

Estimating distances to tipping points from dryland ecosystem images



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1. Introduction
2. The dataset Biocom
3. A minimal model of vegetation dynamics
4. Results of the inference
5. About the futur of these ecosystems

About drylands

- Drylands : resource-limited environments
- Exhibit self-organized spatial patterns of vegetation



Nigerian bush



Departamento de Potosi, Bolivia

Patterns due to biology and interactions between plants

Stress tolerant plants



- Stress-tolerant plants facilitate their local environment by increasing water infiltration, providing shading, and increasing the availability of local nutrients [1, 6, 3, 5, 8]
- Mechanism leads to the aggregation of plants into patches separated by open bare soil areas (two-phase mosaic)

Aims

Drylands : fragile ecosystems that can suddenly degrade

Idea : these patterns could be indicators of approaching tipping points towards ecosystem degradation



Aims : Use the patterns to estimate a distance to tipping points that is comparable across sites from images

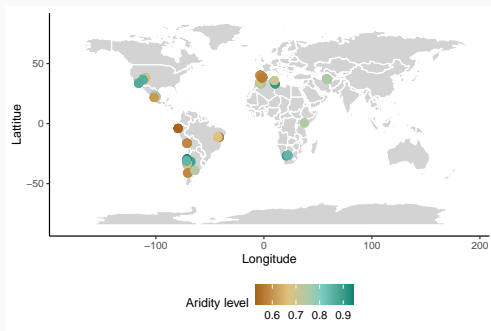
Overview of the work

1. Design a model that is ecologically funded and generates self organized landscapes
2. Infer its parameters from images with ABC algorithm
3. Predict the “future” of ecosystems
4. Explain the distance with aridity projections to pinpoint the most fragile sites among those studied

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Data : Observed vegetation landscapes i

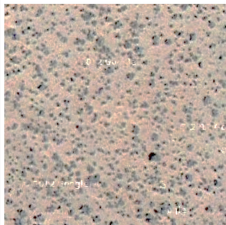
- 293 images from 115 sites located around the globe (13 countries)



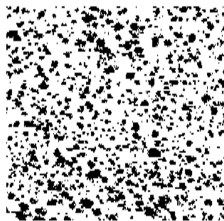
- 50m \times 50m landscapes
- Resolution sufficient to identify vegetation patches (spatial resolution lower than 0.3 meters per pixel).

- The images are binarized

Remotely sensed landscape



Binarized landscape



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Our minimal model

Variation autour de [2, 9]

- Aims at mimicking stressed ecosystems such as drylands or salt marshes :
- Stochastic cellular automaton that describes the temporal evolution of a landscape
- $C \times C$ ($C = 100$) cells that can be in two possible states $I_i(t)$
 - either colonized by vegetation (V)
 - or empty (E).
- Each cell : an individual plant (typically in drylands between $0.25m^2$ and $1m^2$).

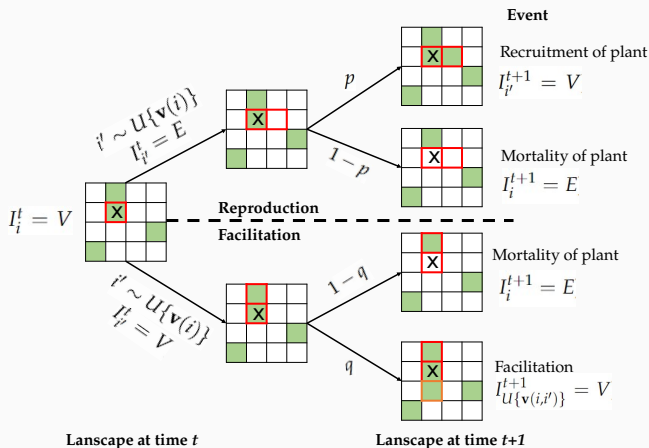
A two parameters model

At each time-step t , the state of the cells $I_i(t)$ in the landscape changes according to two probability parameters :

- p the local reproduction of vegetation,
- q a spatial aggregation parameter that drives the spatial self-organization

$$\forall i \mid I_i(t) = V$$

Perform the following simulations



until stationary state.

Examples of simulations

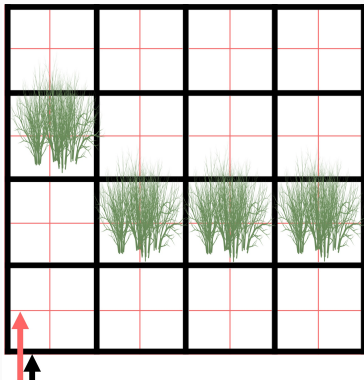


High p , small q



High q , small p

Observation scale



Scale of the model: a pixel corresponds to a plant

Scale of the observation: a pixel does not correspond to a plant

η^2 the number of pixels included in a biological cell.

For any landscape ℓ (image) and pixel i :

$$Y_{\ell,\bullet}(t) = F_{\mathcal{O}}(I_{\ell,\bullet}(t), \eta_{\ell})$$

$$I_{\ell,i}(t) \sim \mathcal{M}_V(p_{\ell}, q_{\ell})$$

$$\theta_{\ell} = (p_{\ell}, q_{\ell}, \eta_{\ell})$$

- Model $\mathcal{M}(\theta)$
- “Easy” to simulate
- Non explicit likelihood

Approximate Bayesian Inference

Let us drop the ℓ index and let Y^{obs} be the image at stake.

For all $m = 1, \dots, M$

▪

$$\theta^{(m)} = (p^{(m)}, q^{(m)}, \eta^{(m)}) \sim \text{prior}$$

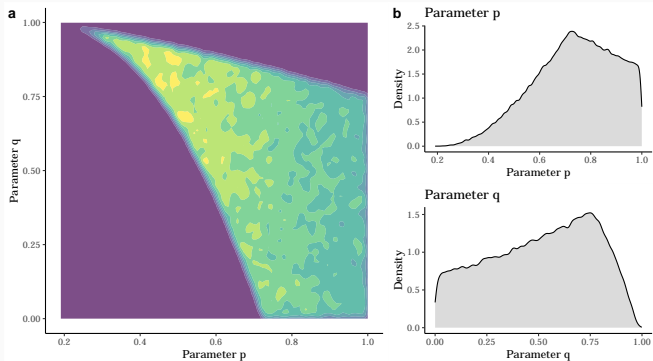
▪

$$Y^{(m)} | \theta^{(m)} \sim \mathcal{M}(\theta^{(m)})$$

- - If $D(Y^{(m)}, Y^{obs})$ is small, keep $\theta^{(m)}$,
 - Otherwise reject $\theta^{(m)}$

Prior distribution

$$\eta \sim \mathcal{U}_{\{1, \dots, 5\}}$$



Prior ensures that vegetation cover $\in [0.05, 0.9]$

Choice of the discrepancy D

Based on 11 spatial statistics summarizing the complexity of the spatial structure.

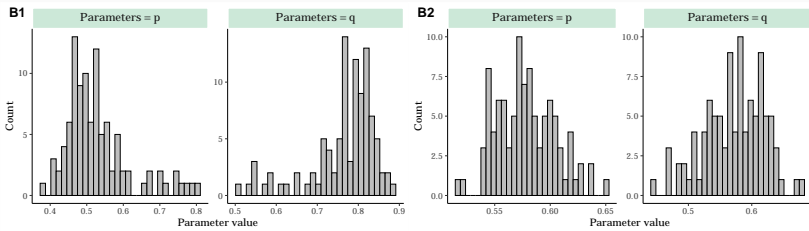
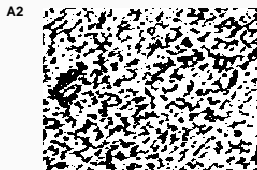
- **Vegetation cover** (3 statistics)
- **Vegetation aggregation** (4 statistics) : R-package spatialwarnings [4].
- **Patch-size distribution** (4 statistics)
- Invariant with the image size
- Combined after a Box-Cox transformation normalisation

Remarks : Correlated but no selection was made

- Simulation showed our ability to recover the parameters (p, q) and scale η .
- No post-treatment of the sample $\theta^{(m)}$
- Computational comments : the same parameters, realizations of the model and spatial statistics are used for all the landscapes.
- $M = 367500$

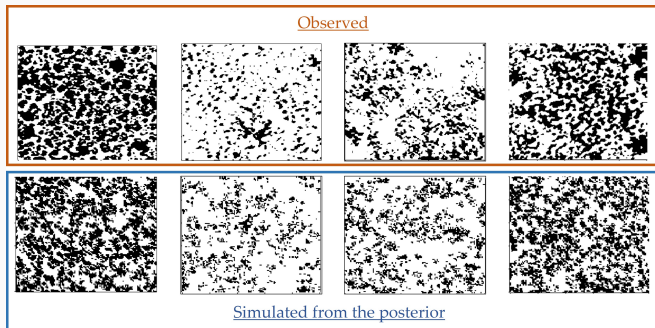
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Two examples of posterior inference

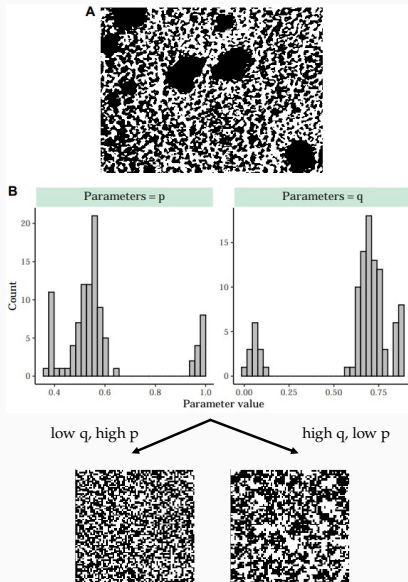


Examples of the posterior distributions of the two parameters (p, q) for two sites with contrasted spatial structure (170-b and 116-c from BIOCOM [7]).

Posterior predictive simulation

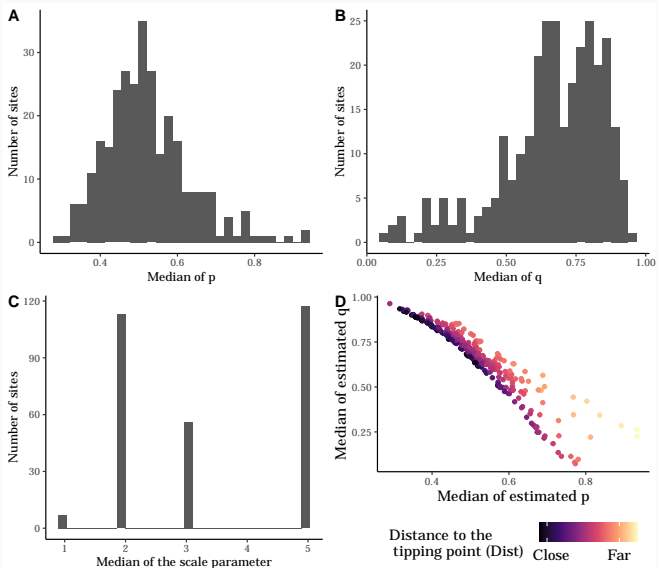


When things fail



Global estimation

Considering all the landscapes



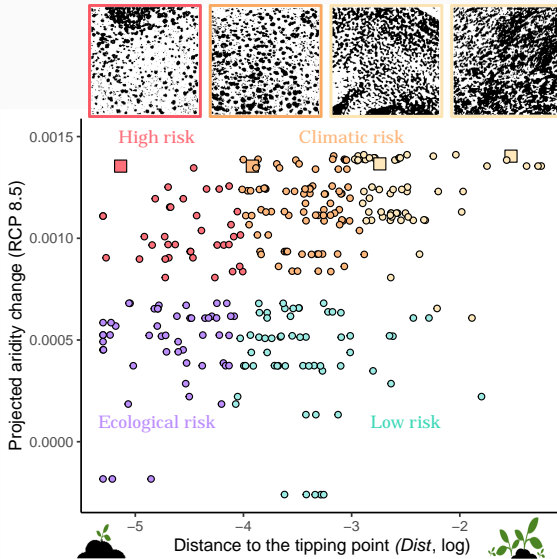
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Increasing of the abiotic stress

- **Aim** : how the observed ecosystems will evolve in case of an increase of the abiotic stress ?
- **Scenario** : decrease the parameter linked to plant reproduction (p).
- **Method**
 - For each landscape l and sample $\theta_l^{(m)}$ from the posterior distribution : decrease $p_l^{(m)}$ with fixed steps (0.005) until we reached 0 vegetation.
 - $p_{\text{crit},l}^{(m)}$: maximal value of the parameter p for which there is still vegetation.
 - Distance to the desertification point

$$\text{Dist}_l^{(m)} = p_l^{(m)} - p_{\text{crit},l}^{(m)}.$$

Distance versus projected aridity



Conclusion

- Simple model but identifiable
- First method to compare the fragility of ecosystems
- Could want to consider two sizes of vegetation (trees and herbs)
- Others pressures such as grazing could be considered ?





Article soumis : *Estimating distances to tipping points from dryland ecosystem images*, B. Pichon, S. Donnet, I. Gounand, S. Kéfi. [bioRxiv](#)

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