

Behaviour of self-organised vegetation patterns in dryland ecosystems

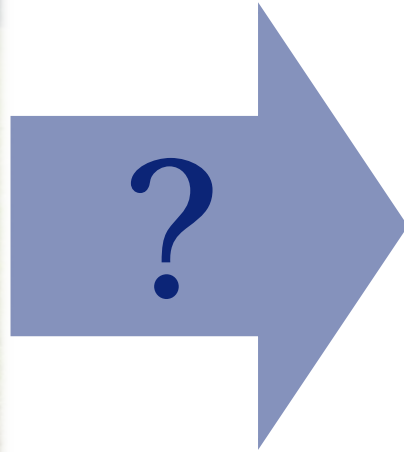
Robbin Bastiaansen

27 August 2019



Universiteit
Leiden
The Netherlands

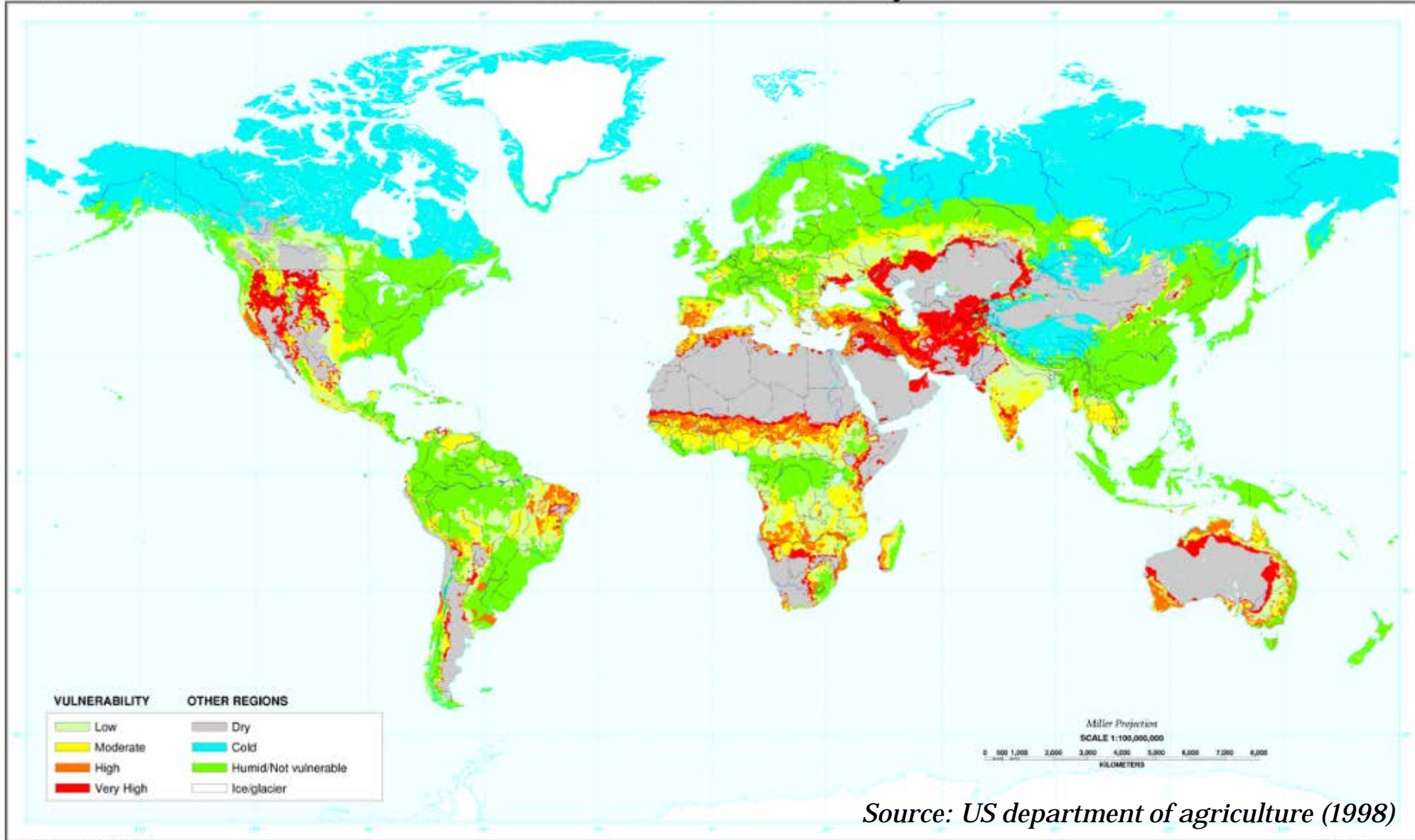
The desertification process



Desertification vulnerability

U.S. Department of Agriculture
National Resources Conservation Service
Soil Survey Division
World Soil Resources

Desertification Vulnerability

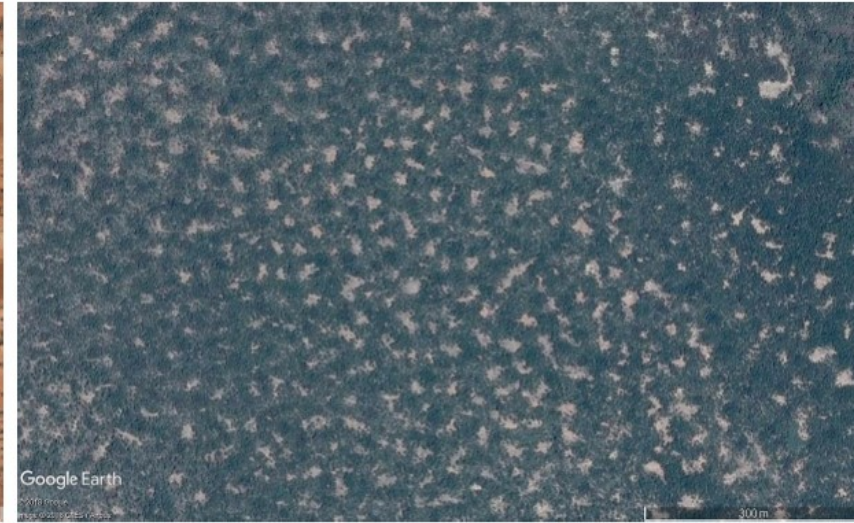


Source: US department of agriculture (1998)

Desertification – emergent patterns



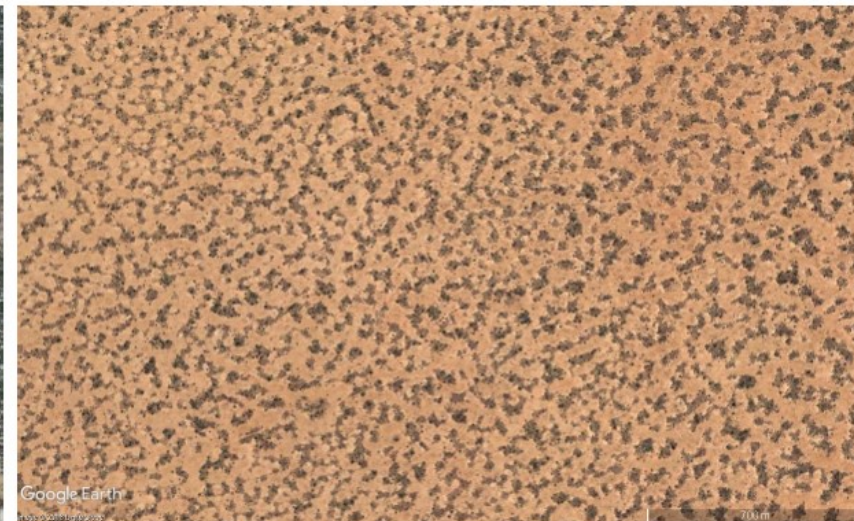
(a) Bands in Somalia



(b) Gaps in Niger



(c) Spots in Zambia



(d) Maze in Sudan

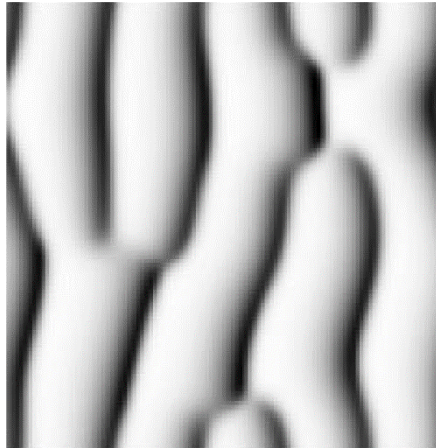
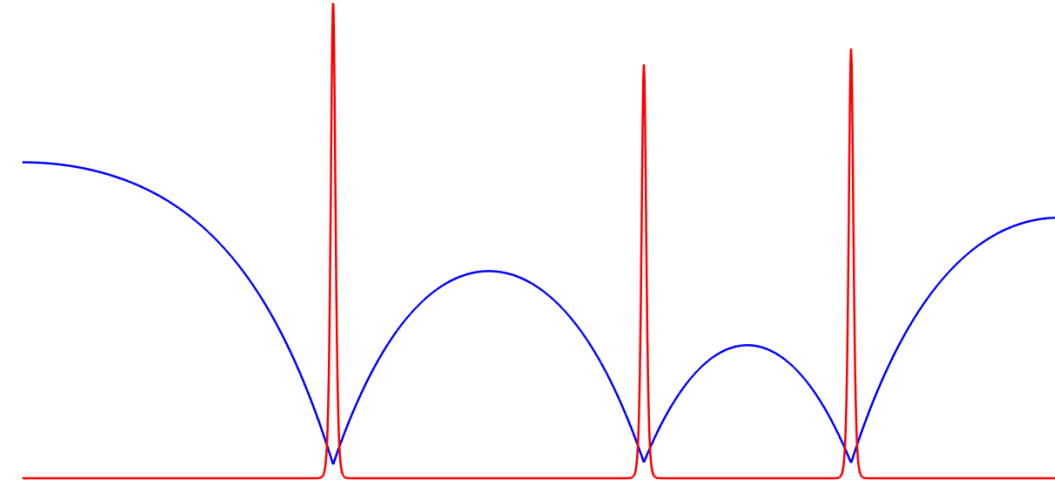
Mathematical treatment

Translating ecology to mathematics:

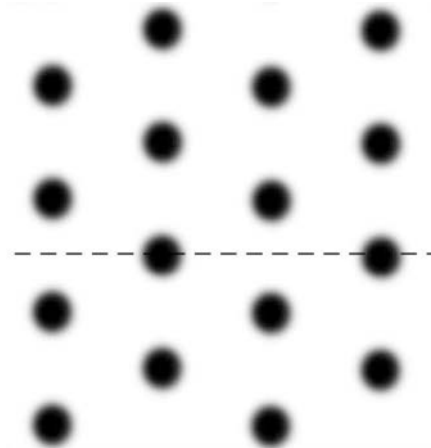
Vegetation patterns \leftrightarrow localized structures

Seperation of scales \leftrightarrow 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

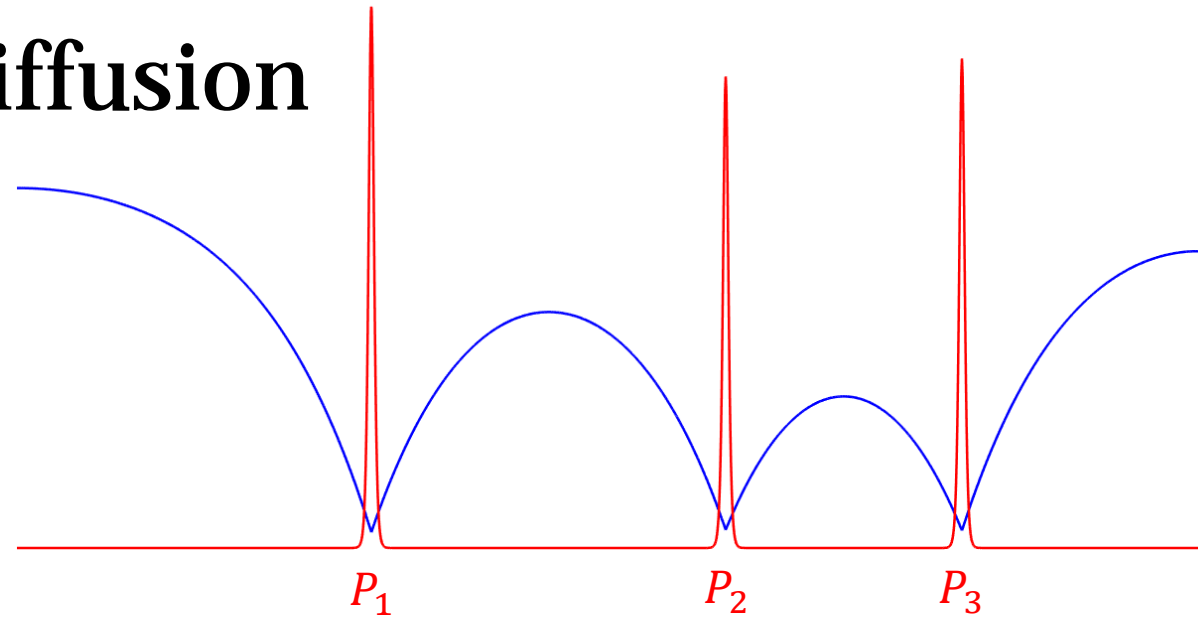
extended-Klausmeier model

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

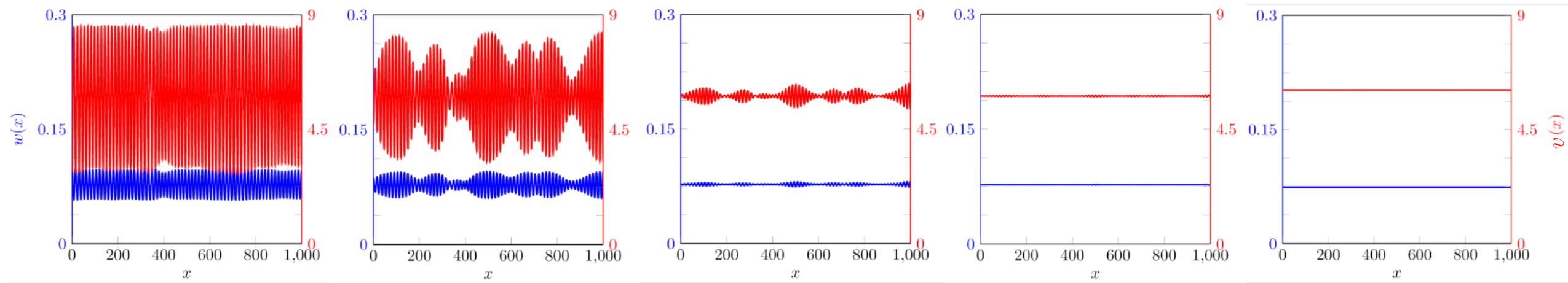
w : water D : ratio of diffusion

v : vegetation a : rainfall

h : height m : mortality



The origin of patterns



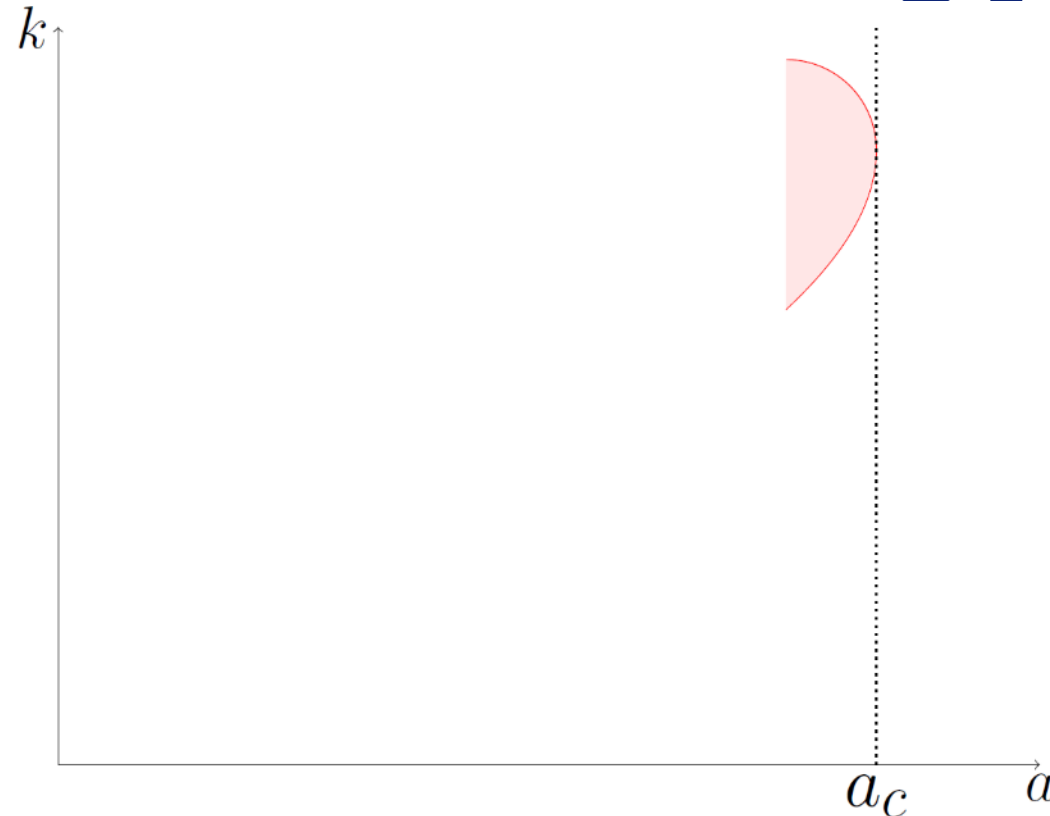
Low rainfall

Critical rainfall
Onset of patterns

High rainfall

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

Wavenumbers of Turing patterns

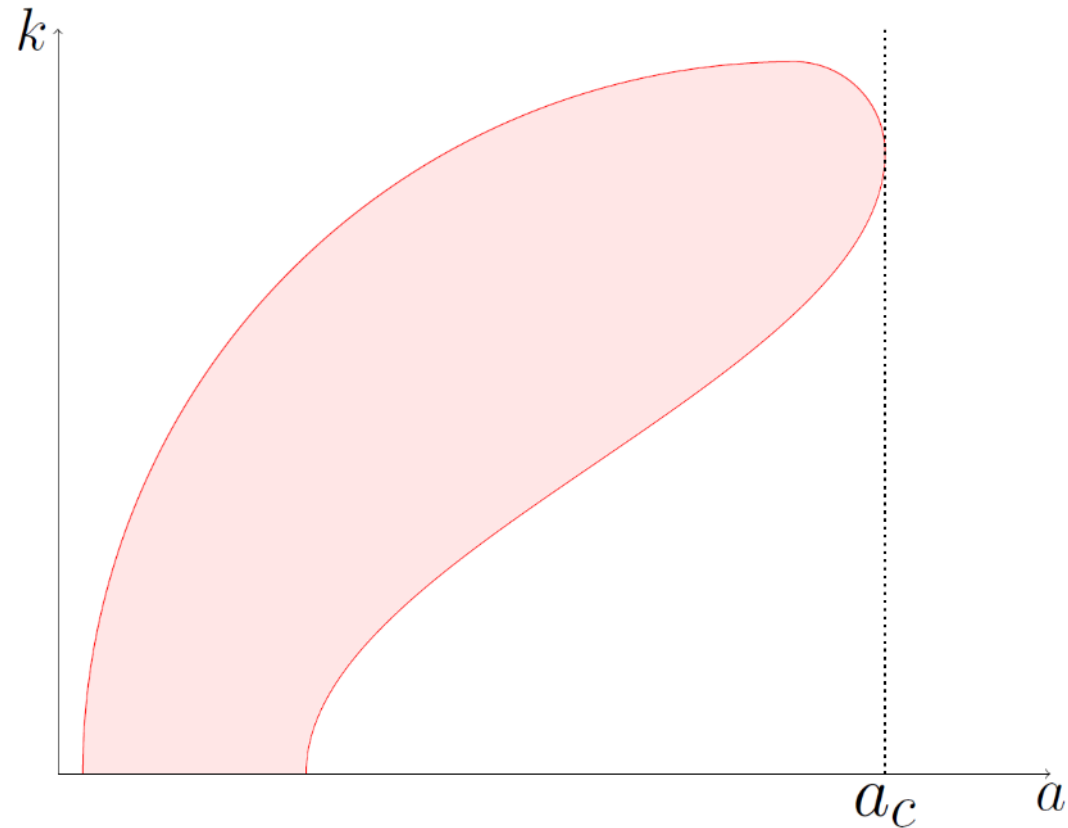


Eckhaus/Benjamin-Feir-Newell instability criterion

[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

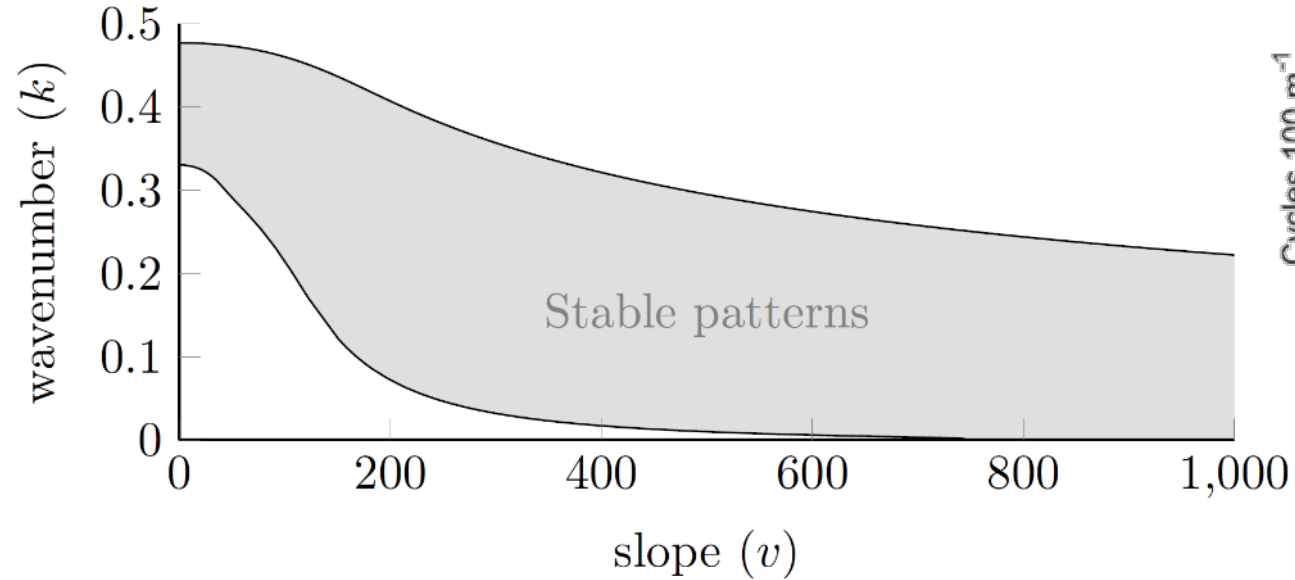
Comparison with reality – study sites

2 sites in Horn of Africa

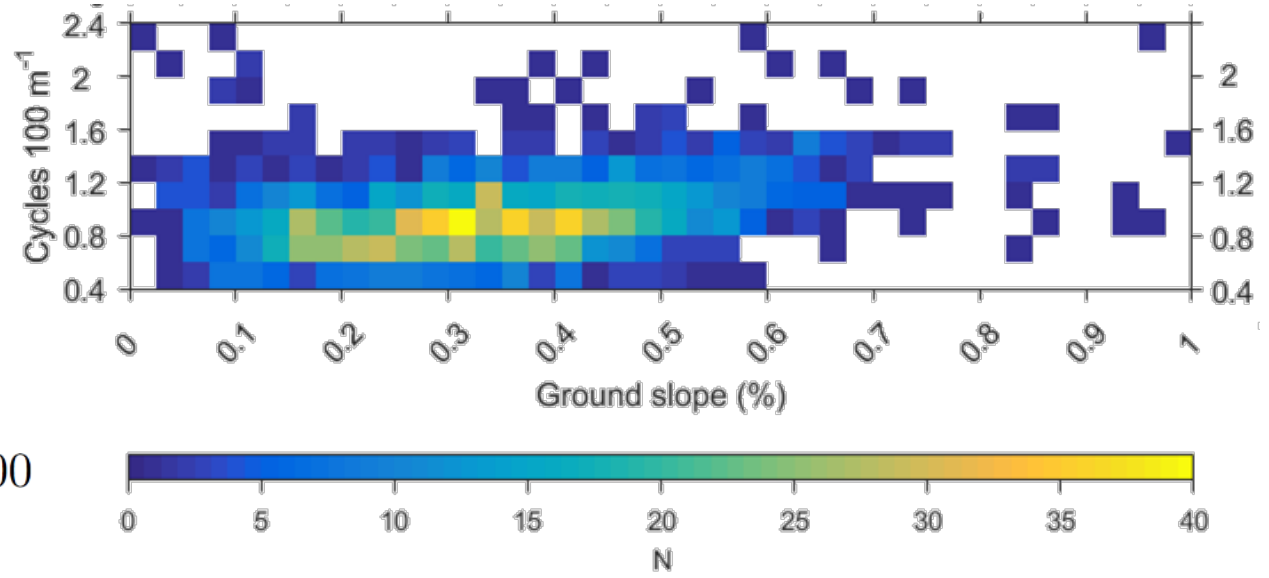
- Environmental conditions constant within site
- Topography main environmental variation



Busse balloon in dryland ecosystems



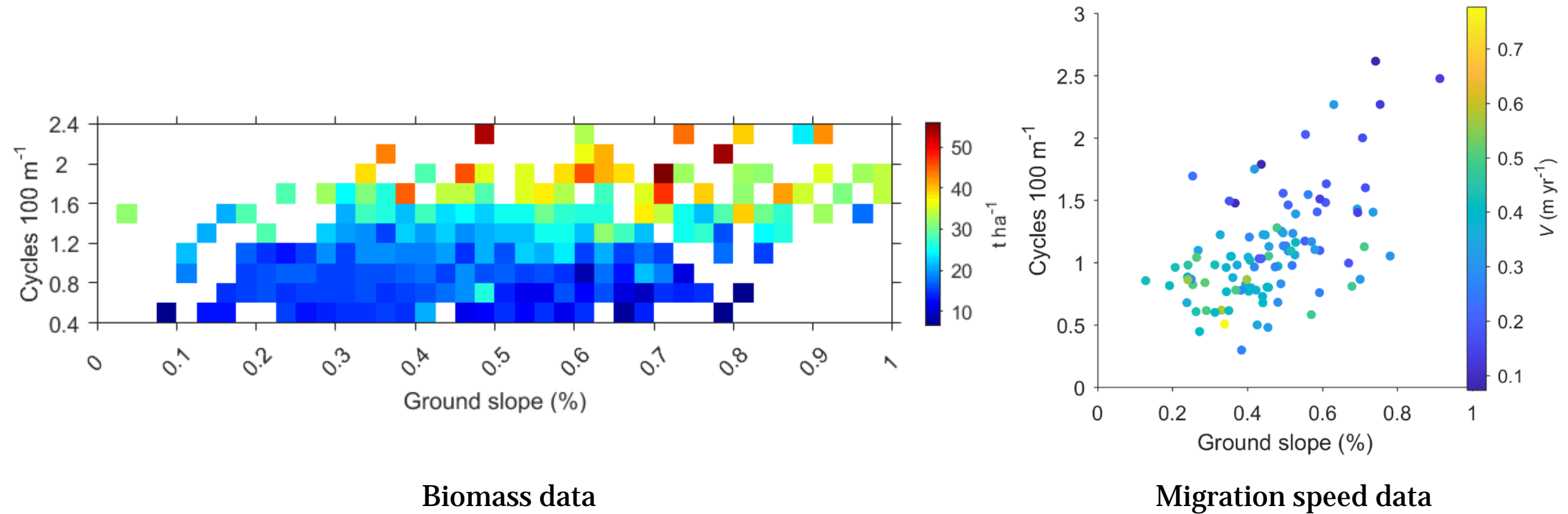
extended-Klausmeier model



Somalia data

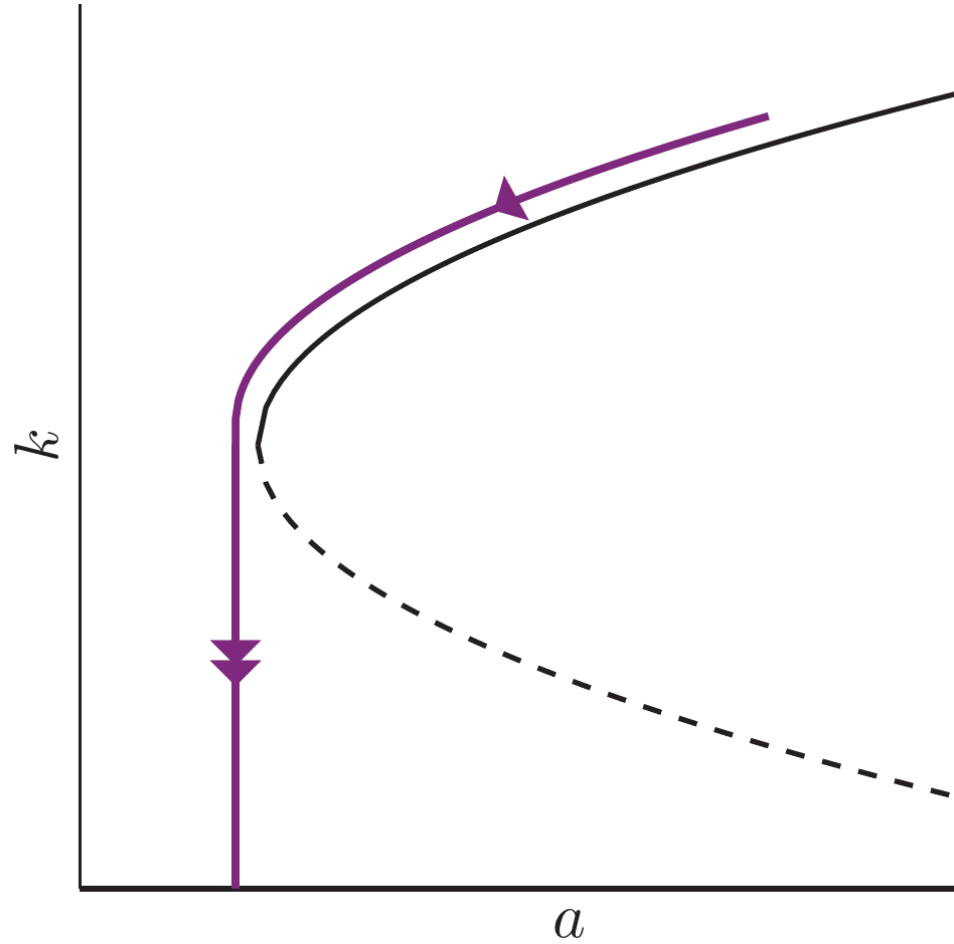
Wide wavenumber spread in both

Wavenumber influences state variables



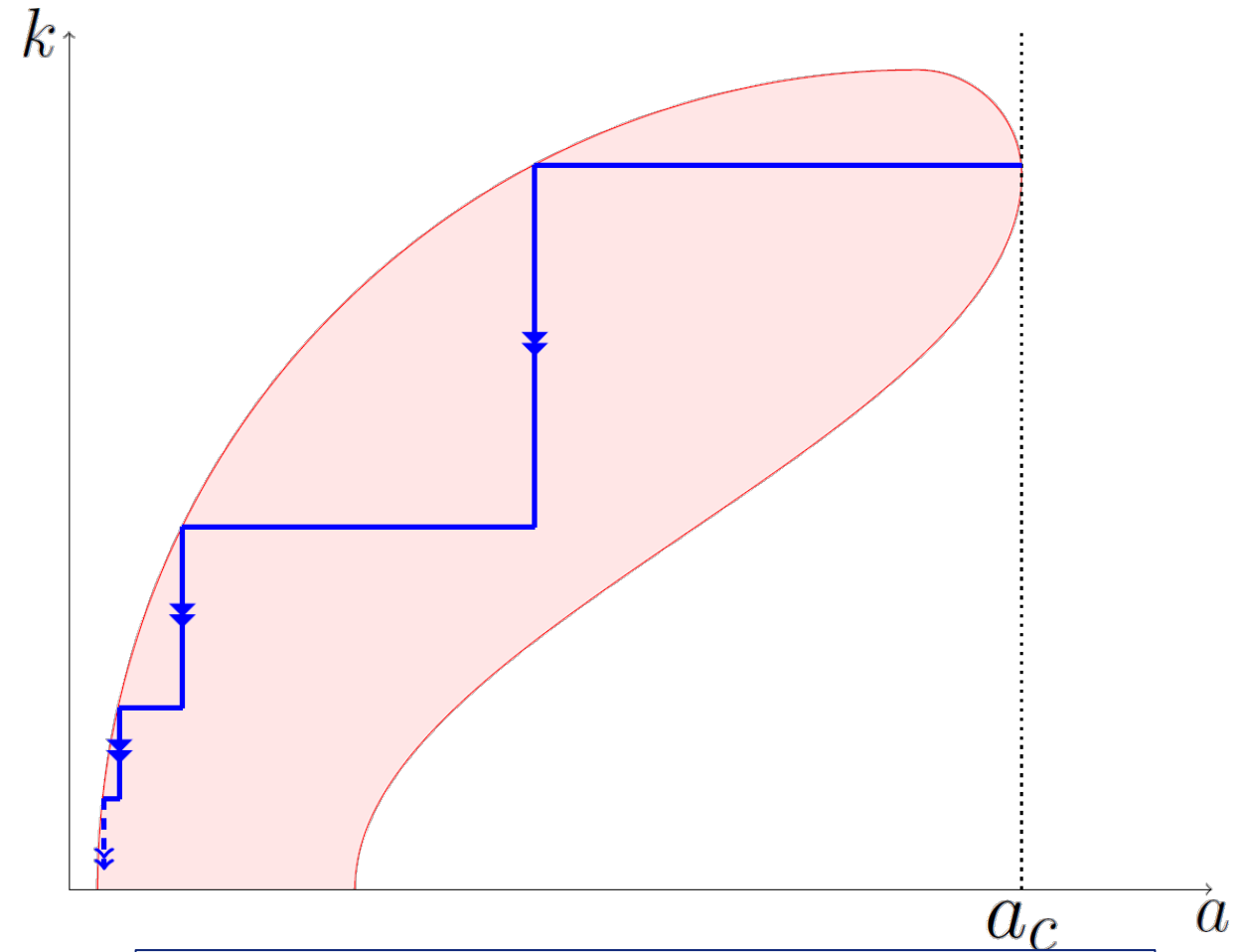
Biomass and migration speed change with wavenumber

Enhanced resilience?



Classical view – fold

e.g. Holling, 1973

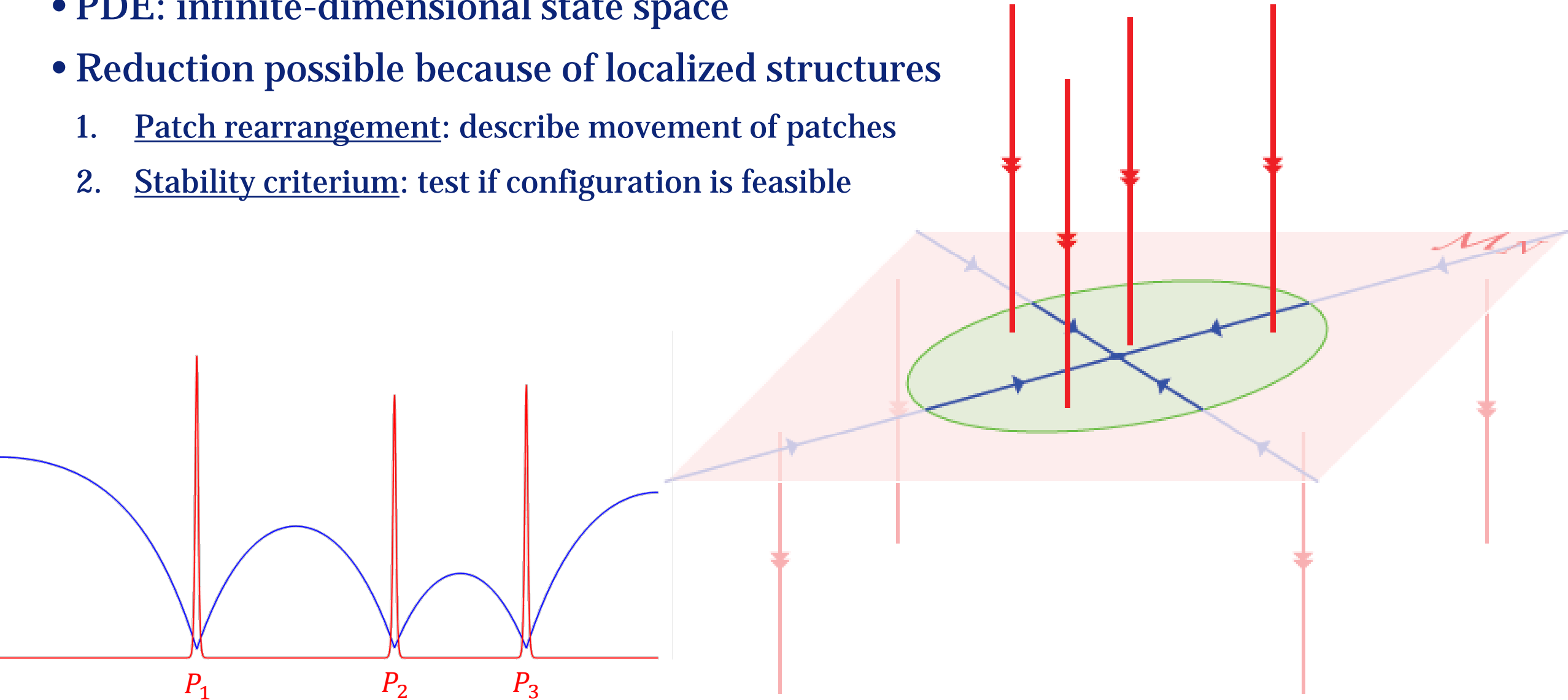


Wavenumber adaptation

Siteur et al, 2014

Understanding patches in the model

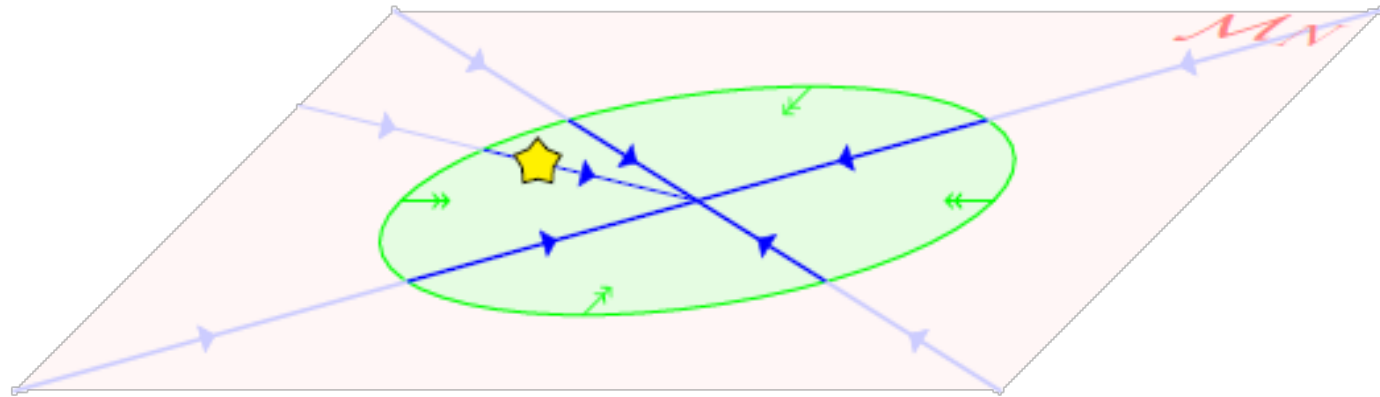
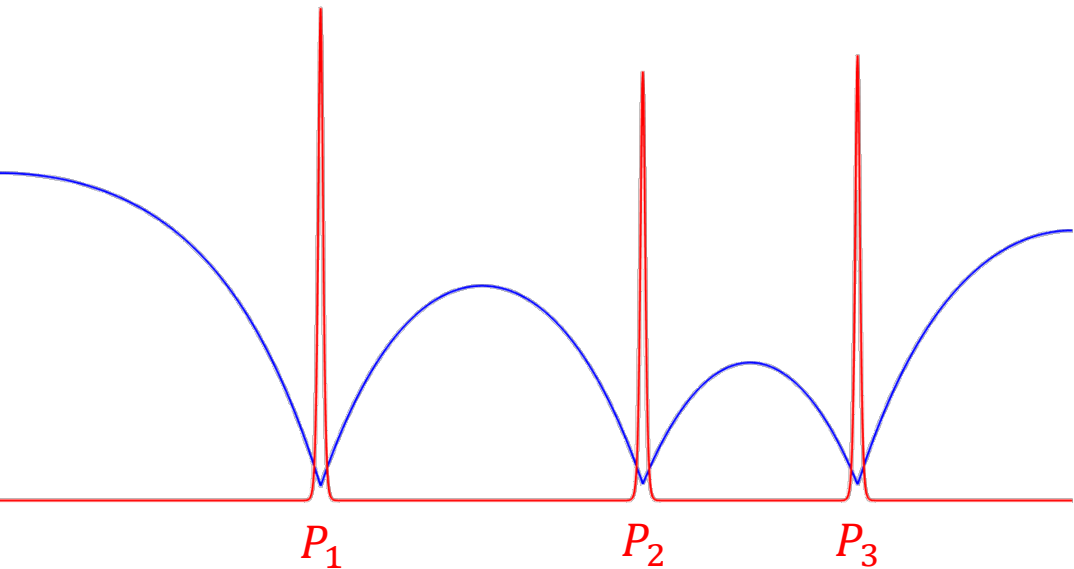
- PDE: infinite-dimensional state space
- Reduction possible because of localized structures
 1. Patch rearrangement: describe movement of patches
 2. Stability criterium: test if configuration is feasible



Patch-location ODE

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

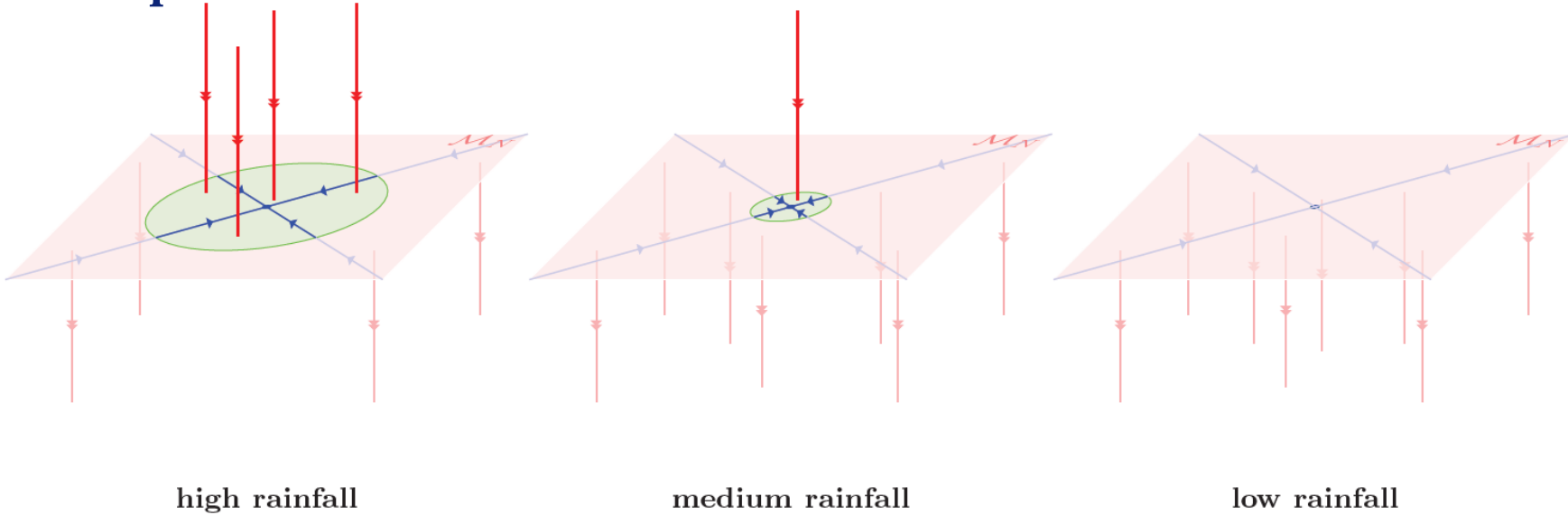
Water availability dictates pulse movement



Stability criterium

Enough resources to sustain all vegetation patches?

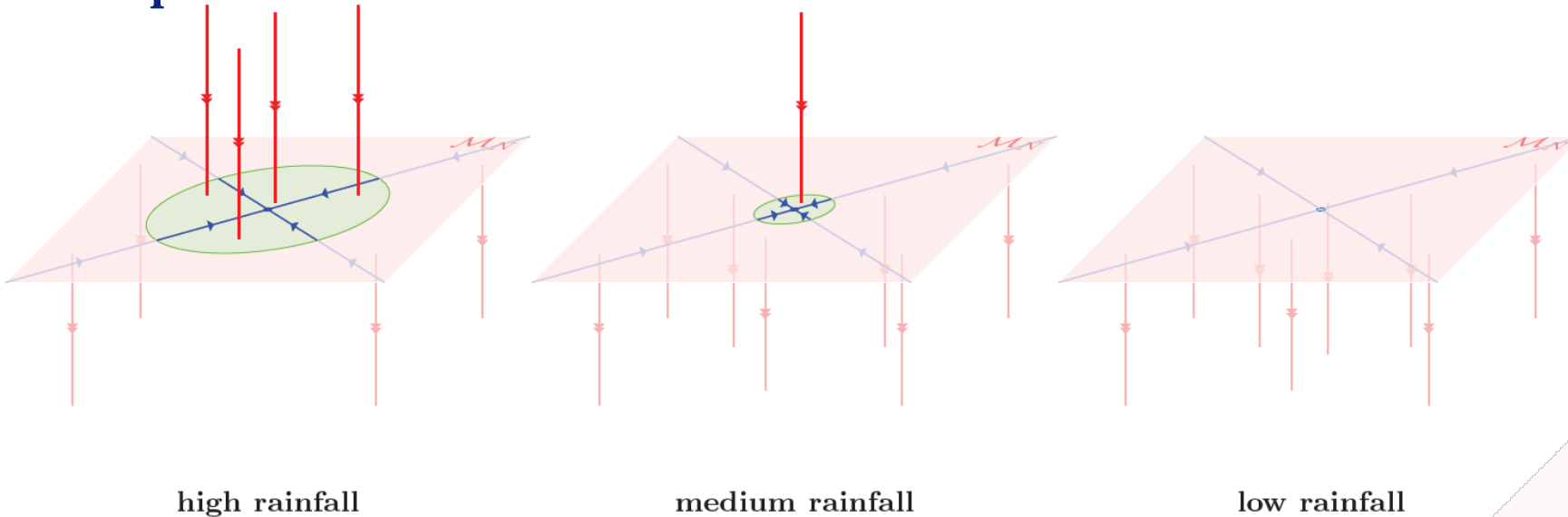
Depends on **amount of rainfall** and **distance between patches**



Stability criterium

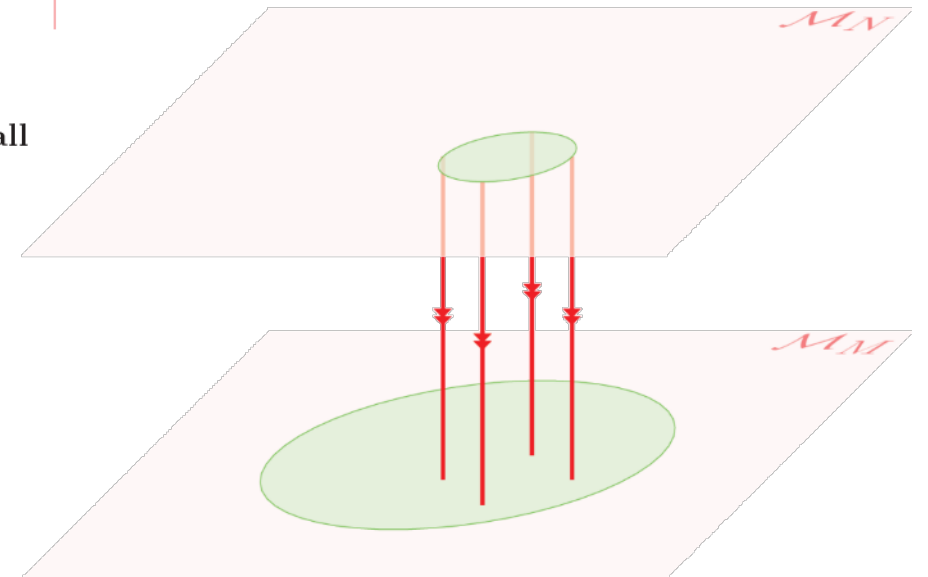
Enough resources to sustain all vegetation patches?

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



What happens when outside feasible region?

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

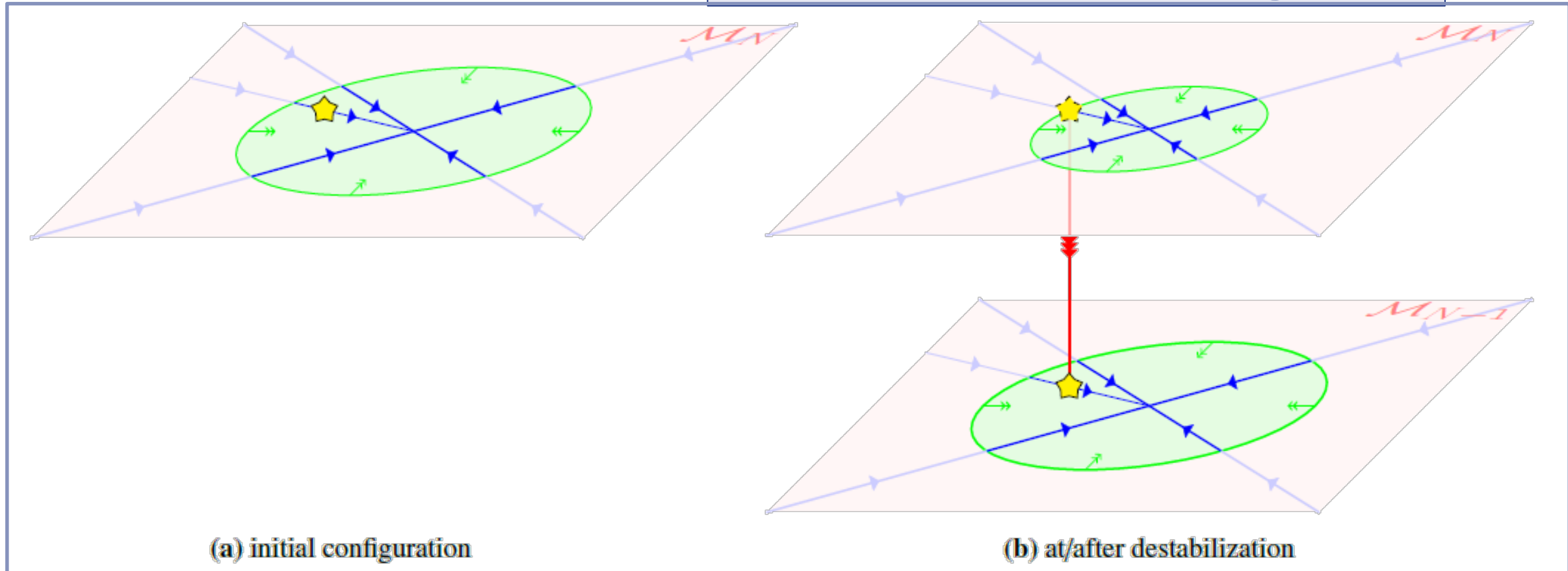


Patches during climate change (1)

Competition of two effects:

1. Patch rearrangement
2. Shrinking of feasible region

fast climate change

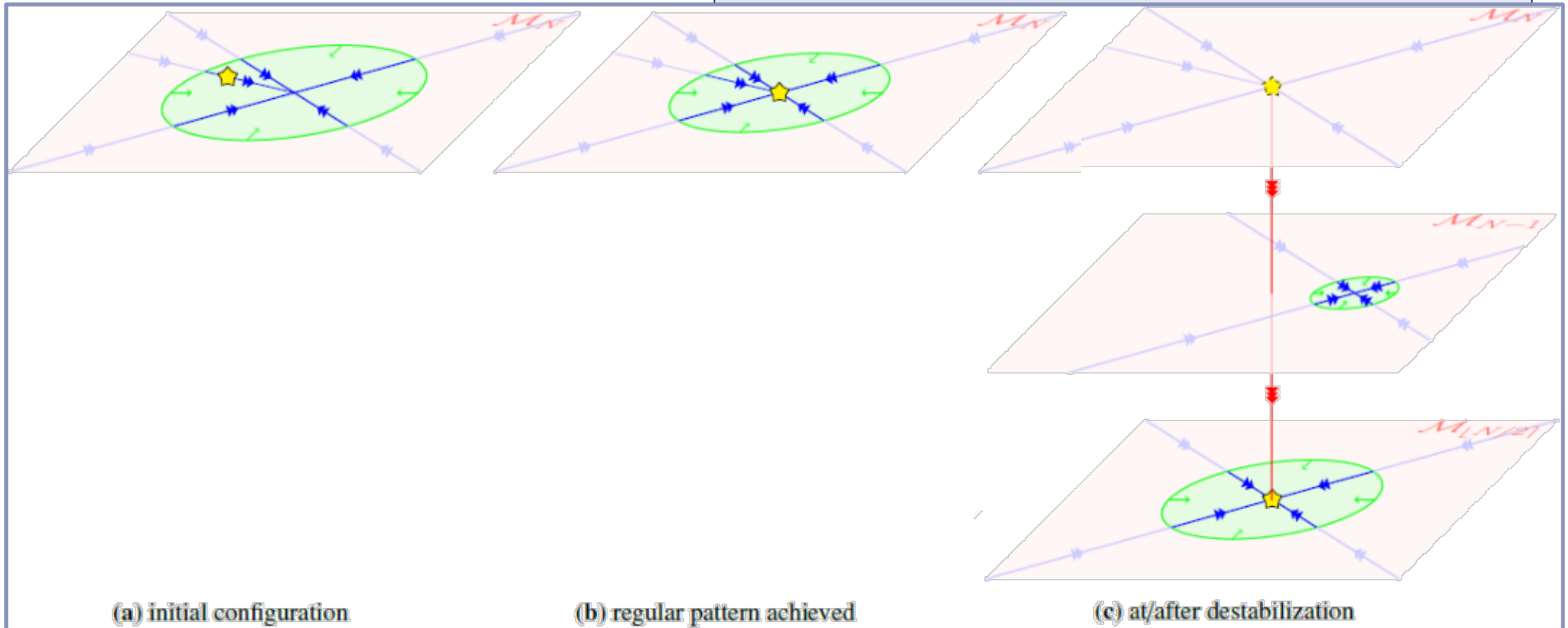


Patches during climate change (2)

Competition of two effects:

1. Patch rearrangement
2. Shrinking of feasible region

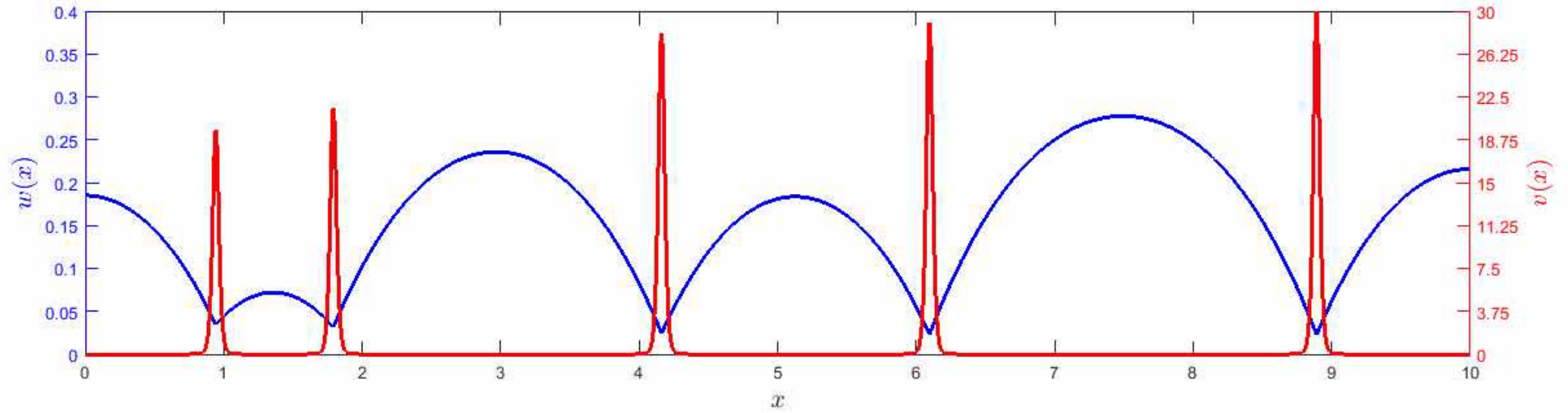
slow climate change



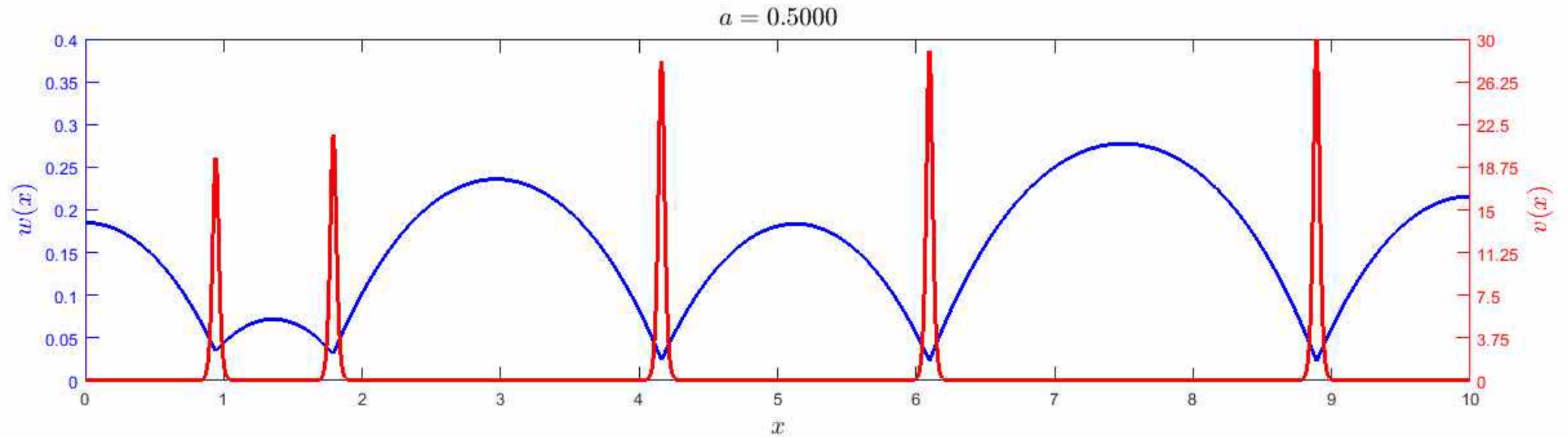
Patches during climate change (3)

Rate of climate change

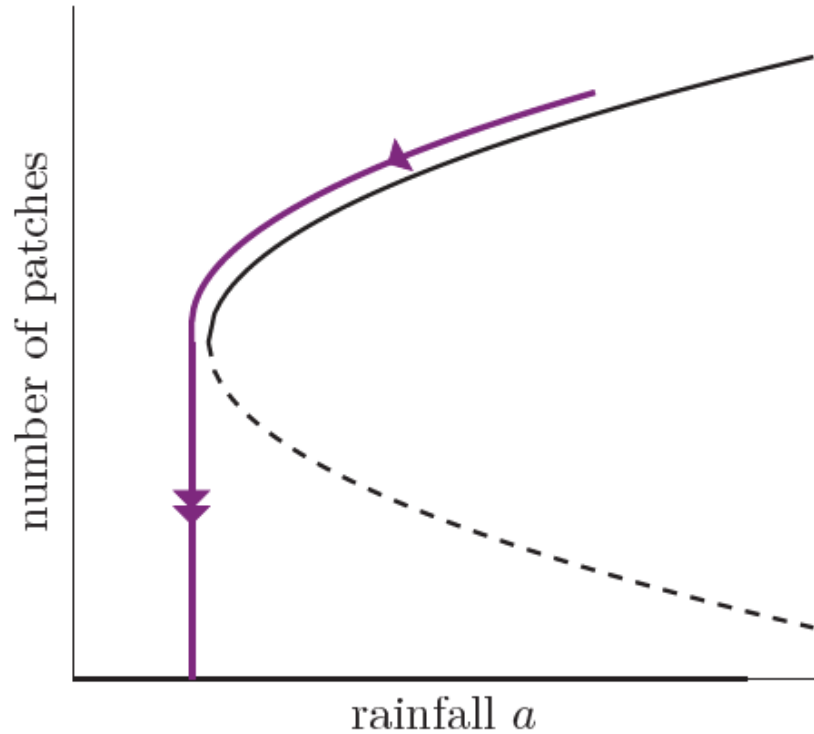
FAST



SLOW

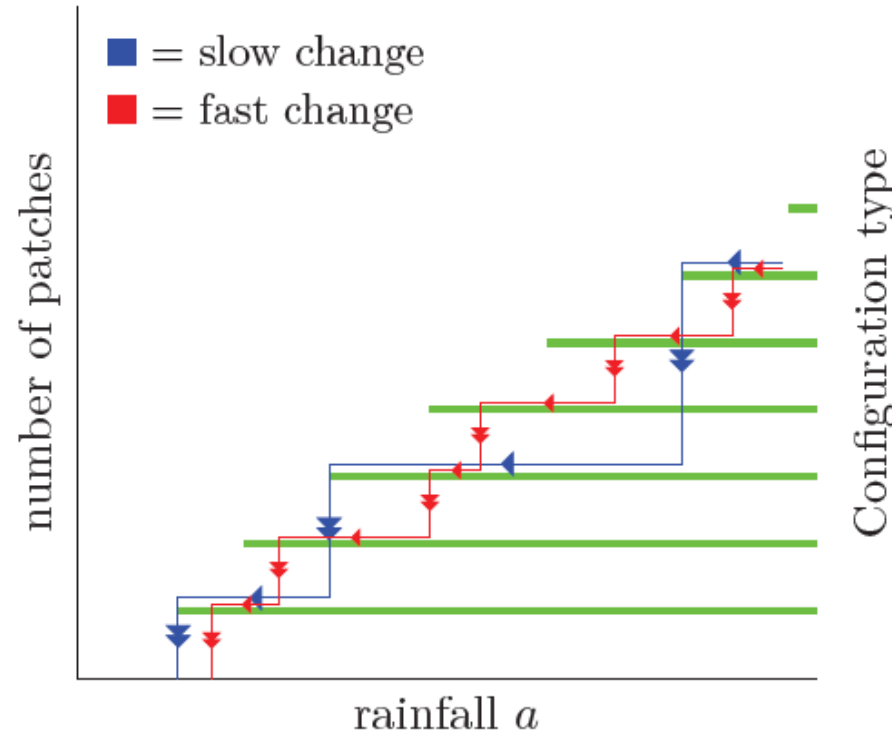


Ecosystem resilience



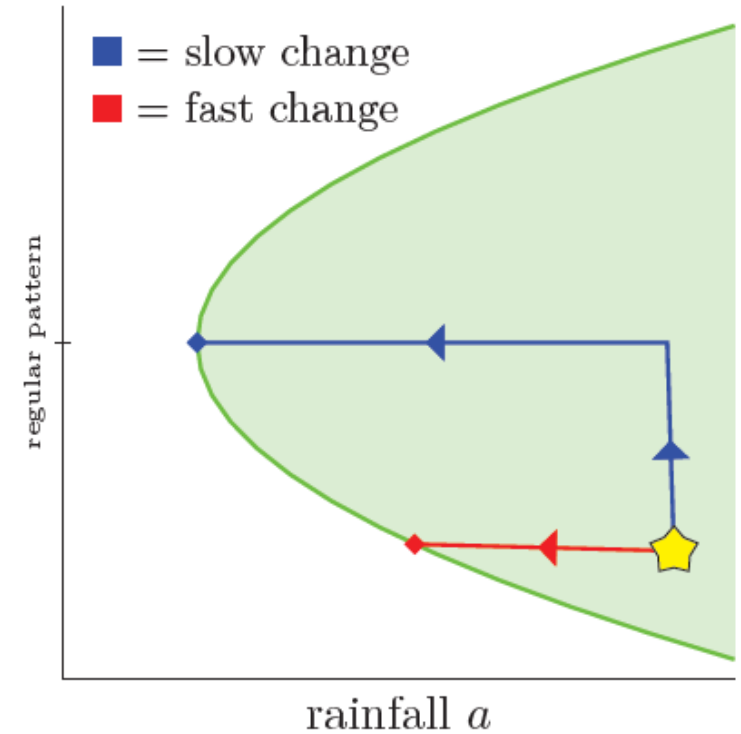
critical transition

Classical view - fold



smaller pattern transitions

Multistable systems



(zoom-in on a line)

Summary

wide wavenumber spread in model & reality

implies

enhanced resilience via ...

- I. Patch 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

~~~ LIST OF COAUTHORS ~~~

Mathematicians	Arjen Doelman (Leiden)	Martina Chirilus-Bruckner (Leiden)	Olfa Jaïbi (Leiden)	Eric Siero (Oldenburg)
Ecologists (theory)	Maarten Eppinga (Zurich)	Max Rietkerk (Utrecht)	Koen Siteur (NIOZ Yerseke)	
Ecologists (data)	Alexandre Bouvet (Toulouse)	Vincent Deblauwe (Yaounde, Cameroon)	Stéphane Mermoz (Toulouse)	