Behaviour of self-organised vegetation patterns in dryland ecosystems

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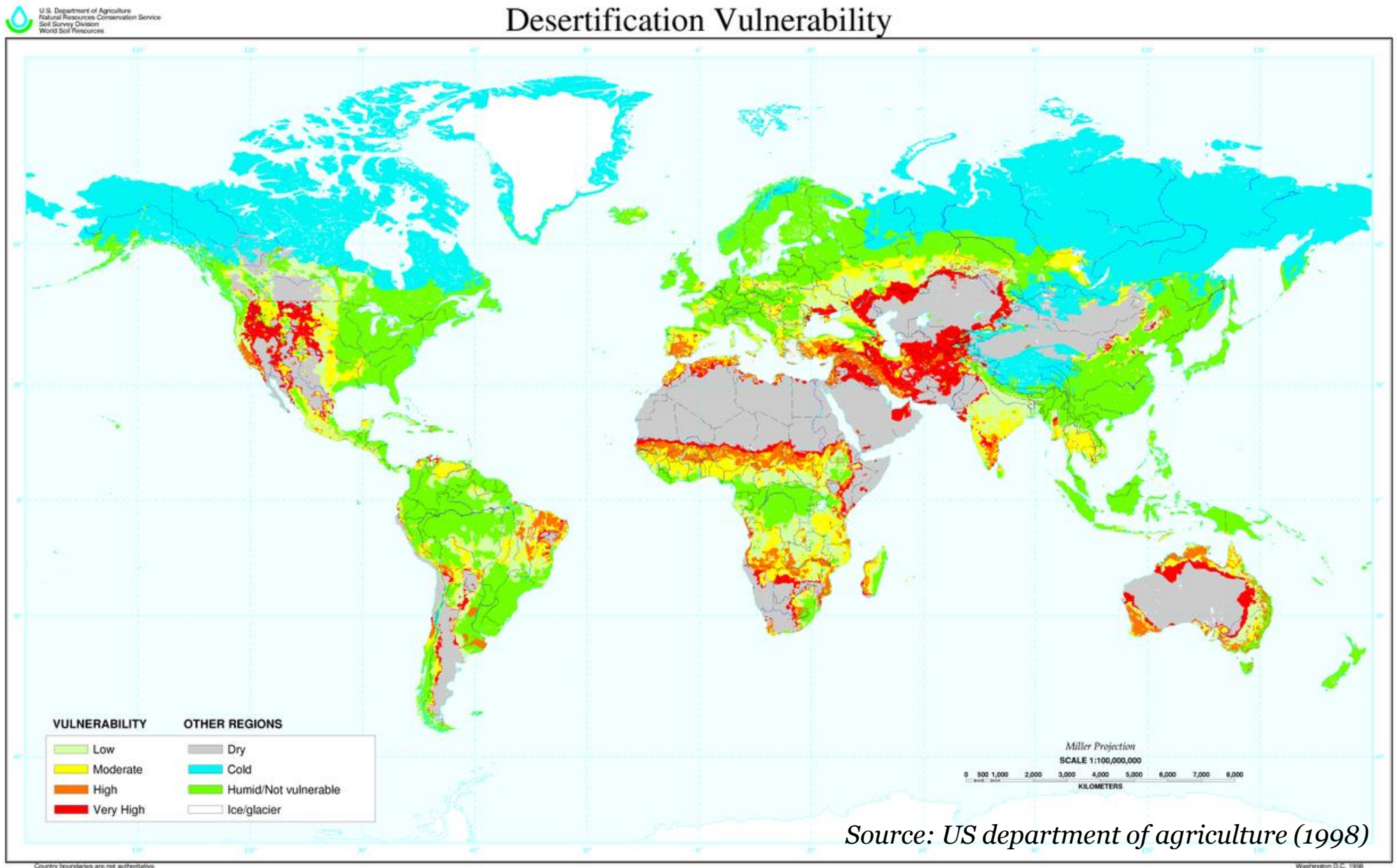
The desertification process

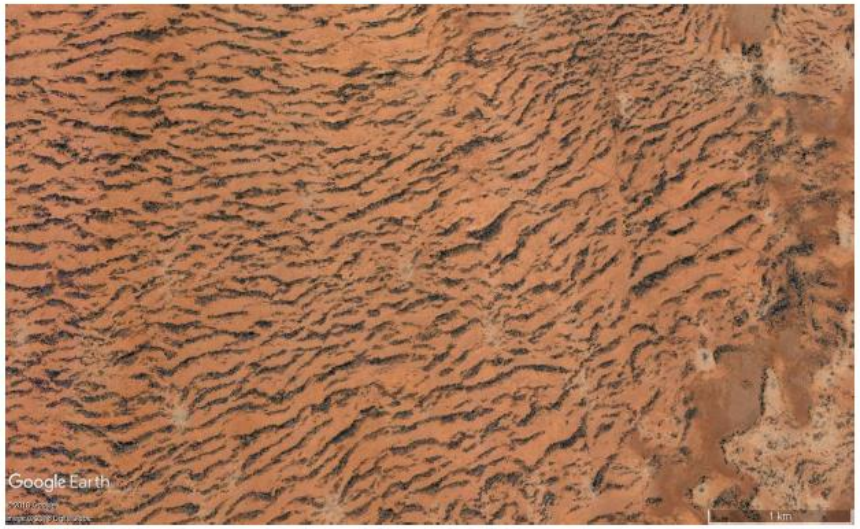
?

Desertification vulnerability

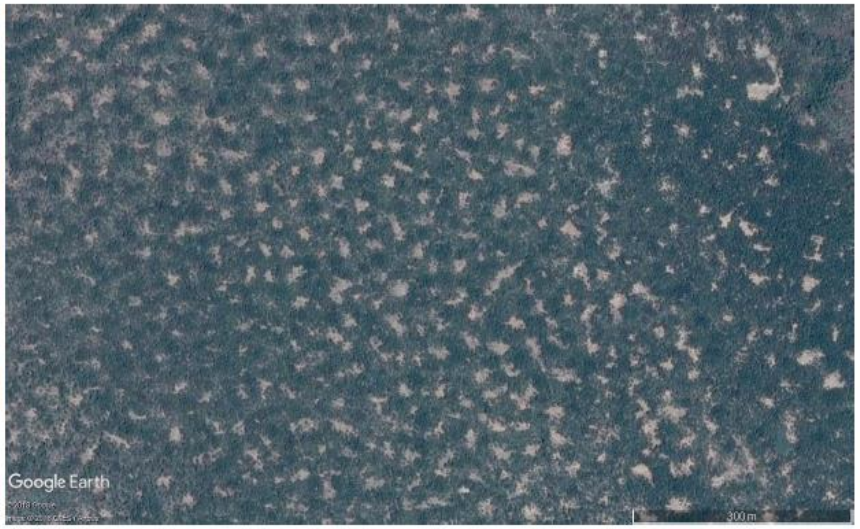


Source: US department of agriculture (1998)

Desertification – emergent patterns

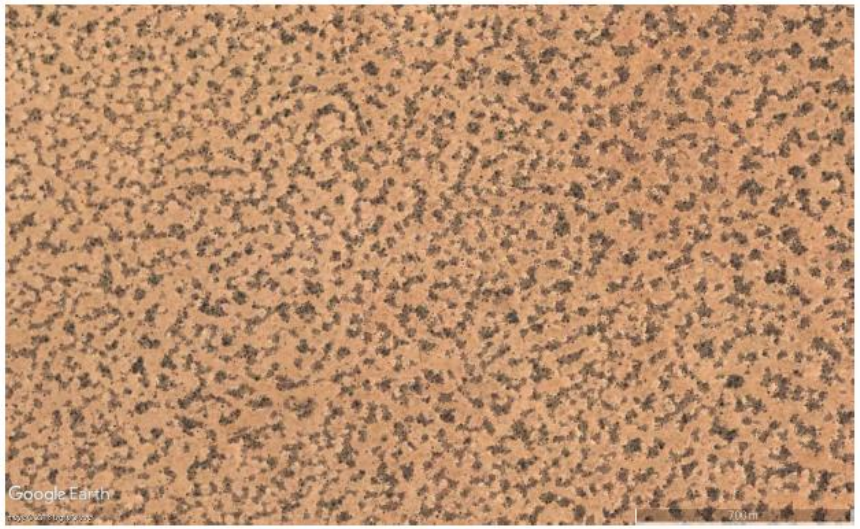


(a) Bands in Somalia



(b) Gaps in Niger

(c) Spots in Zambia



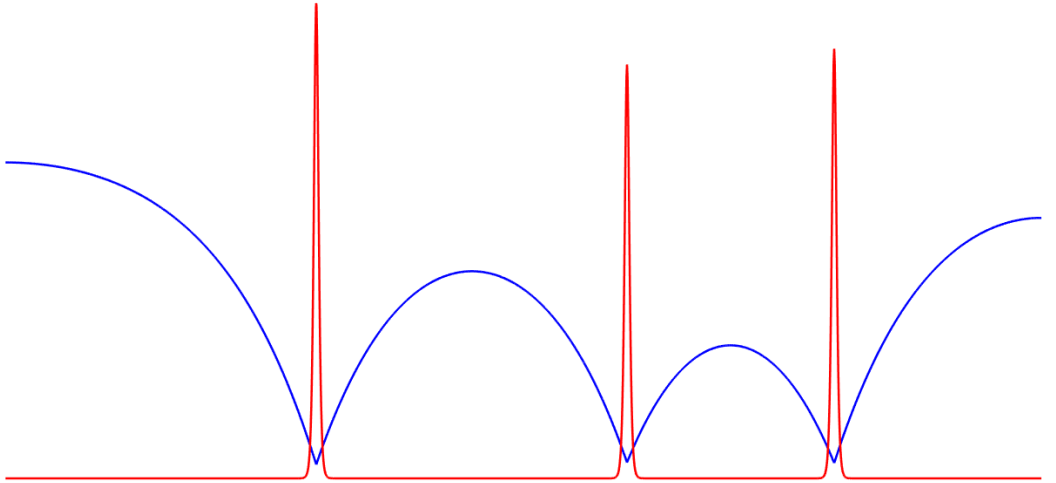
(d) Maze in Sudan

Mathematical treatment

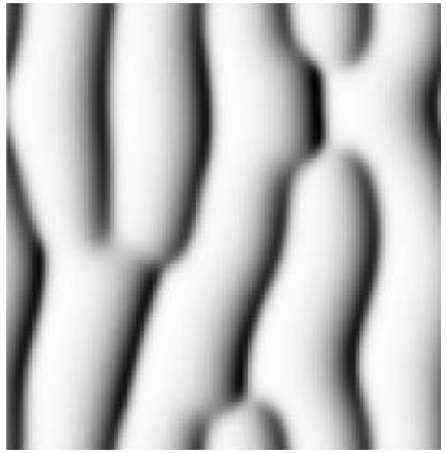
Translating ecology to mathematics:

Vegetation patterns ↔ localized structures

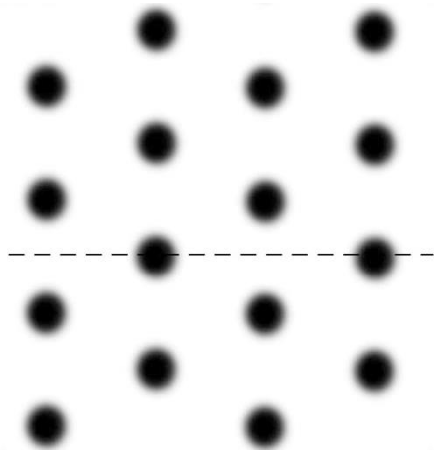
Seperation of scales ↔ small parameter



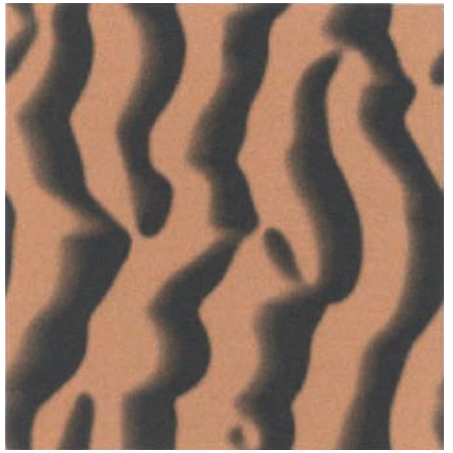
→Reaction-diffusion models model dryland ecosystems



Source: Klausmeier, 1999



Source: Gilad et al, 2004



Source: Rietkerk et al, 2002

Visual similarities with observations

A simple ecosystem model

Extended-Klausmeier model

$$w_t = w_{xx} + (h_x w)_x - w + a - wv^2$$
$$v_t = D^2 v_{xx} - mv + wv^2$$

w : water

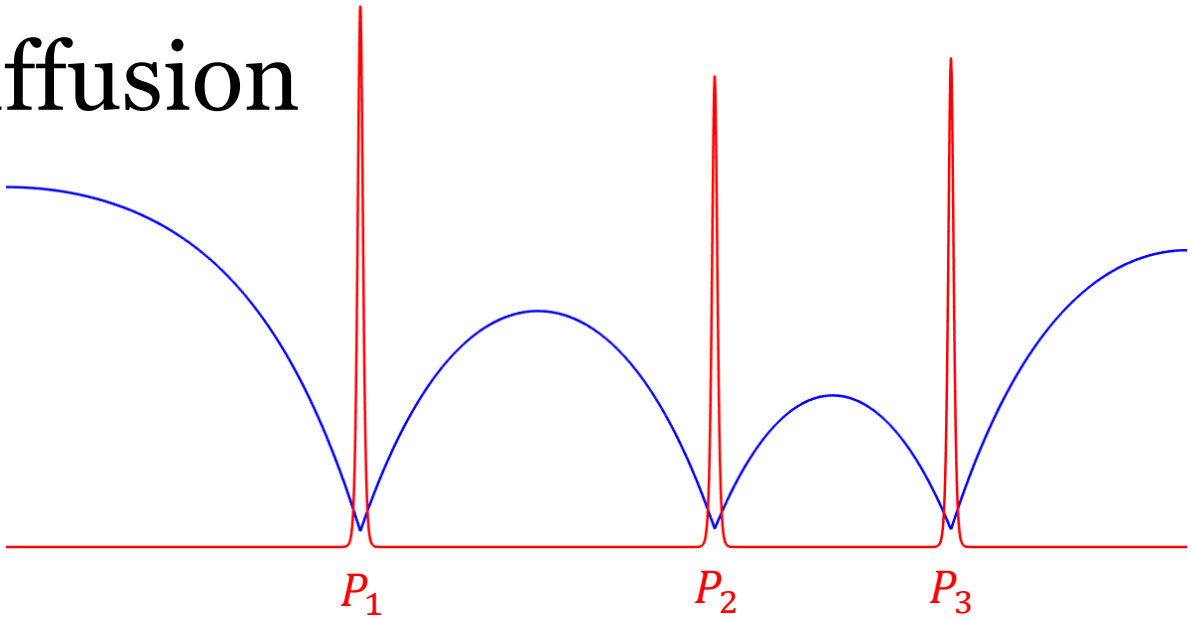
v : vegetation

h : height

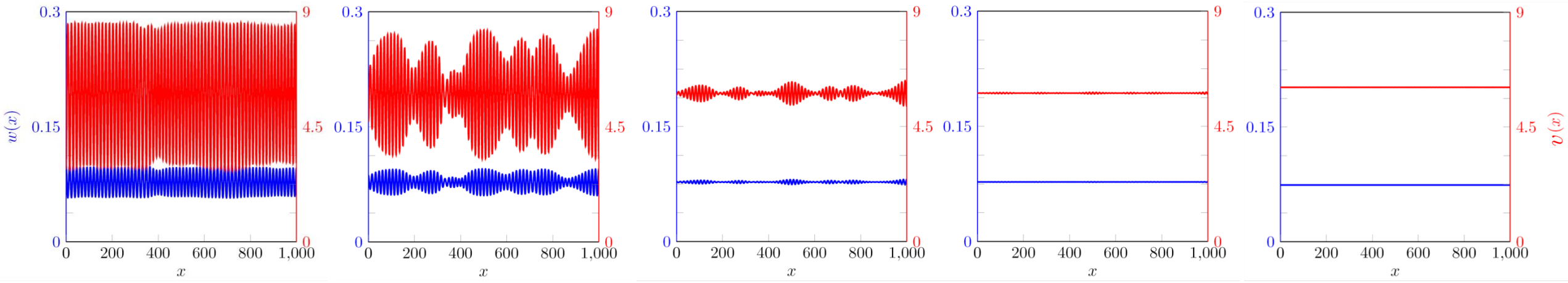
D : ratio of diffusion

a : rainfall

m : mortality



The origin of patterns



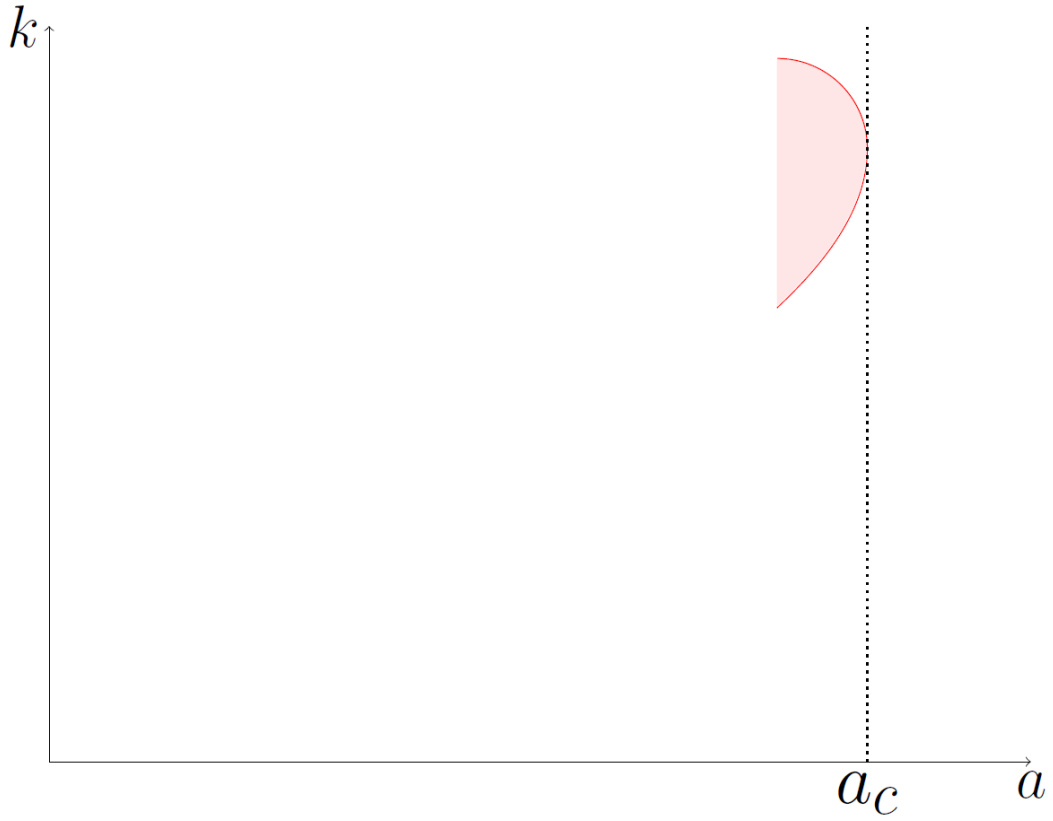
Low rainfall

Critical rainfall
Onset of patterns

High rainfall

Turing Patterns [Turing, 1952]
Found in most reaction-diffusion equations

Wavenumbers of Turing patterns

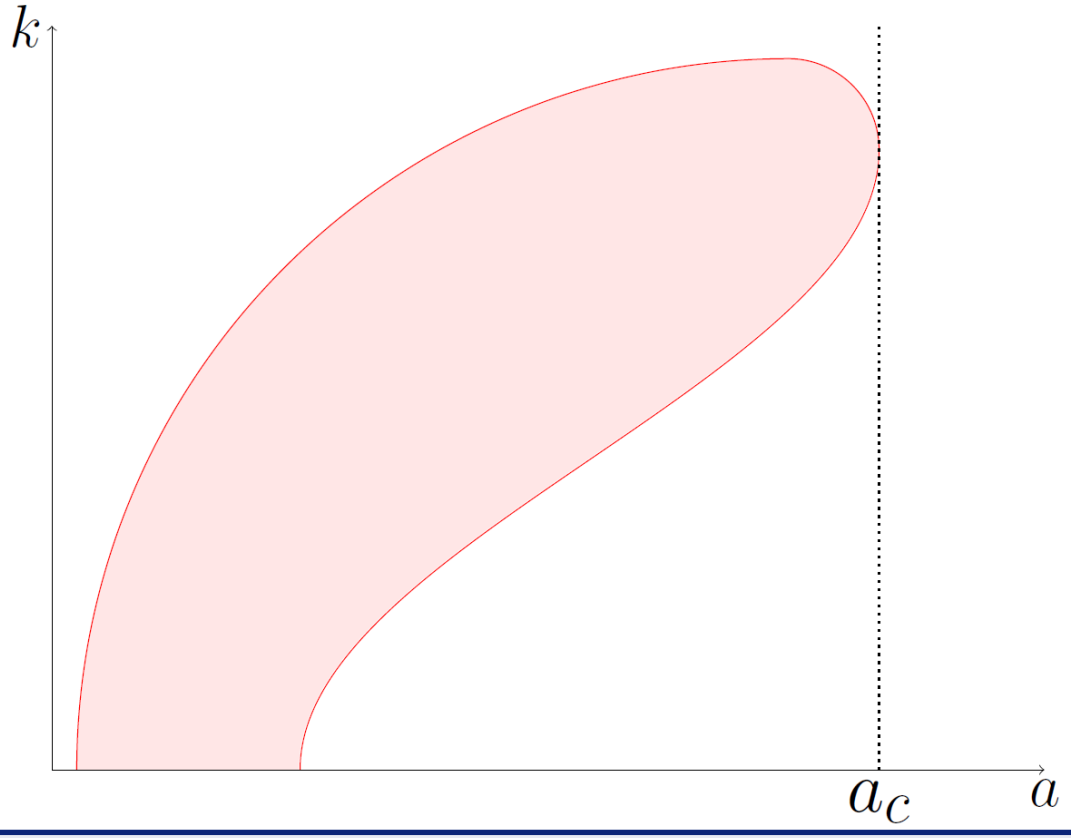


Eckhaus/Benjamin-Feir-Newell instability criterion

[Eckhaus, 1965; Benjamin & Feir, 1967; Newell, 1974]

Determination of the stable Turing patterns

Busse balloon



Busse balloon [Busse, 1978]

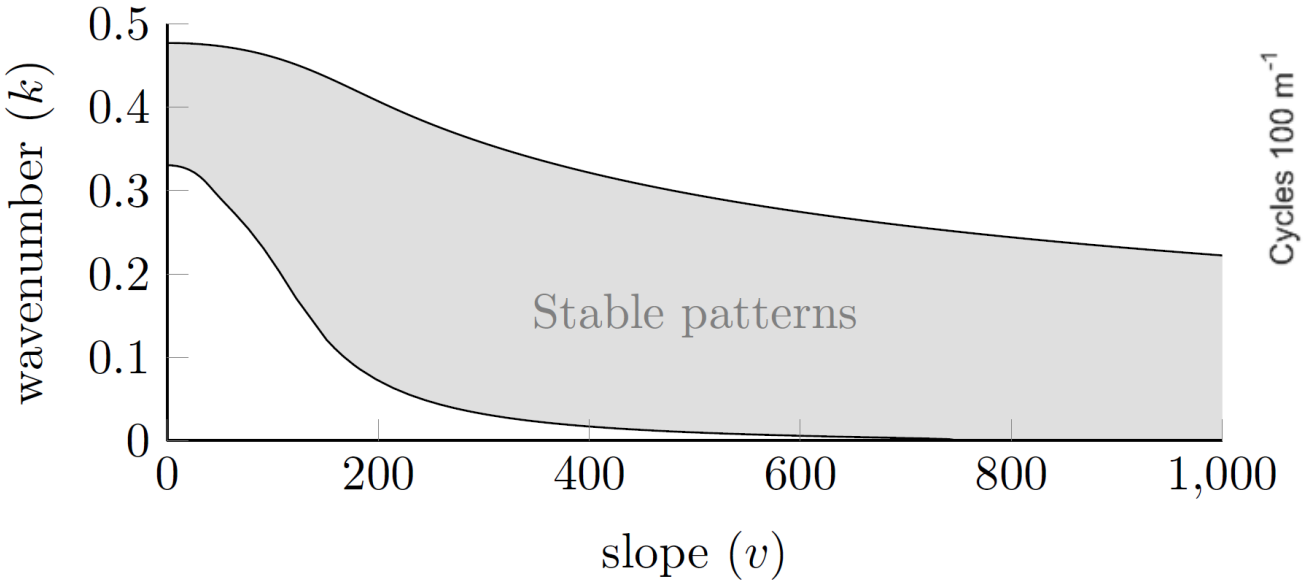
A *Busse balloon* is a model-dependent shape in (*parameter*, *wavenumber*)-space that indicates all combinations of parameter and wavenumber that represent stable solutions of the model

Comparisons with reality – study sites

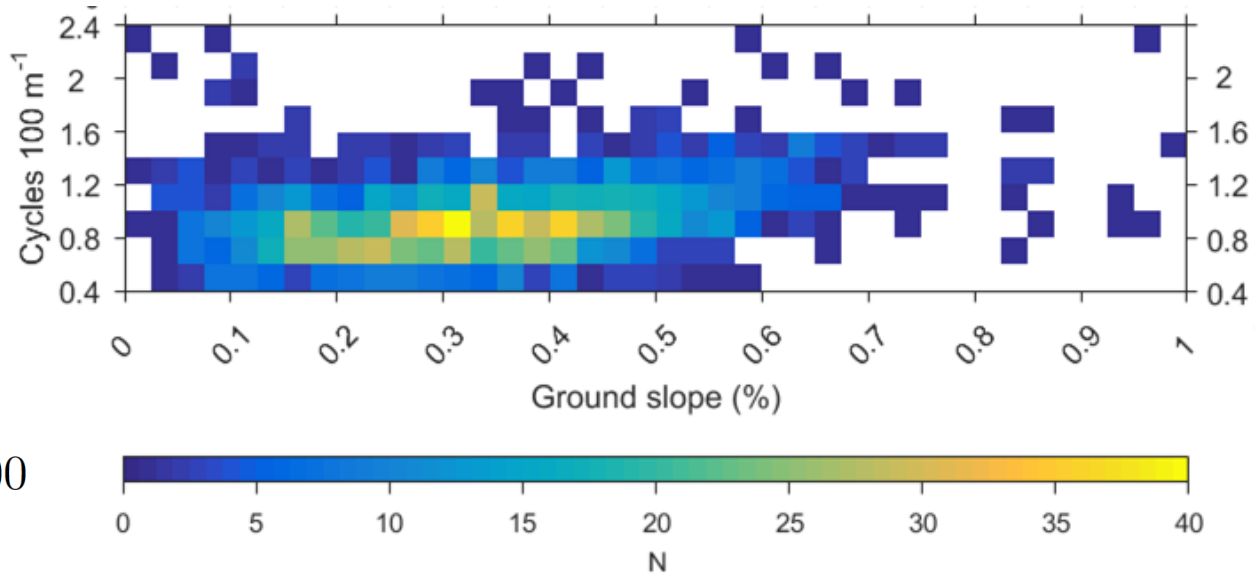
2 sites in Horn of Africa

- Environmental conditions constant within site
- Topography main environmental variation

Busse balloon in dryland ecosystems



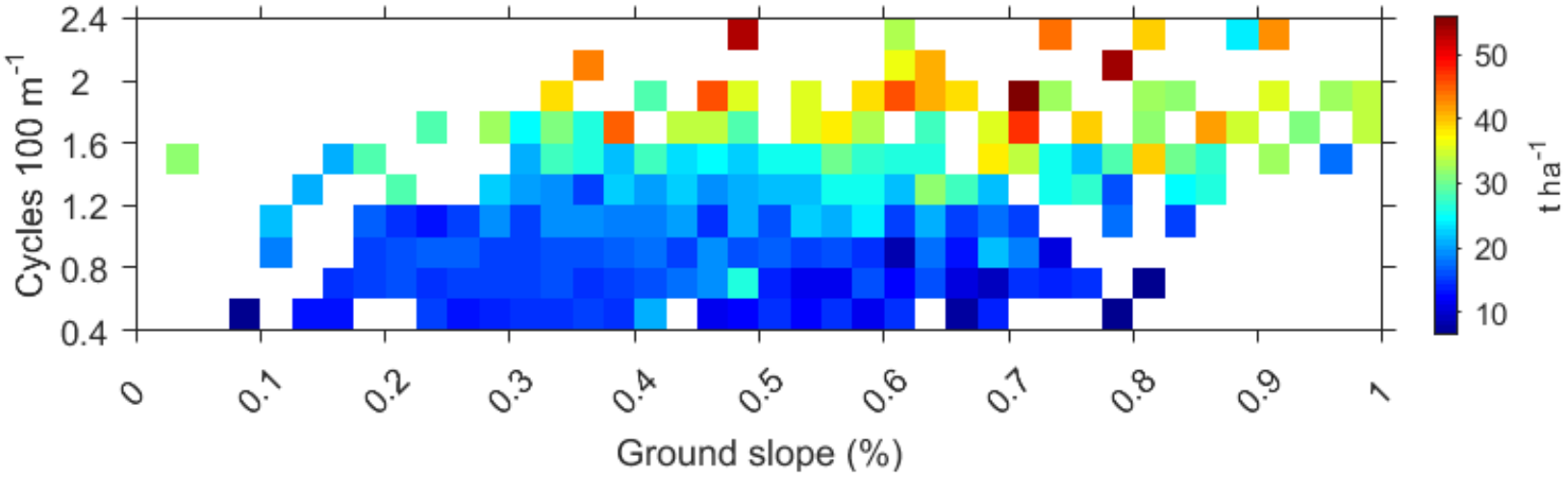
extended-Klausmeier model



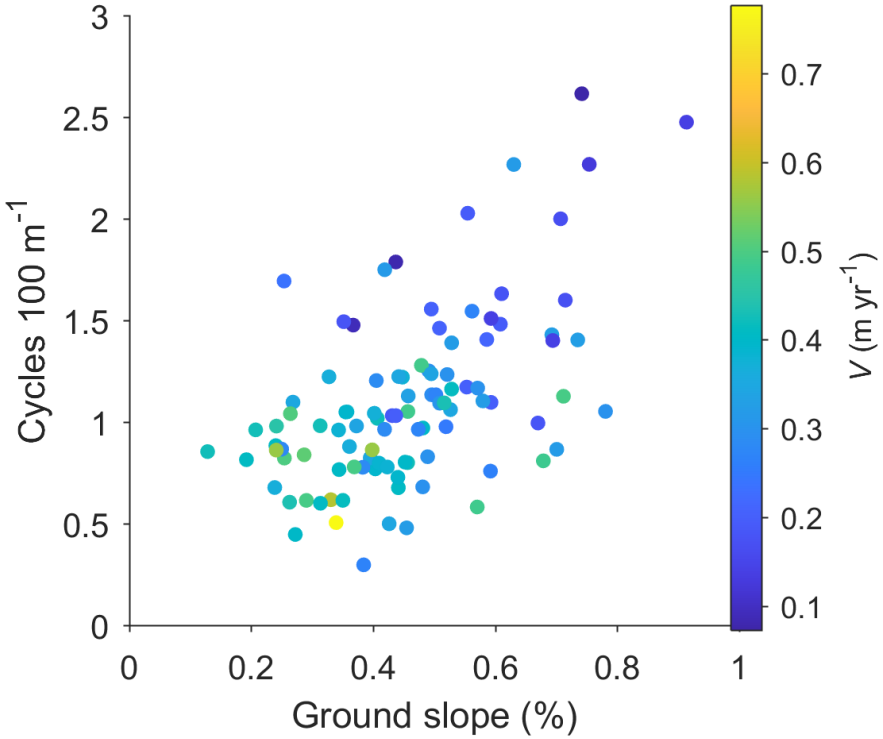
Somaliland data

Wide wavenumber spread in both

Wavenumber influences state variables



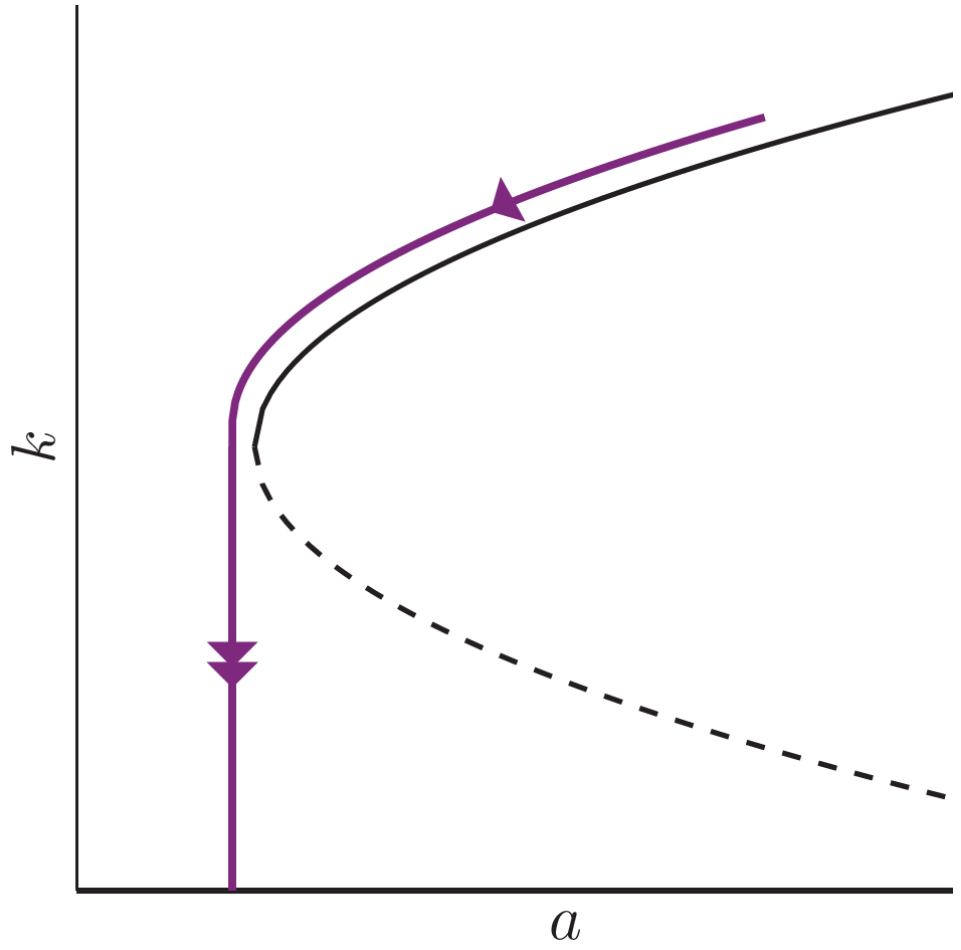
Biomass data



Migration speed data

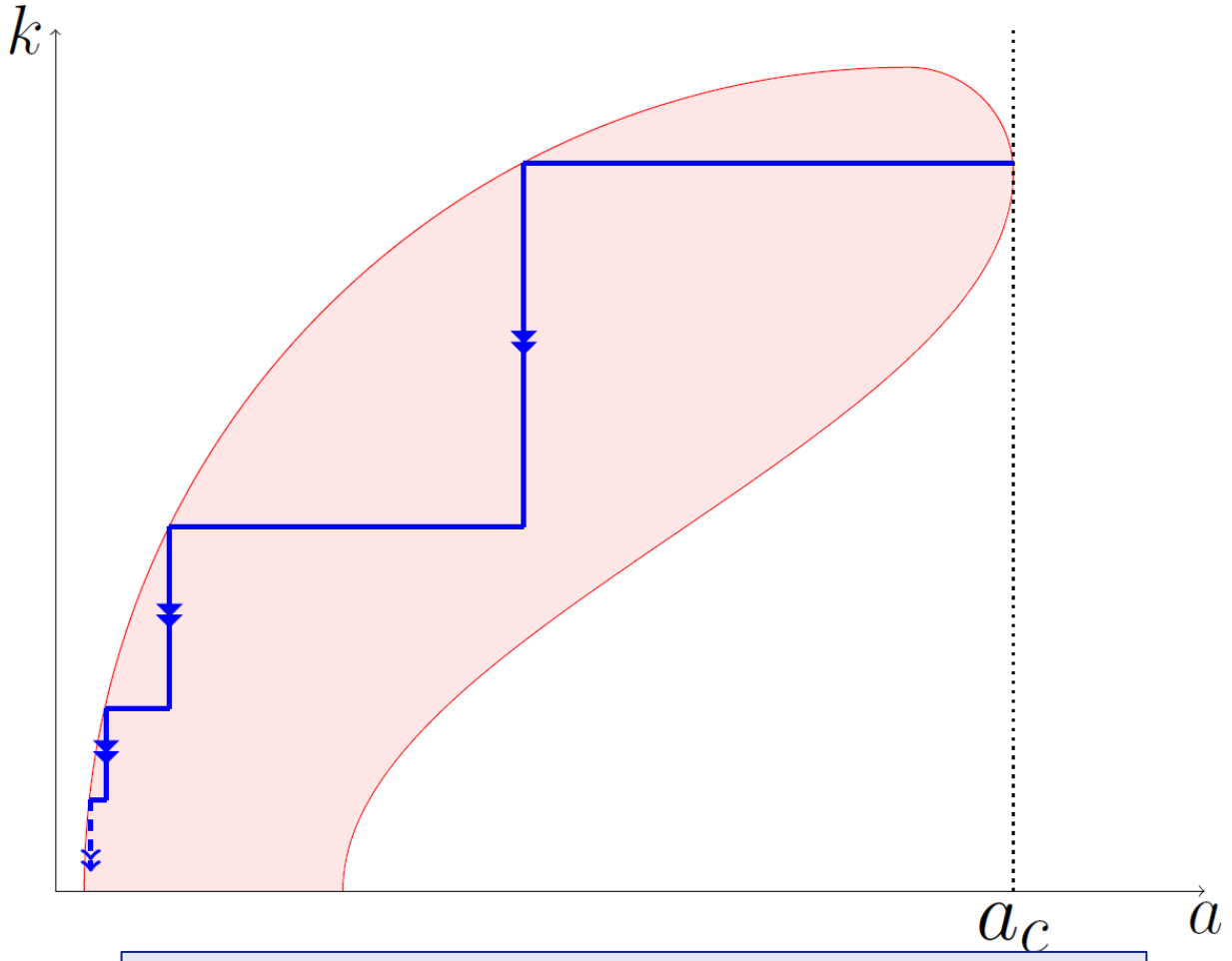
Biomass and migration speed change with wavenumber

Enhanced resilience?



Classical view – fold

e.g. Holling, 1973

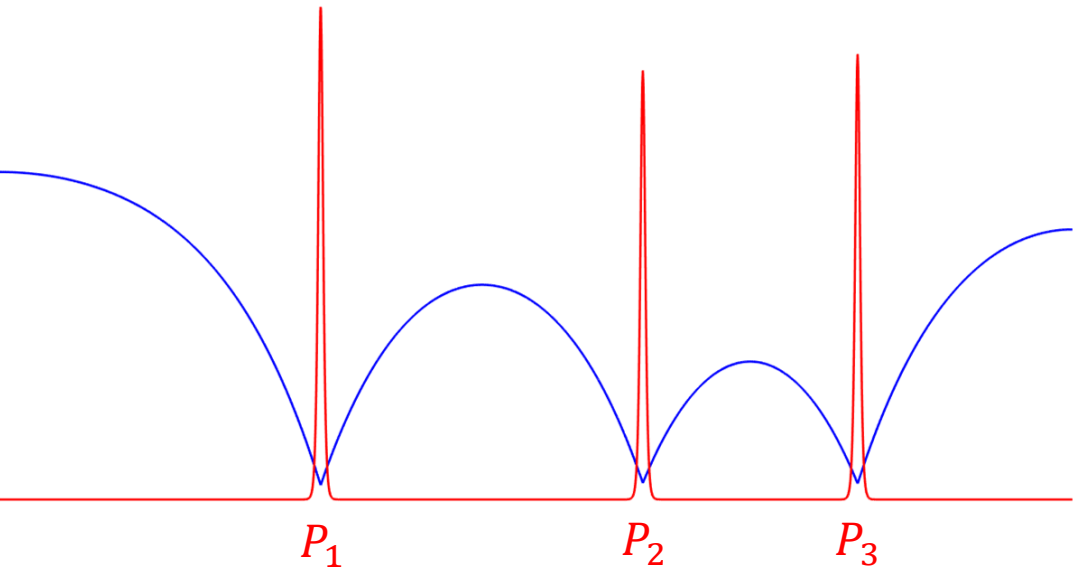


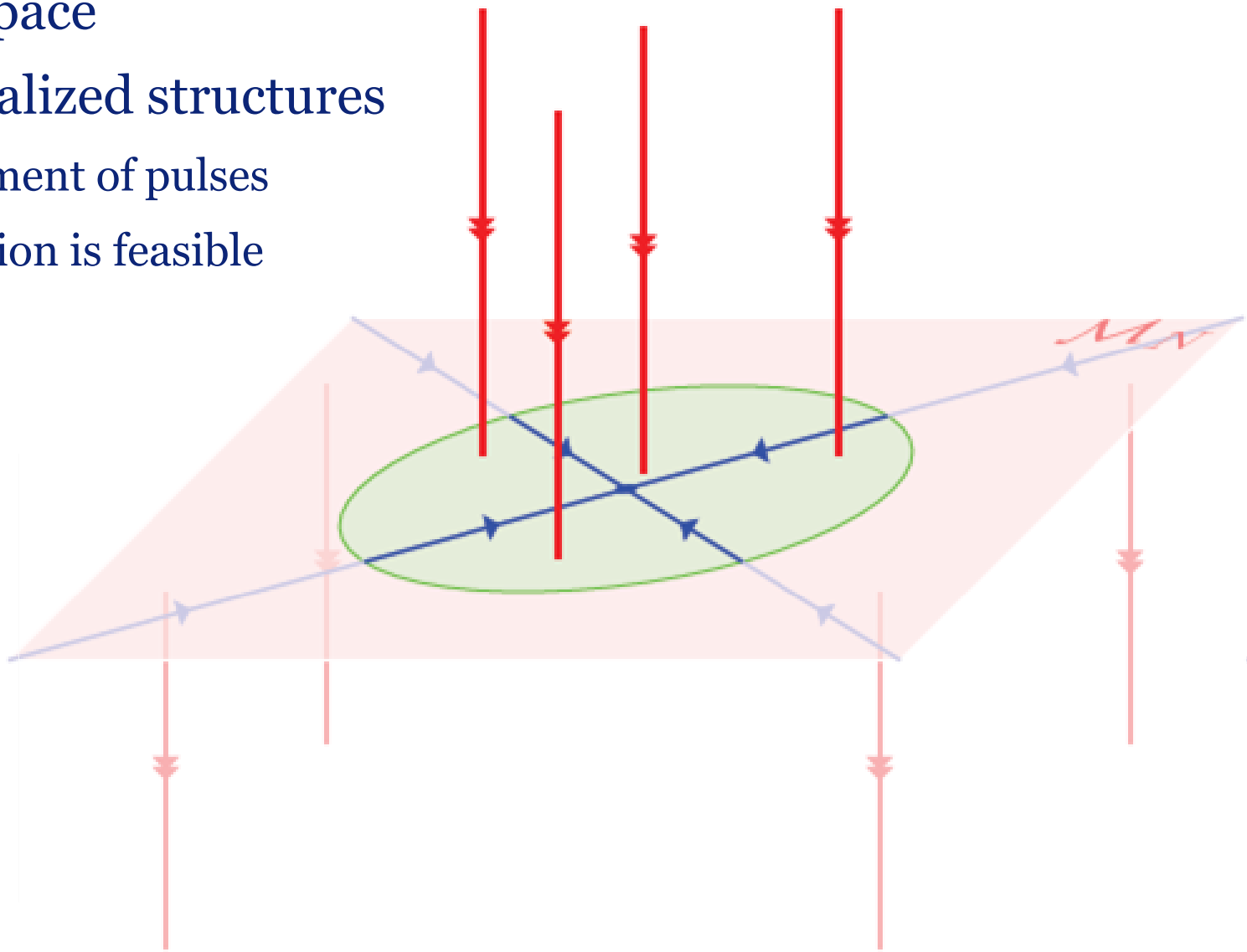
Wavenumber adaptation

Siteur et al, 2014

Understanding pulses in the model

- PDE: infinite-dimensional state space
- Reduction possible because of localized structures
  1. Pulse-location ODE: describe movement of pulses
  2. Stability criterium: test if configuration is feasible

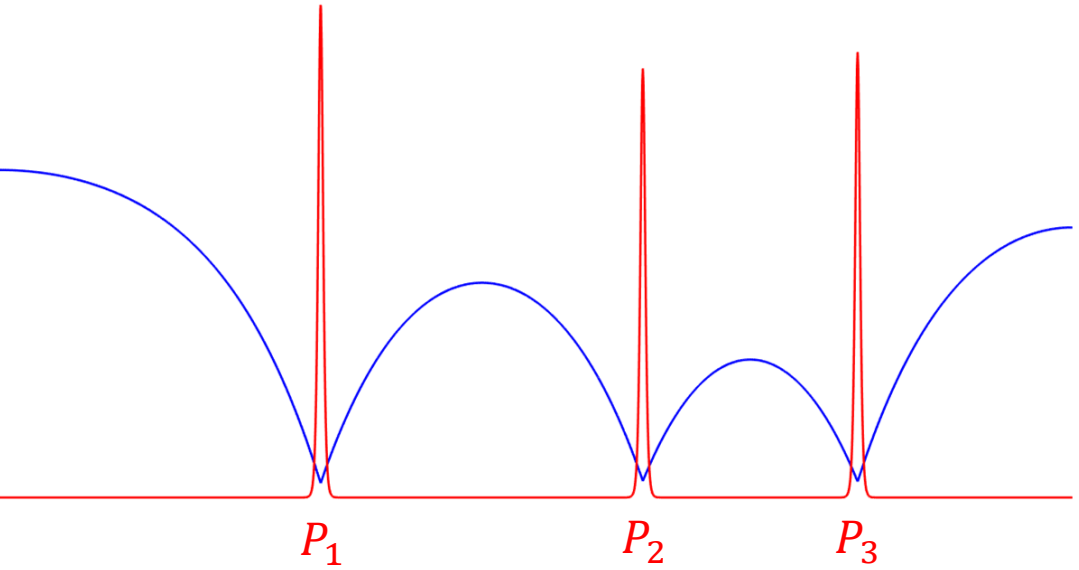


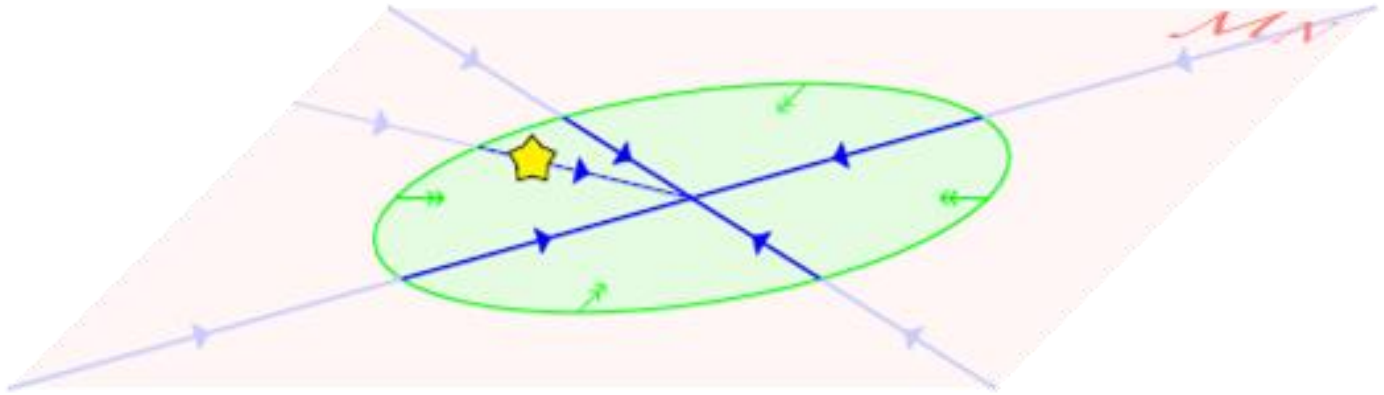


Pulse-location ODE

$$\frac{dP_j}{dt} = \frac{Da^2}{m\sqrt{m}}\left[w_x(P_j^+)^2 - w_x(P_j^-)^2\right]$$

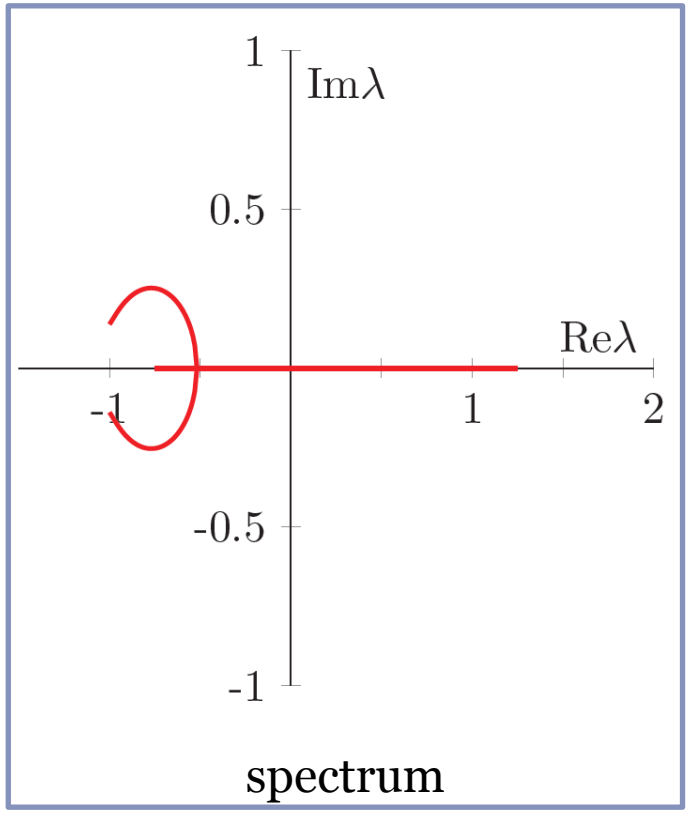
Water availability dictates pulse movement



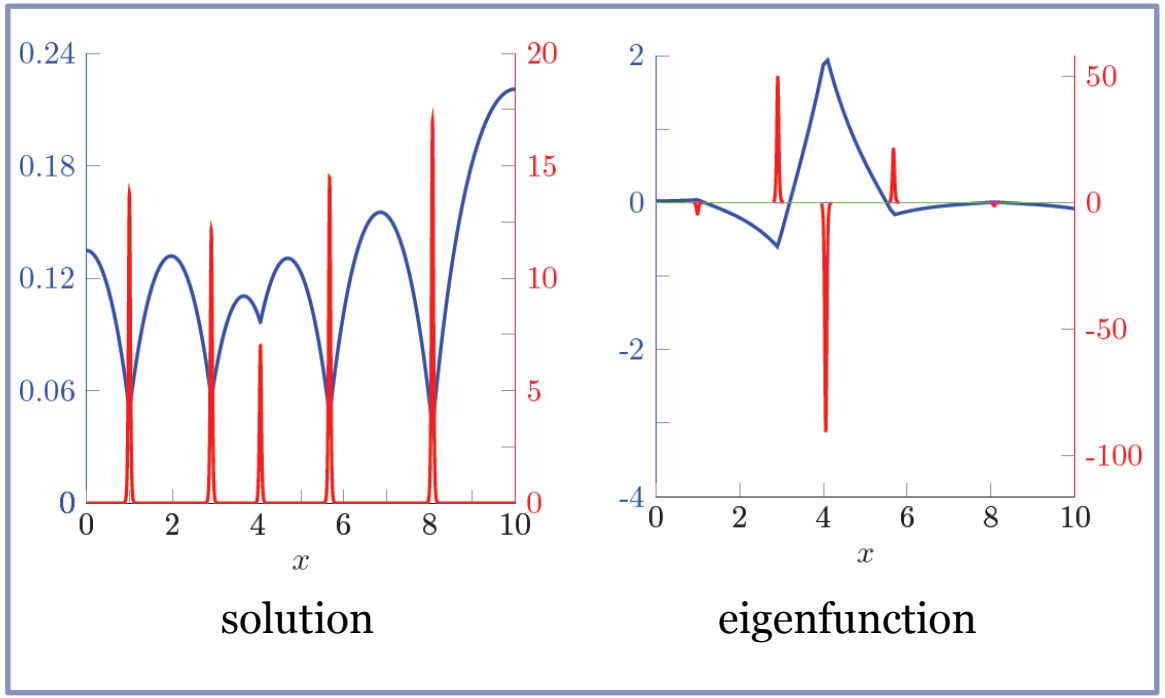


Stability criterium (1)

- Freeze solution in time
- Study (quasi-steady) eigenvalues & eigenfunctions



spectrum



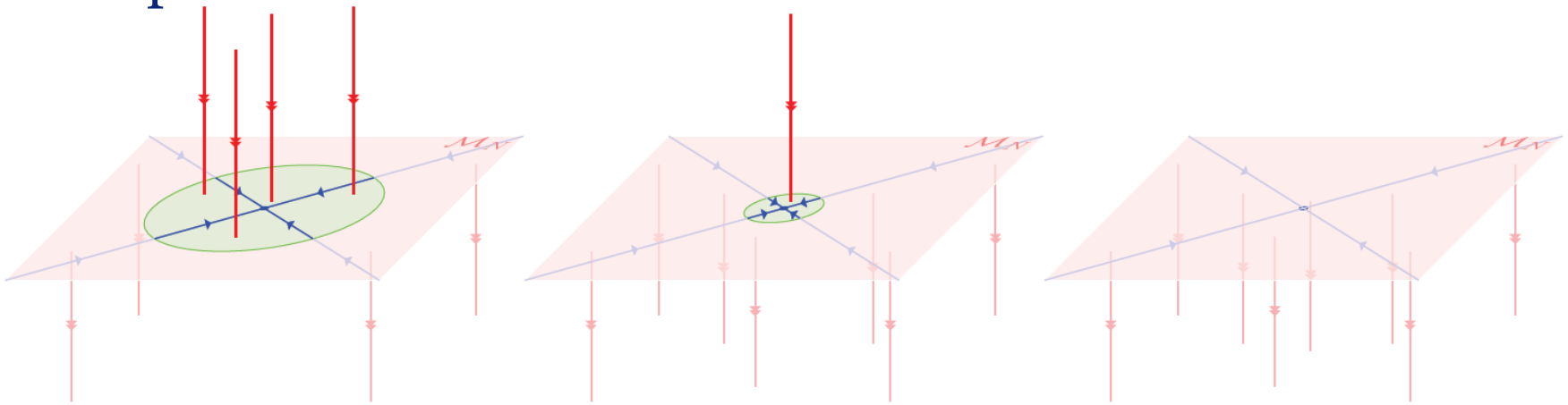
solution eigenfunction

Nonlinear prediction based on linear analysis

Stability criterium (2)

Enough resources to sustain all vegetation patches?

Depends on **amount of rainfall** and **distance between patches**



high rainfall

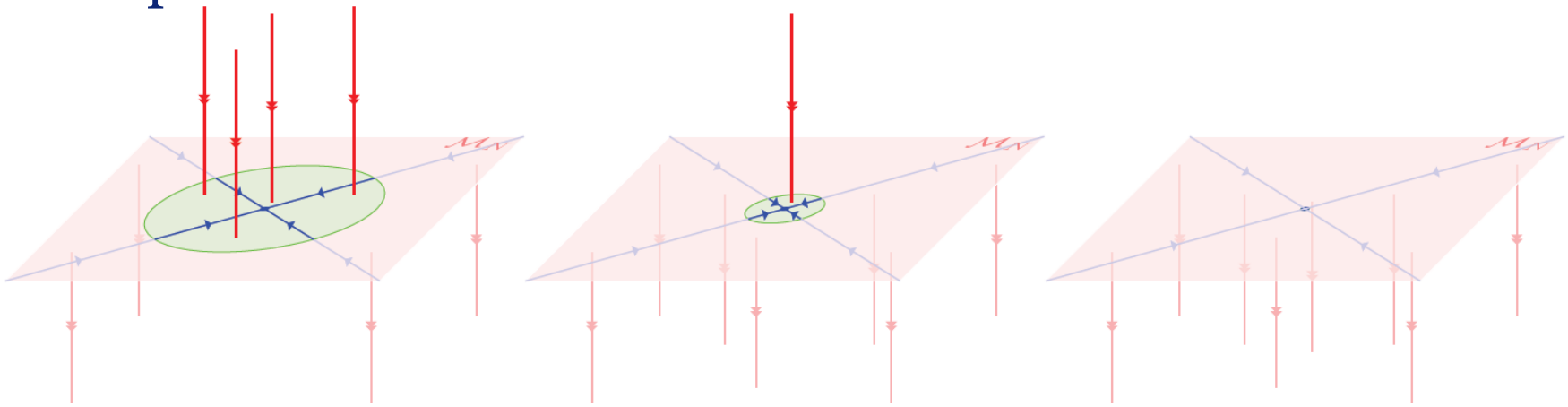
medium rainfall

low rainfall

Stability criterium (2)

Enough resources to sustain all vegetation patches?

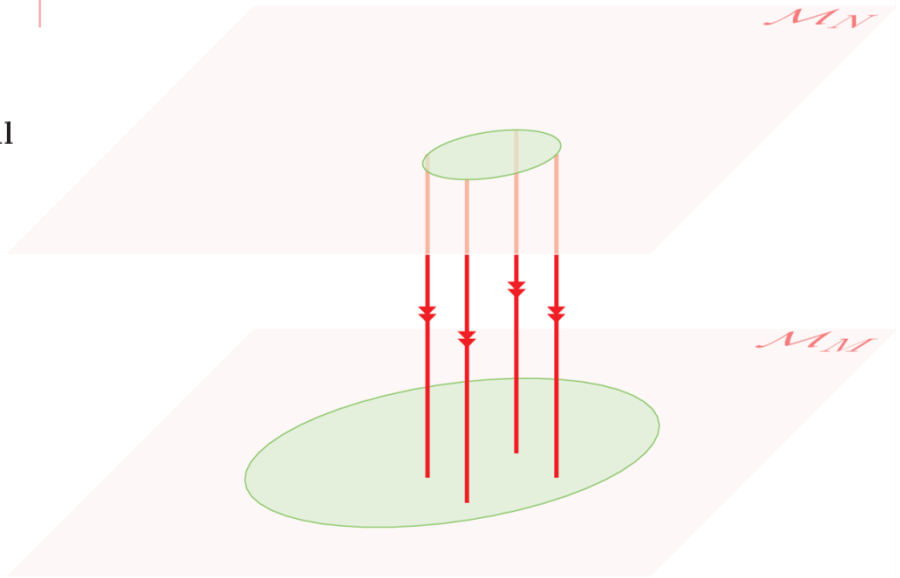
Depends on **amount of rainfall** and **distance between patches**



high rainfall medium rainfall low rainfall

What happens when outside feasible region?

irregular configuration:	**One** patch disappears (least amount of biomass)
regular configuration:	**Half** of the patches disappears (wavelength doubling)

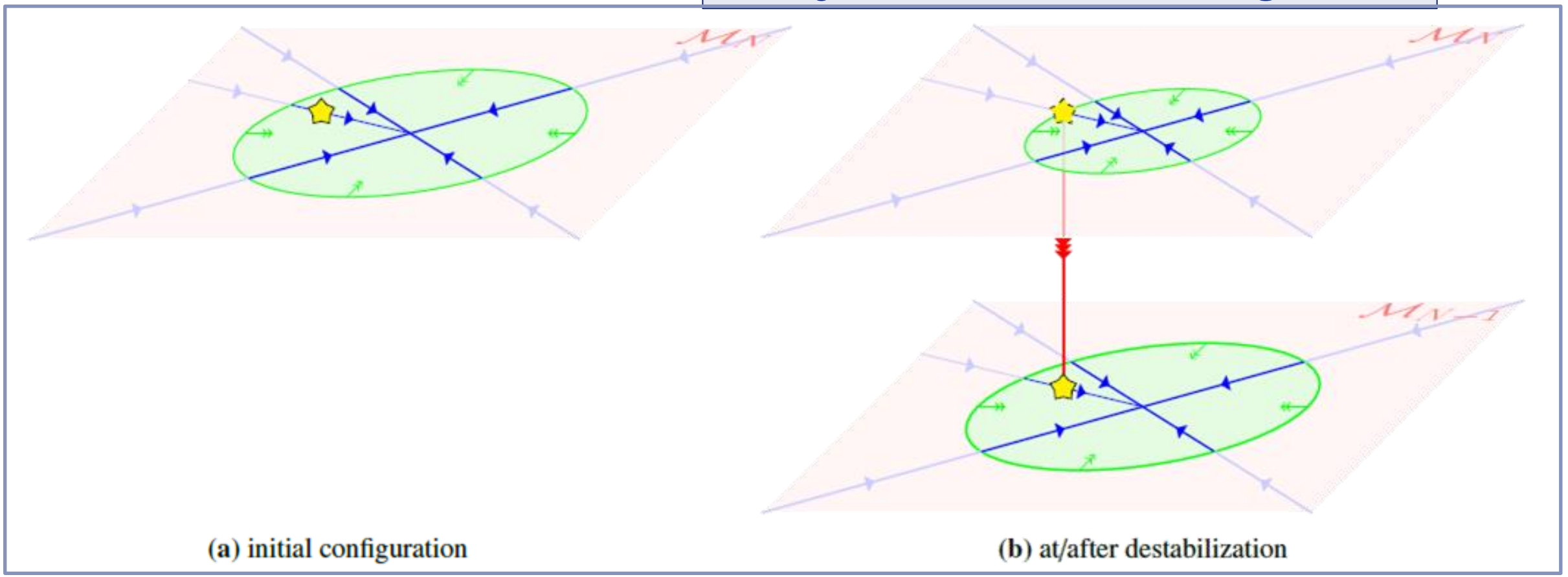


Pulses during climate change (1)

Competition of two effects:

1. Pulse rearrangement
2. Shrinking of feasible region

fast climate change

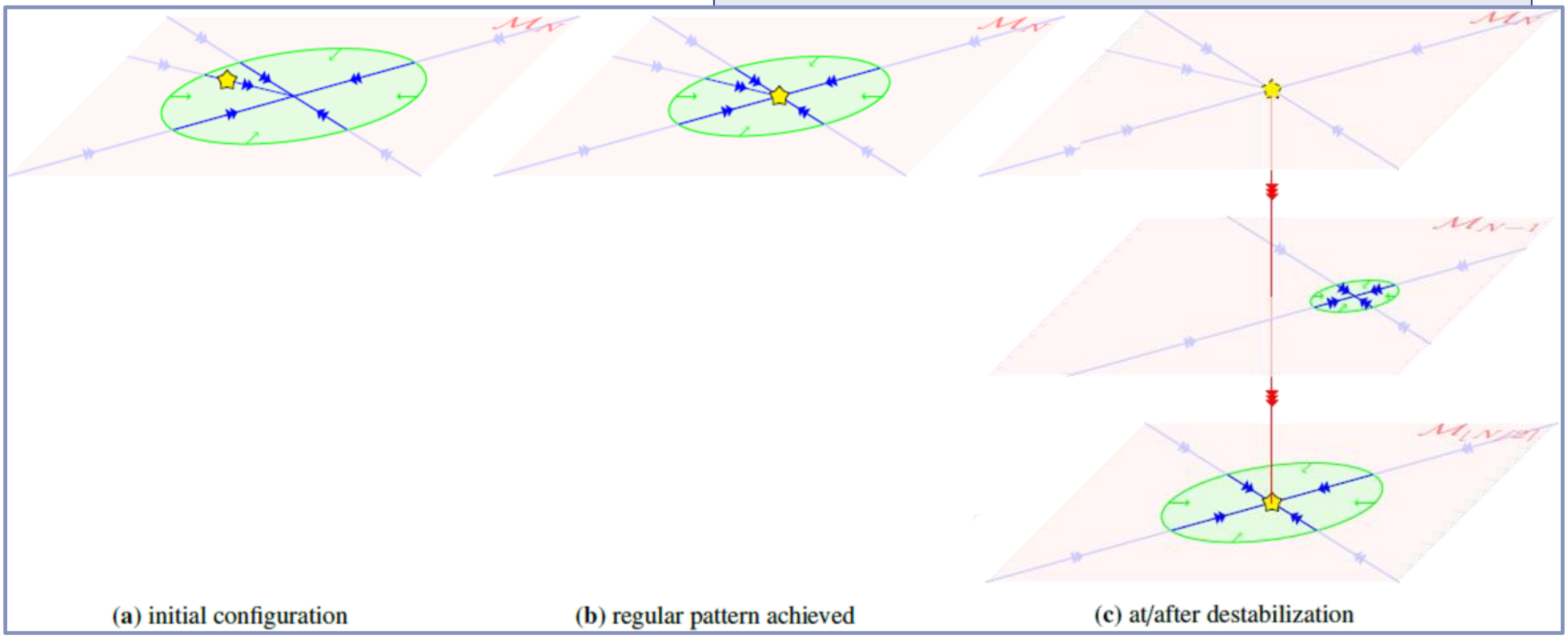


Pulses during climate change (2)

Competition of two effects:

1. Pulse rearrangement
2. Shrinking of feasible region

slow climate change

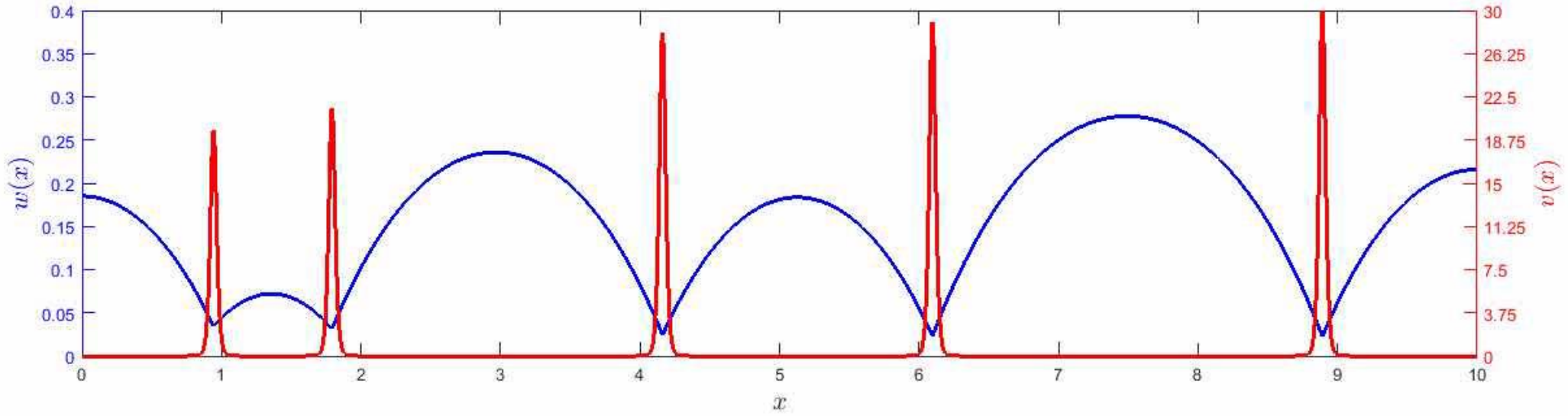


(a) initial configuration (b) regular pattern achieved (c) at/after destabilization

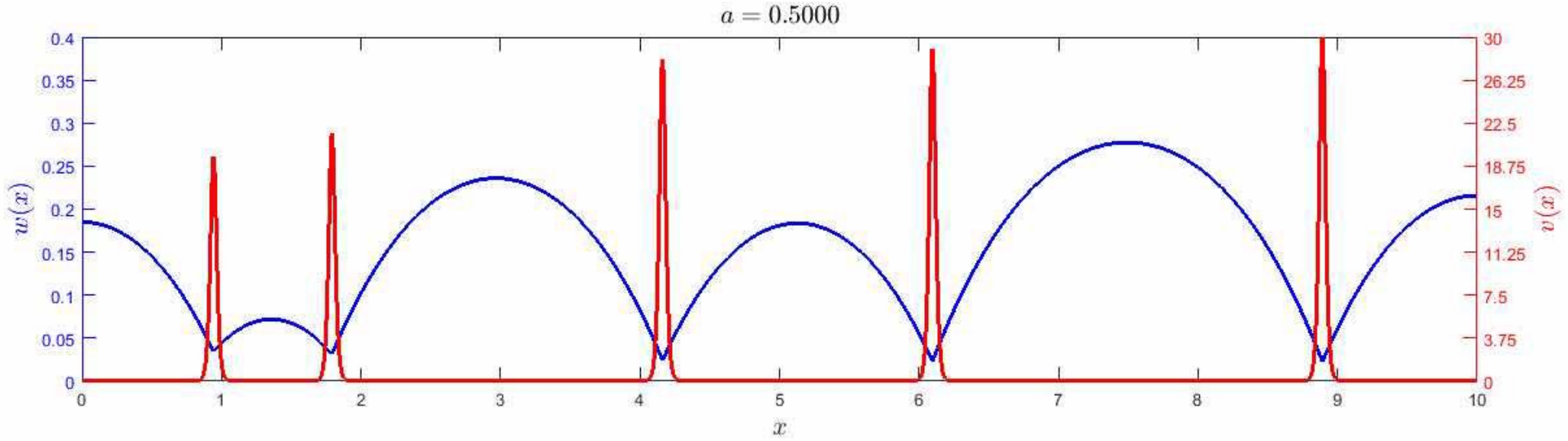
Pulses during climate change (3)

Rate of climate change

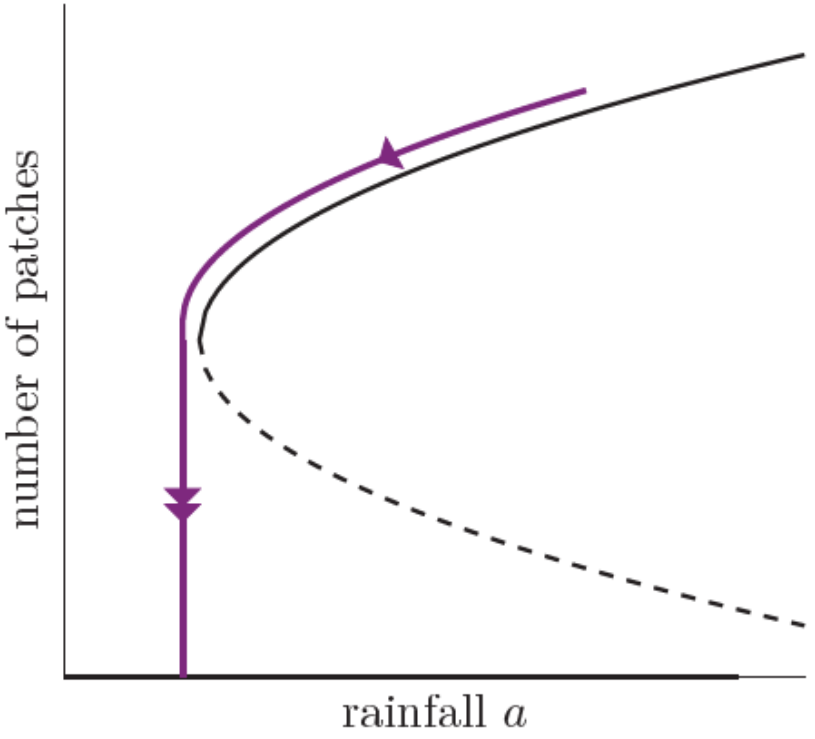
FAST



SLOW

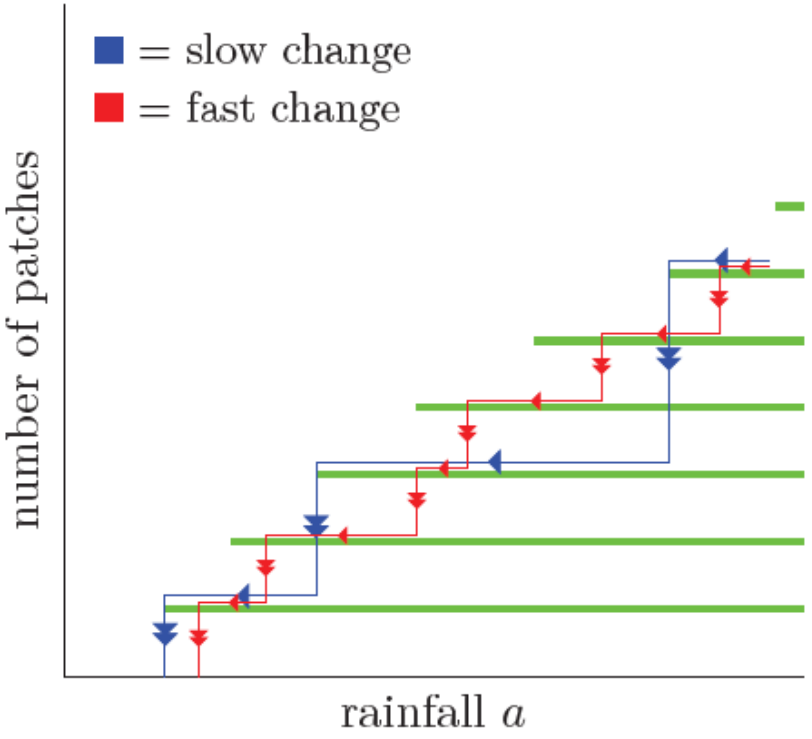


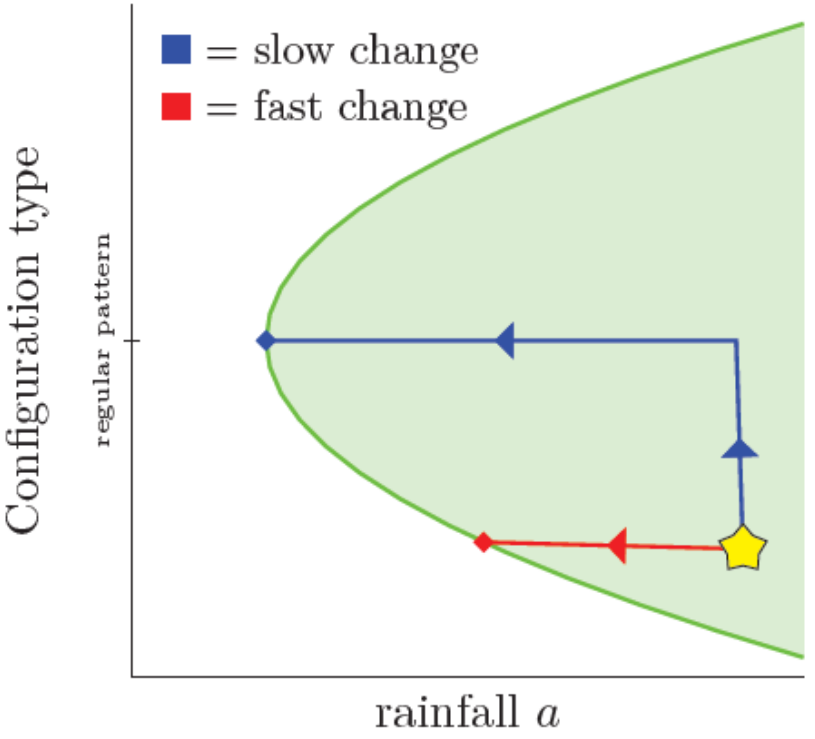
Ecosystem resilience



critical transition

Classical view - fold





smaller pattern transitions

(zoom-in on a line)

Multistable systems

Summary

wide wavenumber spread in model & reality

implies

enhanced resilience via ...

I. Pulse rearrangement
II. Pattern to pattern transitions

PDE to ODE reduction

reveals

importance of rate of climate change

fast: multiple smaller ecosystem shifts

slow: few larger ecosystem shifts

PhD thesis

defence: 27 June 13:45h

LIST OF COAUTHORS ~~~

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