Critical Transitions and Early-warning Signals in Spatial Ecosystems

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Introduction

Ecosystems can be subject to temporal changes or fluctuations in external conditions. Whether an ecosystem is able to buffer these external changes depends on its resilience. Ecosystem resilience depends on internal mechanisms. In spatially patterned ecosystems these mechanisms operate at many different spatial scales and result in a complex global behaviour. In this project we aim to understand the behaviour of spatially patterned ecosystems, subject to changing environmental conditions, with a particular focus on arid ecosystems.

Problem definition

Under decreasing rainfall patterns adapt and patches rearrange. If rainfall decreases too fast, patterns may not be able to adapt. This can result in a critical transition, even at rainfall rates where stable patterned states exist.

Aim

- To isolate mechanisms by which patterned states may destabilize and initiate a critical transition in response to a slowly changing environment.
- To identify characteristic indicators for these mechanisms.
- To analyze the predictive power of these early-warning signals.

Hypothesis

The ability of patches to rearrange depends on the rate at which environmental conditions change. If patches are not able to rearrange, this results in a catastrophic shift.

RATE OF CHANGE IN RAINFALL → ABILITY TO REARRANGE → CATASTROPHIC SHIFT

Figure 1. Hypothesis

Methodology

We use the Generalized Klausmeier-Gray-Scott (GKGS) model that consists of two state variables: surface water (u) and vegetation (v). We study the behaviour of the patterns it produces when changing the rainfall rate (k_0) over time.

$$\begin{cases} \dfrac{\partial u}{\partial t} = k_0 - k_1 k_4 u v^2 - k_2 u + k_3 \dfrac{\partial u}{\partial x} + d_u \dfrac{\partial^2 u^\gamma}{\partial x^2} \\ \dfrac{\partial v}{\partial t} = k_4 u v^2 - k_5 v + d_v \dfrac{\partial^2 v}{\partial x^2} \end{cases}$$

First results

- Patches maximize the distance between each other.
- Competition between patches affects the global behaviour: If one patch goes extinct, this results in growth of its neighbours, which has a negative effect on the neighbours of the neighbours. As a result half of the patches go extinct (figure 2a).
- Low rates of change allow patches to rearrange (at least at high rainfall rates), which allows one patches to go extinct one by one (figure 2b and c).

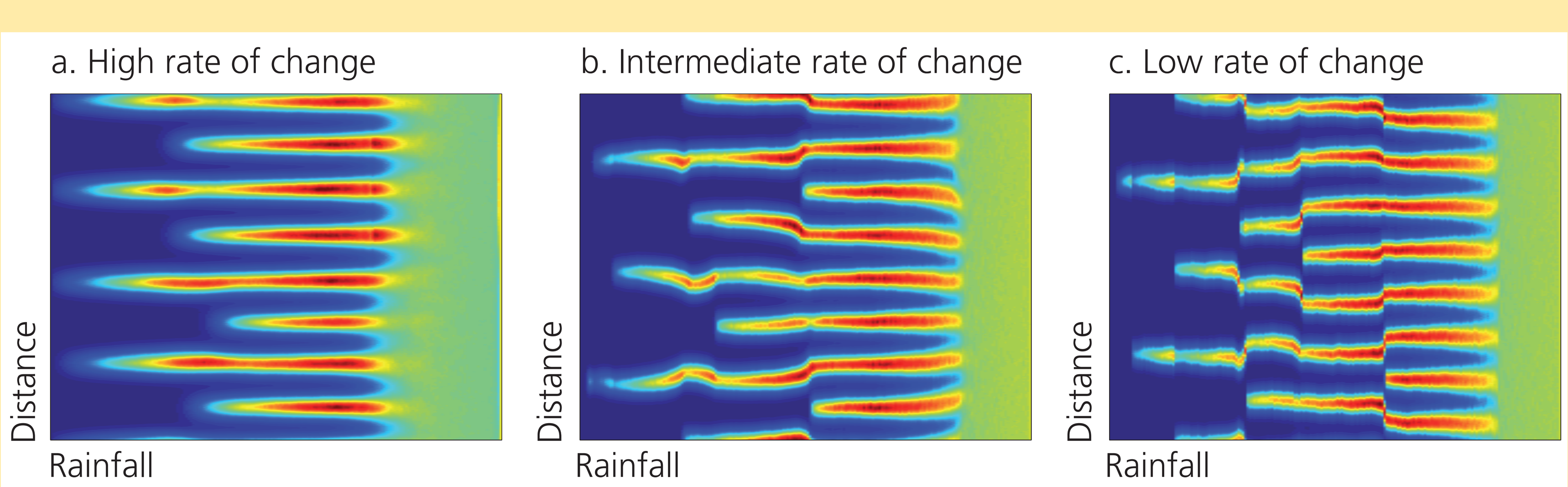


Figure 2. Runs of GKGS model with different rates of change in rainfall

Future work

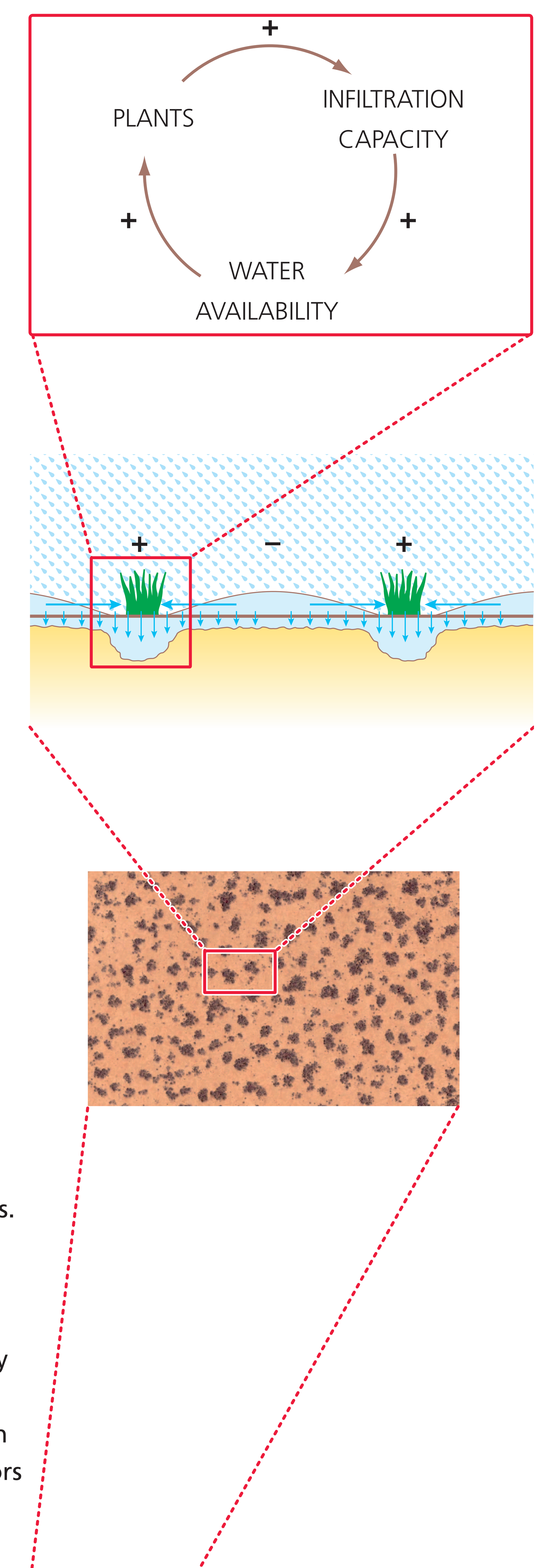
- When are patterns able to adapt?
- How does this work in a two dimensional domain?
- Do vegetation patterns on slopes behave in the same way?
- How does the ability to rearrange depend on spatial structure?

Spatial scale

Short-range facilitation
Plants increase the infiltration capacity of the soil locally, which increases the infiltration of surface water during rain events and thereby soil water availability.

Long-range competition
Short-range facilitation has an effect farther away: surface water moves towards more densely vegetated areas. This causes long-range inhibition.

Self-organization in regular vegetation patterns
Long-range inhibition results in the formation of regular periodic patterns.



Global behaviour
Self-organization enables plants to sustain under harsher conditions. However, it also results in global bistability.
Under changing environmental conditions, the system can abruptly shift from one state to the other. Fortunately, shape and wavelength of patterns can be used as indicators for upcoming transitions.

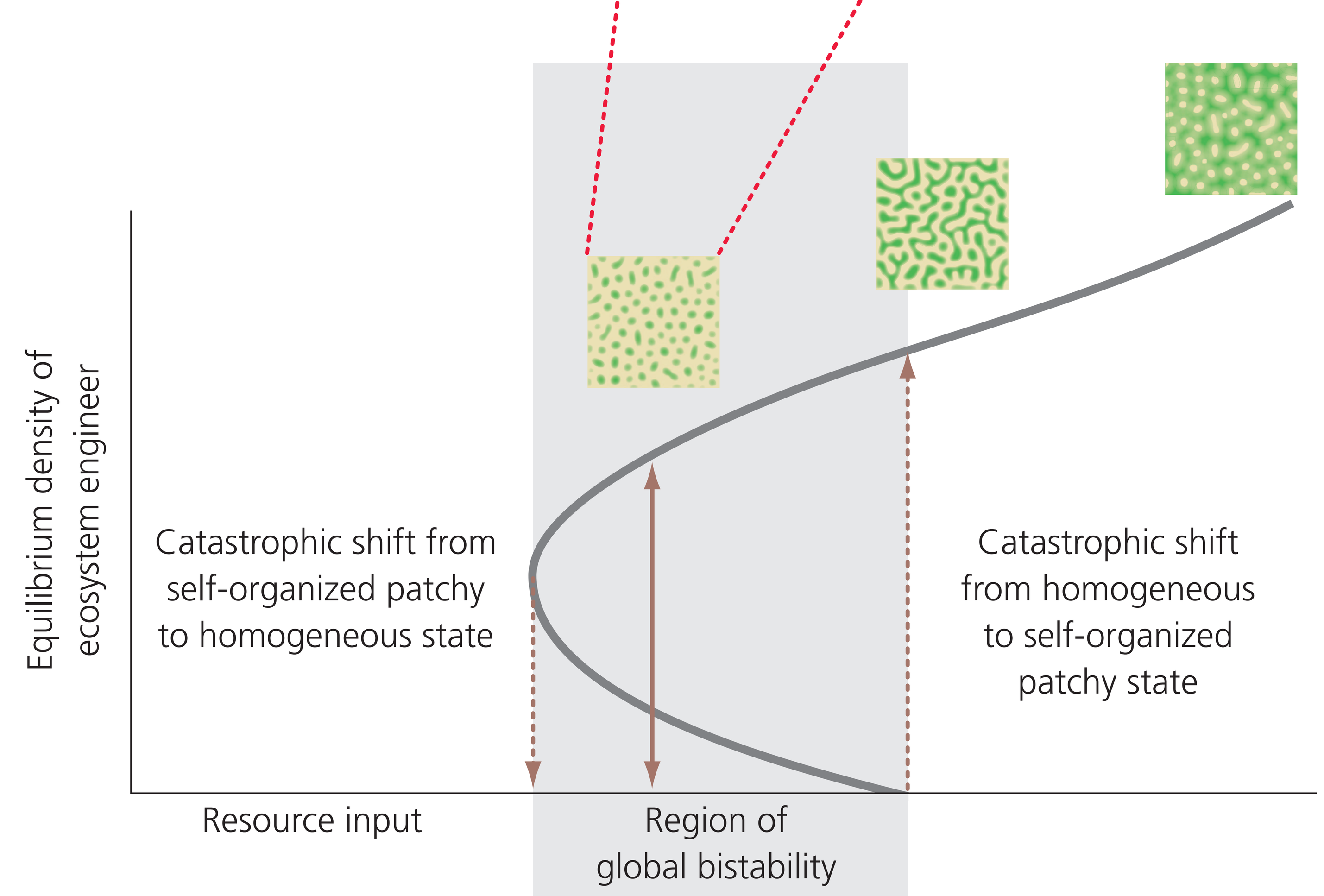


Figure 3. Mechanisms at different spatial scales affect the global behaviour of arid ecosystems

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