# CHARACTERIZING AND INTERPRETING VEGETATION PATTERNS IN NATURAL LANDSCAPES

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**Travaux menés en collaboration avec N. Barbier, R. Lefever, O. Lejeune**

**Winter School: Patterns of vegetation in water controlled ecosystems**

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ICEA

UNIVERSITÀ DEGLI STUDI DI PADOVA

# 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)
- **Lecture II:  From plant-plant interactions to patterns and vice-versa:**
  - Predictions from a simple modelling framework
  - Combining features to distinguishing between classes of patterns
  - Application to real-world patterns
  - **=> group works**

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# I - TEXTURAL ATTRIBUTES

## Spectra of spatial frequencies

# Main approaches to texture
## (Haralick, 1979)

- "Structural" approach
  - landscape = mosaic of patches of distinct types
  - patch identification is a prerequisite to computation of landscape "metrics"
- "Statistical" approach
  - texture is described via spatial autocorrelation of signal values

    (e.g., pixel radiometric reflectance, 'gray-levels')

# Using spatial autocorrelation

- **Coarse vs. fine texture ⇔**

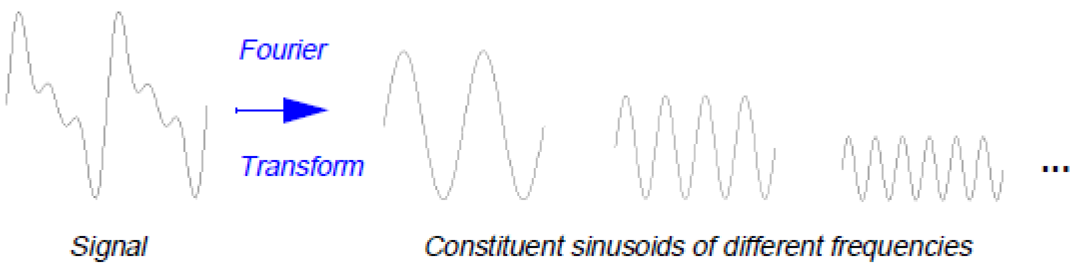
long range vs. short range correlation

- Methods to analyze autocorrelation:
  - correlogram, variogram, blocked-quadrats variance, …
  - use of a mathematical transform

  (enhanced interpretability: spatially-explicit, some desirable statistical properties)

# Fourier (spectral) analysis

- **Several equivalent standpoints**
  - Fourier transform of the signal
  - Fourier transform of the correlogram
  - image modelling based on sine and cosine functions
  - decomposition of image variance




$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt,$$

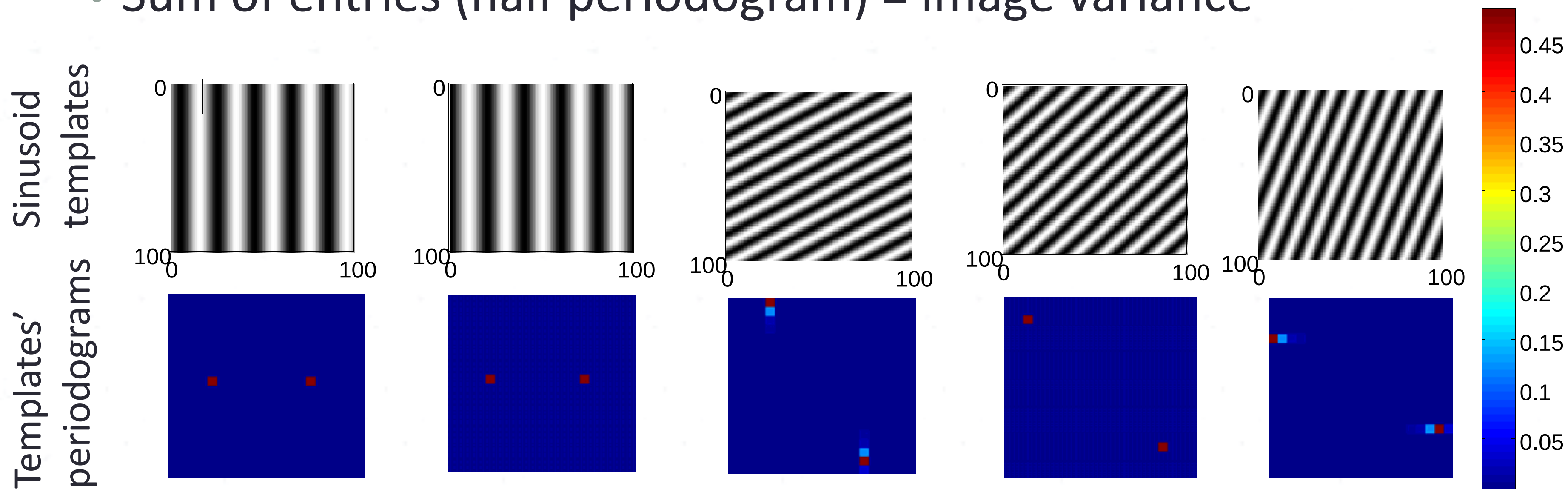
For 1-D signals

Fourier coefficients – F(ω) - when multiplied by a sinusoid of ω frequency yields the constituent sinusoidal component of the original signal

- **There are other mathematical transforms**
  - Walsh, Discrete Cosine, Haar (wavelets)

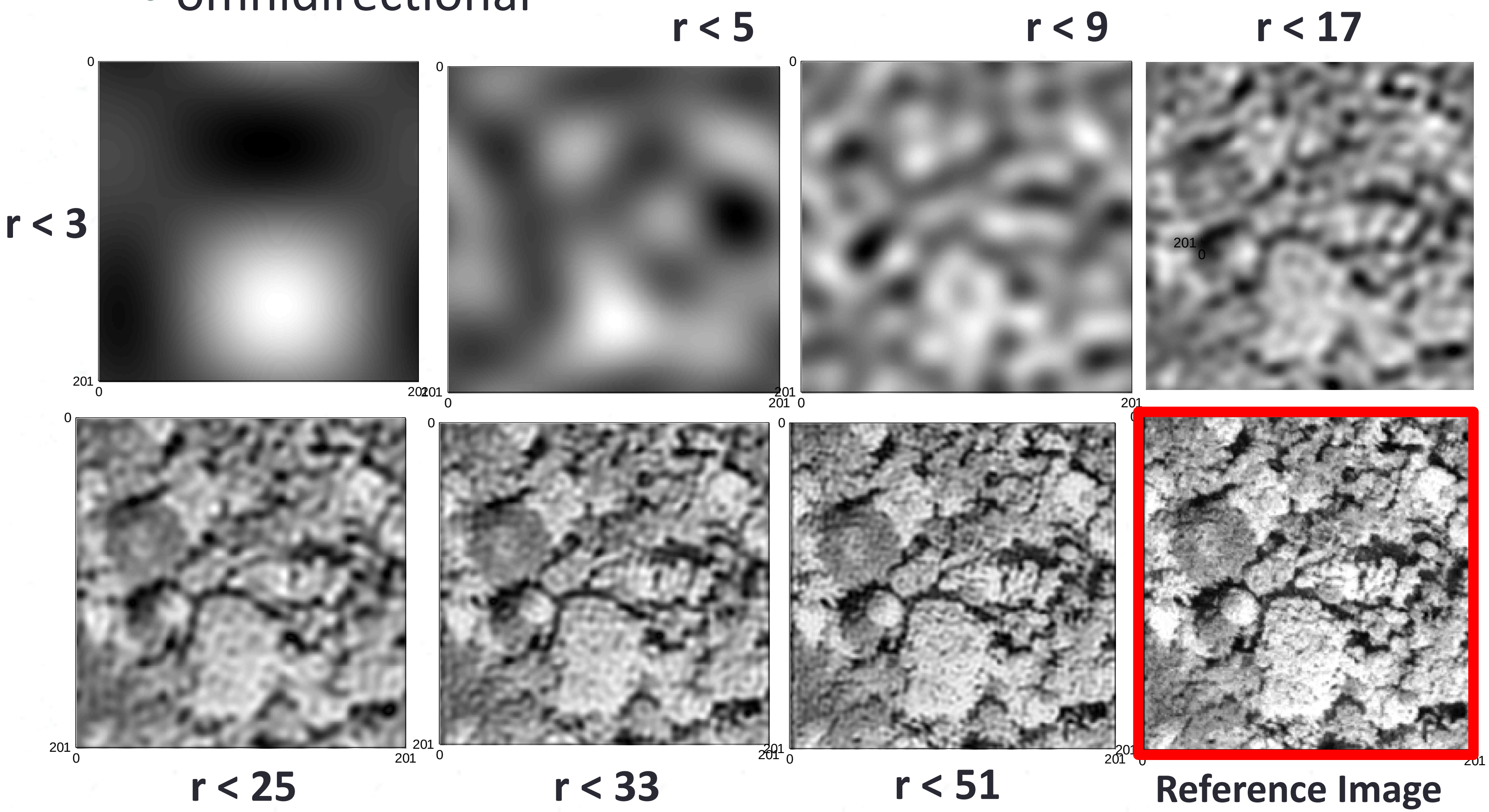
# In 2-D: Generalization

- **Image convolution**
  - with cosine and sine functions (traveling waves)
  - of varying frequencies ( $r$ ) and traveling directions ( $\theta$ )
- **Periodogram (power spectrum):**
  - 2D image
  - Sum of entries (half periodogram) = image variance



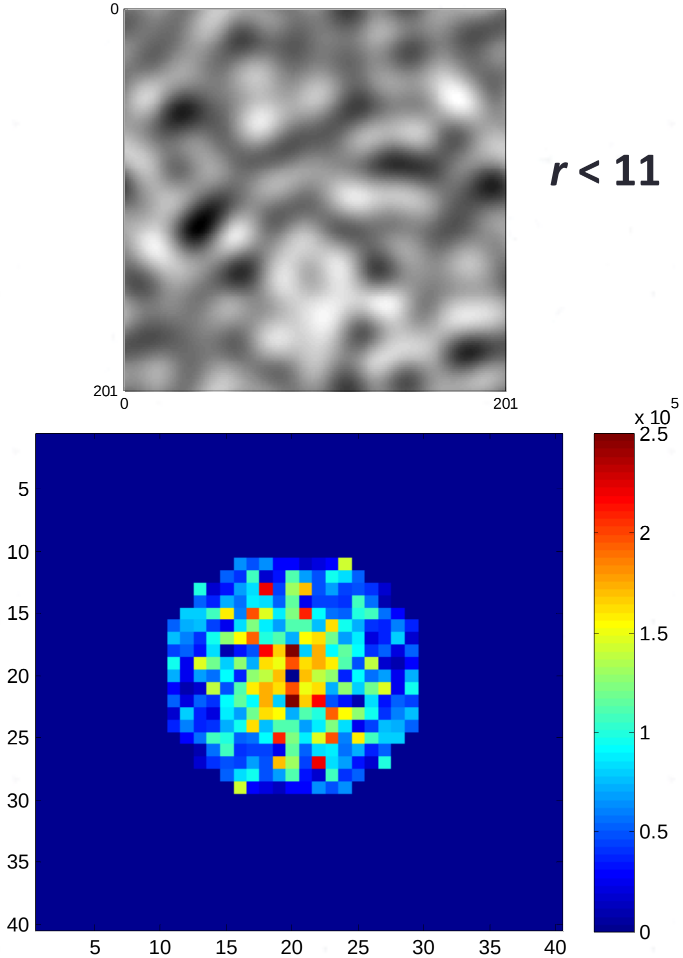
# Another viewpoint on Fourier analysis

- **Image reconstruction: progressive adding of waveforms:**
  - of increasing wavenumbers (r)
  - omnidirectional

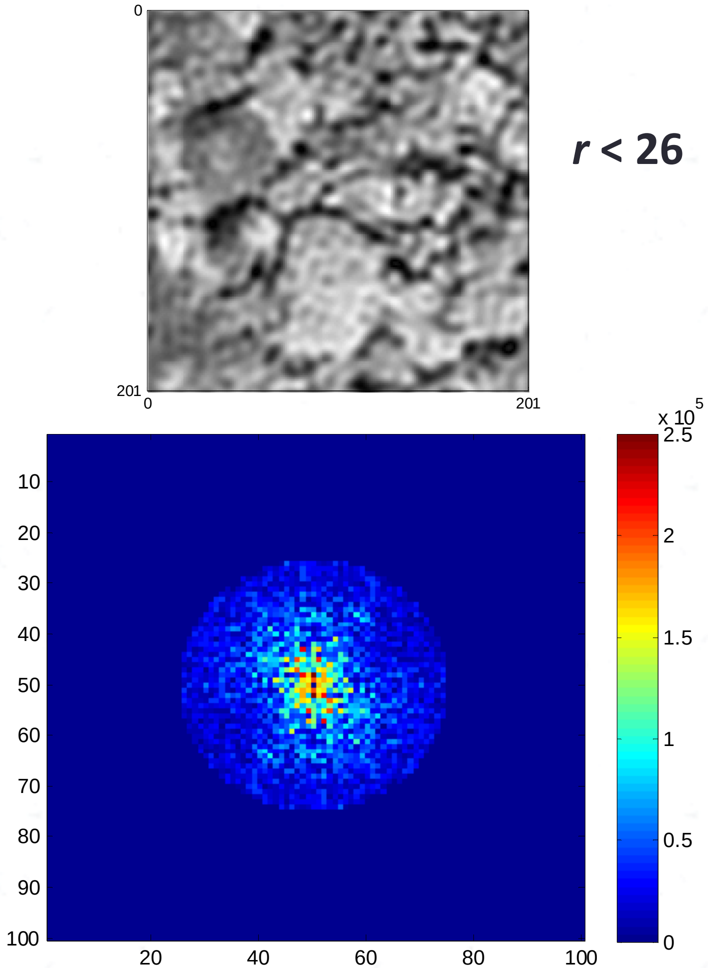


# 2D image reconstruction

- **Increasing the cut-off limit in the 2D periodogram**

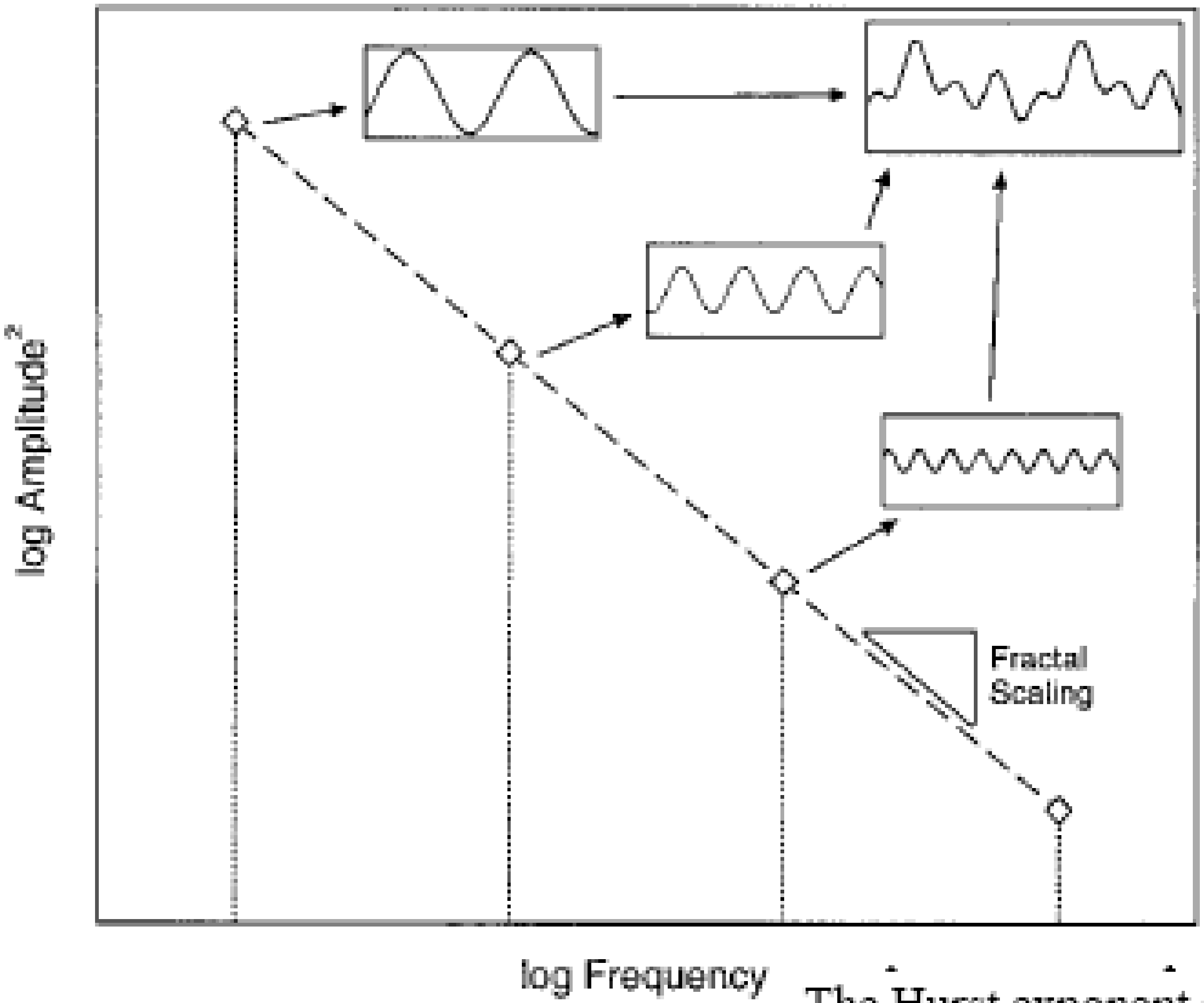



***r* < 11**




***r* < 26**

# Spectral synthesis of images




- **Fractal structure (one option)**

**Beta = 2 + 2H (2D)**

**Beta = slope of « fractal line »**

**Beta = 1 + 2H (en 1D)**

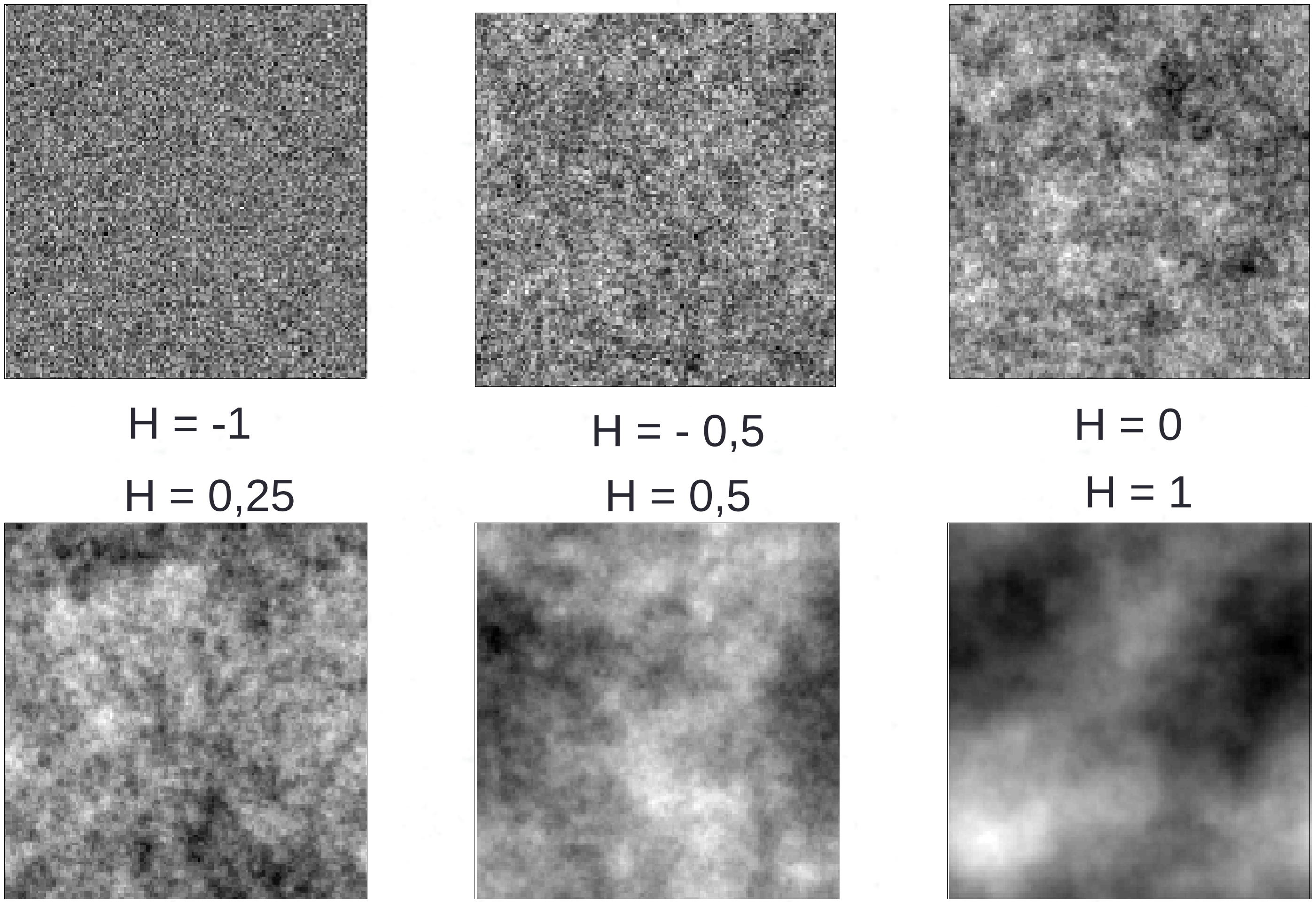
From Keitt, 2000

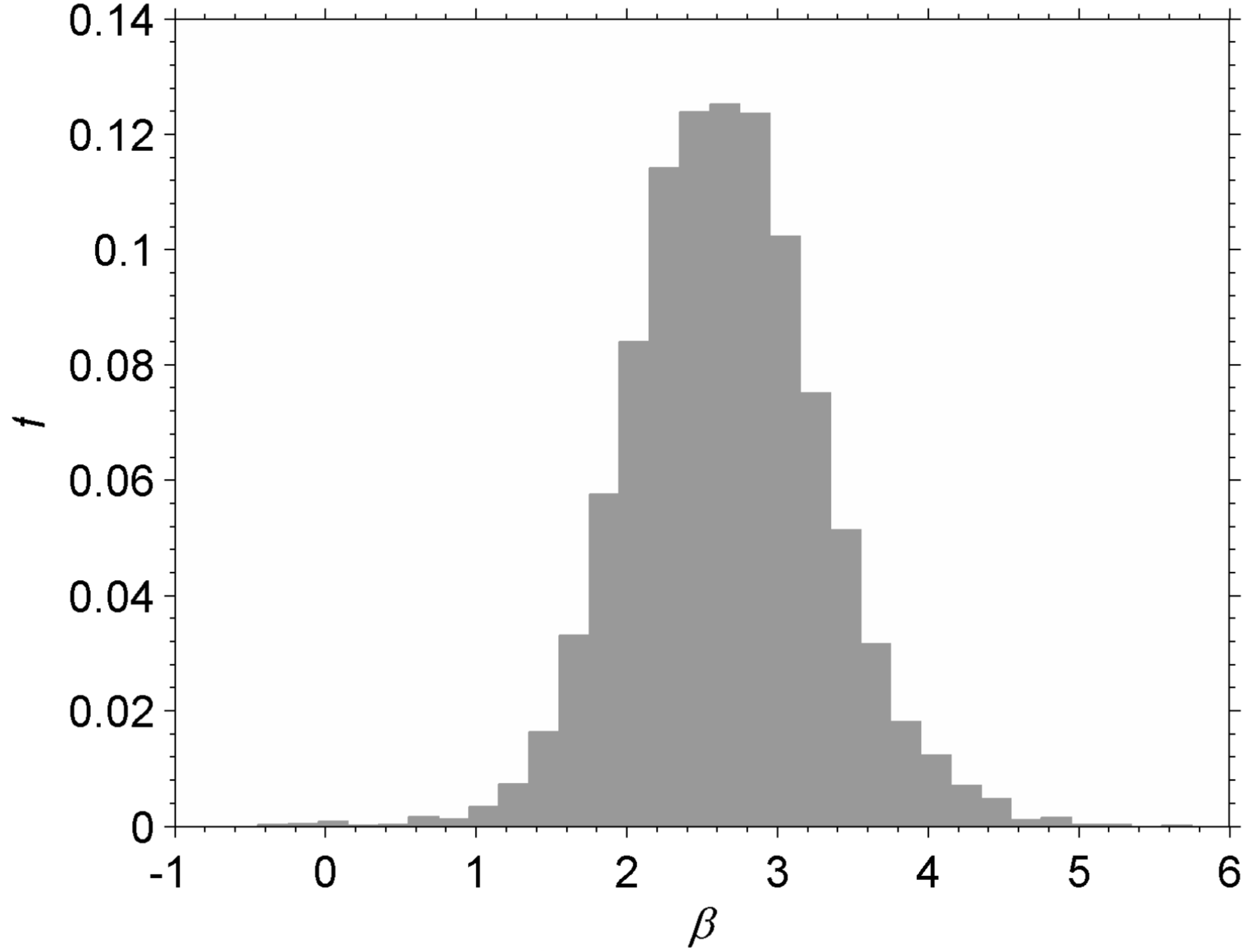
The Hurst exponent defines a scaling relation

$$E[(X_t - X_{t'})^2] \propto (t - t')^{2H},$$

# Gradient of autocorrelation range in simulated images

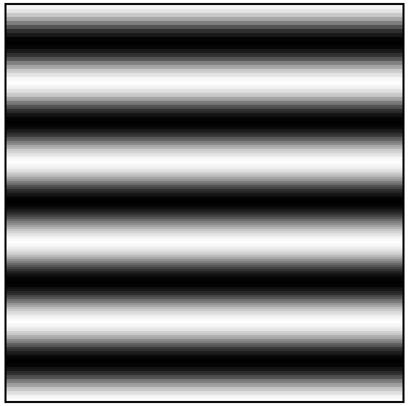
- **Fractal structures**
  - H = Hurst's parameter
  - Beta = 2H +2 (2D)

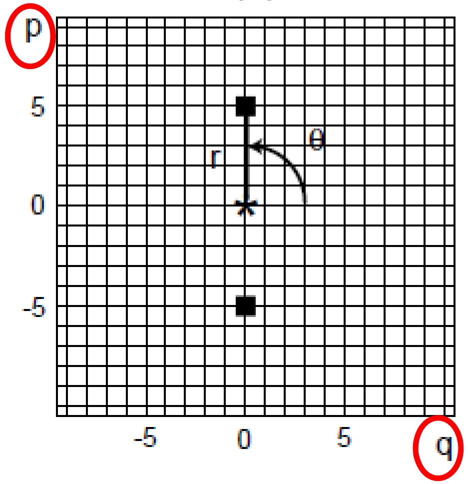


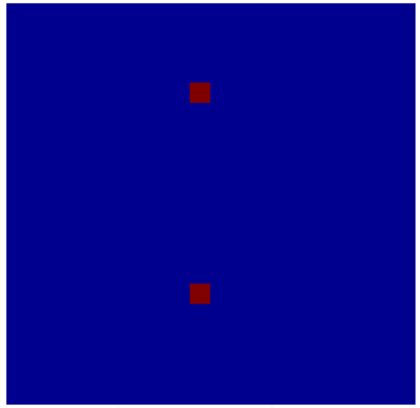



Worldwide distribution of the scaling parameter β describing the auto-correlation pattern on digital elevation models (DEM from the SRTM 1.3° × 1.3° windows). Deblauwe et al. 2012, PlosOne

# Back to periodogram interpretation (periodic template)

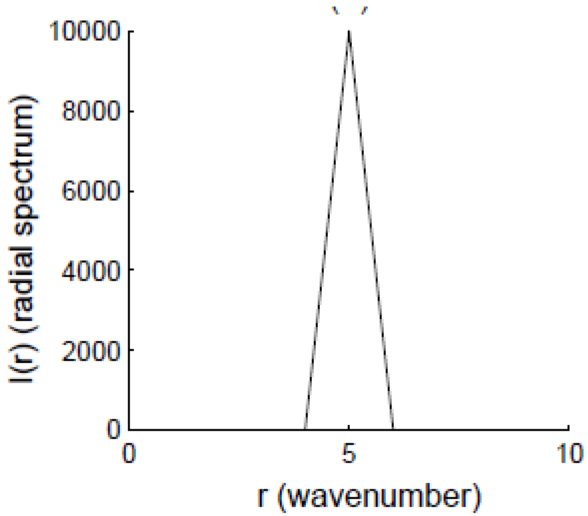


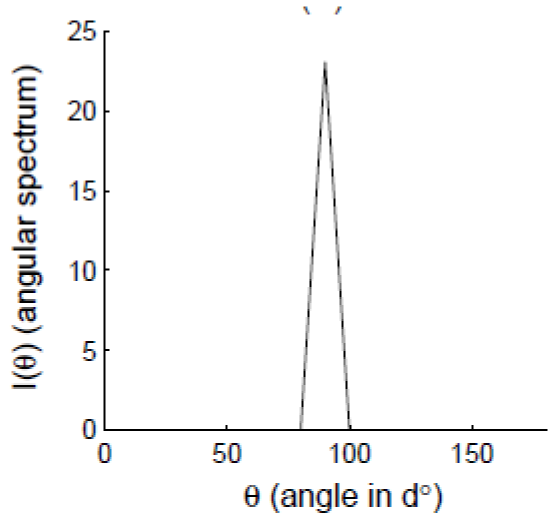


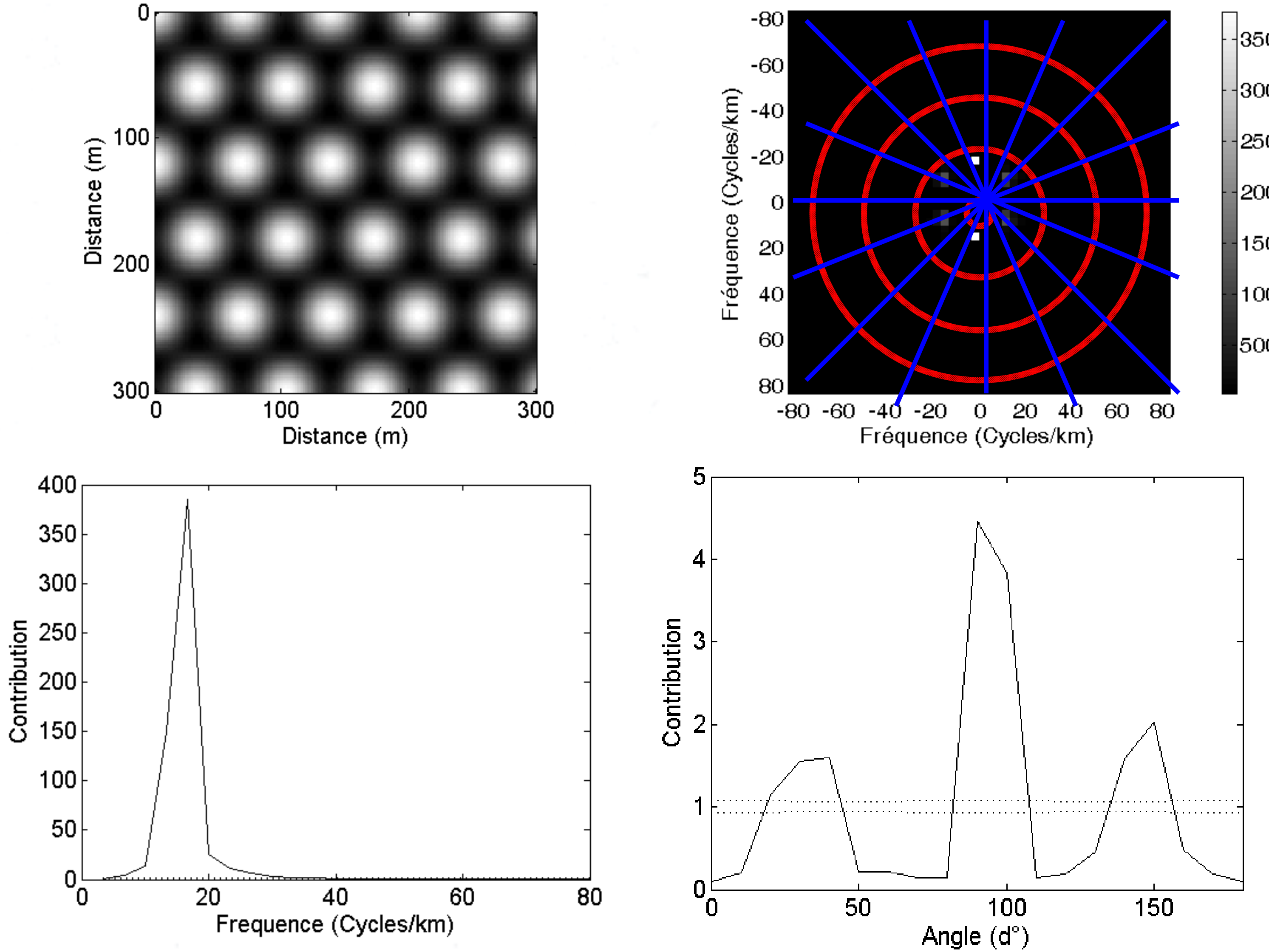
p: spatial frequency Y-direction
q: spatial frequency X-direction

- **Polar form:**
  - R-spectrum (radial)
  - θ-spectrum (angular)



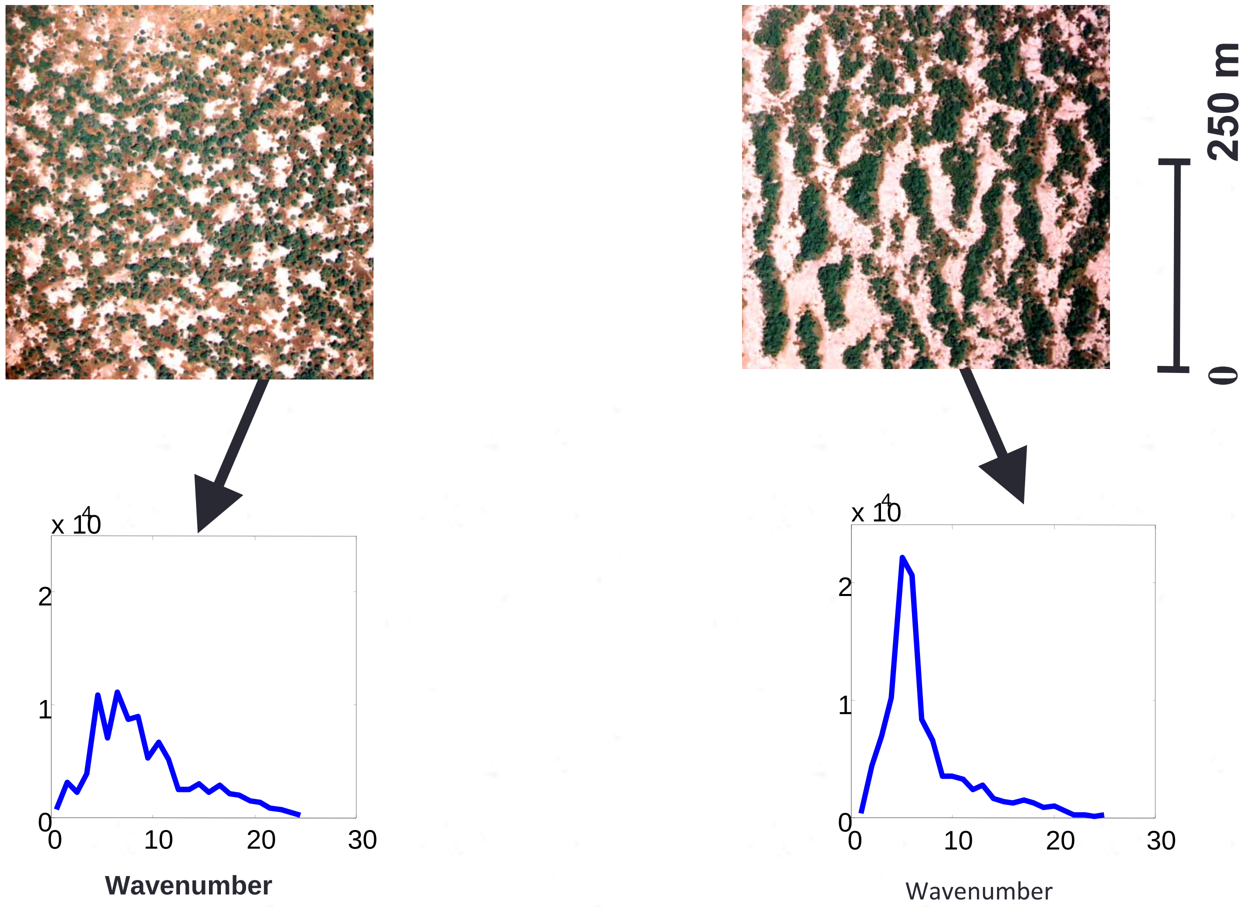



# Summarizing Periodograms into radial & angular spectra

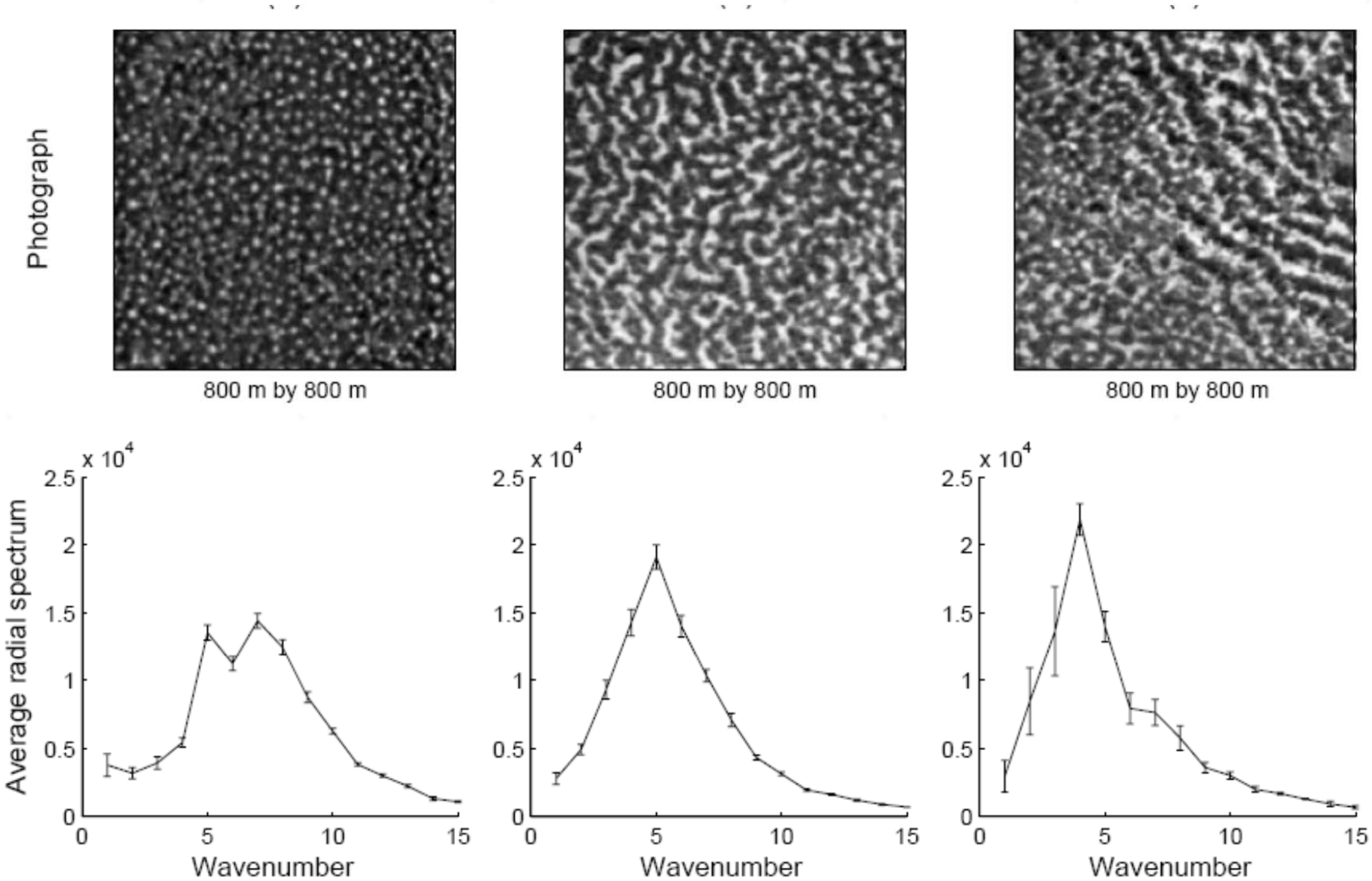


# For real-world patterns:

**The radial r-spectrum enables to quantify dominant scales**



# Shared property of those patterns: a (locally) well-defined dominant wavelength

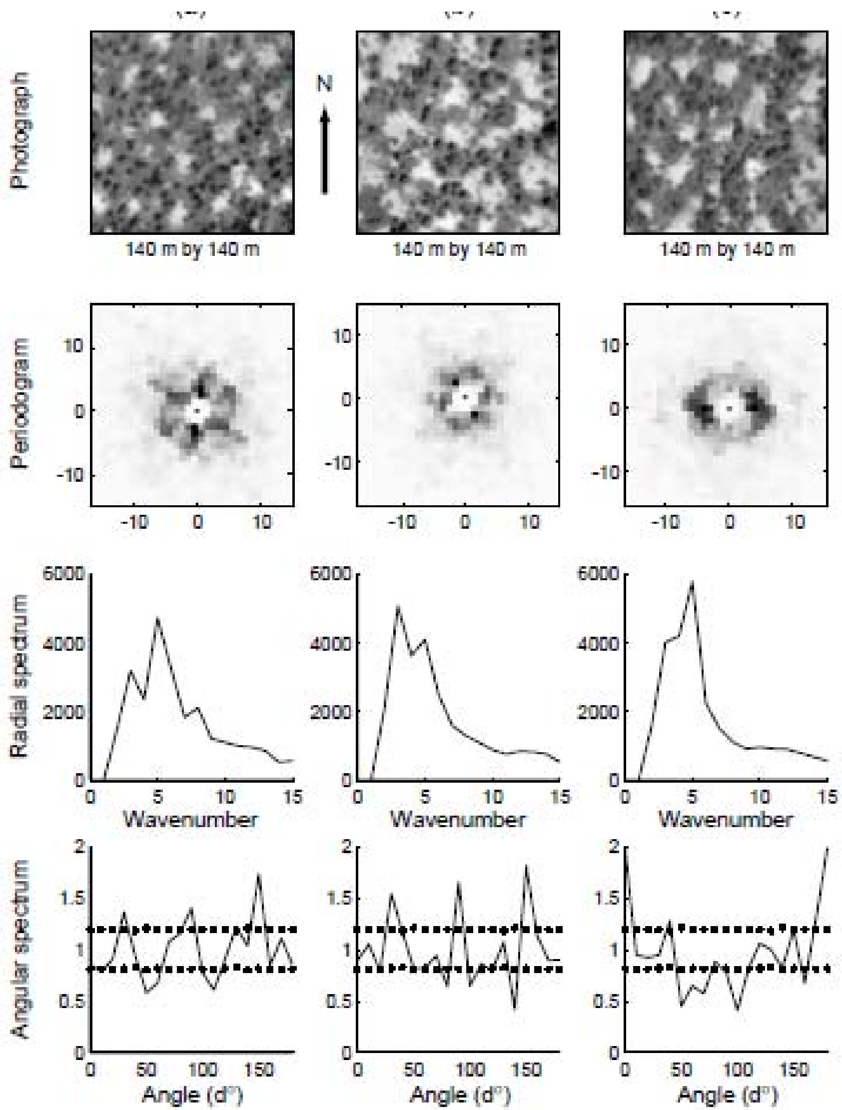


# Real-world: gapped periodic patterns

2D periodogram

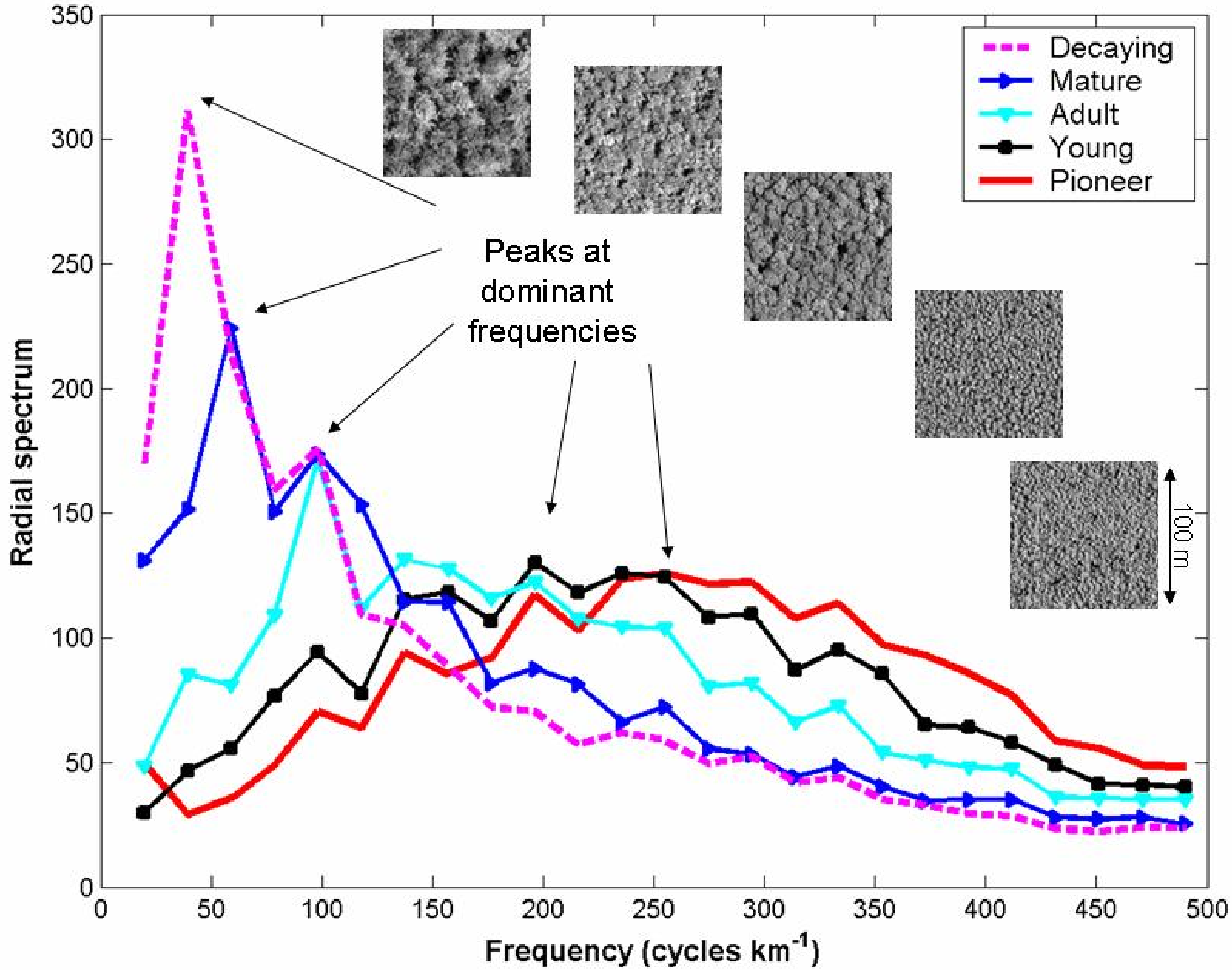
r-spectrum

θ-spectrum




Couteron & Lejeune, 2001, J Ecol

# Signatures along a coarseness-fineness gradient




Proisy et al. 2007, RSE

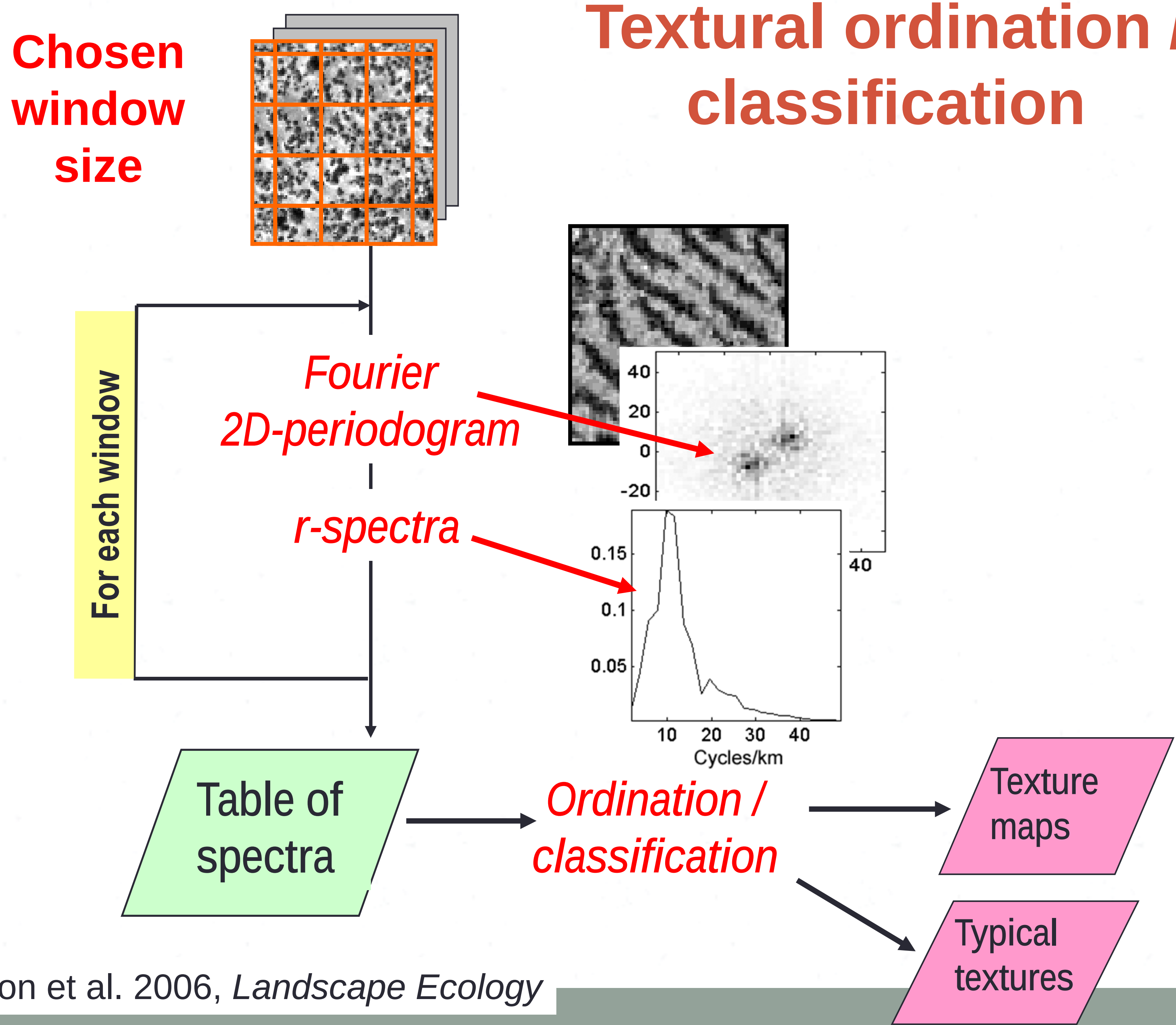
## Textural ordination

- Systematic partition of large images

  => square sub-images (windows)

- r-spectrum :
  - computed for each sub-image
  - gathered in a table of spectra
- Analysis of the table of spectra :
  - Principal Components Analysis (PCA)
  - sub-image = individuals
  - wavenumbers = quantitative variables

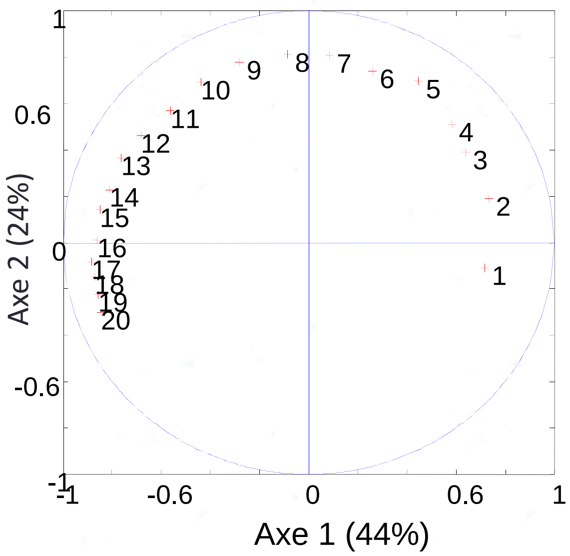
# Textural ordination / classification

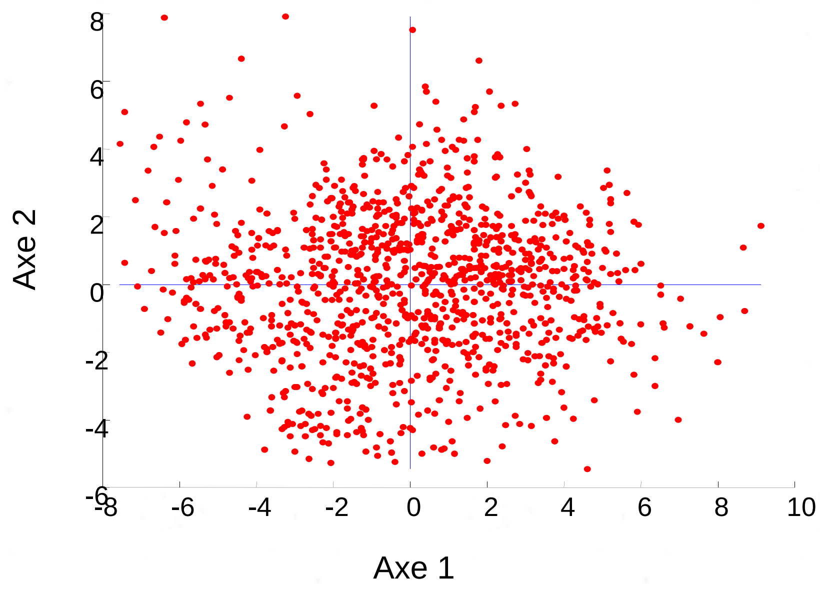



Couteron et al. 2006, *Landscape Ecology*

# PCA on the table of spectra

medium
texture




fine
texture

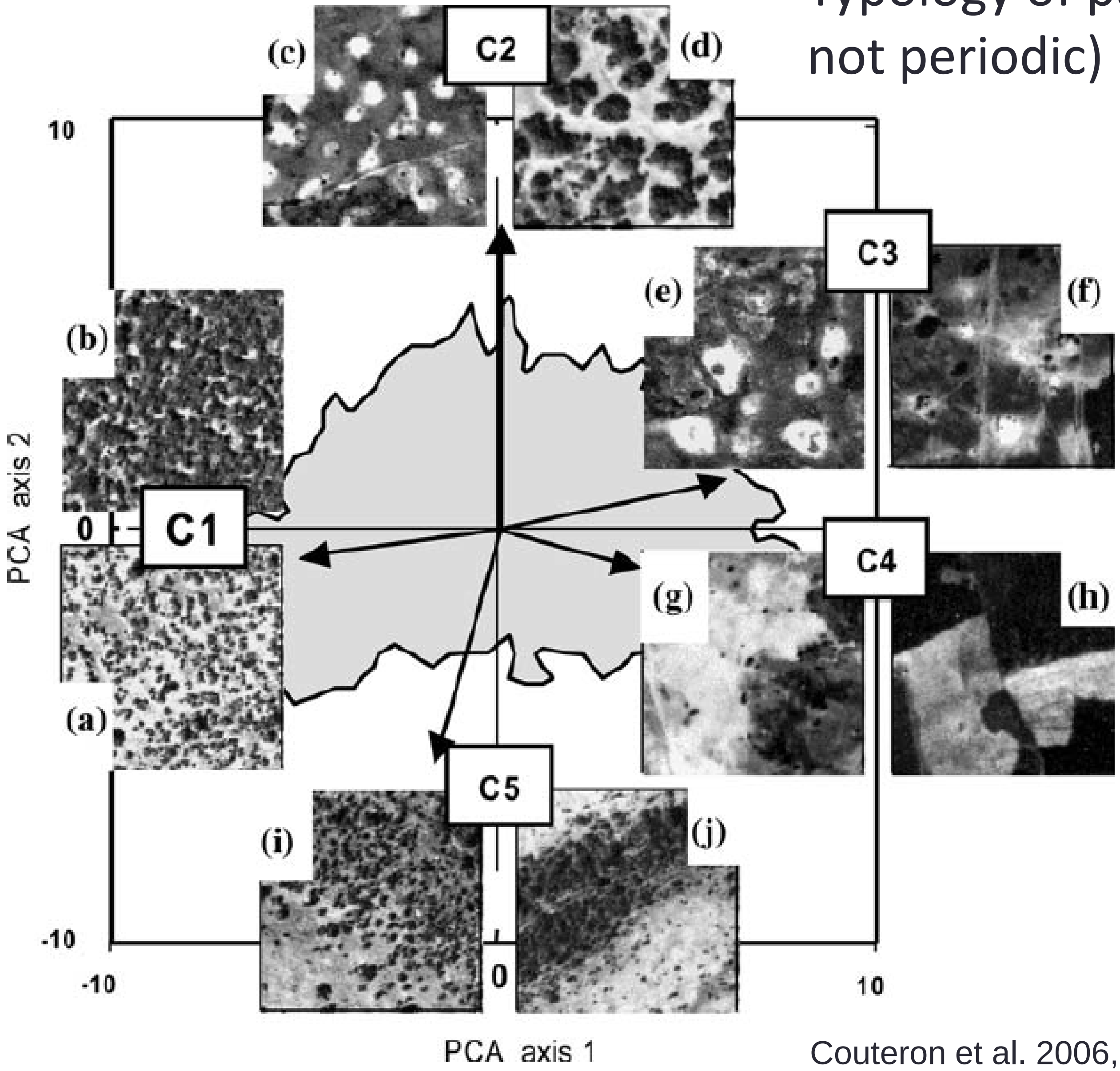
coarse
texture

**Example :**
900 sub-images
of 300 m by 300 m
from 100 air photos (Cameroon)

Couteron et al. 2006, *Landscape Ecology*

# PCA on the table of spectra

Typology of patterns (here not periodic)




Couteron et al. 2006, *Landscape Ecology*

# Catching up with patterns in a 'new' territorv

- **Bolivian altiplano. Sajama National Park**

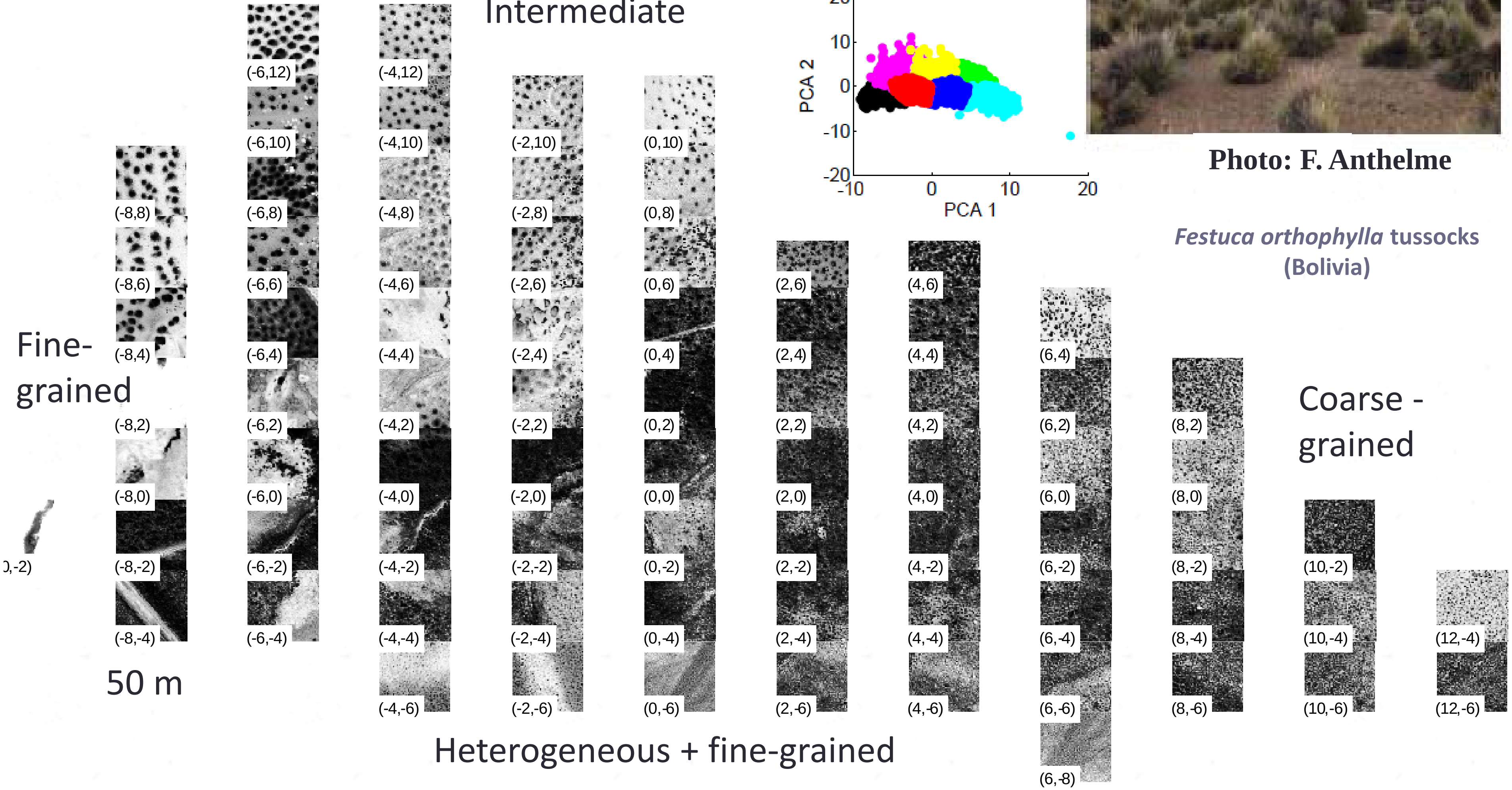


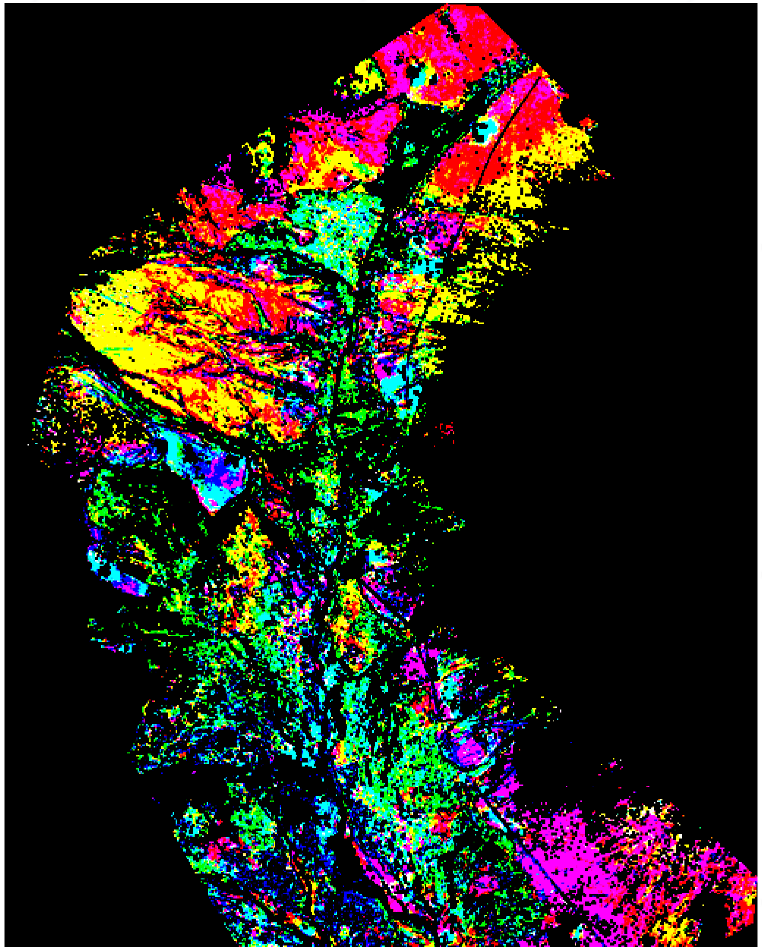


**Photo: F. Anthelme**

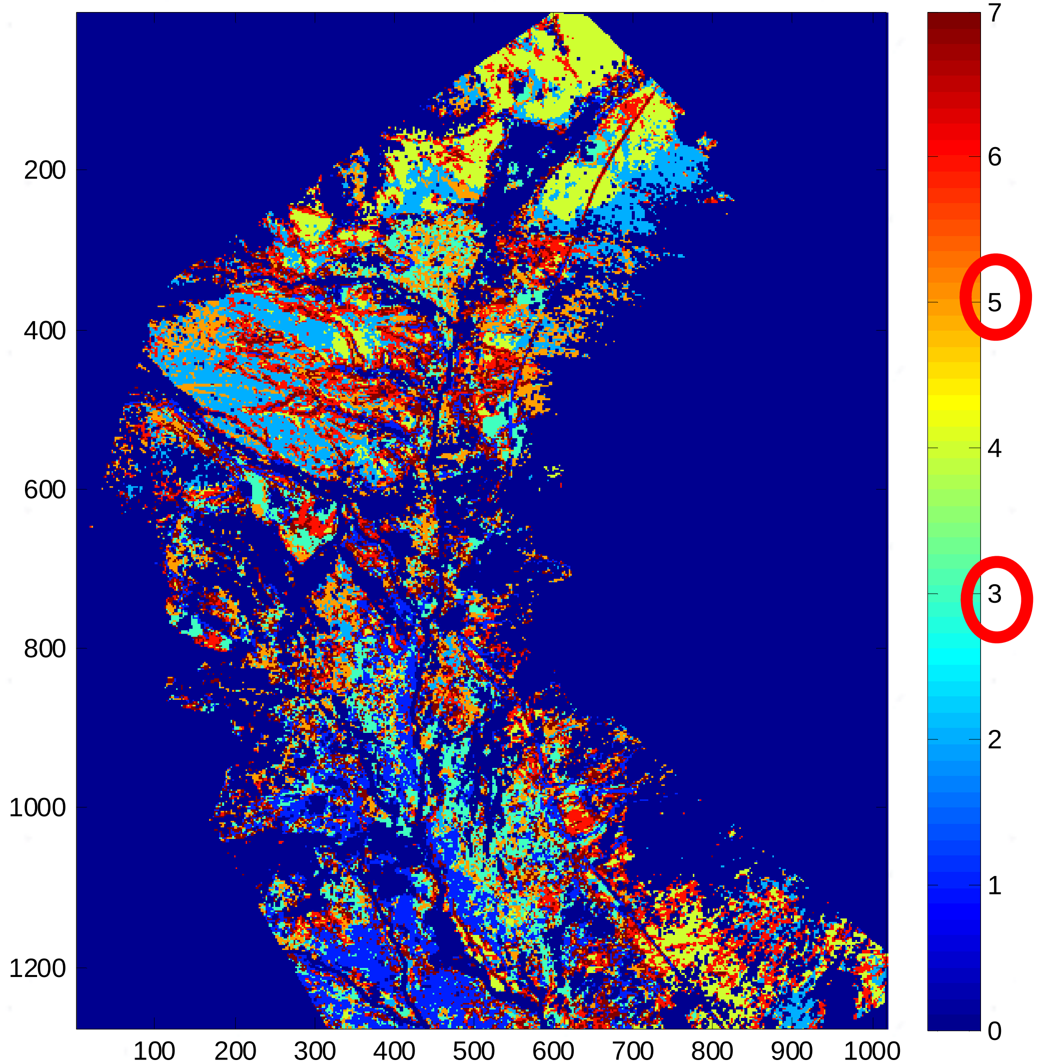
*Festuca orthophylla* tussocks
(Bolivia)

- **Bolivian altiplano. Sajama National Park**

- **RGB map of PCA scores**



- **Texture classes**



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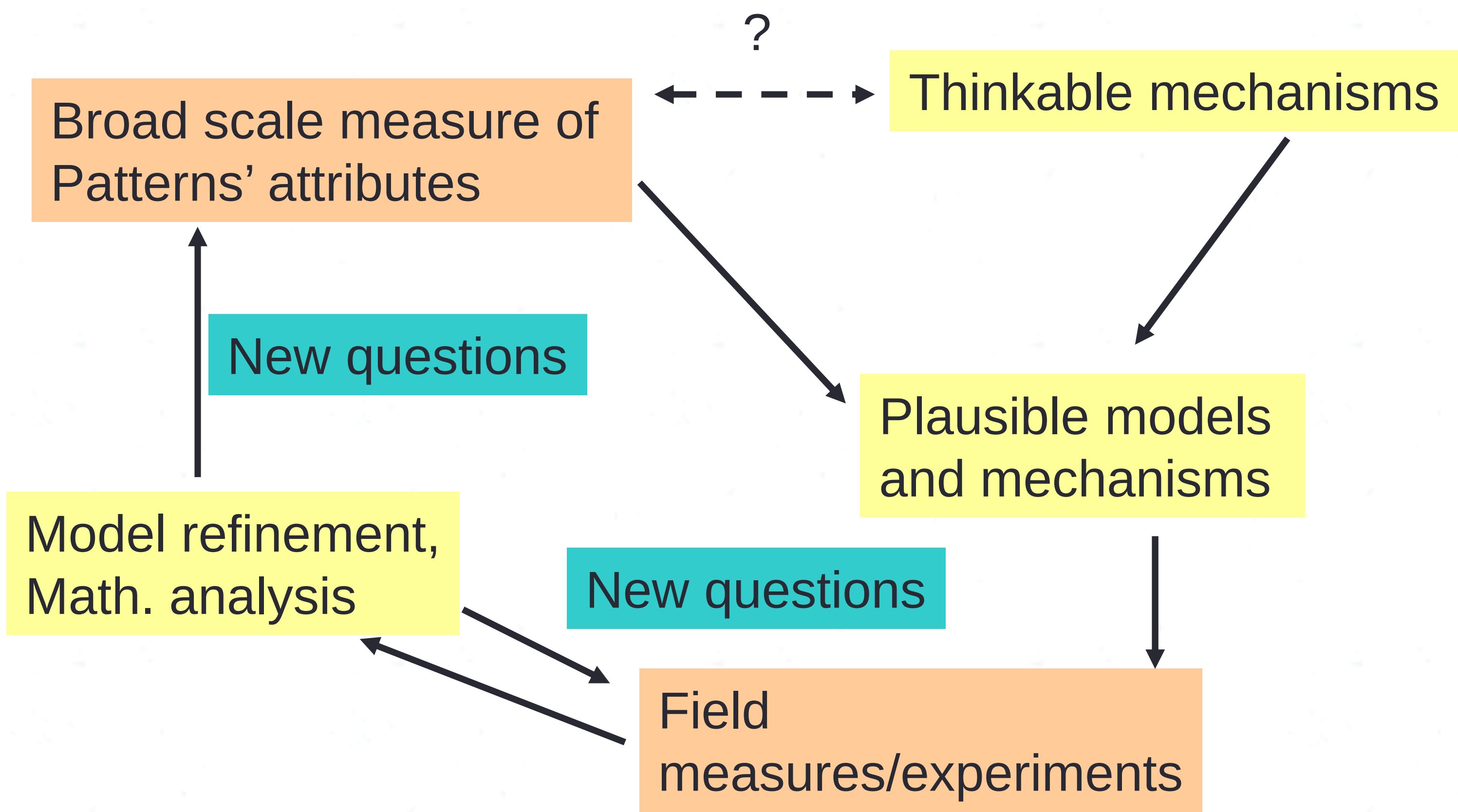
# Patterns, mechanims, models



# II - FROM PLANT INTERACTIONS TO PATTERNS METRICS (AND VICE VERSA)

# Motivation

- **Emergent vegetation patterns:**
  - Vegetation is liable to produce self-organized, environment-modulated, broad scale patterns
  - The scale of which are one order of magnitude above the size of individual plants
  - Yet patterns may emerge through “short range” plant-plant interactions … that reflect plant morphology and function
  - Timely, ‘hot’ topics: patterns may provide information on imminent transitions and on the history of ecosystems
- **Modelling to:**
  - bridge the spatio-temporal scale gap between patterns (remote-sensing) and plants’ forms and functions
  - study slow ecosystems dynamics
  - orient field experiments in under-studied ecosystems

# Modeling: plant interactions & biomass dynamics

- **A minimal integro-differential framework**
  - Seminal paper: Lefever & Lejeune 1997, BMB
  - Subsequent papers (Lefever et al. 2009, Lefever & Turner 2012)
  - A single equation (biomass)

$$\frac{\partial}{\partial t} b(\mathbf{r},t) = f_1(1-f_2) - \mu f_3 + \int \Phi_D\left(\left|\mathbf{r}'\right|^2/L_D^2\right) b(\mathbf{r}+\mathbf{r}',t)\,\mathrm{d}\mathbf{r}'$$

$$\nabla^2 b(\mathbf{r},t)$$

  - Logistic growth (*f1, f2*) + decay term (*f3*)
  - Source of propagules from other locations (phi_D kernel)
  - Related to the framework of Fisher, Kolmogorov, Petrovsky, Piscounov (F-KPP) equation. But:
    - Some changes
    - Explicit non-local plant-plant interactions via kernels

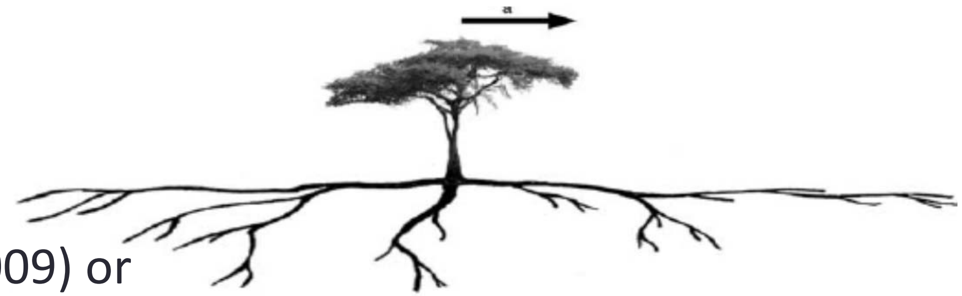
# Recall: Plant-Plant interactions

- **Dual influences in harsh environments**
  - Plants often help plants (facilitation)
  - Especially the aerial part of large plants (shade, litter, water funneling, …) is facilitating (in drylands)
  - Plants also compete for soil limited resources
- **Large plants are:**
  - the most influential
  - source of interactions having the largest spatial ranges

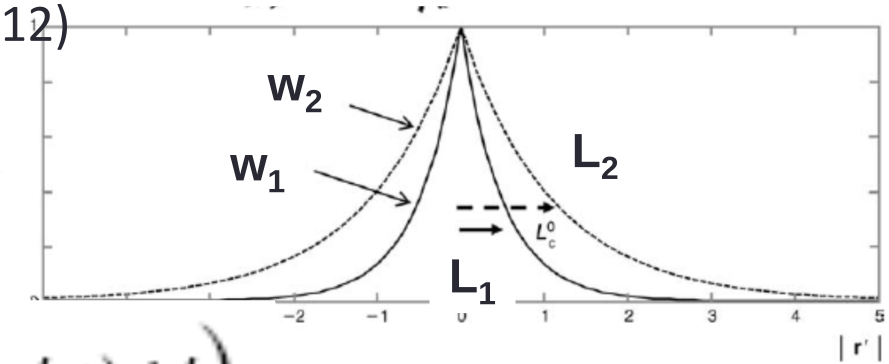
# Kernel modelling of non-local plant-plant interactions

(Lefever et al. 2009, JTB; Lefever & Turner, CRAS2B)

$$\frac{\partial}{\partial t} b(\mathbf{r},t) = f_1(1-f_2) - \mu f_3 + \int \Phi_D\left(\left|\mathbf{r}'\right|^2/L_D^2\right) b\left(\mathbf{r}+\mathbf{r}',t\right) \mathrm{d}\mathbf{r}'$$



**Several options:**
**Facilitation** => *f1*
**Competition**:
- *f3* ('Harsh competition', Lefever et al. 2009) or
- *f2* ('mild competition', Lefever & Turner 2012)

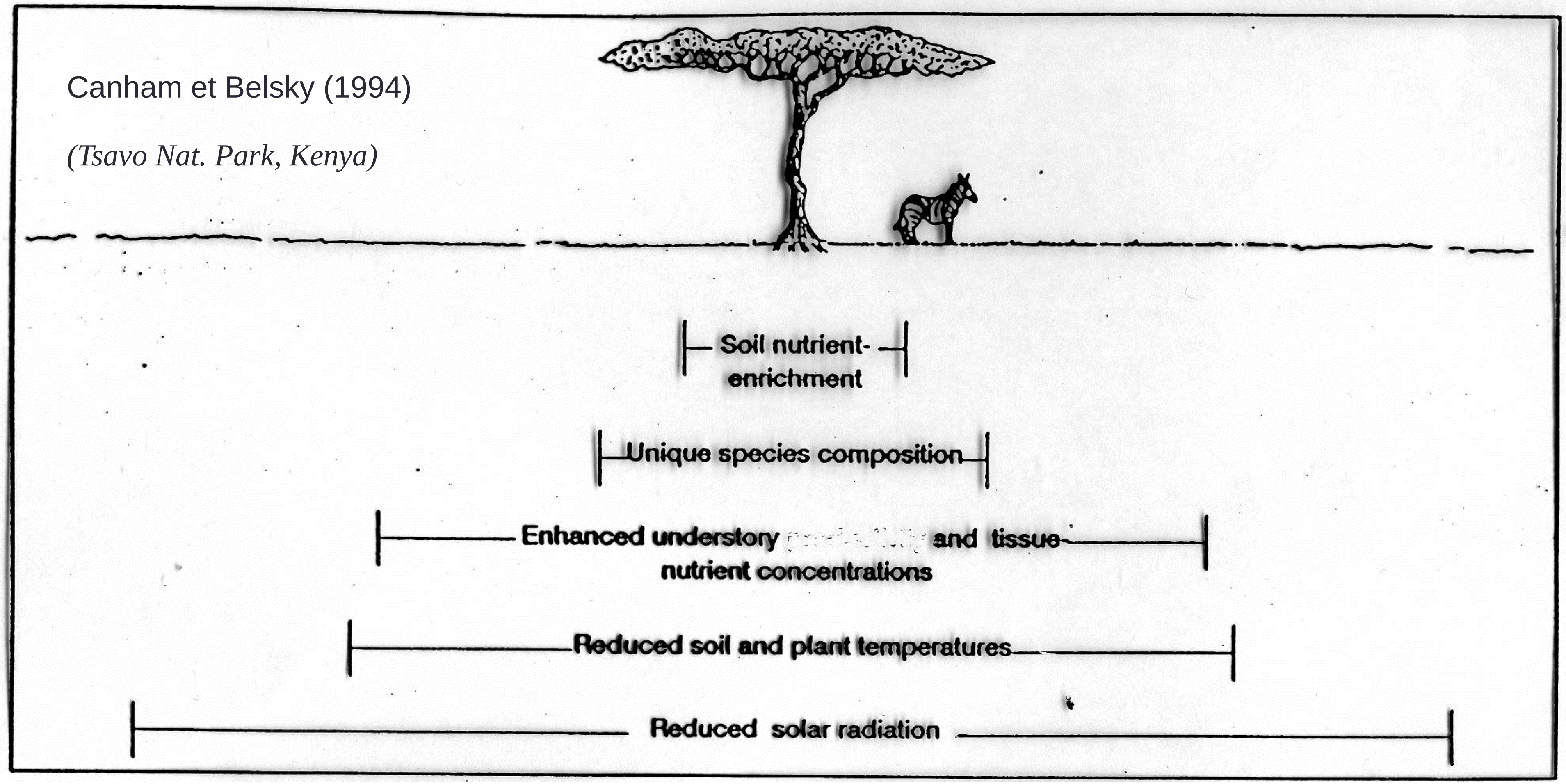



$$f_2 = \frac{\int w_2(|\mathbf{r}'|/L_2) b(\mathbf{r}+\mathbf{r}',t)\,\mathrm{d}\mathbf{r}'}{\int w_2(|\mathbf{r}'|/L_2)\,\mathrm{d}\mathbf{r}'}$$

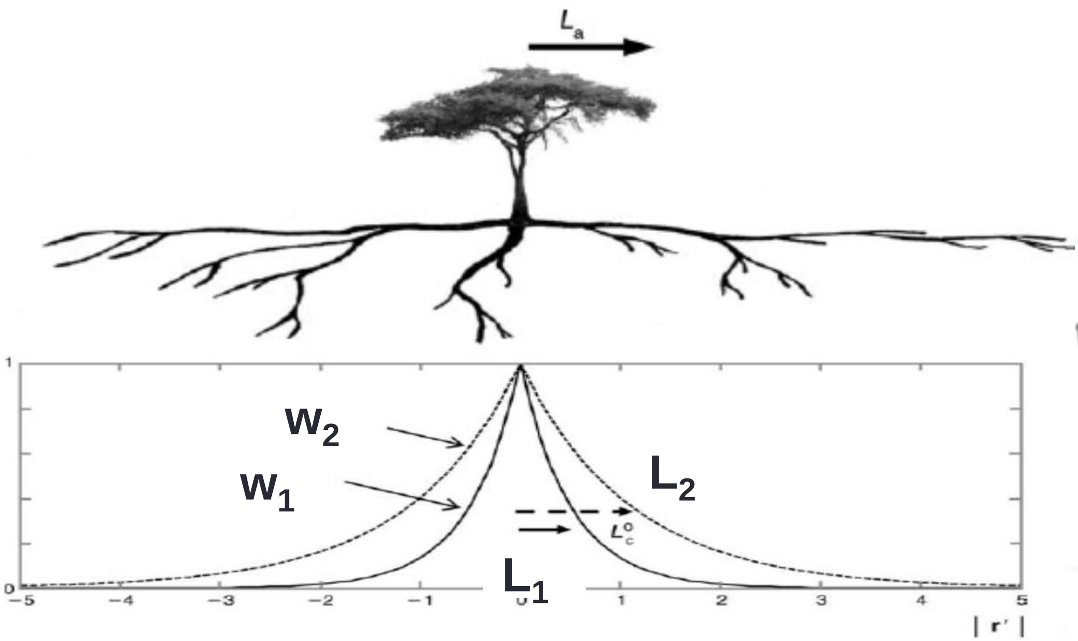
$$f_1 = b(\mathbf{r},t)\frac{1}{2\pi}\exp\left(\int w_1(|\mathbf{r}'|/L_1) b(\mathbf{r}+\mathbf{r}',t)\,\mathrm{d}\mathbf{r}'\right)$$

$$w_i(|\mathbf{r}'|/L_1) = \exp(-|\mathbf{r}'|/L_i), \quad i = 1, 2$$

# Ranges of influences from an isolated tree



# Kernel modelling of facilitation and competition




$$w_i(|\mathbf{r}'|/L_1) = \exp(-|\mathbf{r}'|/L_i), \quad i = 1, 2$$

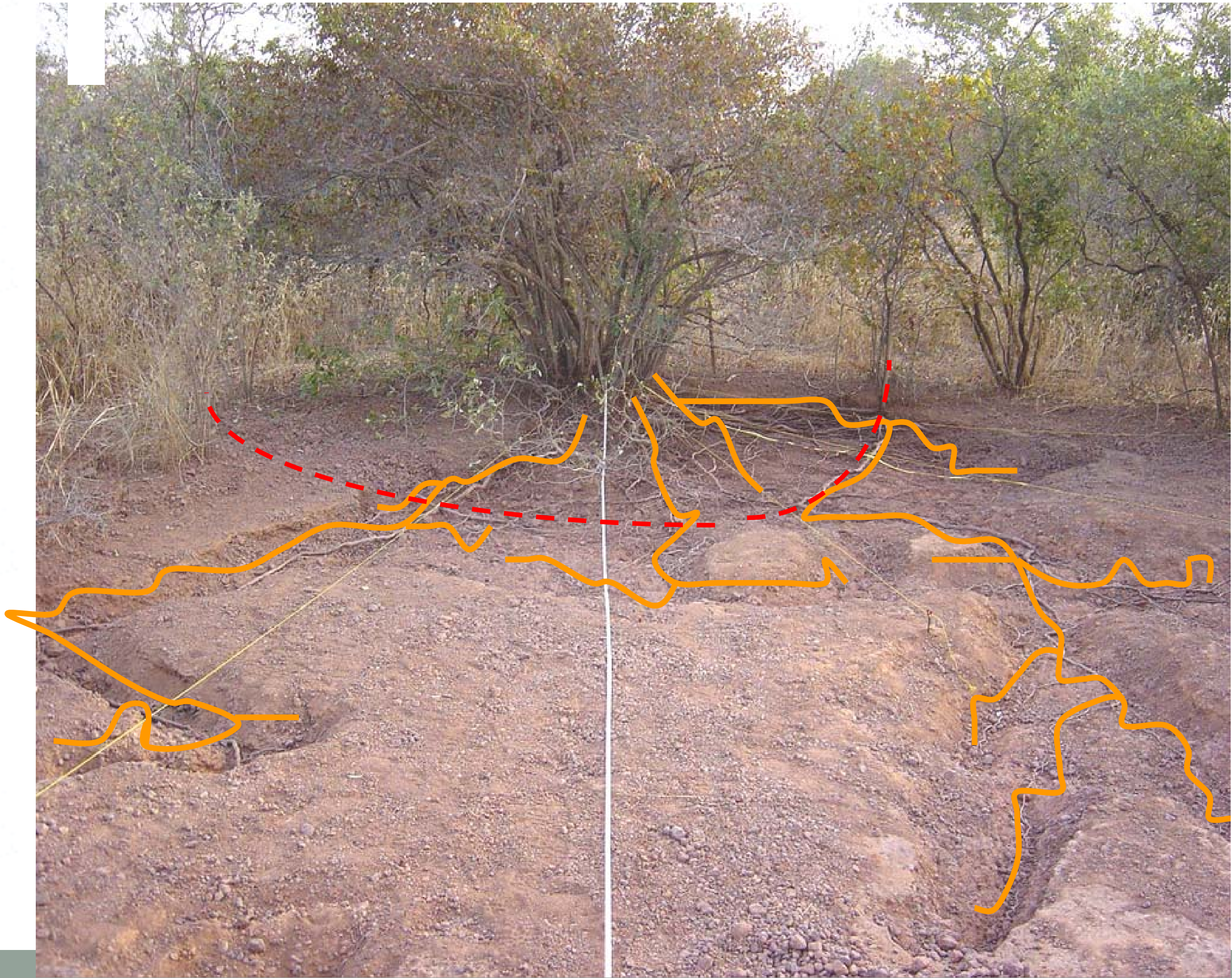
$$L_i = L_i^0 b(\mathbf{r}+\mathbf{r}', t)^p, \quad i = 1$$

Plant-plant interactions modulated by the biomass through the *p* allometric exponent

Necessary condition for patterning on spatial ranges of facilitation (1) vs. competition (2)

$L_1 << L_2$

# Crown and root extents



- W Nat. Park, Niger, *Combretum micranthum*
- *Barbier et al. 2008, Ecology*

# Results from the non-local F-KPP model

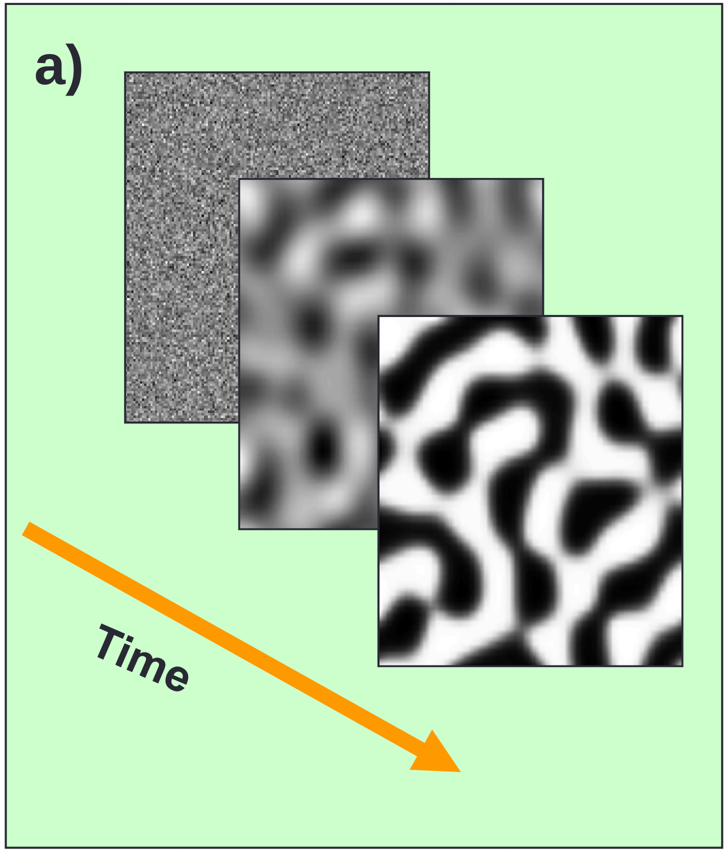
- **Plant shape parameters are central:**
  - Allometric exponent *p* alone determines the critical point that allows self-organization, *p* is assessable in the field (e.g. 1/3)
  - *La* (crown size), $L°_1$ & $L°_2$ facilitation and competition ranges are also measurable

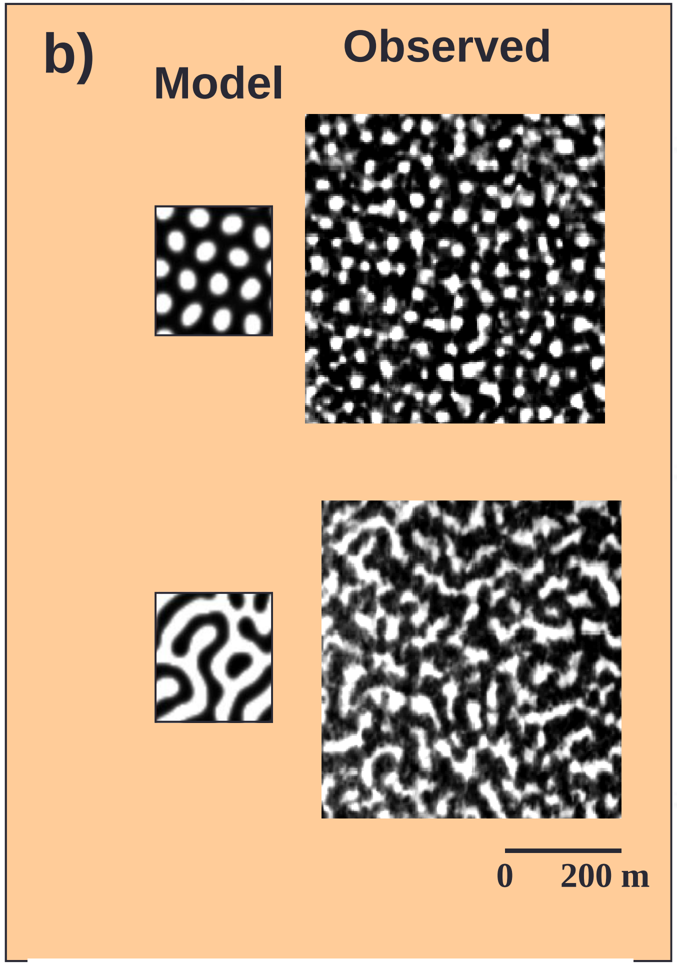
$$b_c = \frac{2p}{1+2p} \qquad \tilde{\mu}_c = \frac{b_c e^{b_c}}{2p}$$

Lefever & Turner (2012), CRAS2B

- Close to the critical point ('self-assembly hypothesis'):
  - There is a close form expression linking the dominant wavelength of the pattern to parameters (and to maximal crown size) => no free parameter left
  - Wavelengths are large compared to plant size

# Pattern simulation from homogeneous (noisy) initial condition




Couteron & Lejeune 2001, *J. Ecol.*

# « Isotropic patterns »:
## thickets with periodic « gaps » (bare ground )

« W » Nat. Park, Niger, W. Africa, MAP ~ 600 mm $y^{-1}$

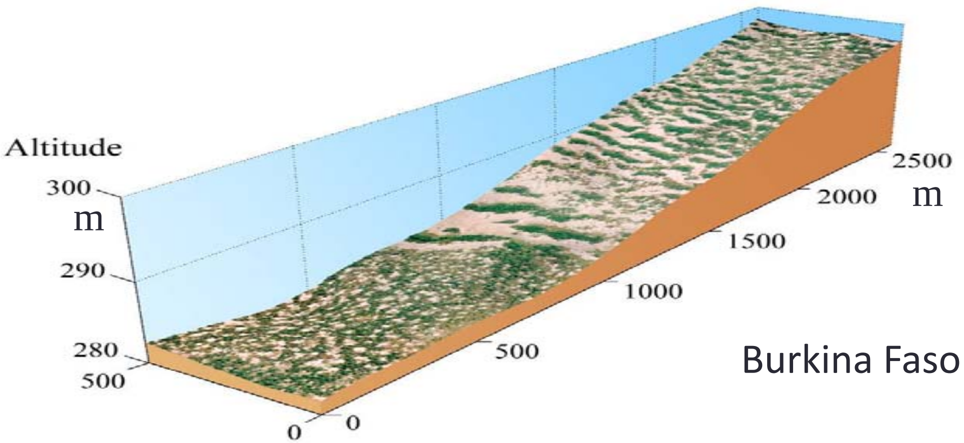

Self-organized vegetation patterning as a fingerprint of climate and human impact on semi-arid ecosystems

*Journal of Ecology* 2006 94, 537–547

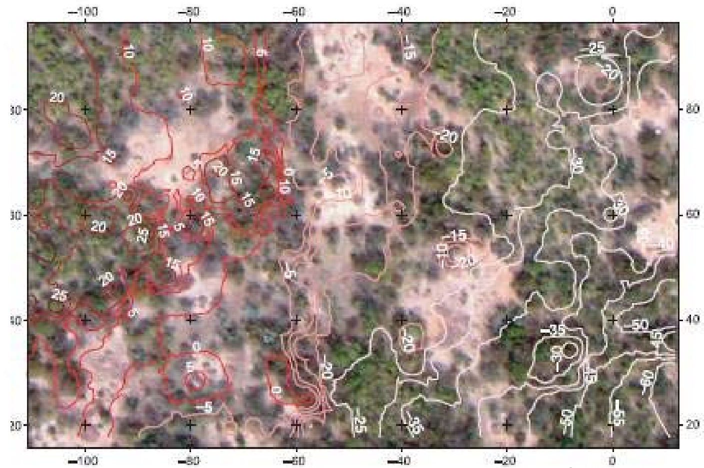
NICOLAS BARBIER, PIERRE COUTERON*, JEAN LEJOLY, VINCENT DEBLAUWE† and OLIVIER LEJEUNE‡

# Some expectations (quite demanding ...)

- **Empirical observations in the sub-Saharan Sahel**
  - Pattern wavelength is very large compared to plant dimension
  - Gaps do exist and are ‘deep’ (~0 vs. > bmax/2)
  - Gaps, labyrinths, spots + bands are observable for a same dominant species (*Combretum micranthum* of broad distribution)
  - Increase of wavelength along the symmetry gradient can be strong (+ 70%)



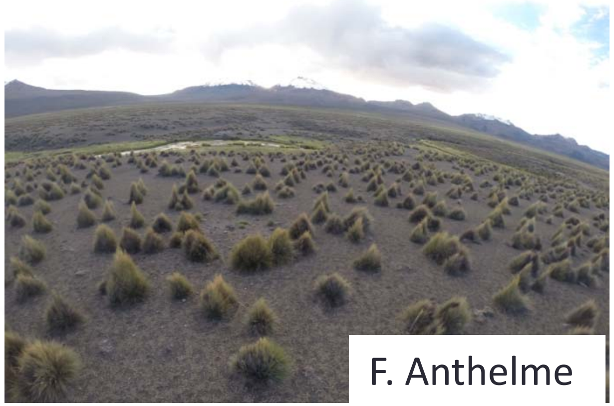
Burkina Faso



Niger, Barbier et al. 2006

# Besides periodic patterns.

- **Tussocks and cushions in tropical alpine ecosystems:**
  - Clonal patch or individual?
  - Independent structures or systems?
  - Localized strucures?

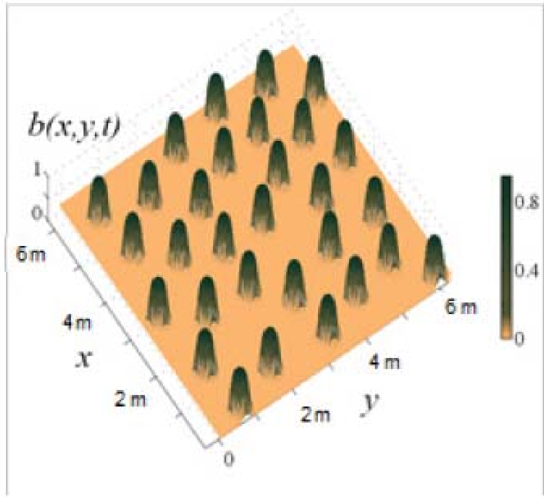


F. Anthelme

$$\partial_t b = b\,(1-b)\,\mathcal{M}_f - \mu b \mathcal{M}_c + D\mathcal{M}_d$$

$$\mathcal{M}_{c,f} = \exp\left[\xi_{c,f}\int K_{c,f}(|\mathbf{r}'-\mathbf{r}|)b(\mathbf{r}',t)d\mathbf{r}'\right]$$

$$\mathcal{M}_d = \int K_d(|\mathbf{r}'-\mathbf{r}|)\,(b(\mathbf{r}',t)-b(\mathbf{r},t))\,d\mathbf{r}',$$




Couteron et al. 2014, PTRA

# Spectral attributes for simulated patterns

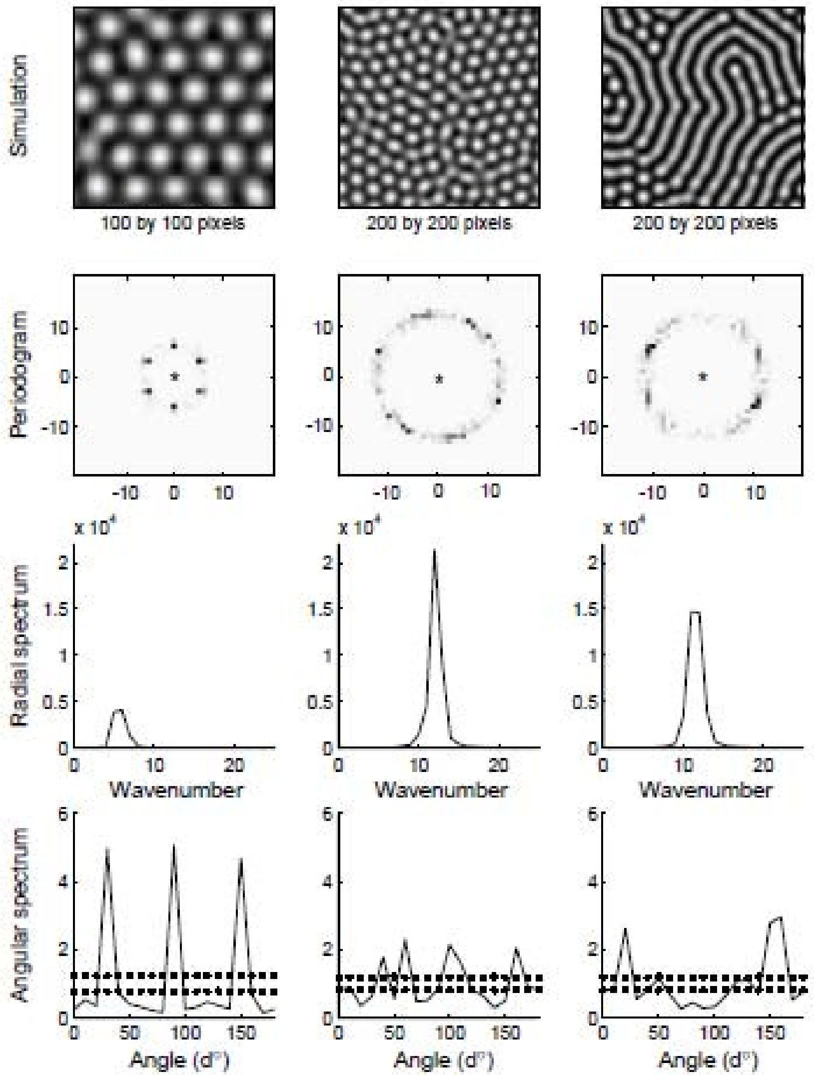
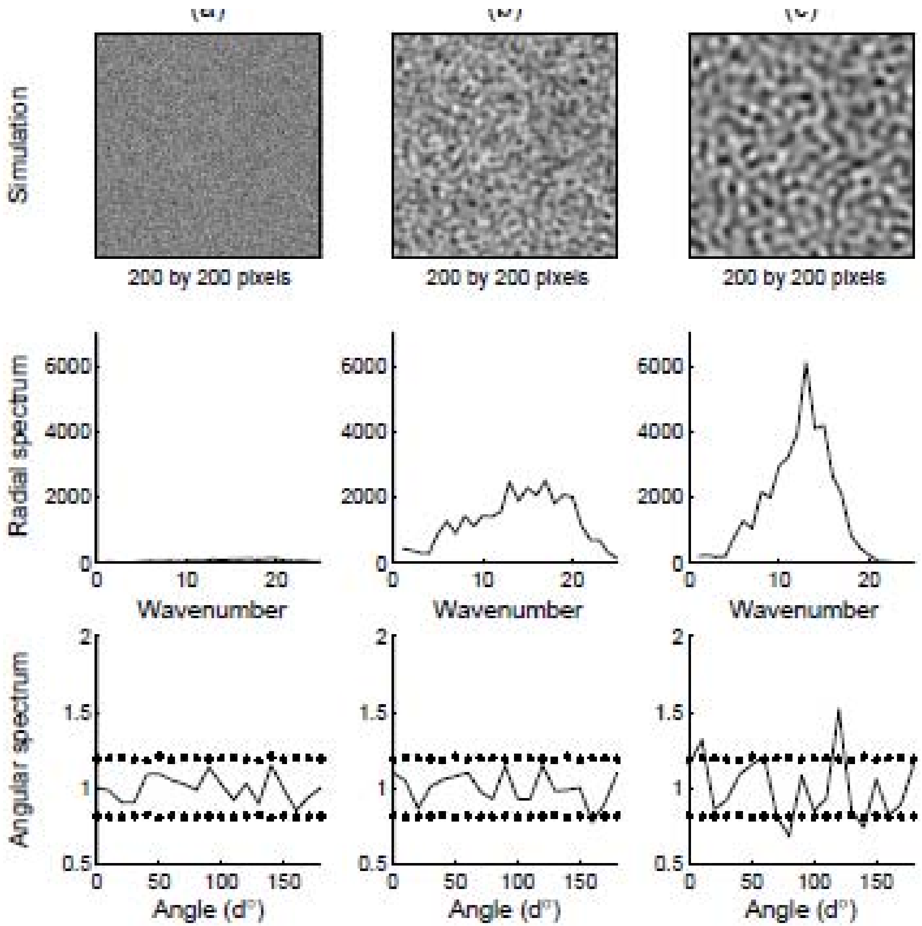



**Fig. 2** Spectral attributes for some patterns obtained with the isotropic version of the PI model for parameters $\Lambda = 1.2$ and $L = 0.2$ ($\mu = 0.98$ for spots and 1.0 for bands). (a) Spotted pattern as perceived through a small window selected for its clear hexagonal symmetry. (b) The same pattern as perceived through a larger window. (c) Banded pattern from a large window. For angular spectra, the dotted lines indicate the 5% bilateral confidence interval computed from the $\chi^2$ distribution.

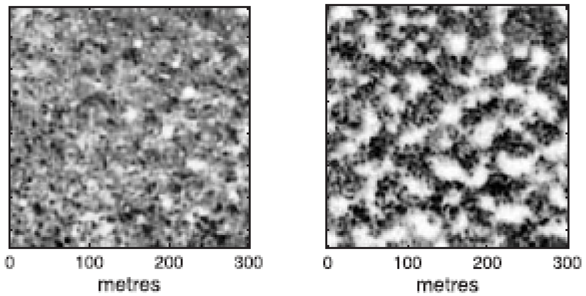
# Emergence of a dominant wavelength (simulations)



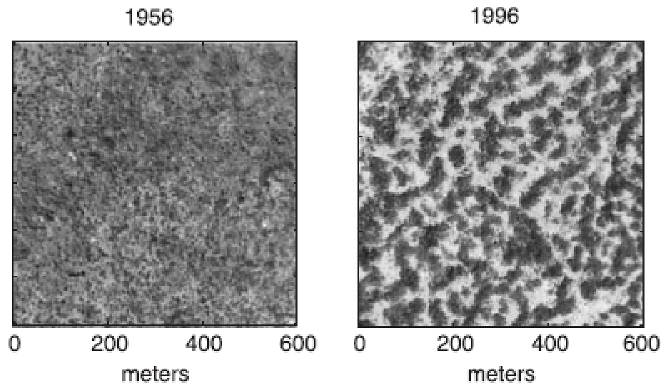
# Self-organization monitoring
# Quantifying drought-related changes

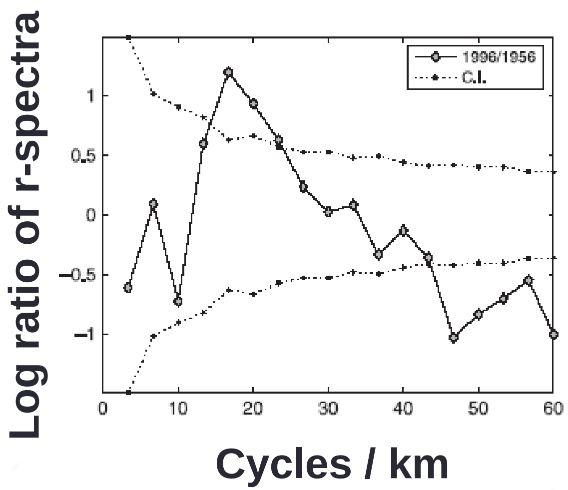
- **Niger, « W » National Park** (Barbier et al. 2006, *J. Ecol.)*

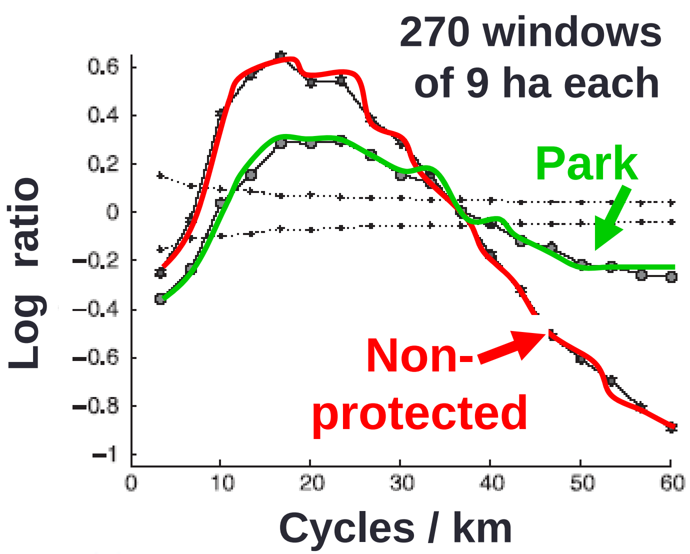
**1956** **1996**



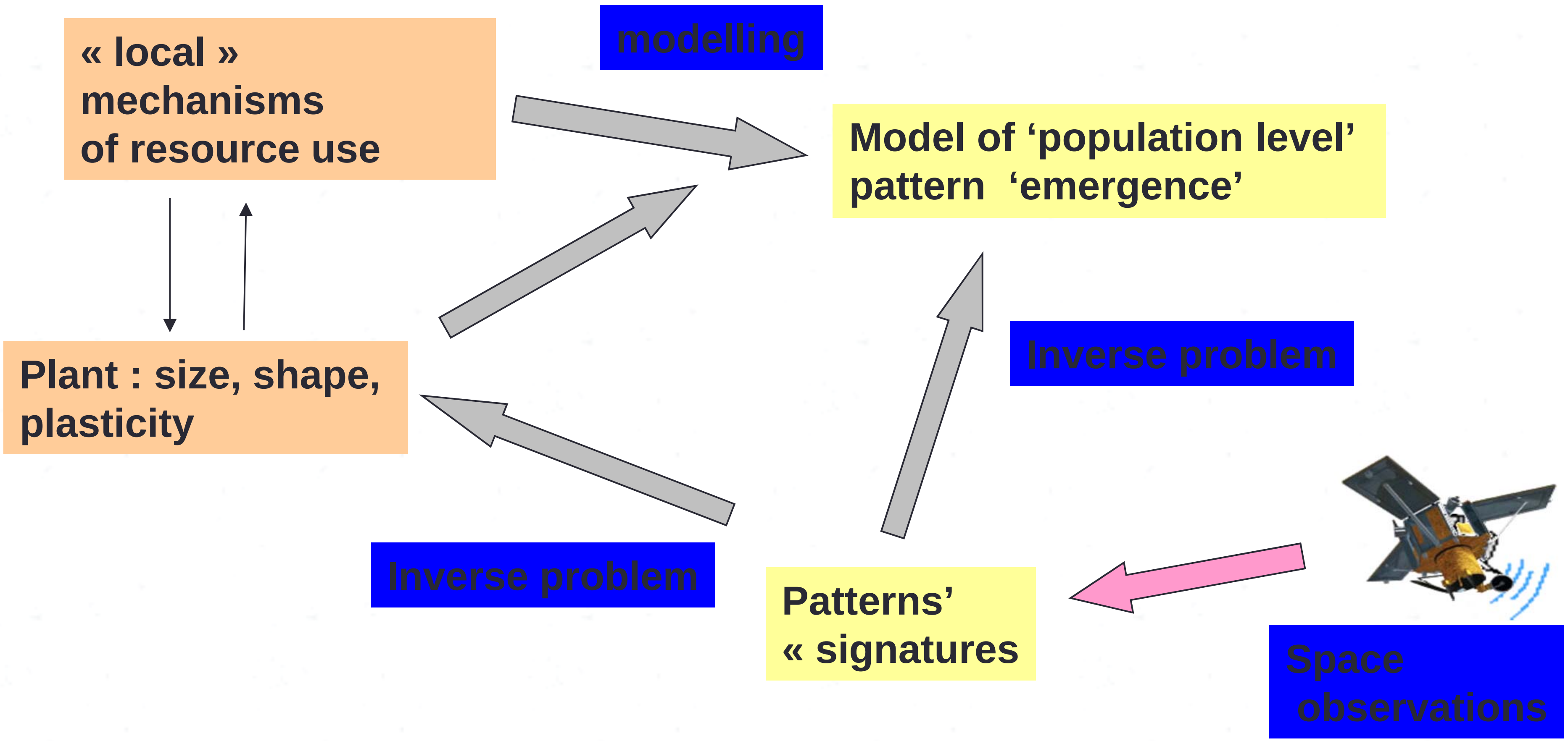

**Droughts :**
**1970 - 1990**



# Relating local to broad-scale



# Main references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# GROUP WORK

- *Let’s consider a dryland region which has not yet been studied in terms of patterns and for which suitable remotely sensed images are accessible.*
- *Make a preliminary map of those vegetation pattern that may be hypothesized to result from self-organization processes. From internet, try to identify the vegetation types and the dominant plant lifeforms which seem to be involved in the patterns.*
- *Compare the spatial distribution of the main types of patterns and spatial variation in pattern characteristics with environmental variables (e.g. relief).*
- *Build hypotheses based on existing models to explain the main types of patterns observed.*