Vegetation pattern characterization: Statistical tools & applications

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- Projet ECOPAS/UE/Parc W (BURKINA FASO, BENIN, NIGER)

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Highlights

Lecture I: characterization tools for diverse patterns

- The diversity of patterns and the worldwide distribution of periodic patterns
- Features for pattern characterization (from images):
  - Patch-oriented attributes
  - Textural attributes (features)

Lecture II: From plant-plant interactions to patterns and vice-versa:

- Types of simulated patterns from a simple model
- Using features to distinguishing classes of patterns
- Application to both simulated and real-world patterns
- **=> group works**

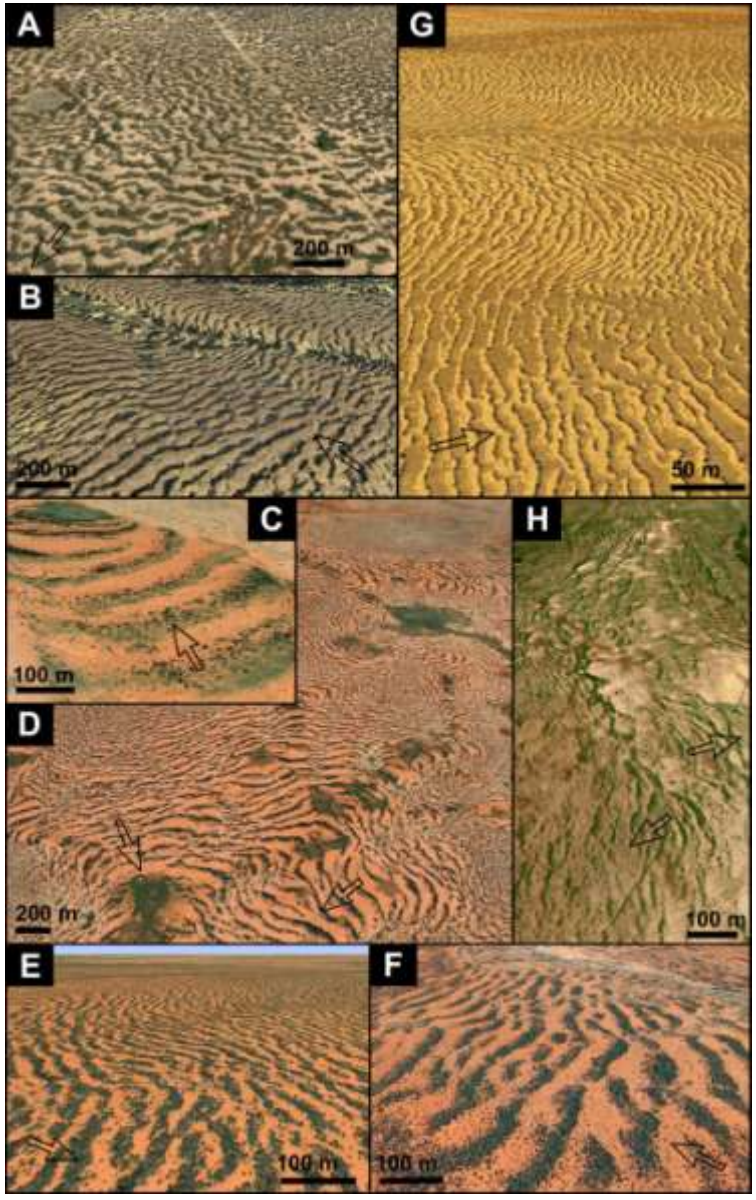
The diversity of patterns in nature

Origin: template-induced or selforganised patchiness?

Australia, Northern territory

→ field studies

Selforganised patchiness



Tiger bush: periodic bands parallel to countour lines

Uniform soil, bedrock, slope

→not imposed by external factors

(A) Dosso, **Niger**

(B) Trans-Pecos, **Texas**

(C) Haud, **Somalia**

(D) Haud, **Somalia**

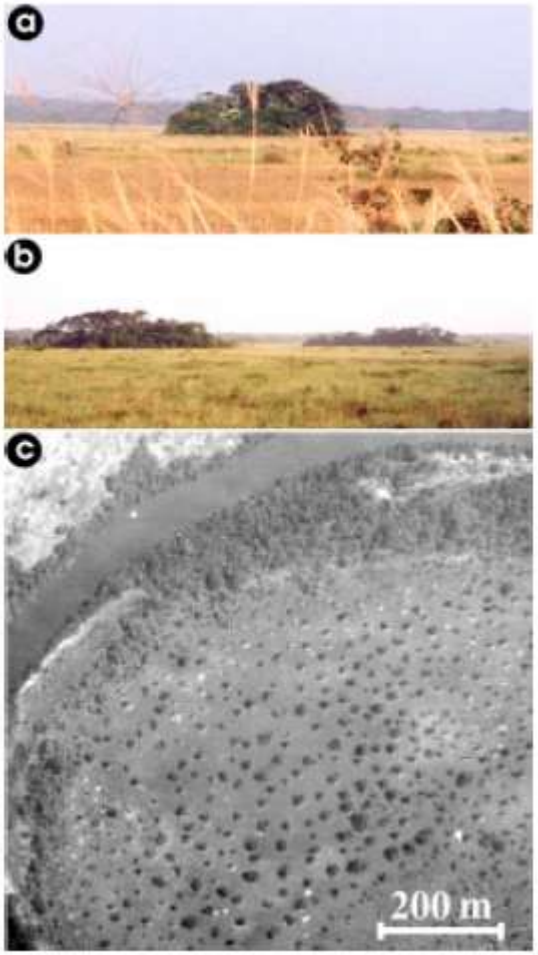
(E) Alice Springs, **Australia**

(F) Ogaden, **Ethiopia**

(G) Broken Hill, **Australia**

(H) Butana, **Sudan**

« other » kinds of structures



Lejeune & Tlidi 2002

Juergens et al 2015

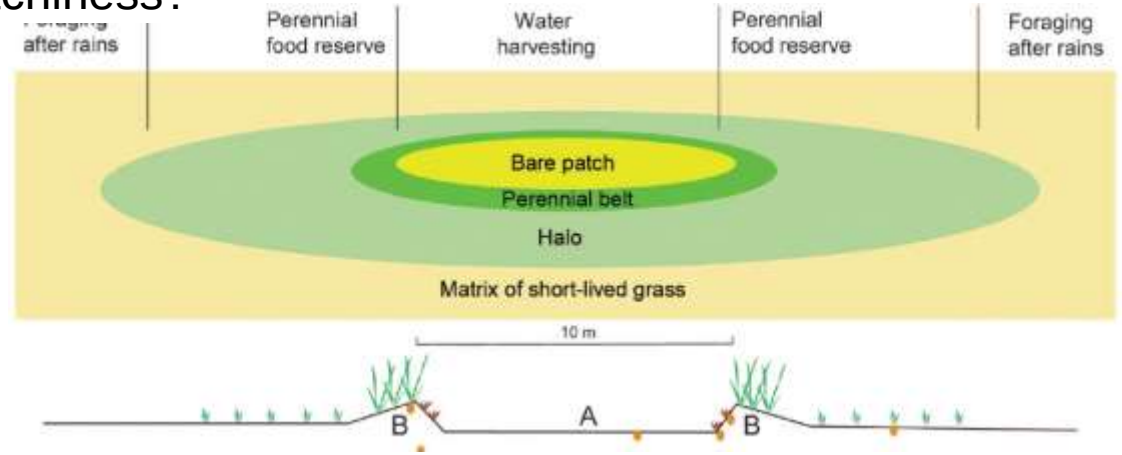
Namib Desert fairy circles

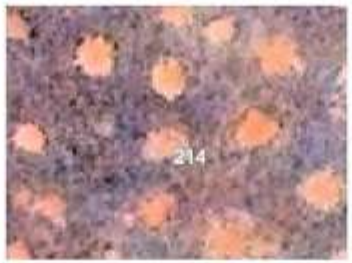
Repulsion distance

Hexagonal pattern

Dynamic

→ Self organized patchiness?

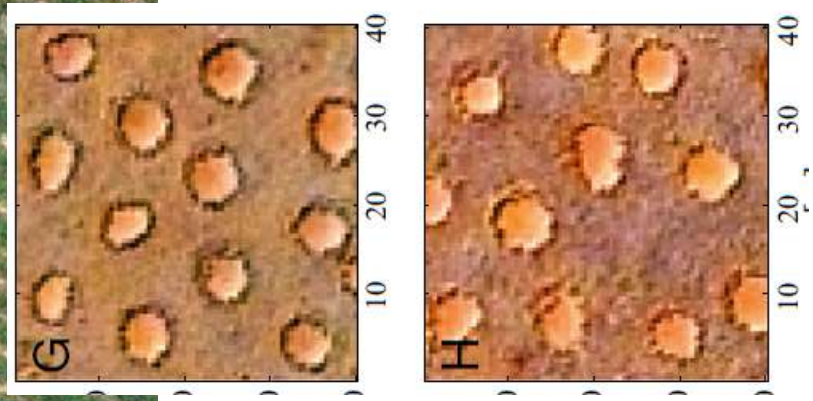




Not only in drylands

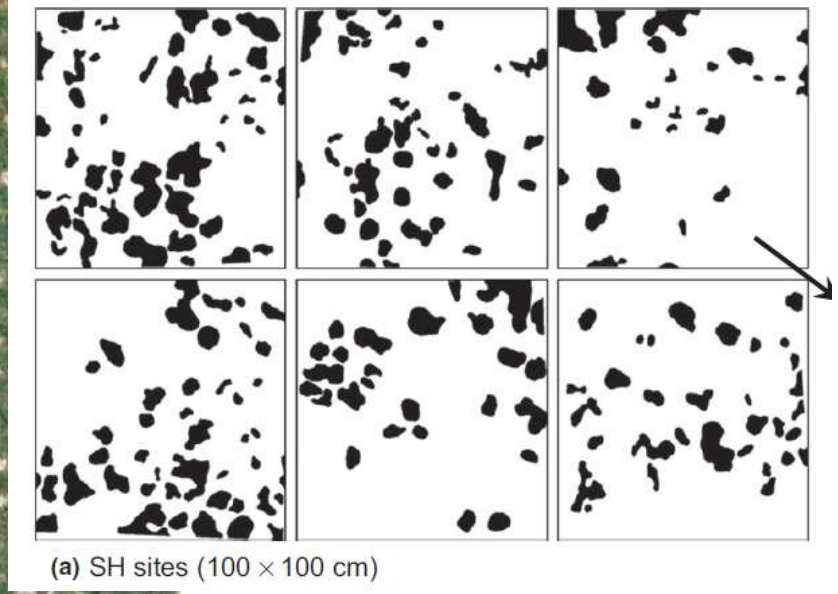
Gabon, forest-savanna interface

Periodic, aperiodic, scale-free?

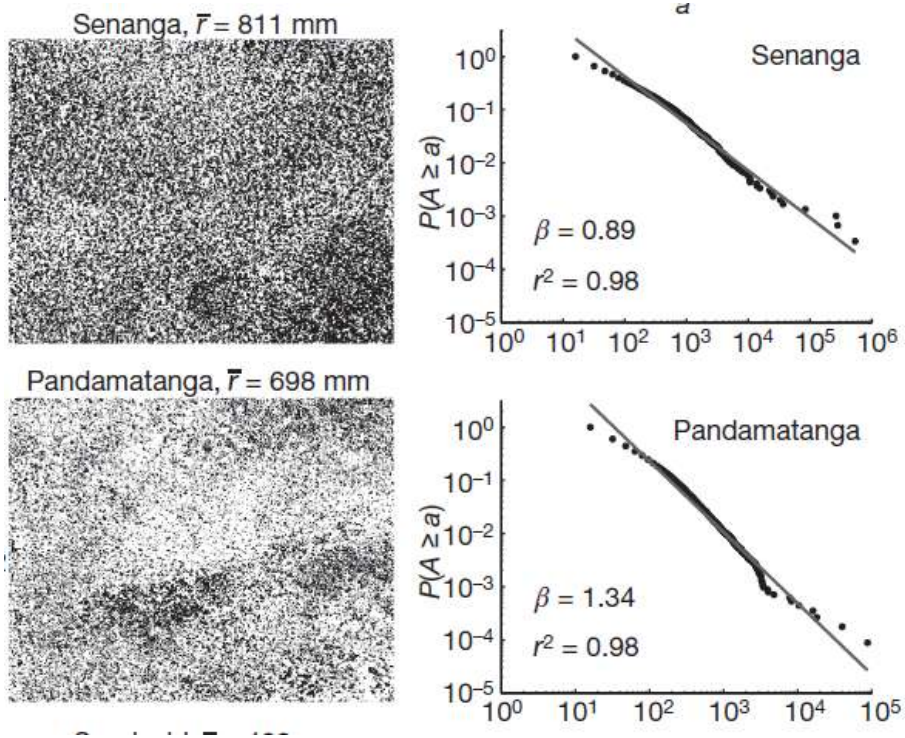


- Spatially confined transitions between alternative stable states
- Mixtures of template-induced and selforganised patchiness
- Scale free patterns

Zelnik et al. 2015, PNAS



Sheffer et al. 2012, Ecol Lett



Scanlon et al. 2007, Nature

Individual or colony? Examples in Tropical Alpine exosystems

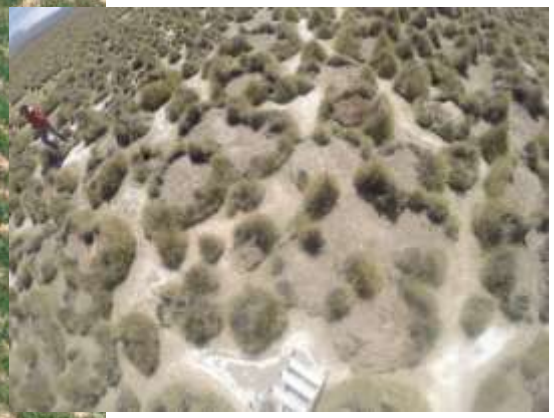


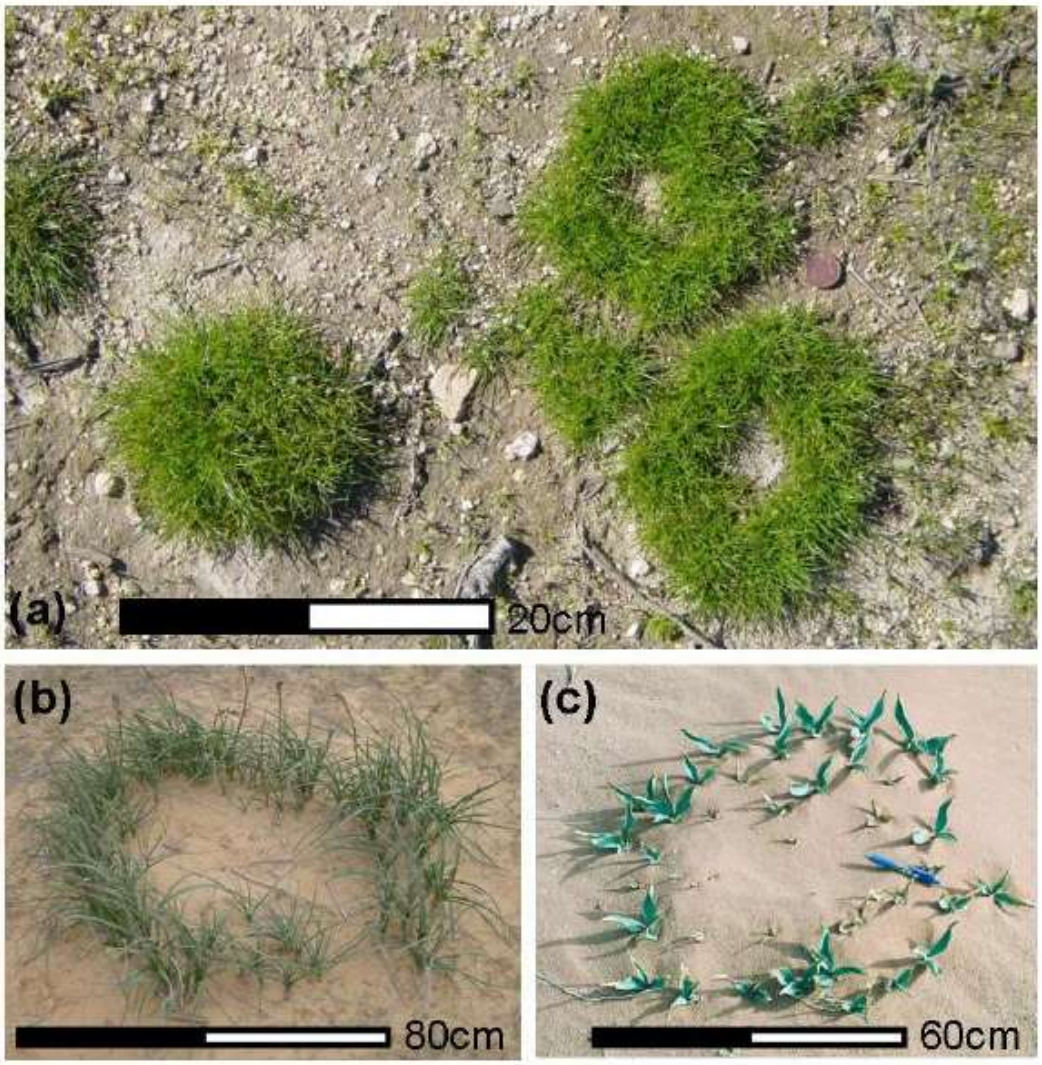
Photo Anthelme

Couteron et al. 2014, PTRS-A

Couteron et al. 2014, PTRS-A

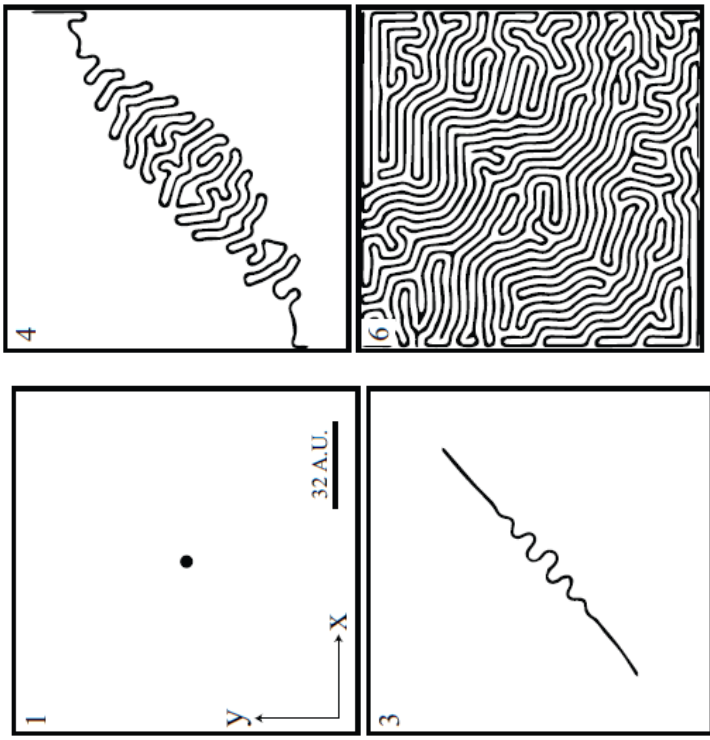
Photo Couteron

Ring-shaped tufts



Meron et al. 2007

Bordeu et al. 2015



Phot: Anthelme

Photo Anthelme

Photo Anthelme

Independent structures or systems?

Clonal patterns

- **Tussocks, cushions:**
  - patch « genets » often far larger than ramets
  - modal patch size (often)
  - patterns either periodic or aperiodic

Photo: F. Anthelme

***Panicum turgidum* Steppe (Niger)**

Photo: F. Anthelme

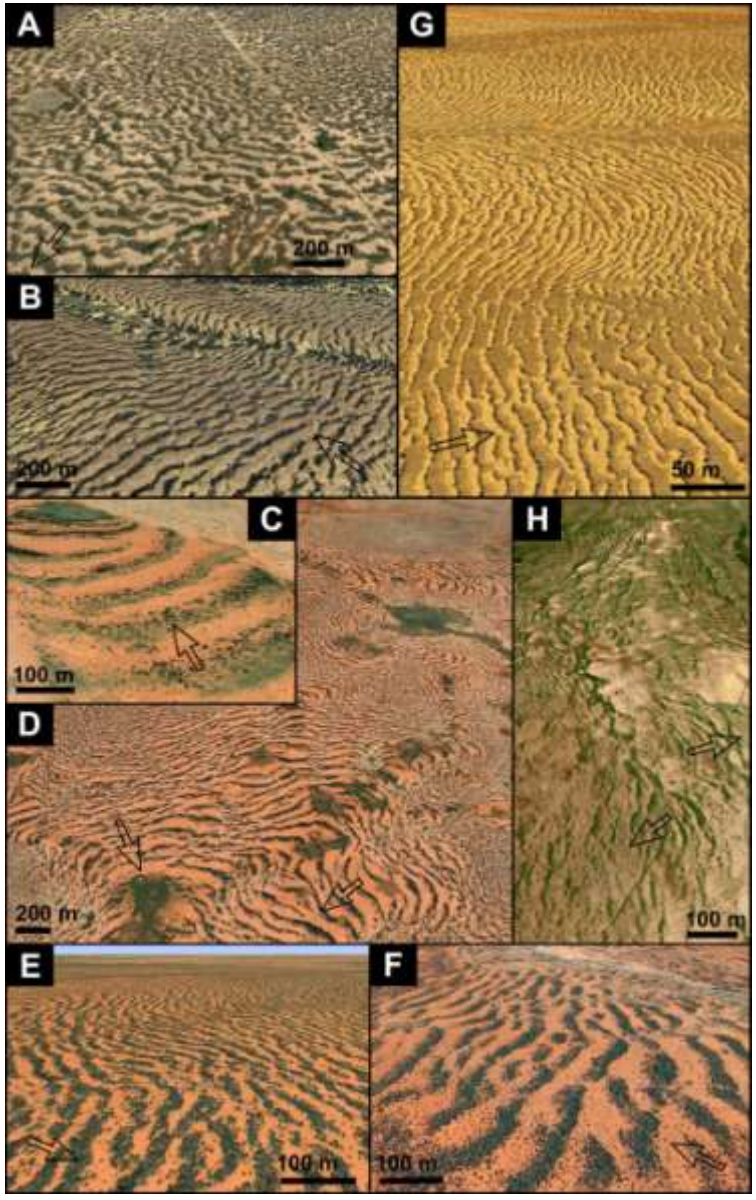
***Festuca orthophylla* tussocks (Bolivia)**

Ladakh

Photo Couteron

Venezuela, *Gran Sabana*

Global distribution

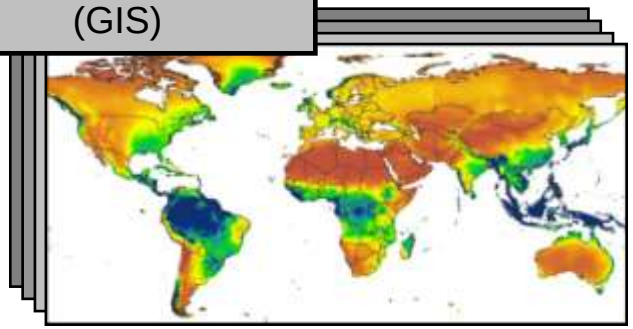


The patterns emerge under globally **coherent** physical conditions

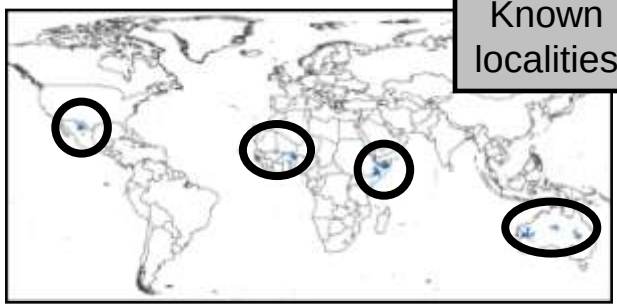
- *Climate*: semi-arid to arid, rare but violent rain pulses, PET >>1500 mm (feedback !)
- *Soil*: shallow, compact and crusted (feedback !), low OM and nutrient contents (feedback !)
- *Vegetation*: variable plant form & phylogeny but roots are superficial & extended

Can we predict the emergence of self organized vegetation ?

Bioclimatic predictors (GIS)

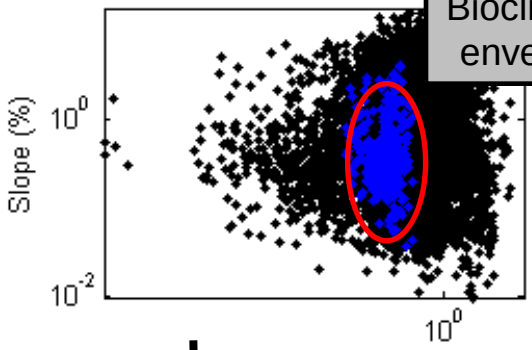


Known localities

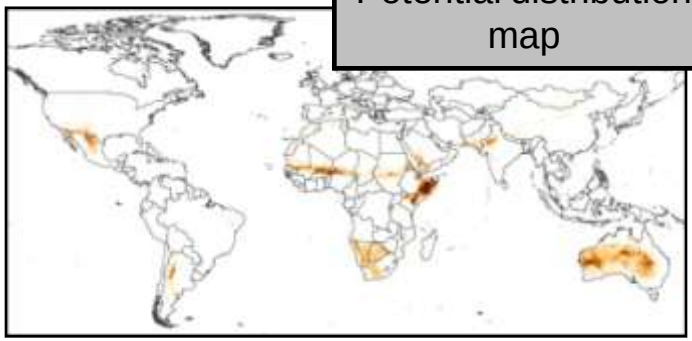


Model the probability of occurrence on the basis of the environmental conditions at known occurrence locations of periodic vegetation patterns

Bioclimatic envelope

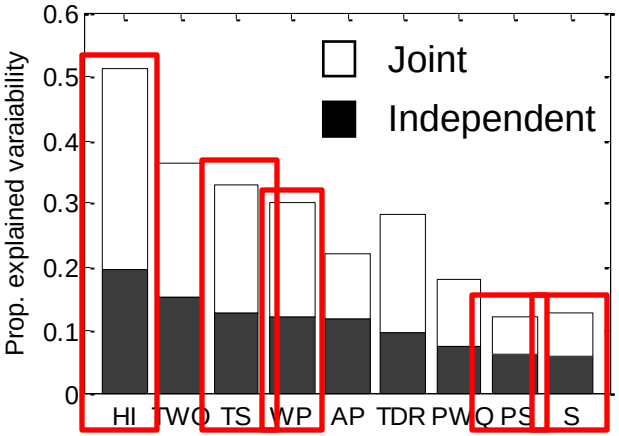


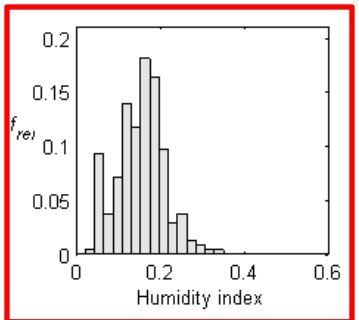
Potential distribution map

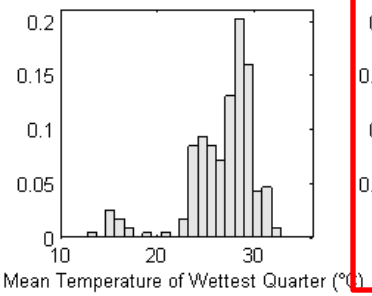


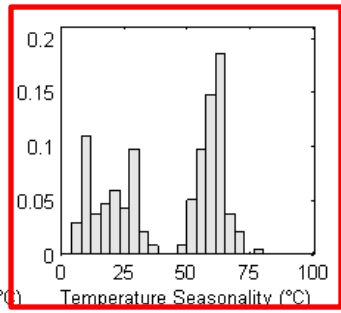
Relative contributions

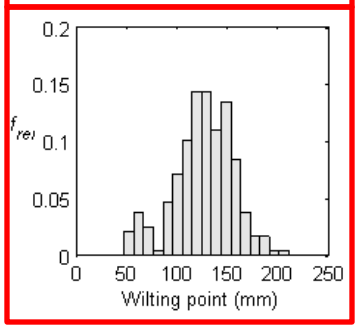
Relative importance of predictors

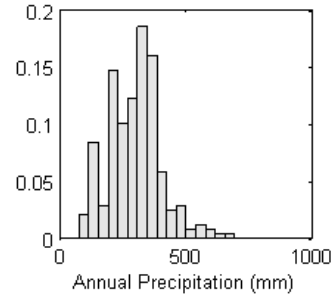


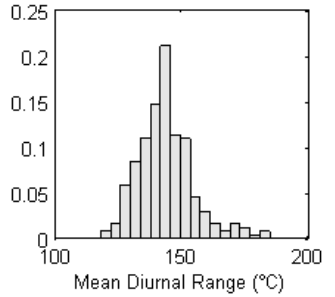


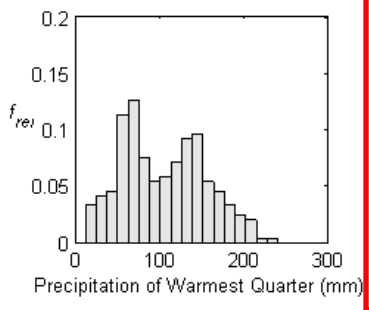


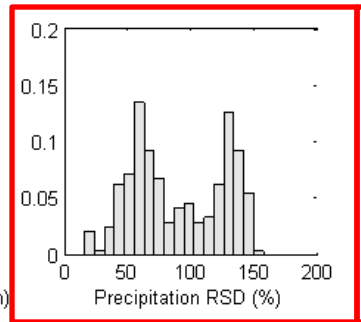


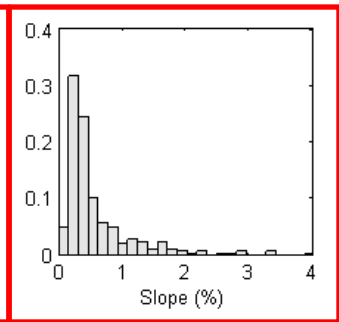


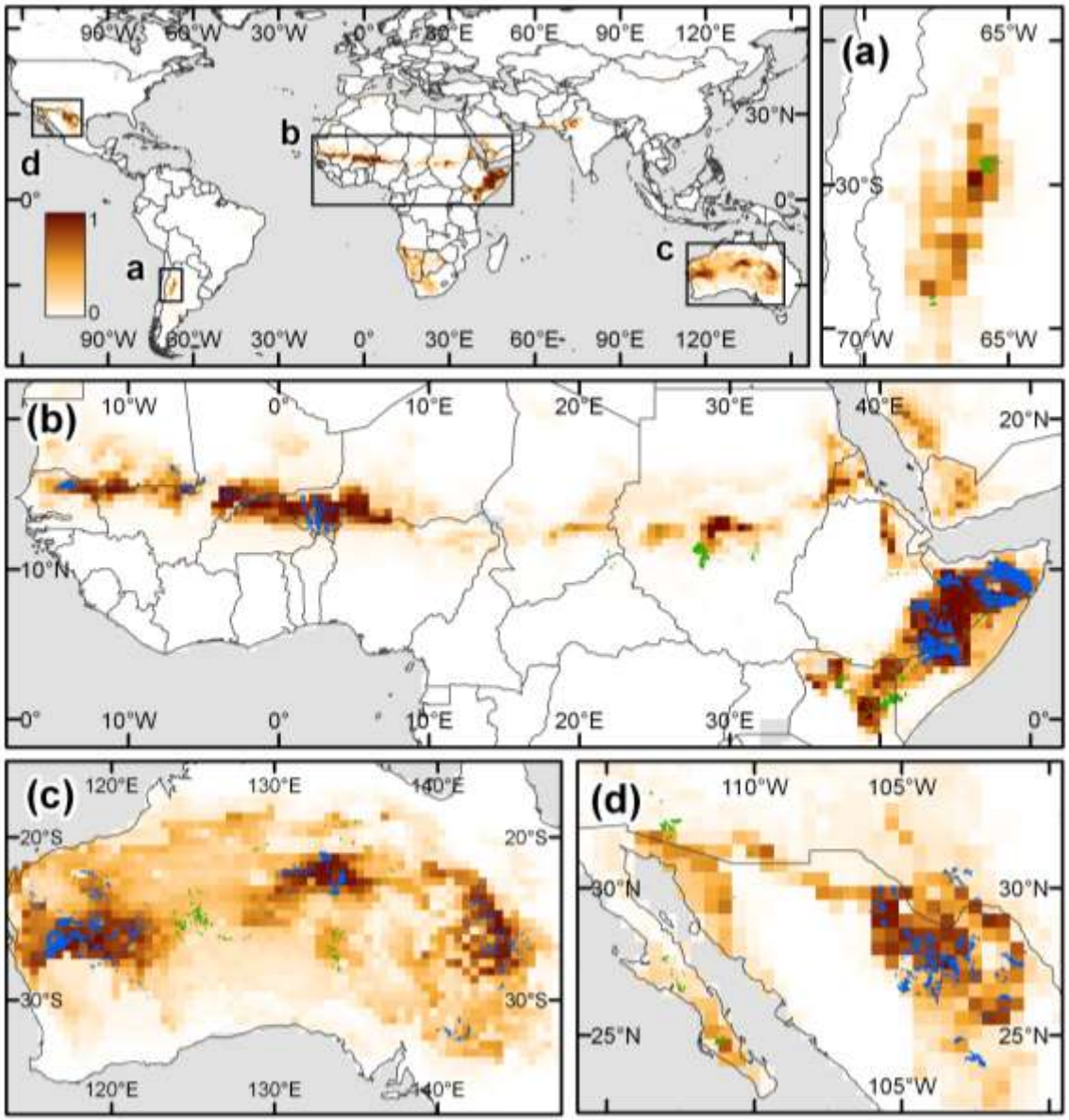






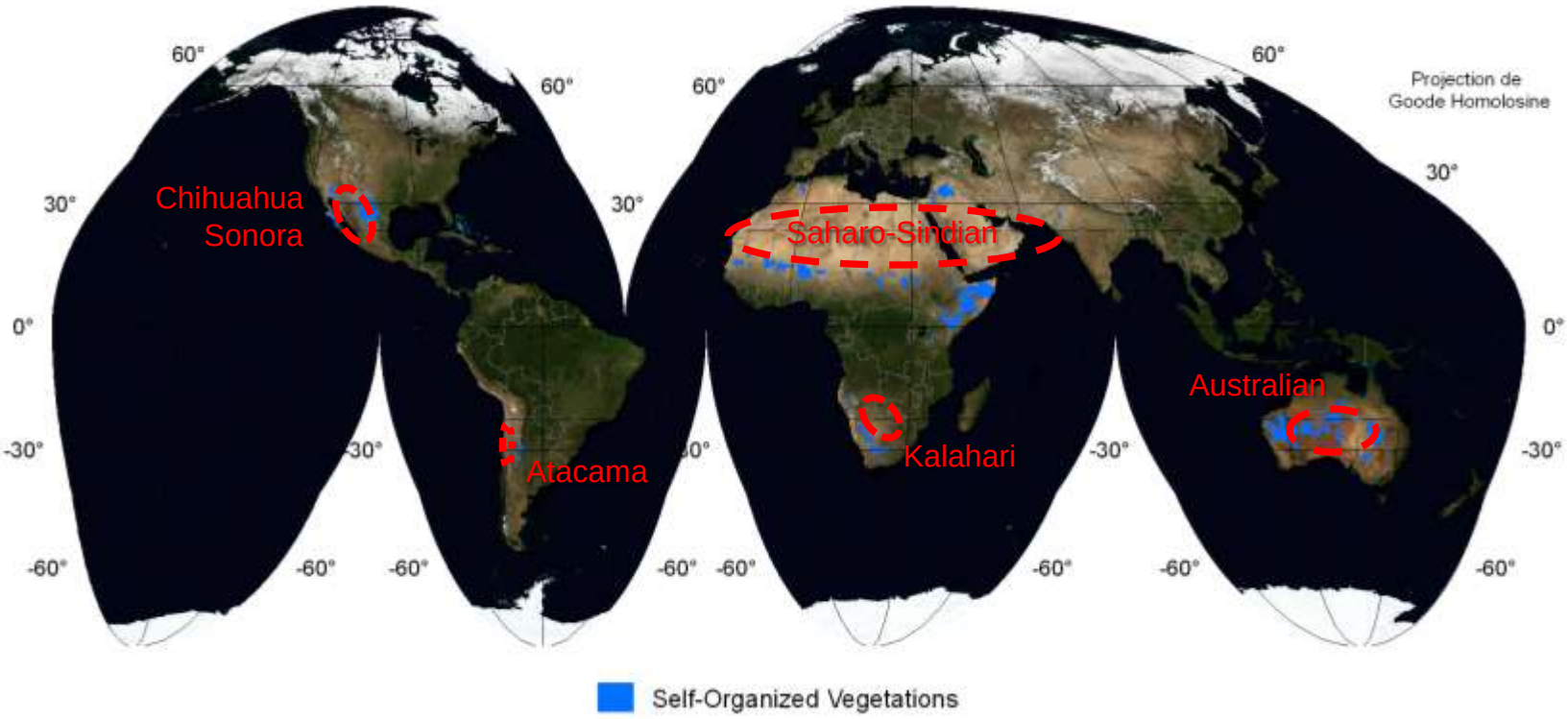




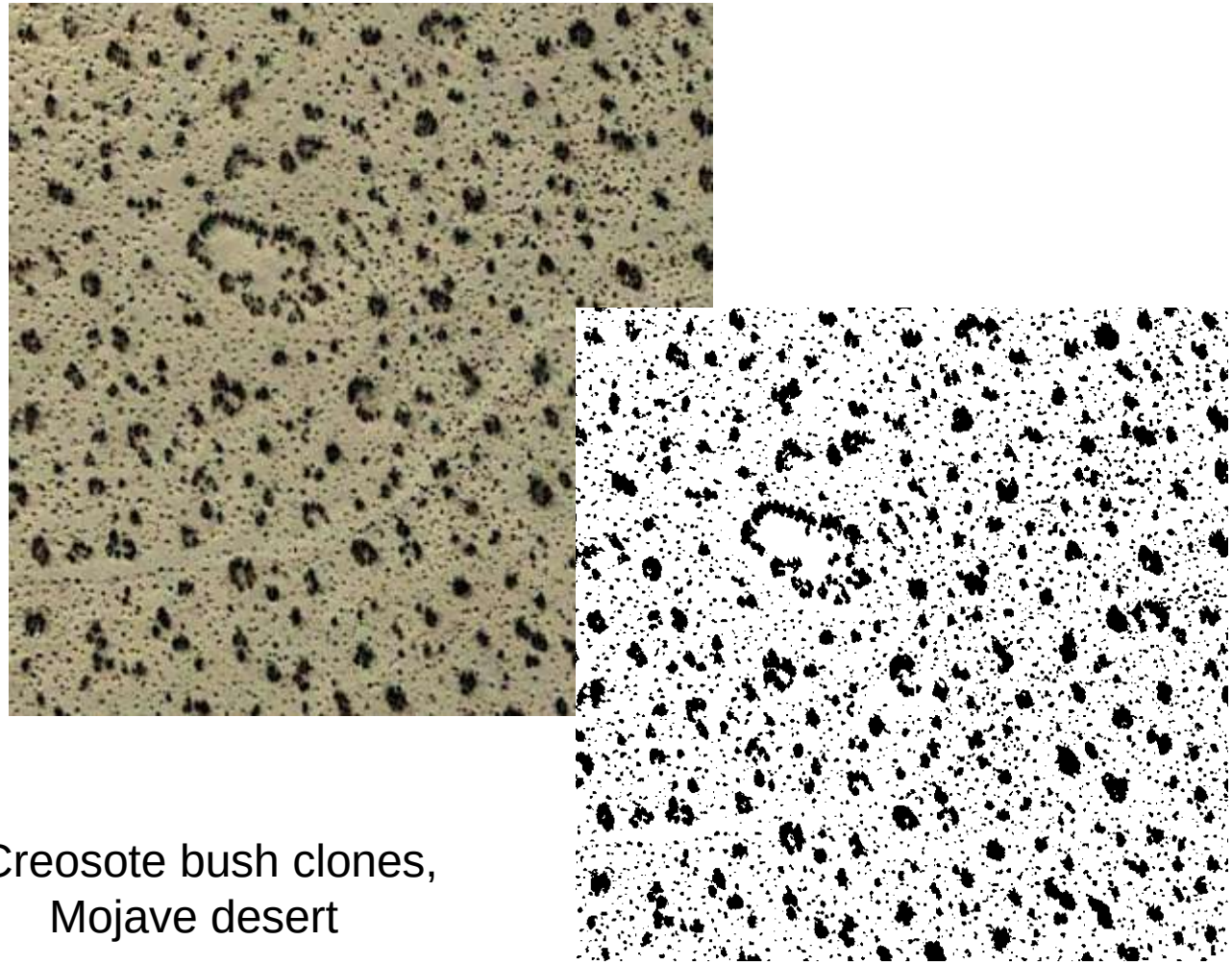


■ Training localities ■ New localities

- Demonstration of the **zonality** of periodic patterns at the border of every tropical deserts
- Mitigate the particular differences between distant vegetation patterns (**generality**)



Patch-oriented attributes: atch size distribution



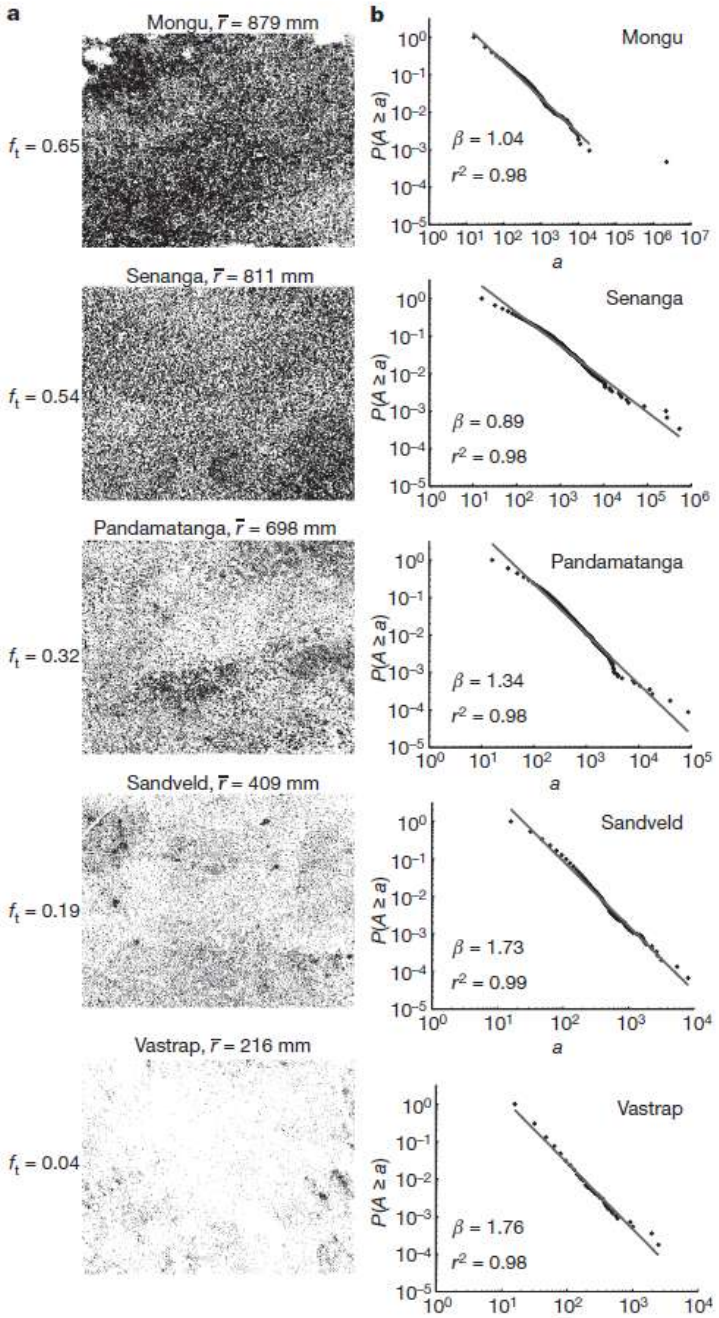
Creosote bush clones,
Mojave desert

Characterize patch size distribution

Irregular patterns may be characterized by a scale-free patch-size distribution, which means that there is **no typical patch size** in the ecosystem.

Power law: $P(S \geq s) = C\, s^{-\beta}$

where β is the estimated scaling exponent of the model, and C is a constant

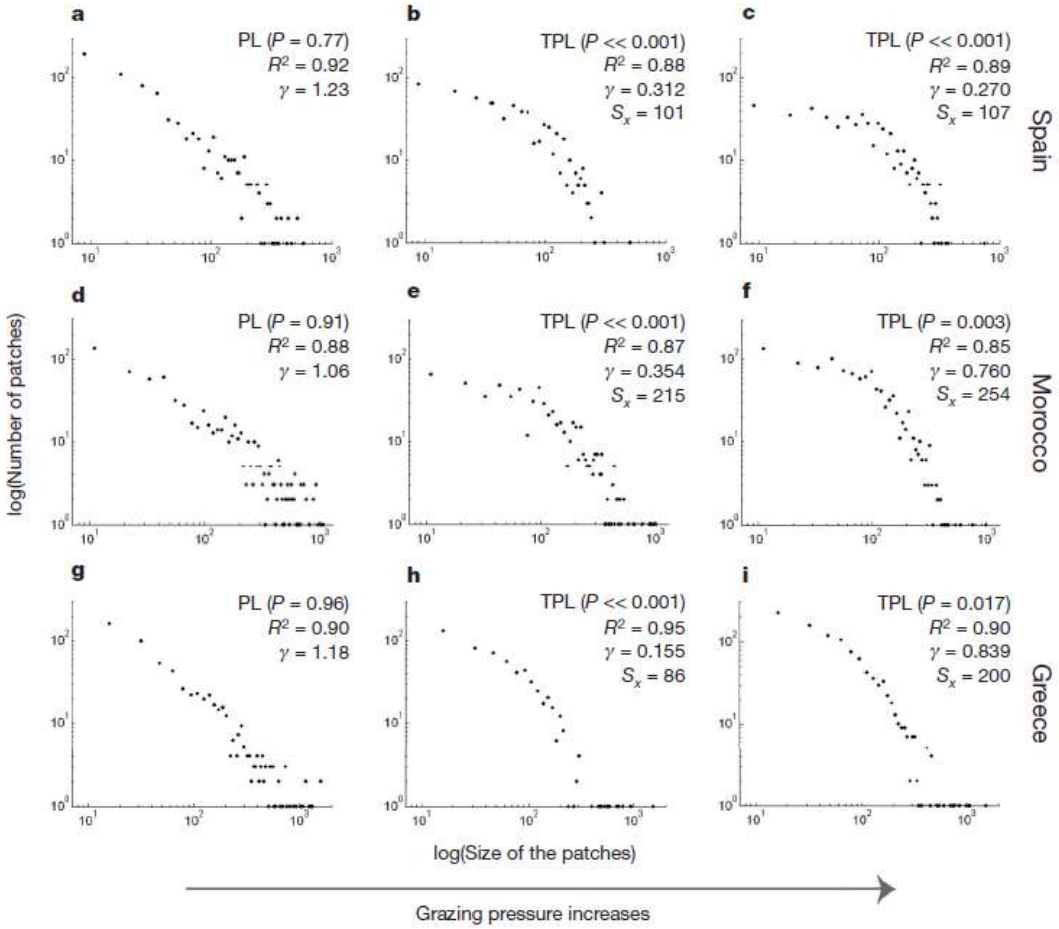


Scanlon et al 2007 Positive feedbacks promote power-law clustering of Kalahari vegetation, Nature

Scattered matorral (scrubland), Spain

Dense matorral (shrubland), Greece

High mountain Grassland, Morocco



absence of degradation: power law:

$N(S) = C\ S^{-\beta}$ where β is the estimated scaling exponent of the model, and C is a constant

presence of degradation: truncated power law:

$N(S) = C\ S^{-\beta}\ e^{-(S/Sx)}$, *Sx* the patch size above which *N(S)* decreases faster than in a power law

Kefi et al 2007 Spatial vegetation patterns and imminent desertification in mediterranean arid ecosystems, Nature

Highlights

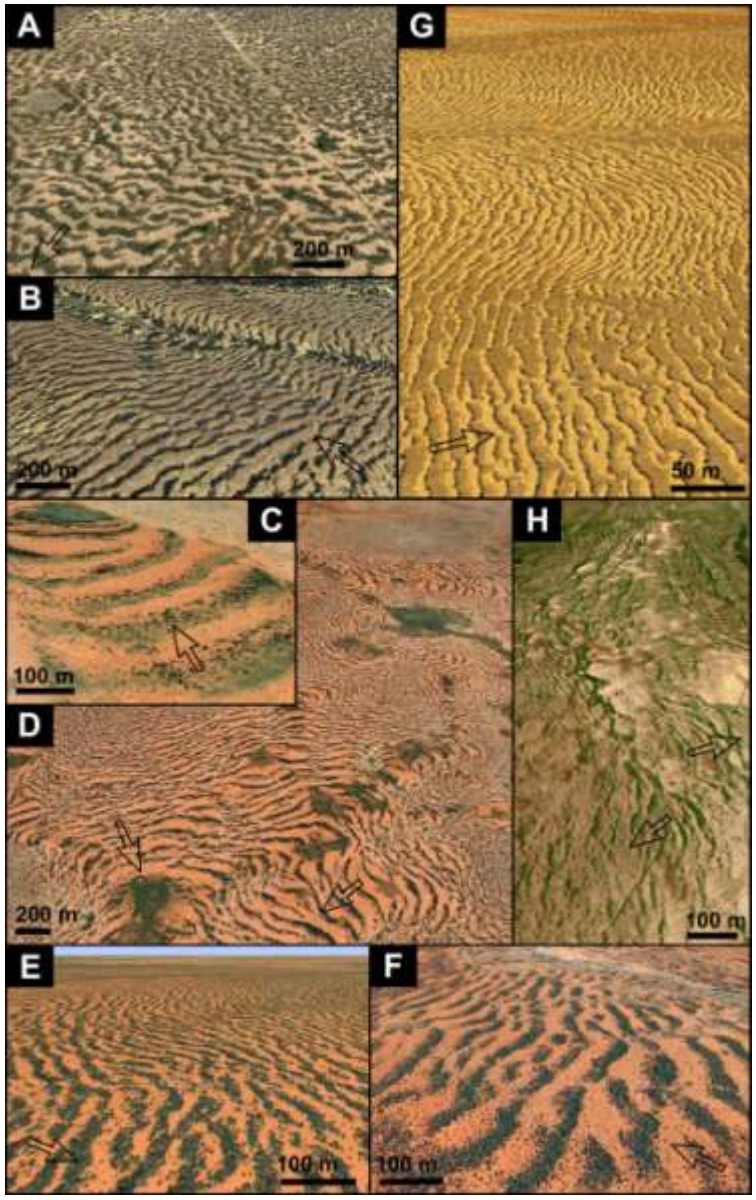
Lecture I: characterization tools for diverse patterns

- The diversity of patterns and the worldwide distribution of periodic patterns
- Features for pattern characterization (from images):
  - Patch-oriented attributes
  - Textural attributes (features)

Lecture II: From plant-plant interactions to patterns and vice-versa:

- Predictions from a simple modelling framework
- Combining features to distinguishing classes of patterns
- Application to real-world patterns
- **=> group works**

Case studies in semi-arid landscapes



Tiger bush: periodic bands parallel to countour lines

(A) Dosso, **Niger**

(B) Trans-Pecos, **Texas**

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(F) Ogaden, **Ethiopia**

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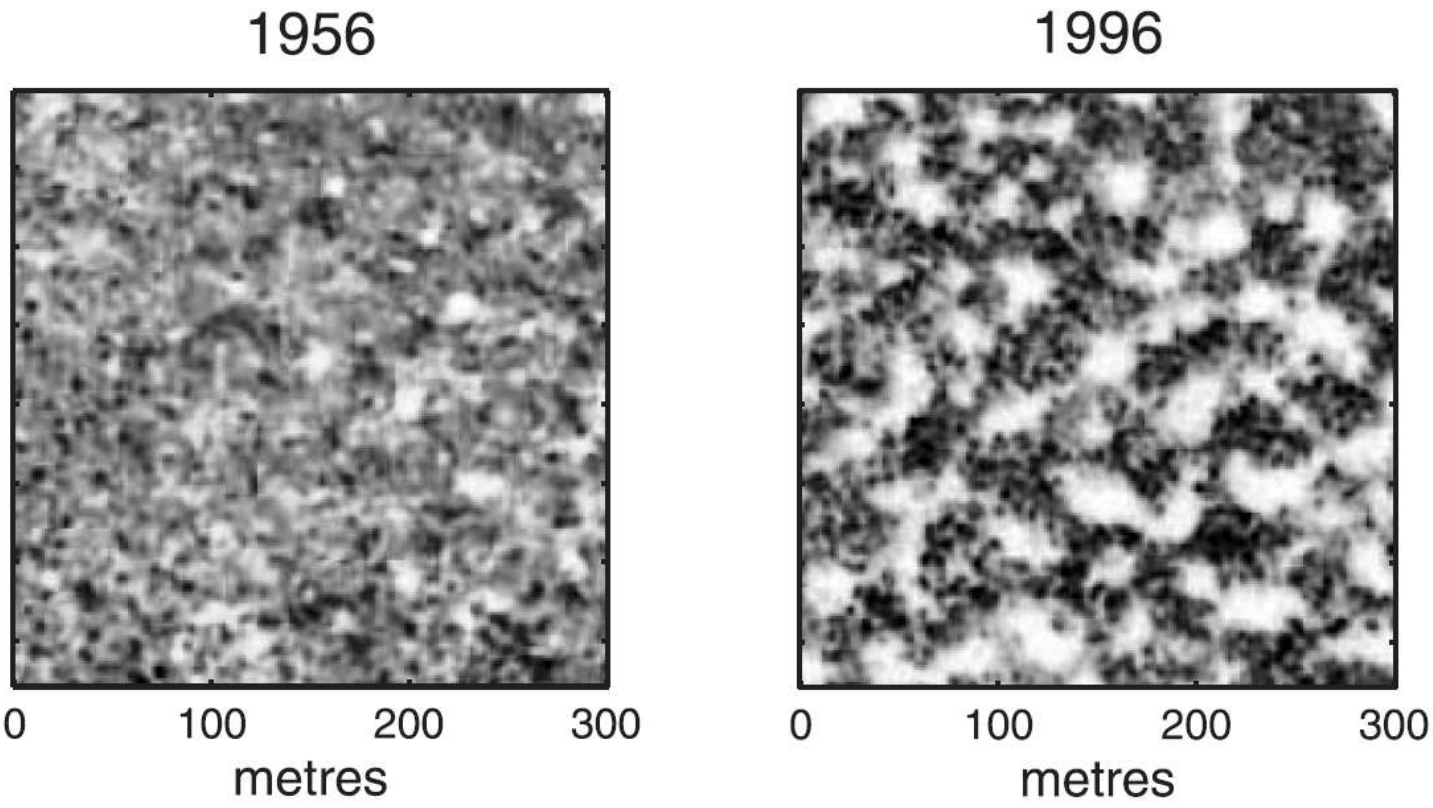
(H) Butana, **Sudan**

Self-Organized vegetation

- Pattern (macroscopic scale) emerge as a result of local interactions (microscopic scale) between plants (and ressources):
  - **Short-range facilitation** processes: evapotranspiration, soil permeability, sediments, seed trapping , etc. → positive feedback loop
  - **Long-range competition** processes: surface and underground water transport, water suction by plant roots, etc.



Barbier, N., Couteron, P., Lejoly, J., Deblauwe, V. & Lejeune, O. (2006) *Journal of Ecology,* **94,** 537-547.

I. Types of simulated patterns: cellular automaton

One state variable

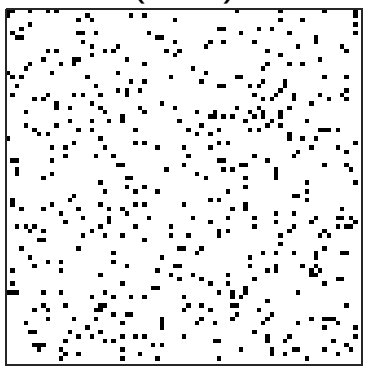
- Biomass (*B*)

Ecological processes

- Long range competition
- Short range facilitation

B_t

Homogeneous poissonian distribution (CSR)



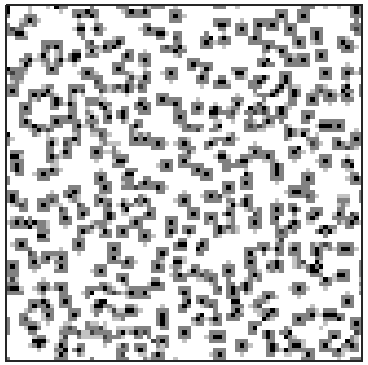
Convolution

Interaction kernel

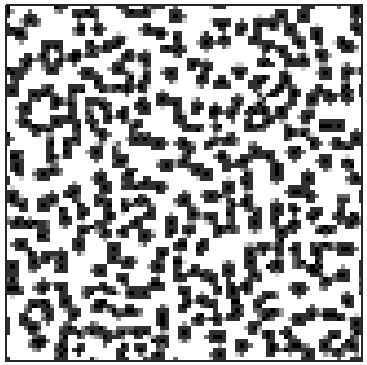
-2	-2	-2	-2	-2
-2	4	4	4	-2
-2	4	4	4	-2
-2	4	4	4	-2
-2	-2	-2	-2	-2

$B_{t+1} = B_t * K$

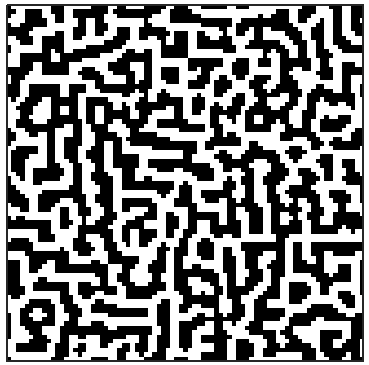
B_{t+2}



B_{t+10}



B_{t+100}



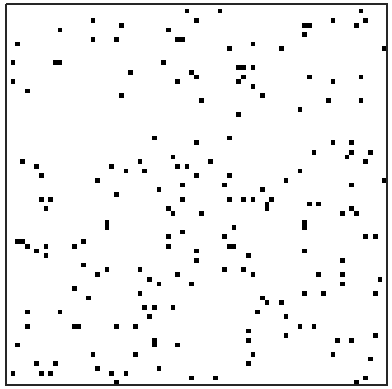
Interaction kernel

-2	-2	-2	-2	-2
1	4	4	4	1
1	4	1	4	1
1	4	4	4	1
-2	-2	-2	-2	-2
0	-2	-2	-2	0
0	-2	-2	-2	0
0	-2	-2	-2	0
0	0	-2	0	0

B_t

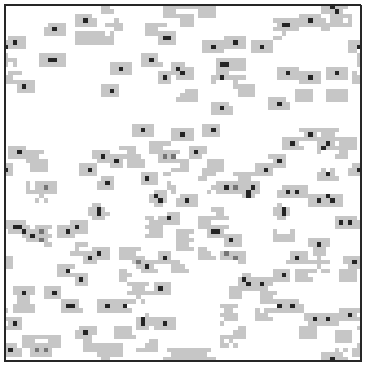
Homogeneous poissonian distribution (CSR)

Convolution

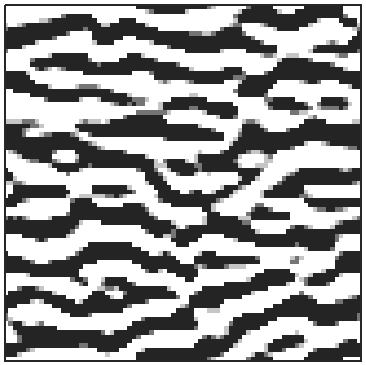


$B_{t+1} = B_t * K$

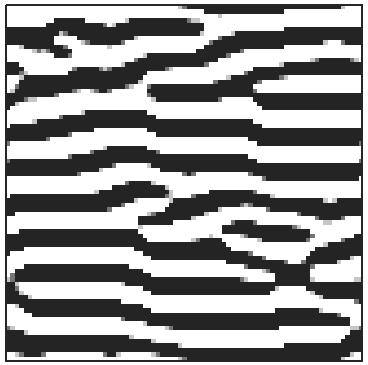
B_{t+2}



B_{t+5}

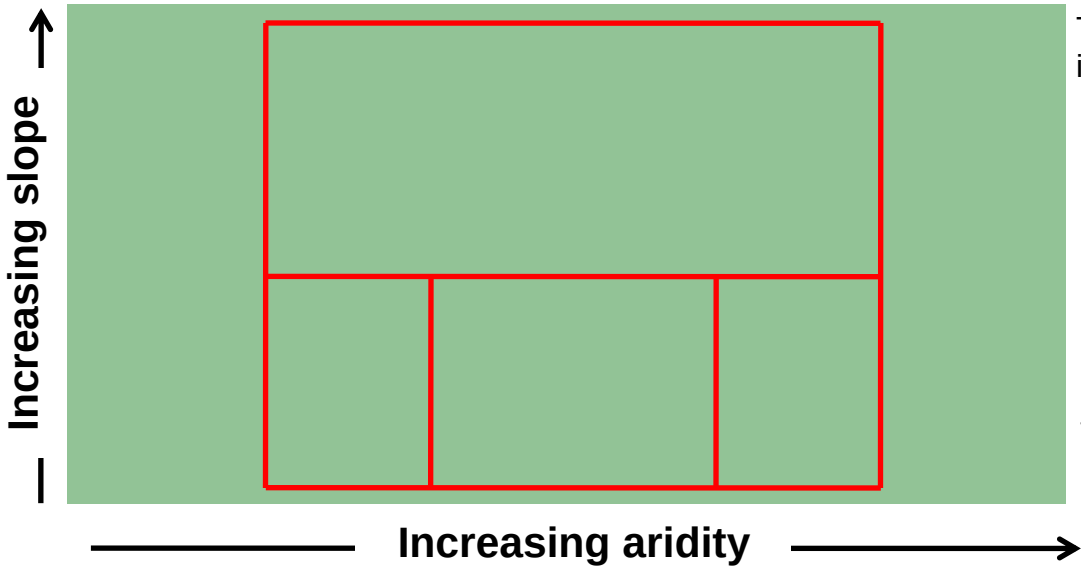


B_{t+100}



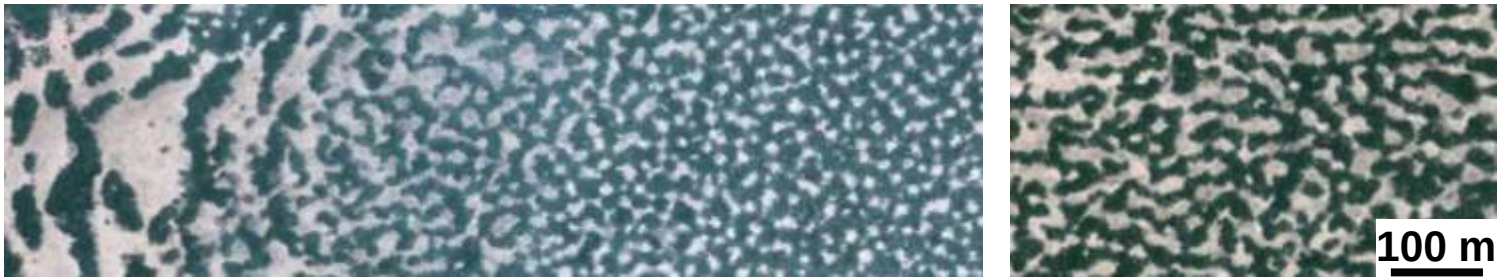
Macroscopic model predictions

System instability models (reviewed by Borgogno *et al.* 2009) invoking different local processes **agree on fundamental predictions**



The vegetation appears in green

Model from Lefever, R., Barbier, N., Couteron, P. & Lejeune, O. (2009). *Journal of Theoretical Biology,* **261,** 194-209.



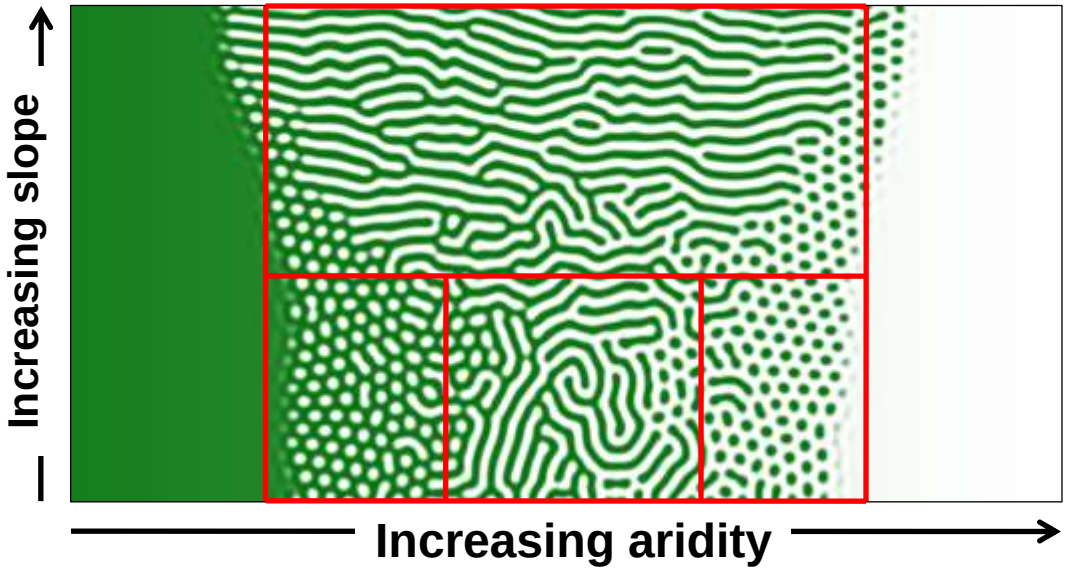
Patterns are dynamically related

Suggest modulation in **wavelength and symmetry** by environmental conditions

Continuous **upslope migration** of the oriented bands

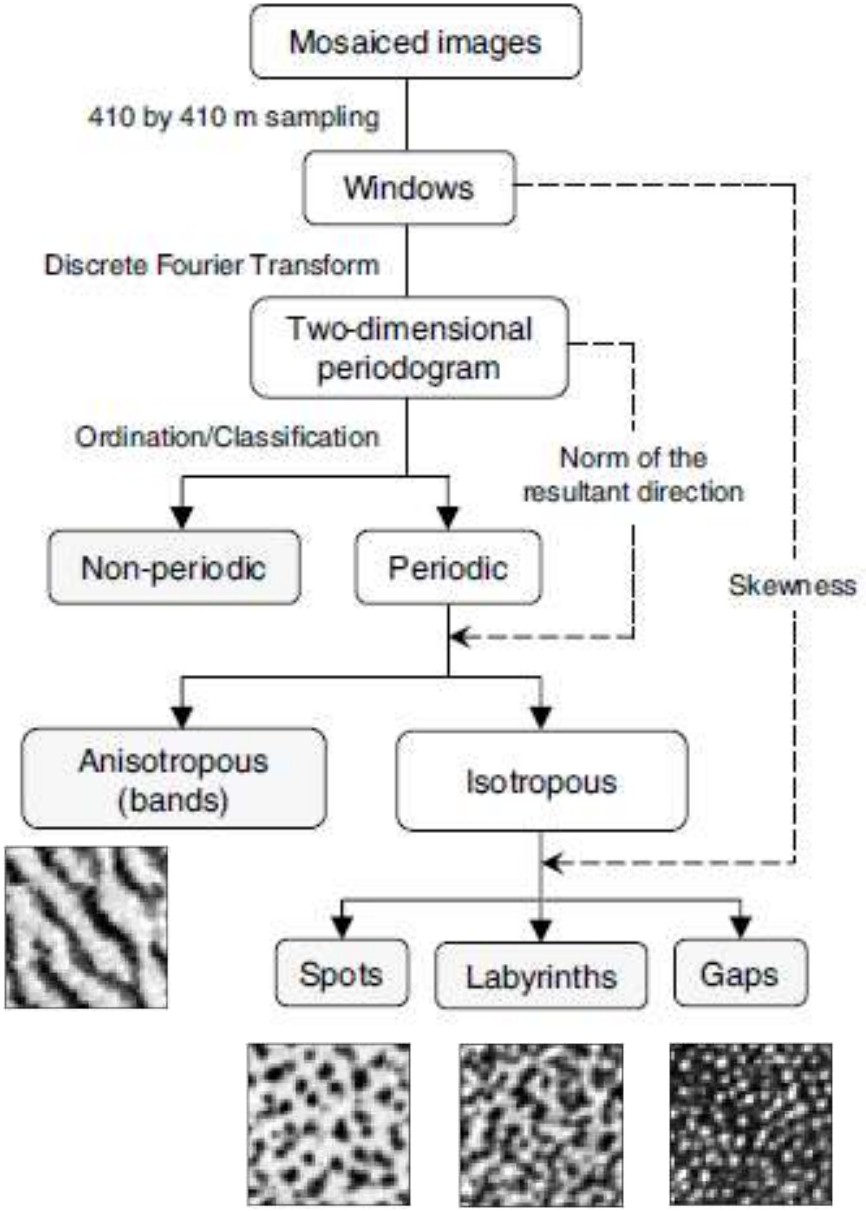
Symmetry and wavelength

- Existence of a pattern **sequence** at the transition between homogeneous vegetation and desert: gapped, labyrinthine and spotted with increasing aridity
- Transition to **parallel bands** above a given slope threshold
- **Wavelength** is proportional to aridity level



Barbier N, Couteron P, Lejoly J, Deblauwe V, Lejeune O (2006) Self-organized vegetation patterning as a fingerprint of climate and human impact on semi-arid ecosystems. *Journal of Ecology* 94: 537-547.

Deblauwe V, Couteron P, Lejeune O, Bogaert J, Barbier N (2011) Environmental modulation of self-organized periodic vegetation patterns in Sudan. *Ecography* 34: 990-1001.


Mosaiced images
410 by 410 m sampling
Windows
Discrete Fourier Transform
Two-dimensional periodogram
Ordination/Classification
Norm of the resultant direction
Non-periodic
Periodic
Skewness
Anisotropous (bands)
Isotropous
Spots
Labyrinths
Gaps

Discrete Fourier Transform (DFT)

Spatial domain

115	156	145	171	221
102	161	127	140	253
124	143	138	106	171
102	119	135	47	67
152	189	71	0	130

DFT

IDFT

Frequency domain

-98 + 27 i	235 + 32 i	-37 + 101 i	192 + -59 i	-61 + 39 i
15 + -133 i	380 + 149 i	-249 + 382 i	-60 + -230 i	96 + -168 i
-374 + -188 i	220 + 20 i	3288 + 0 i	220 + -20 i	-374 + 188 i
96 + 168 i	-60 + 230 i	-249 + -382 i	380 + -149 i	15 + 133 i
-61 + -39 i	192 + 59 i	-37 + -101 i	235 + -32 i	-98 + -27 i

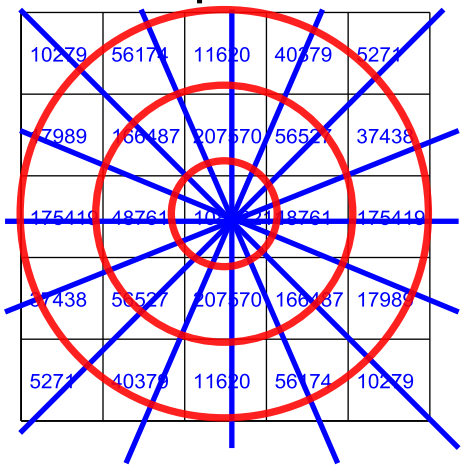
radial-spectrum

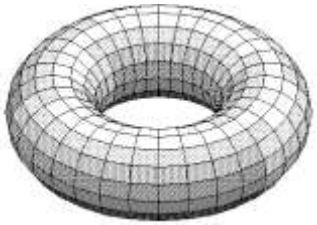
polar-spectrum

Phase angle

2.87	0.14	1.92	-0.30	2.57
-1.46	0.37	2.15	-1.83	-1.05
-2.68	0.09	0.00	-0.09	2.68
1.05	1.83	-2.15	-0.37	1.46
-2.57	0.30	-1.92	-0.14	-2.87

Amplitude





Assumptions: **stationary** signal, **periodic boundary** conditions , ie. torus (windowing, wavelet)

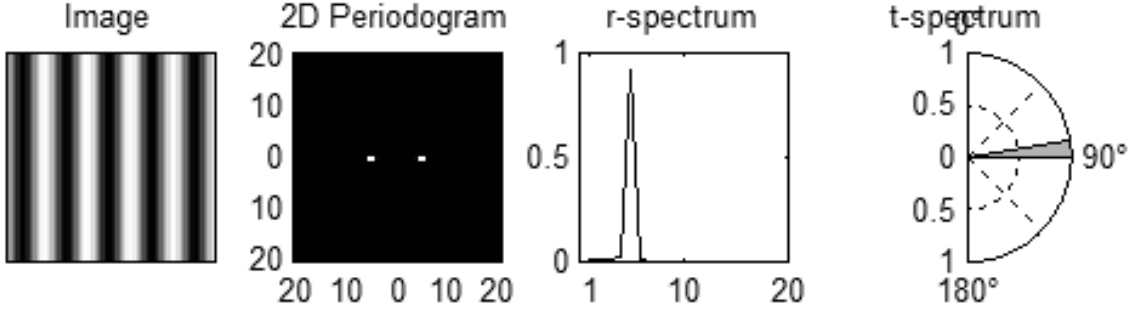
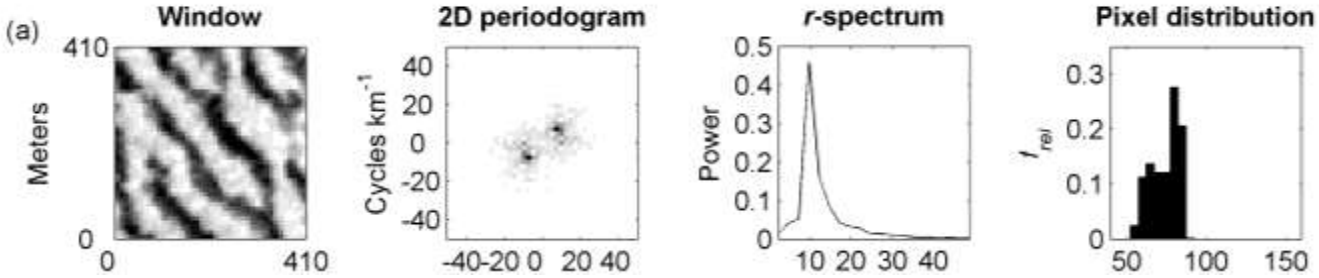


Image
2D Periodogram
r-spectrum
t-spectrum
20
10
0
10
20
20 10 0 10 20
1
0.5
0
1 10 20
0°
90°
180°

Quantify pattern symmetry from 2D periodogram

Bands

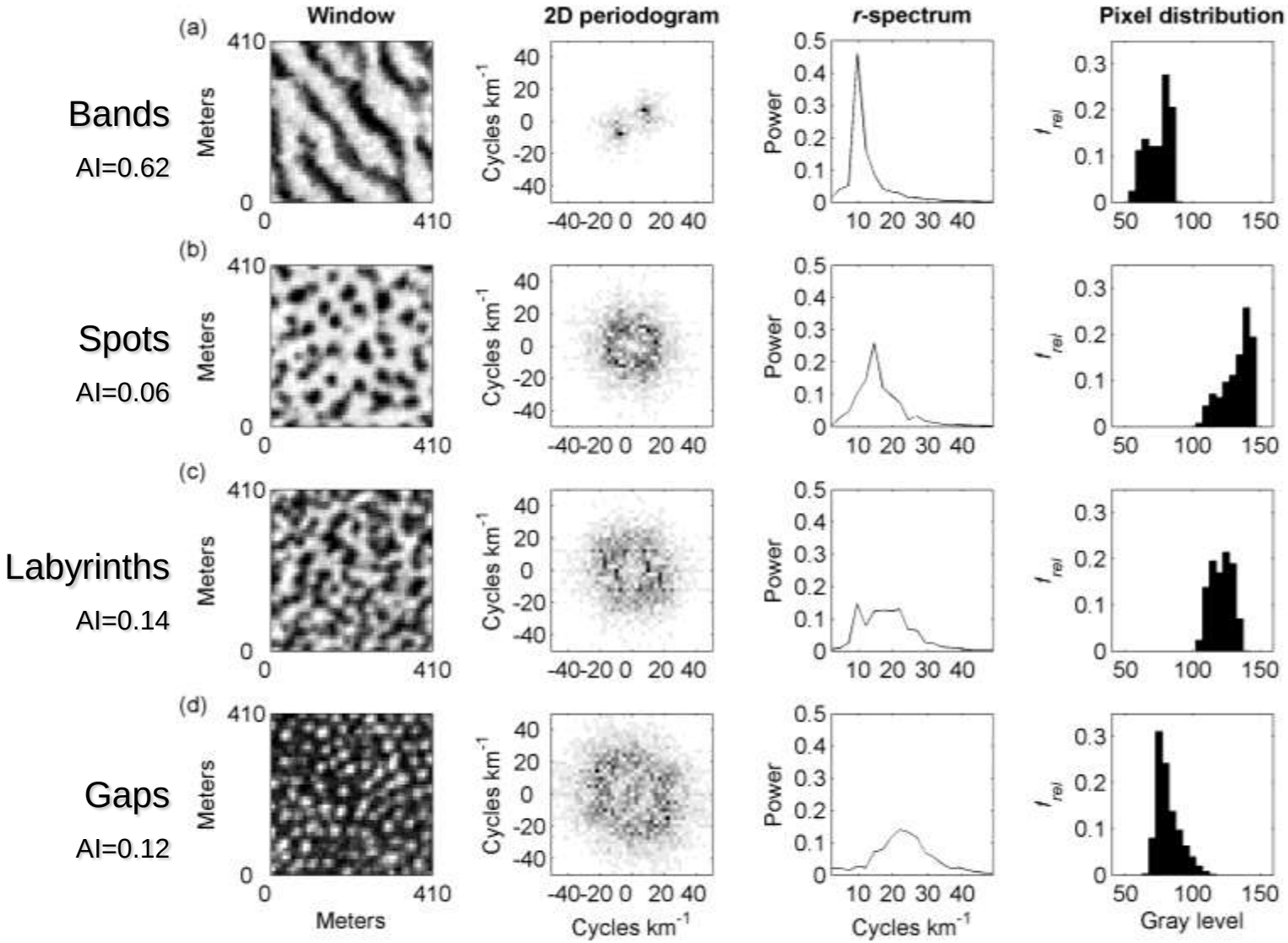
AI=0.62



Considering the periodogram entries as a set of **vectors** characterized by direction and amplitude, we can calculate the direction and **norm** of the resultant vector (anisotropy index)

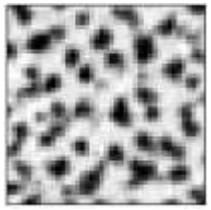
Deblauwe *et al* 2011 Environmental modulation of self-organized periodic vegetation patterns in Sudan

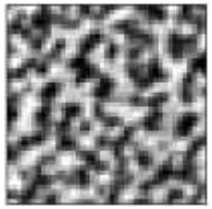
Determine pattern type from 2D periofogram

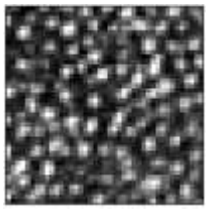


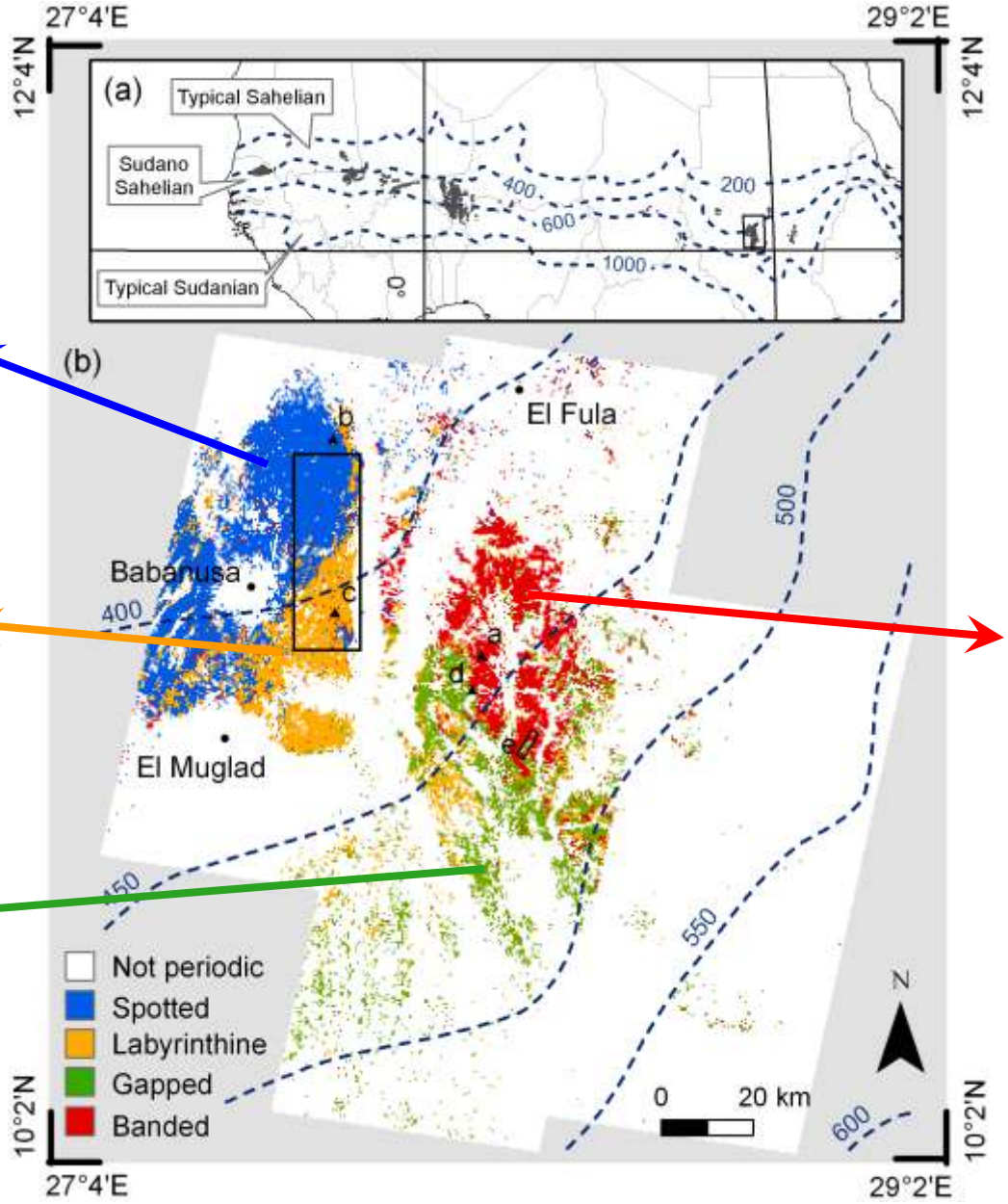
Deblauwe *et al* 2011 Environmental modulation of self-organized periodic vegetation patterns in Sudan

Spatial dynamics

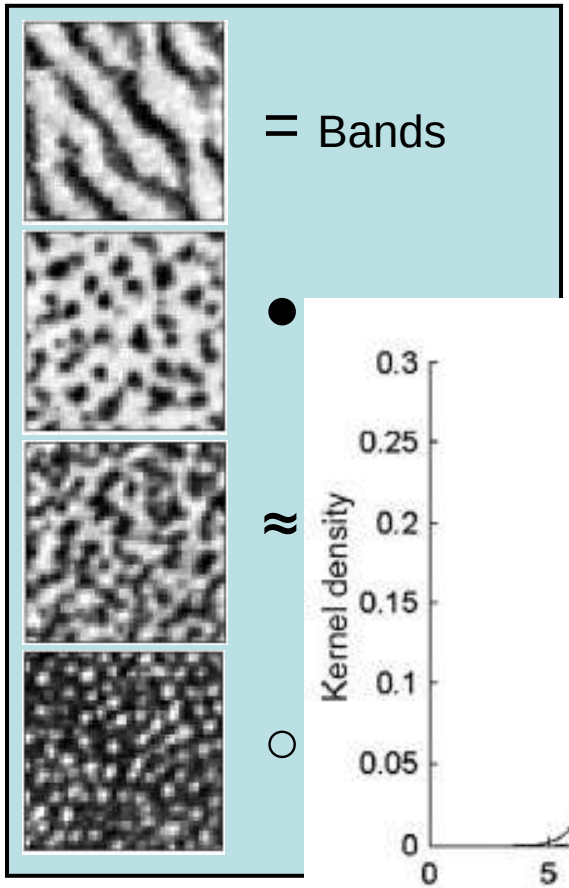


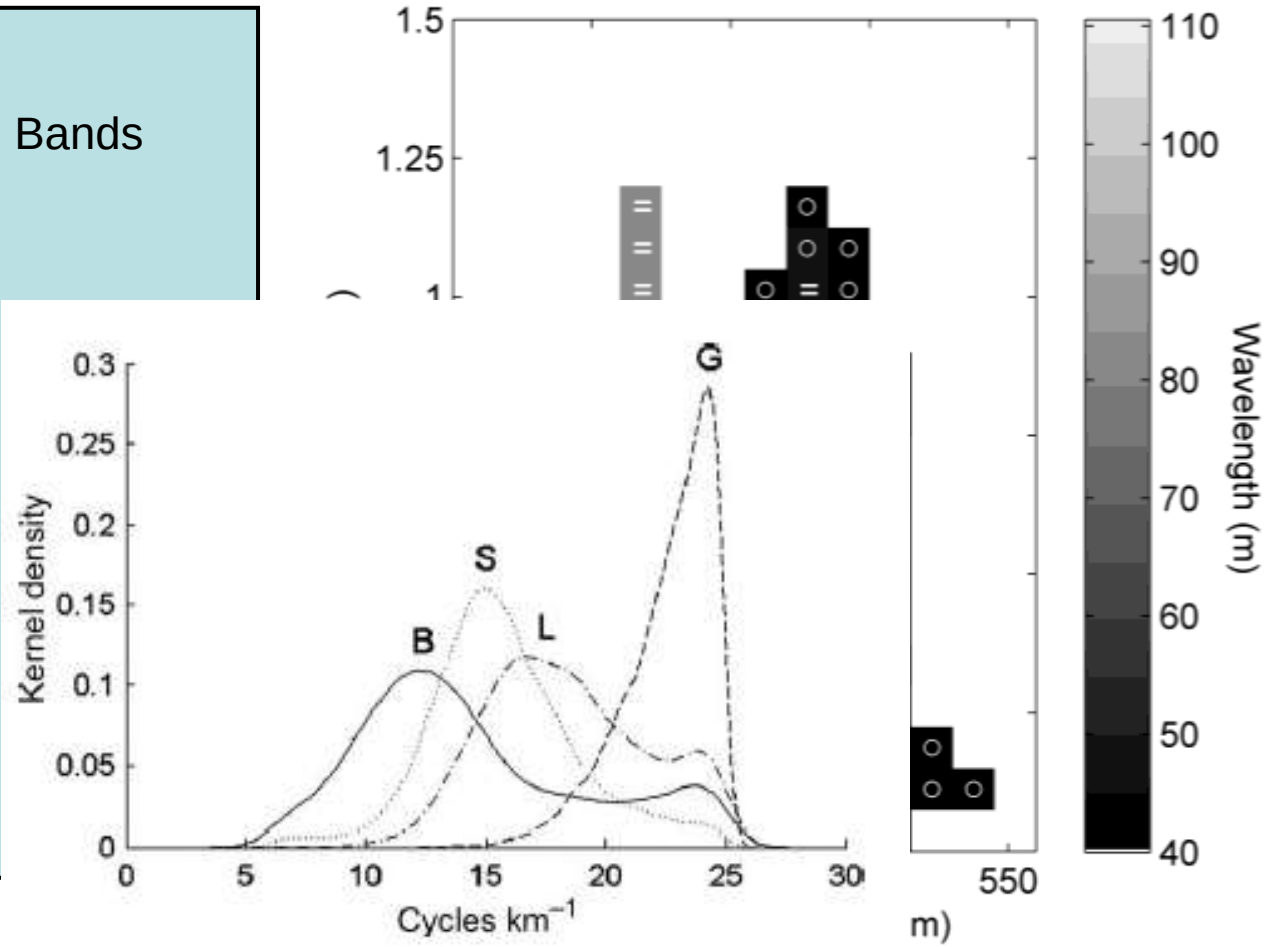


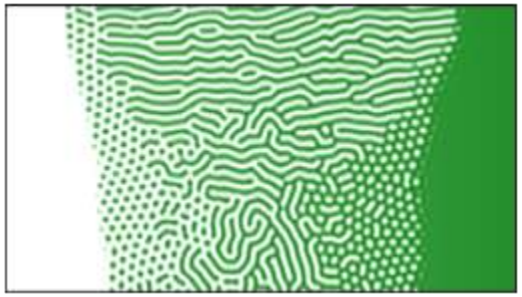




Spatial Dynamics

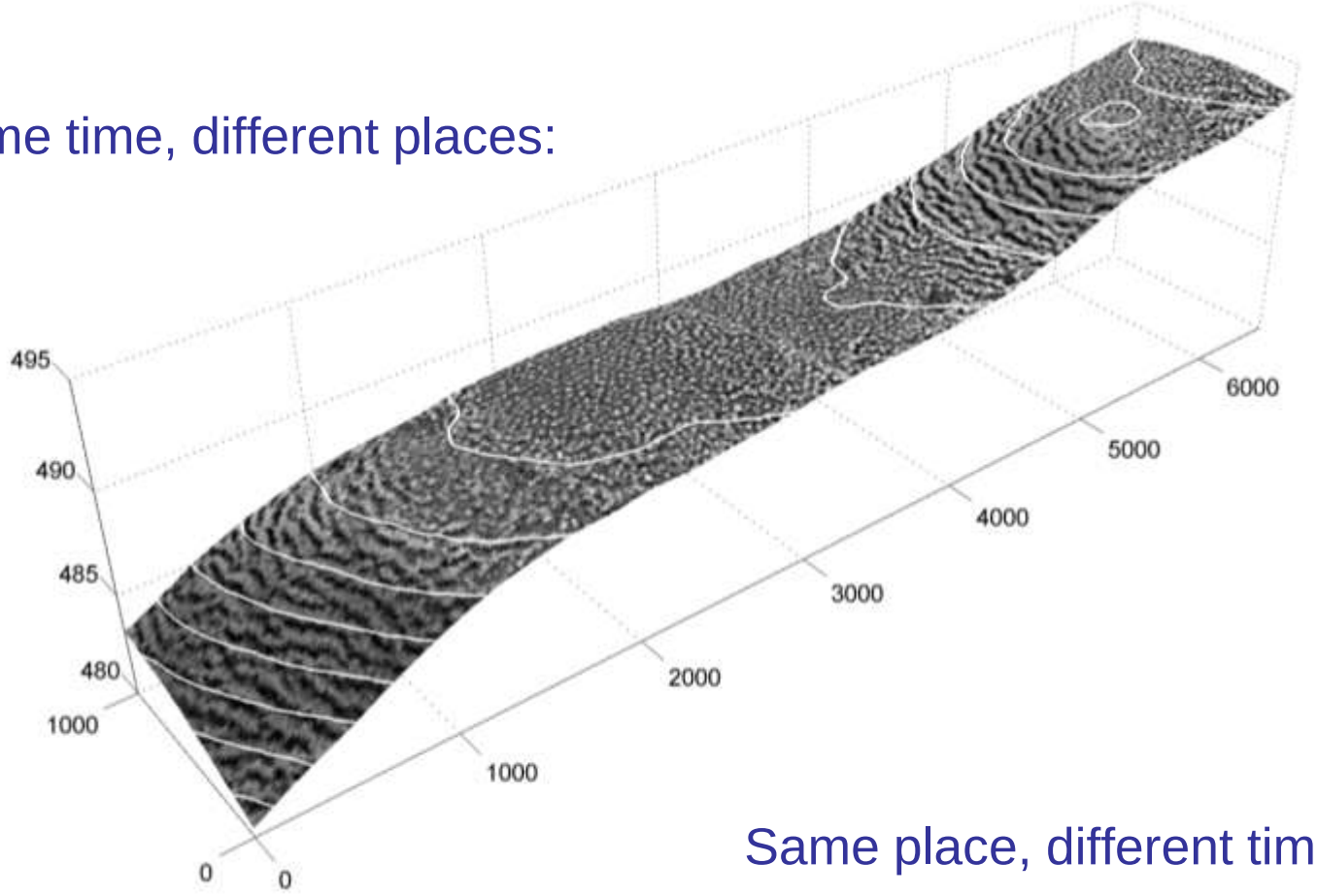




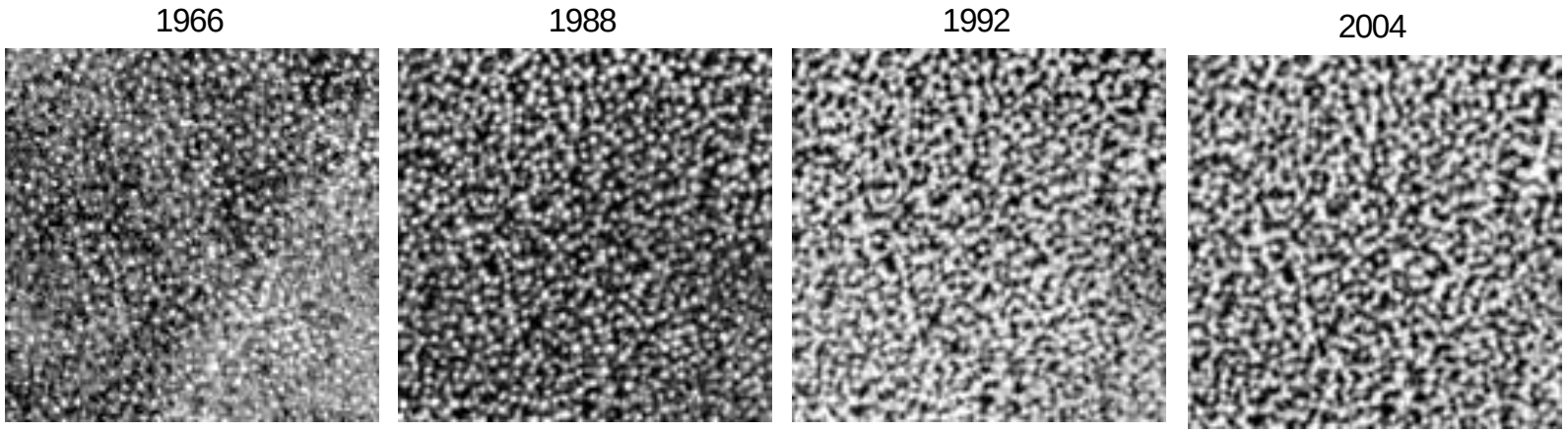


- Pattern **sequence** along aridity gradient
- Transition to **parallel bands** on sloping ground
- **Wavelength** is positively correlated with aridity

Same time, different places:



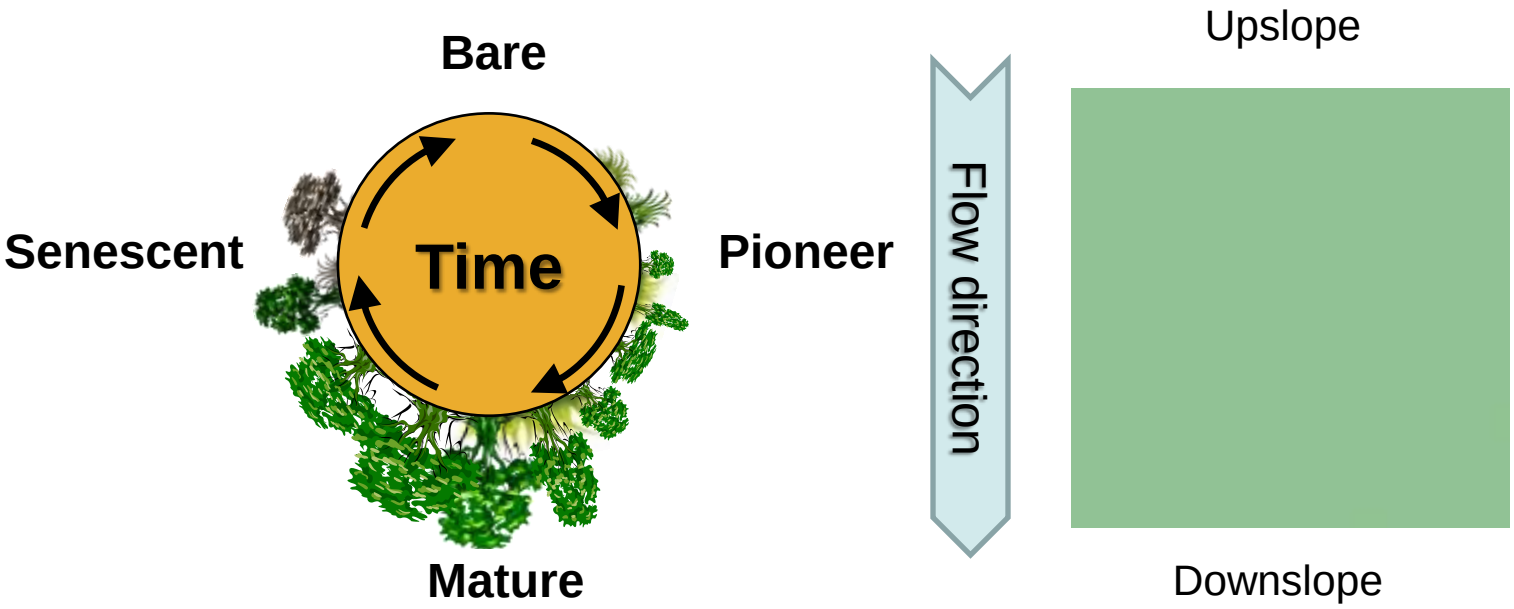
Same place, different times:



Pattern migration

Soil evolution, physiology, ecological communities, mathematical models:

The banded patterns which occur on sloping terrains undergo a slow **upslope migration** which is **continuous** and **synchronous** on both band edges

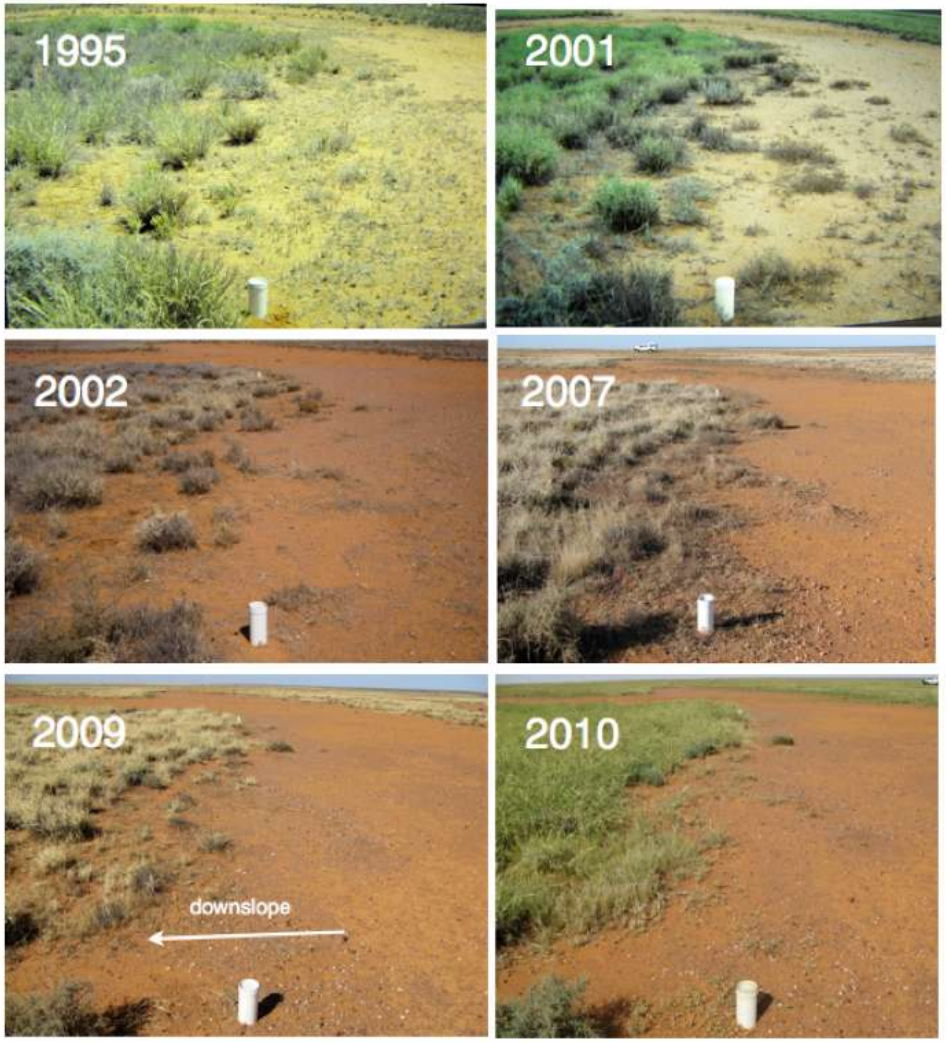


Deblauwe V, Couteron P, Lejeune O, Bogaert J, Barbier N (2012) Determinants and dynamics of banded vegetation pattern migration in arid climates. *Ecological Monographs* 82: 3-21.

But no field evidences...

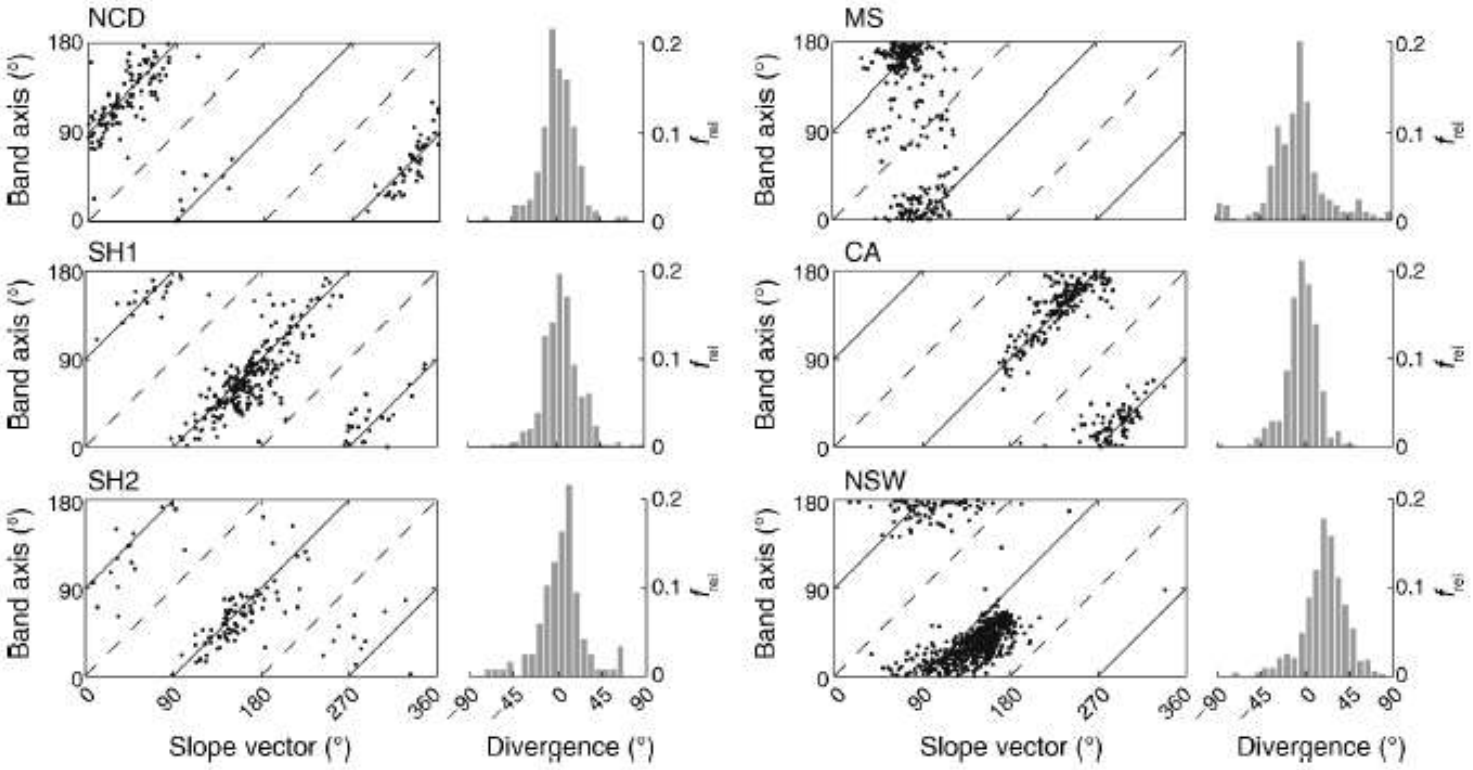
Reality check 2: Menindee banded vegetation: grove edge monumented since 1995

Note no detectable shift in 16 years despite SOI in range -28.5 (March 1988) to +27.1 (December 2010)

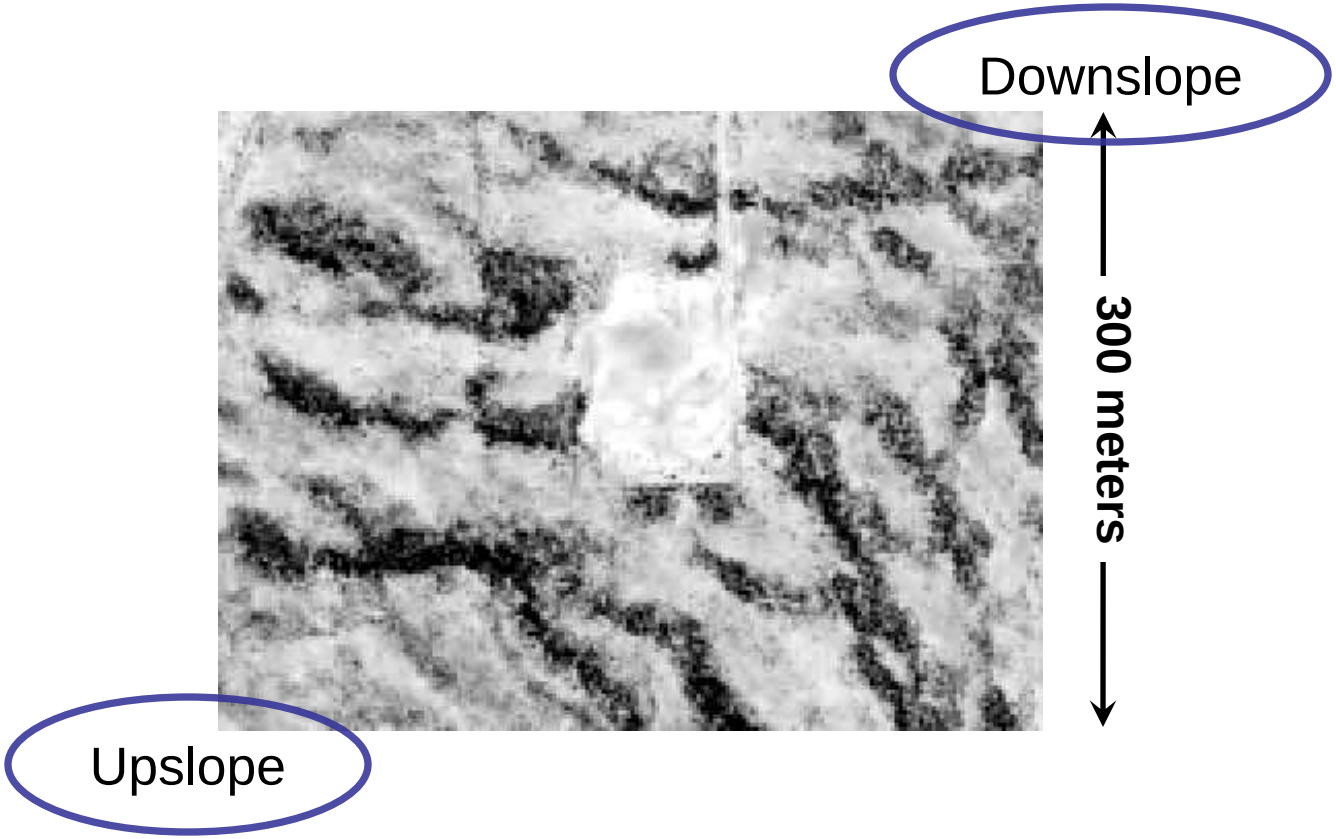


Courtesy of David Dunkerley

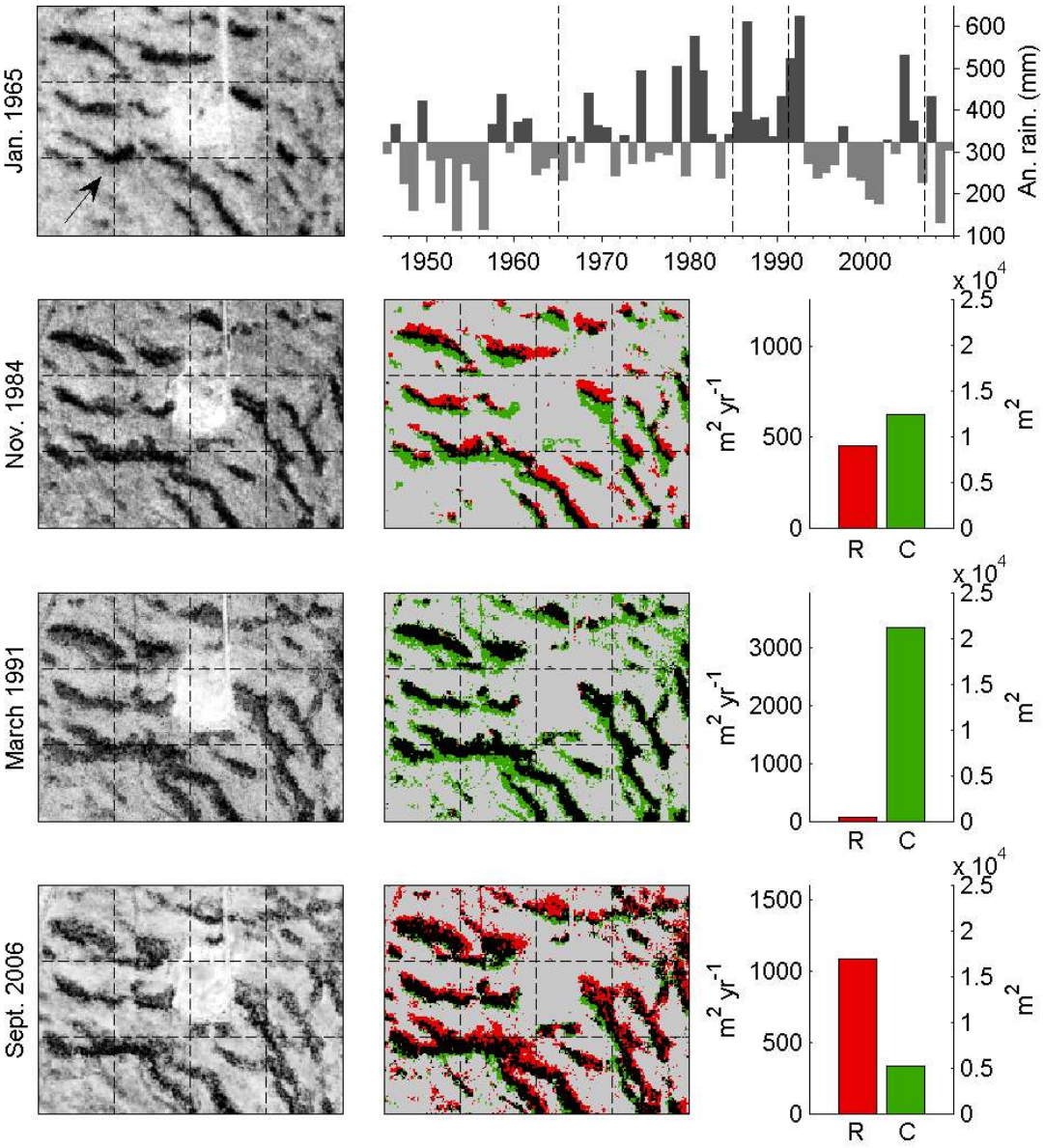
Is the pattern oriented parallel to the contour lines?



Diachronic satellite record for the northeastern Chihuahuan Desert (Texas) from 1965 to 2006



Climate driven dynamics in Northeastern Chihuahuan Desert (Texas)

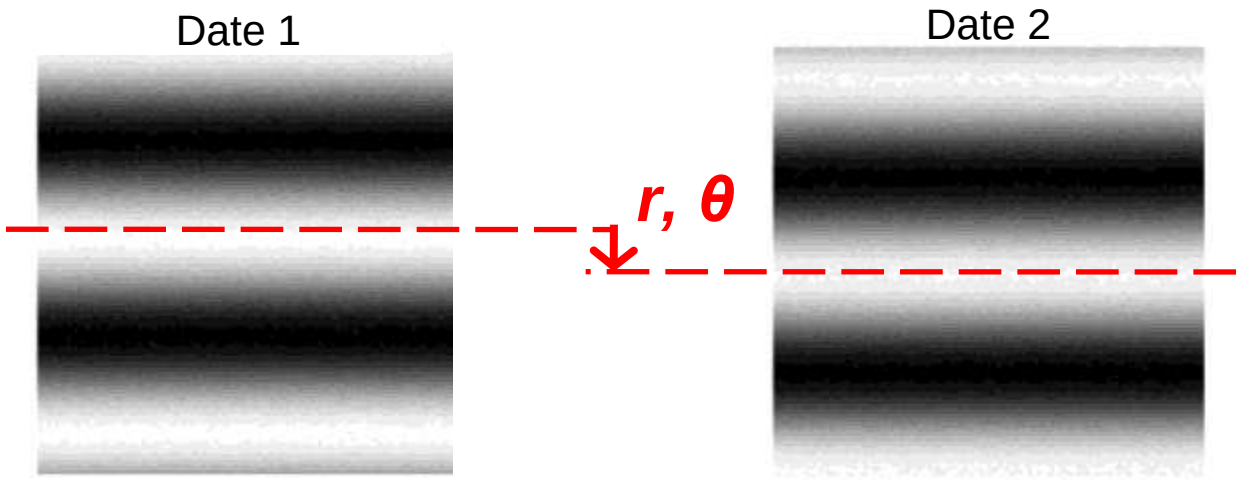


The dynamic is not continuous

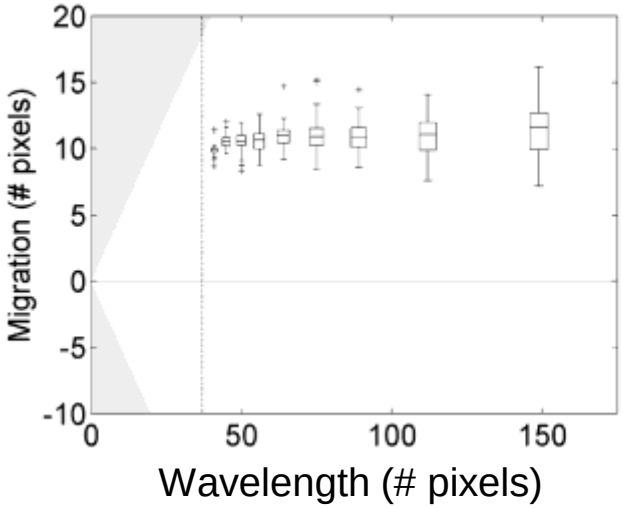
Migration is not an intrinsic property of the system but it is driven by climatic fluctuations

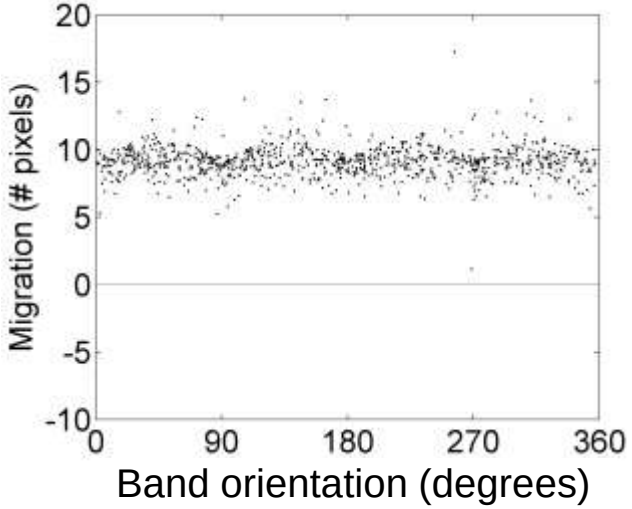
Cross-spectral analysis

- Estimation of phase difference: **direction** (θ) and **distance** (r) of migration



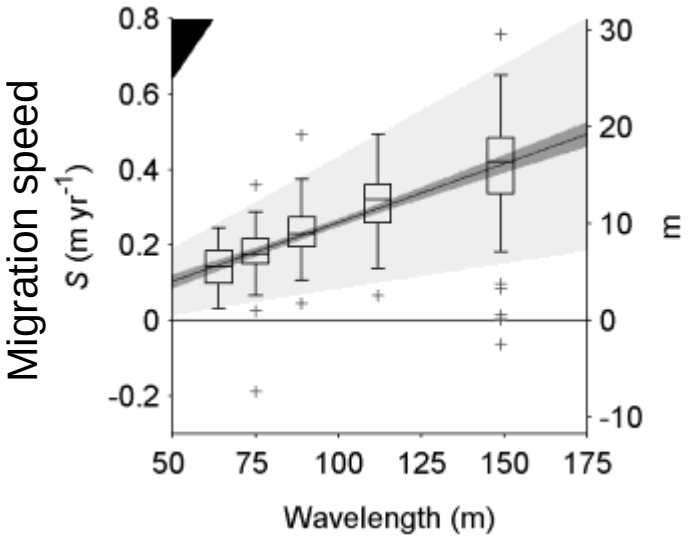
Example for 1000 artificial pairs of window with random wavelength, random orientation and a fixed migration distance (10 pixels):



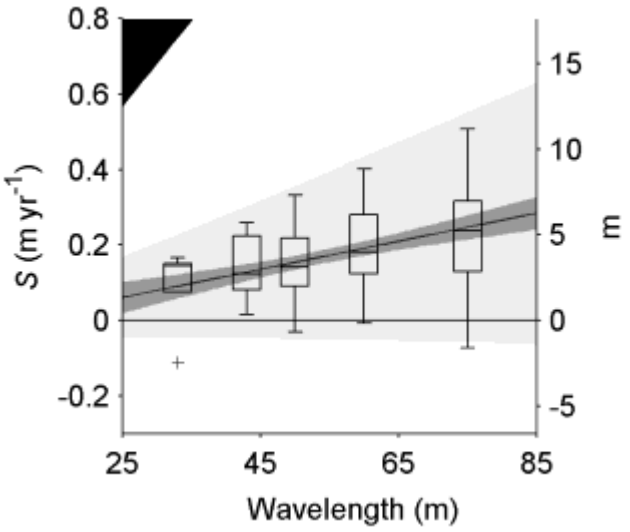


Static and mobile banded systems

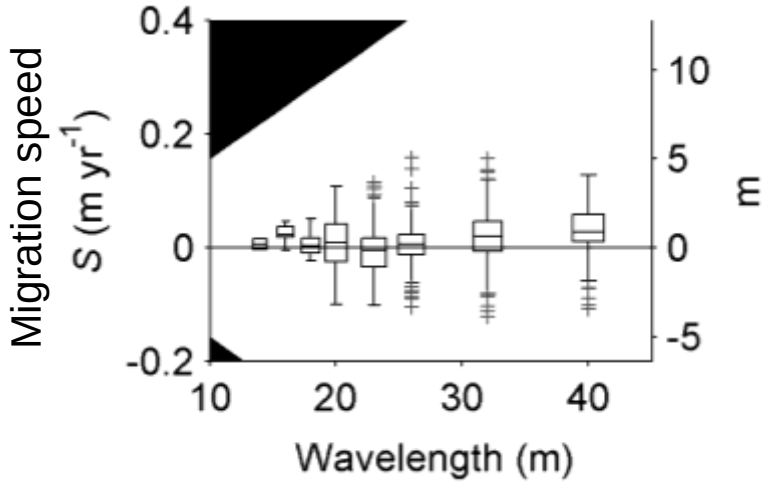
Somalia Haud 1



Trans-Pecos, Texas

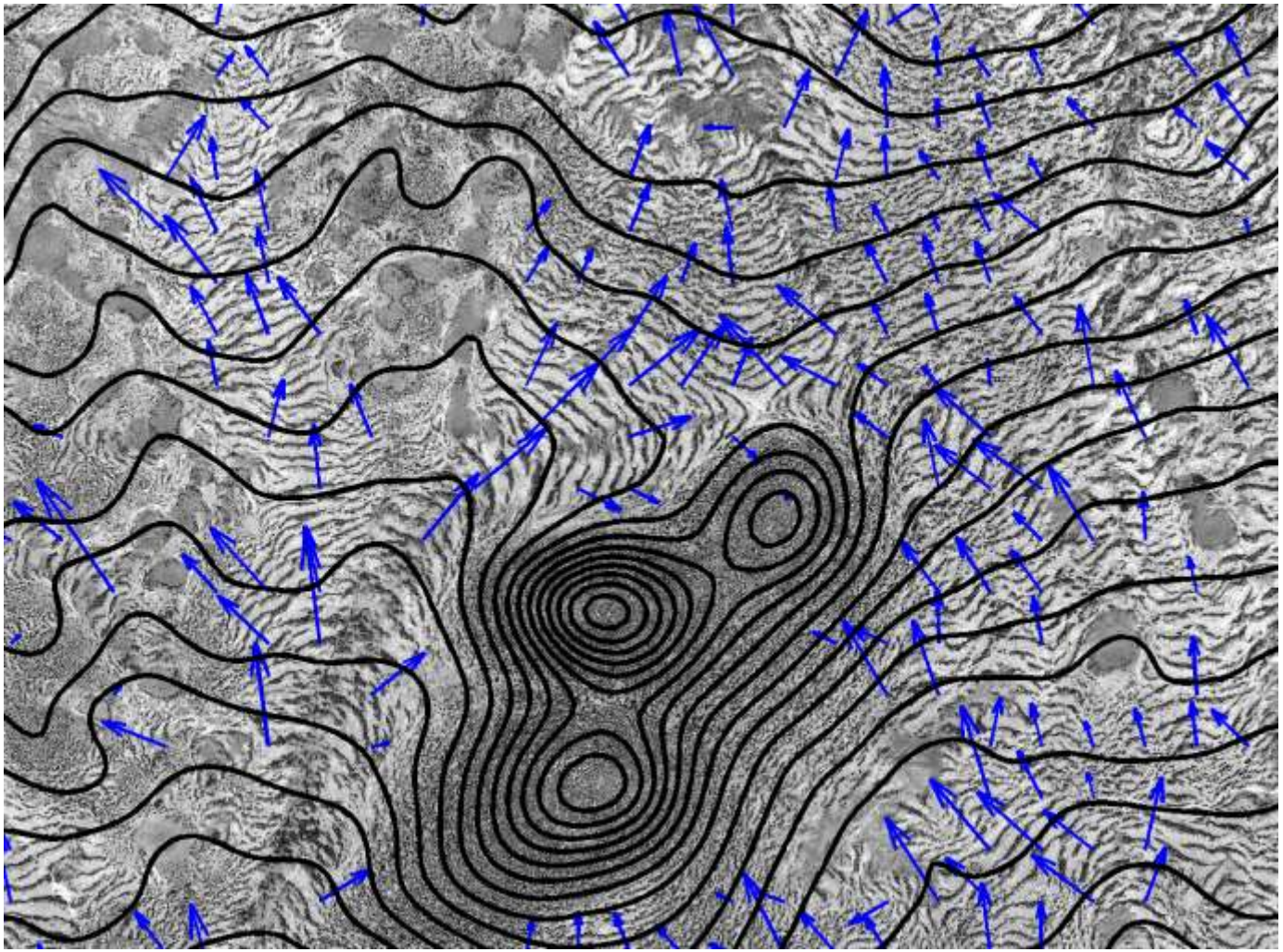


Broken Hill, Australia



Angular effects ?

- Co-registration artifact
- Shadow
- wind



Perspectives

Self-Organisation modelling

- We gave the **quantitative** description of pattern dynamics confirming the general validity, and allowing to fine-tune the models
- A higher level of **realism** and **predictive power** will be reached by a better **parameterization**, taking into account
  - **climate fluctuations**
  - **soil characteristics**
  - diversity in **plant associations**
  - **respective importance of processes**

Data are still challenging the theory

- The lack of **hexagonality**
- The absence of **isotropic patterns** outside of sub-saharan Africa
- **Hysteresis and catastrophic shifts?**
- **Oblique** banding