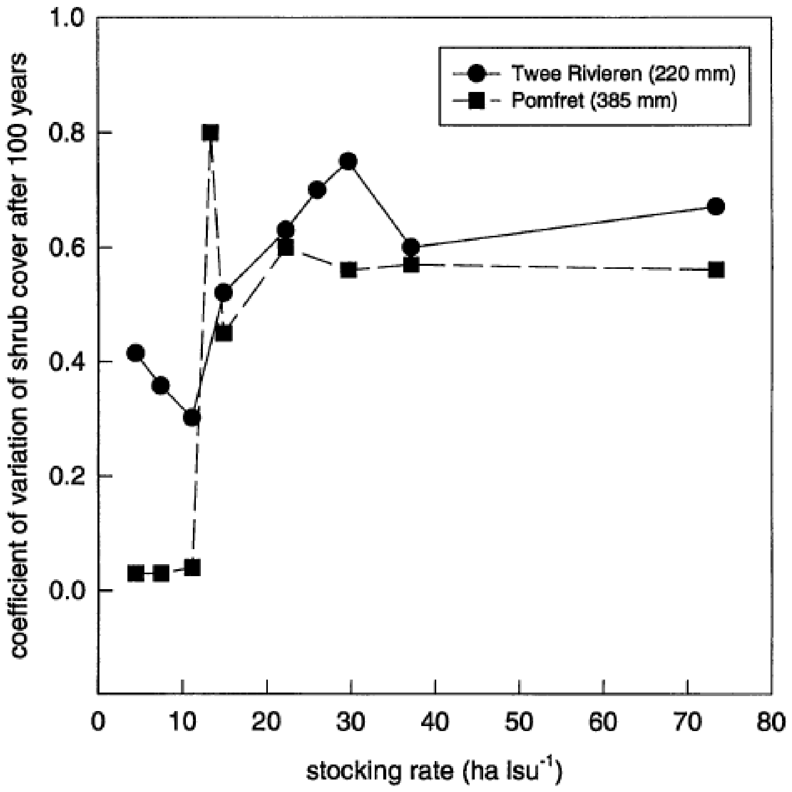
Marten Scheffer[1], Jordi Bascompte[2], William A. Brock[3], Victor Brovkin[5], Stephen R. Carpenter[4], Vasilis Dakos[1], Hermann Held[6], Egbert H. van Nes[1], Max Rietkerk[7] & George Sugihara[8]

Complex dynamical systems, ranging from ecosystems to financial markets and the climate, can have tipping points at which a sudden shift to a contrasting dynamical regime may occur. Although predicting such critical points before they are reached is extremely difficult, work in different scientific fields is now suggesting the existence of generic early-warning signals that may indicate for a wide class of systems if a critical threshold is approaching.

It is becoming increasingly clear that many complex systems have critical thresholds—so-called tipping points—at which the system shifts abruptly from one state to another. In medicine, we have spontaneous systemic failures such as asthma attacks[1] or epileptic seizures[2,3]; in global finance, there is concern about systemic market crashes[4,5]; in the Earth system, abrupt shifts in ocean circulation or

considered to capture the essence of shifts at tipping points in a wide range of natural systems ranging from cell signalling pathways[14] to ecosystems[7,15] and the climate[6]. At fold bifurcation points (F_1 and F_2, Box 1), the dominant eigenvalue characterizing the rates of change around the equilibrium becomes zero. This implies that as the system approaches such critical points, it becomes increasingly slow in re-





(Jeltsch et al.1997)

TO TELL YOUR FRIENDS ABOUT RESILIENCE

- **Ecologists like „stability“**
- **Engineers‘ vs. ecological resilience**
- **„Buzz“ Holling and the Resilience Alliance**
- **Regime shifts and alternative states**
- **Adaptive cycle and panarchy (no, don‘t tell this)**
- **Organismic notion of ecosystems**
- **Need more mechanistic, individualistic approaches**
- **Buffer mechanisms and capacity**
- **Indicators of regime shifts (early warning signals)**