SELF-ORGANIZED VEGETATION PATTERNING

AS A FINGERPRINT OF CLIMATE AND HUMAN IMPACT O SEMI-ARID ECOSYSTEMS

Barbier et al, Journal of Ecology 2006

Regular, landscape-scale patterns in Southern Niger “are manifestly within the province of botany and ecology; the essential background concerns geomorphology and meteorology; the causes must be investigated by physics and mathematics; and the whole matter must be studied on air photographs.” (Macfayden 1950)

VEGETATION PATTERNS

- Patterns have been observed in dry zones of Africa, Australia, Mexico and the Middle East
- Soils: sandy to silty to clayey
- Occur at transitions between tropical savannas and hot deserts, thus **aridity** is the probable triggering factor
- Possible explanations: vegetation patches overcome aridity as a result of water sheet flow from upslope bare ground

MODEL TYPES

First class

- Vegetation stripes form along elevation contours
- Soil heterogeneity is the reason for regularly spaced bare spots on nearly flat territory
- Transition from homogeneous to striped vegetation

Second class

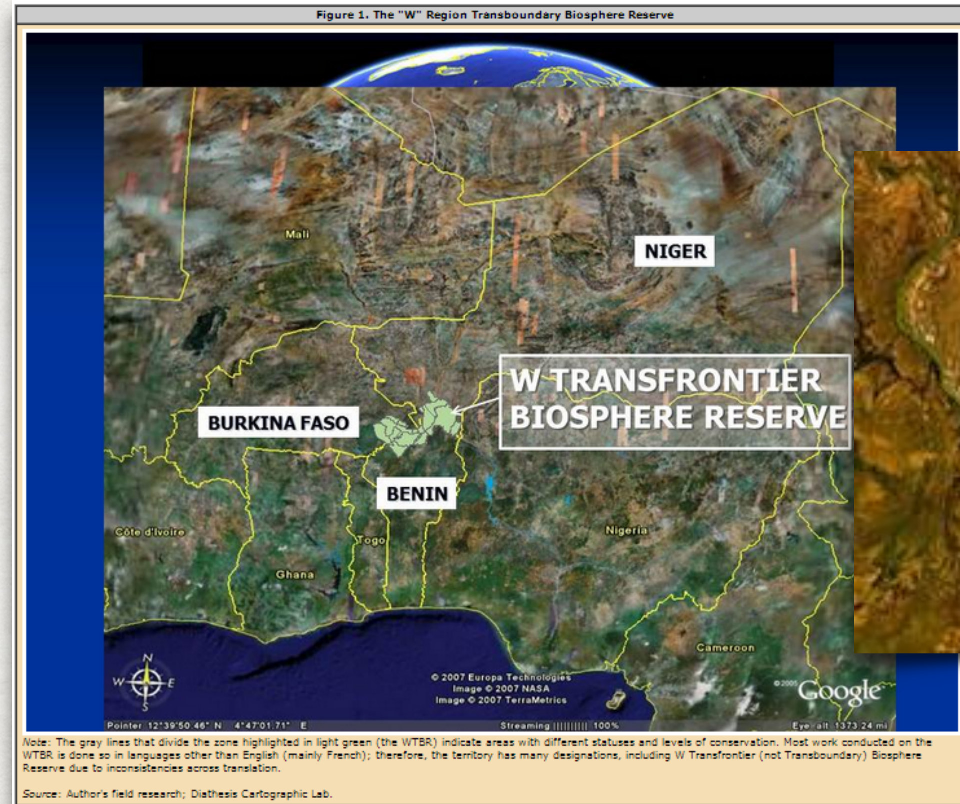
- Can generate stripes and spots even in homogeneous and non-sloping environments
- Patterns are generated by instability that leads to disruption of spatial symmetry (Turing)
- Slope anisotropy is a secondary effect that leads to stripes rather than spots
- Homogeneous to bare spots to labyrinthine stripes

Model similarities

- All models involve **competitive effects** related to soil water consumption and **facilitative effects** from soil water budget enhancement by vegetation.
- For pattern formation, competition must have a longer range than facilitation (**short-range activation and long-range inhibition**)
- Patterning occurs when vegetation growth decreases, eg. as a result of **reduced water availability**.

STUDY AREA

- South-west Niger
- Includes protected area (rainfall decrease) and unprotected area (rainfall decrease and increasing human pressure)
- Patterns formed by dense thickets of tall shrubs and annual grasses



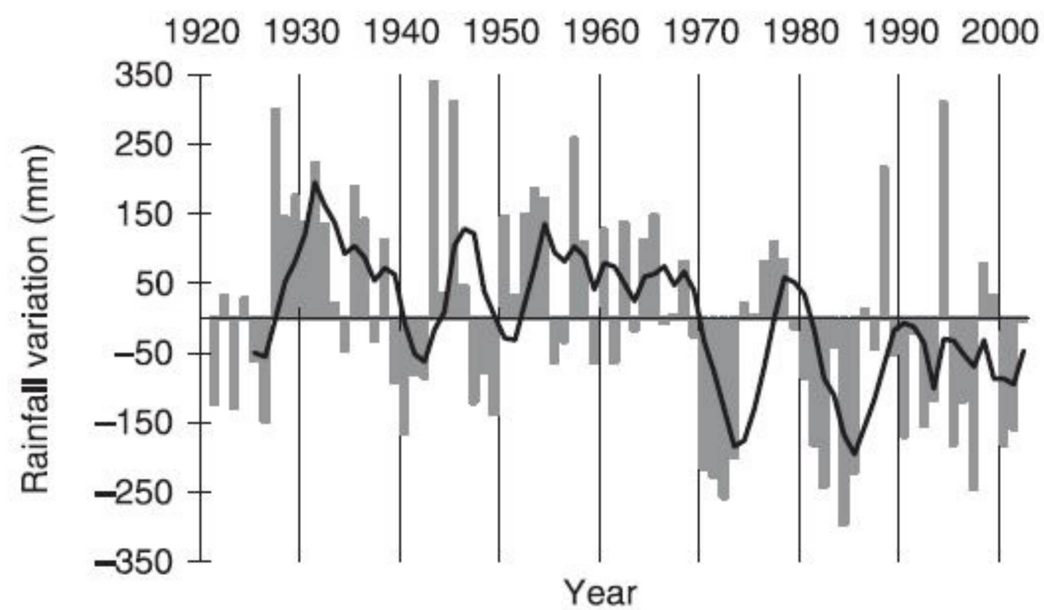


Fig. 2 Rainfall data for 1921–2002 at the meteorological station of Say (source: Direction Météorologique Nationale, Niger) expressed as annual variation (bars) around the interval mean (619.5 mm). The continuous line shows the moving average of the five preceding years.

REMOTELY SENSED DATA

- Aerial photographs turned to greyscale: bight pixels (bare soil), dark pixels (woody vegetation), greyscale pixels (continuous grass cover)
- Sampled rectangular study regions in and outside the park
- Data from 1956 and 1996

Fig. 1 Typical spotted pattern (bare soil is light coloured) and field study set up: perspective oblique view showing transects (three 50-m transects for soil survey, one 250-m transect for vegetation-relief correlation study) and a 120-m by 70-m area for topographical mapping.

PATTERN ANALYSIS AND CLASSIFICATION

- 2D Fourier transform and 2D periodogram (power spectrum)
- 2D periodogram values were summed on ring-shaped or wedge-shaped frequency regions to compute the r-spectra and the θ-spectrum
- r-spectrum: partition of the image variance across spatial frequencies
- θ-spectrum: partition among spatial orientations; also calculated index of pattern isotropy by computing Shannon's entropy on this spectrum
- Compared r-spectra using the log-ratio technique

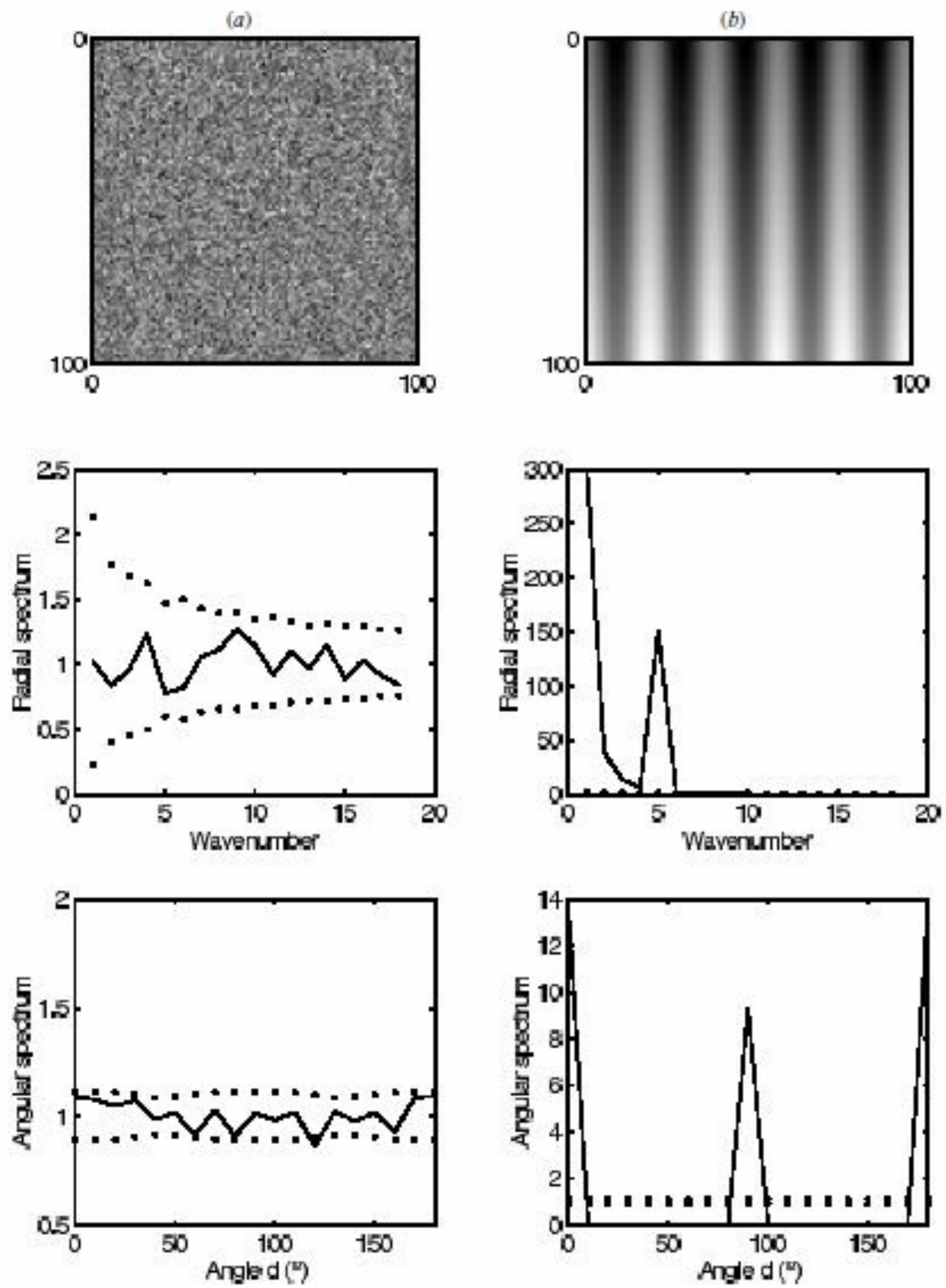


Figure 3. Examples of polar spectra from two computer-generated images (100 by 100 pixels). The solid lines denote the spectra whereas the dotted lines stand for the 5% bilateral interval around 1 (expected value in the absence of spatial structure). (*a*) No spatial structure: each pixel value was generated according to a Gaussian white noise (WN), with $\mu = 10\sigma$. (*b*) Superimposition of a cosine wave (bands) of amplitude β, a WN with $\sigma = 0.1\beta$, and a linear trend of amplitude β.

Periodograms and spectra
Couteron 2002

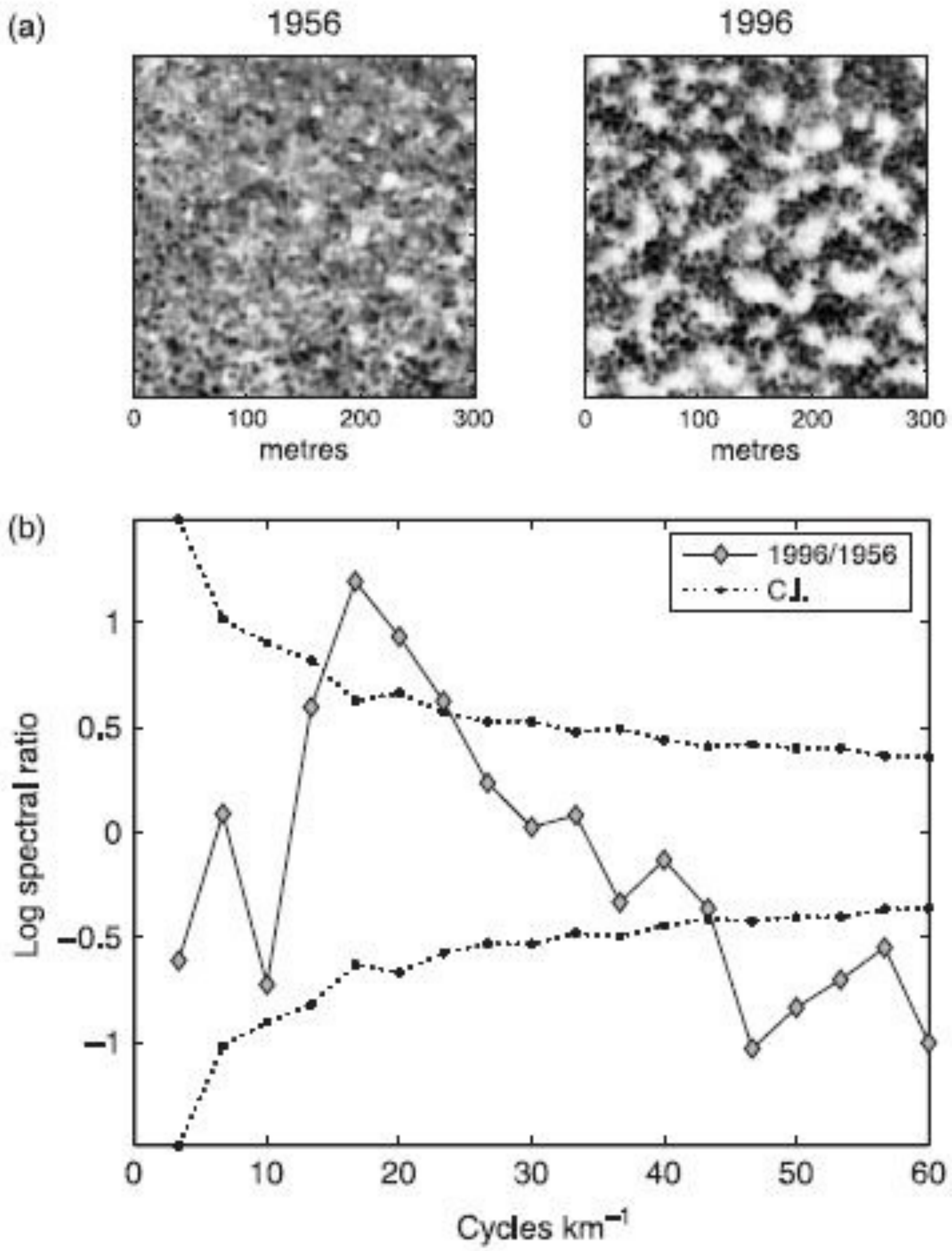


Fig. 3 Diachronic comparison of vegetation aspect in a particular window: (a) aerial photographs (windows 300 m on a side); bare soil appears in white and vegetation in grey (light to medium for herbaceous cover, dark for bushes, thickets and trees). (b) Log ratio between the 1996 and 1956 Fourier r-spectra. Dashed lines represent the 95% confidence interval (CI) computed under the null hypothesis of absence of change between 1956 and 1996.

- Shift from homogeneous savanna to spotted vegetation characterized by emergence of peak in the **r-spectrum**
- **Log-ratio** of the spectra shows which spatial frequencies have undergone a statistically significant increase.

FIELD MEASUREMENTS

- Picked typical spotted vegetation sites for intensive **field investigations** (soil depth, particle size, bulk density).

- Computed **Fourier coherence spectrum** between vegetation cover and local elevation: no significant relationship

- Vegetation was not restricted to local depressions (thus spotted patterns don't directly match pre-existing substratum irregularities)

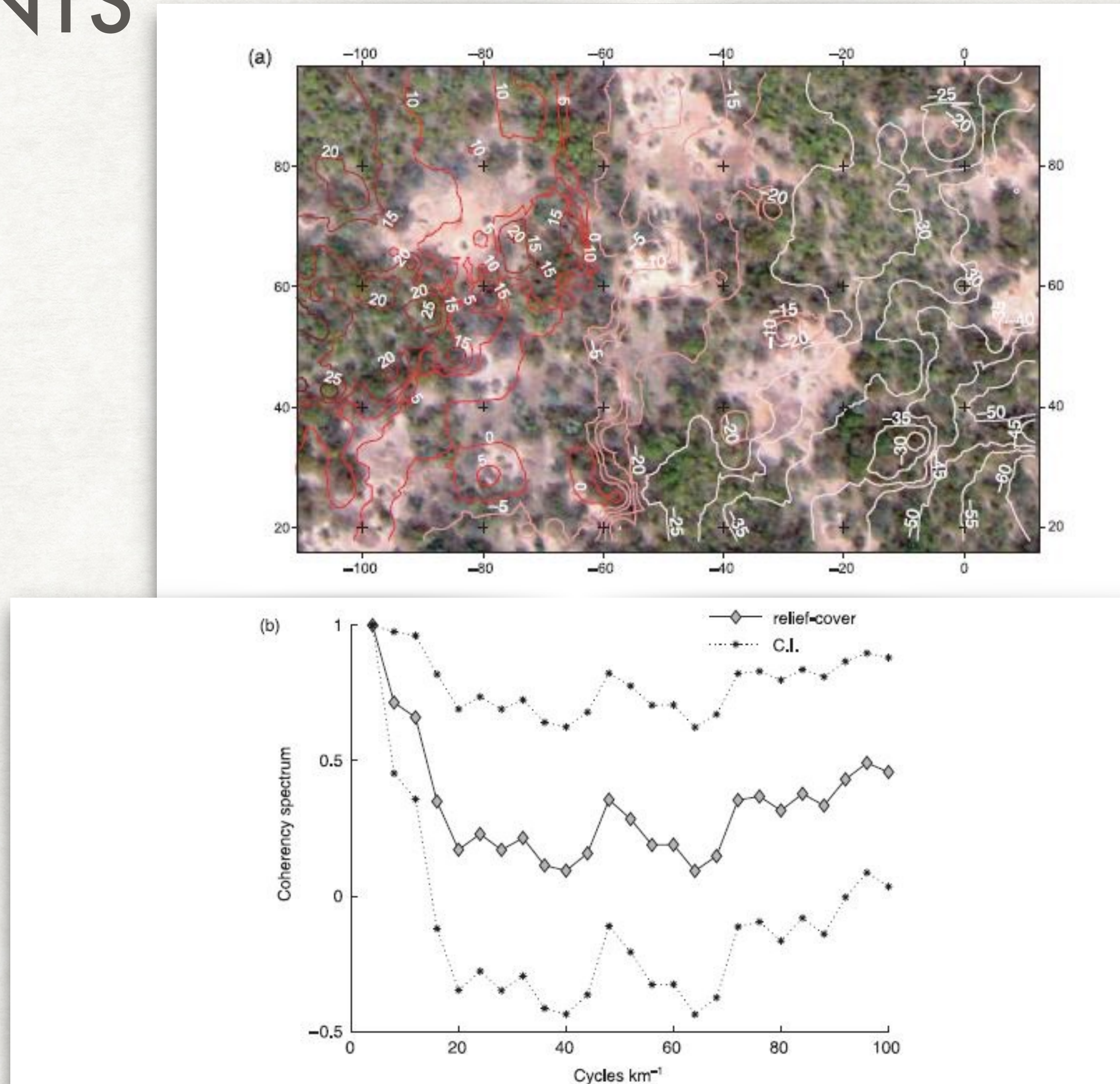


Fig. 4 Test of independence between vegetation pattern and microelevation. (a) Contour levels (5-cm spacing, relative altitudes in cm, distances in m) superimposed on a vertical view in the 120-m by 70-m quadrat. (b) Coherence spectrum between cover and local elevation along the transect. The dashed lines represent the 95% pointwise confidence interval (CI) based on two standard errors in each direction.

CLASSIFICATION

- Performed non-hierarchical, unsupervised **clustering** of r-spectra using K-means algorithm and Euclidean distance.

- **Inside park:** limited change, spotted patterns on the plateaus

- **Outside park** (heavy human pressure): crops, and extensive spotted patterns

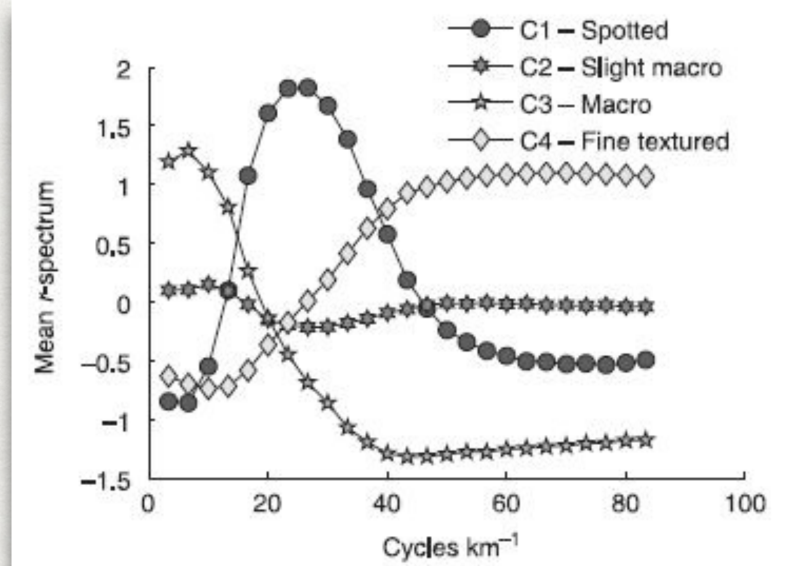


Fig. 5 Standardized mean r-spectrum of each class of land-cover pattern (K-means clustering).

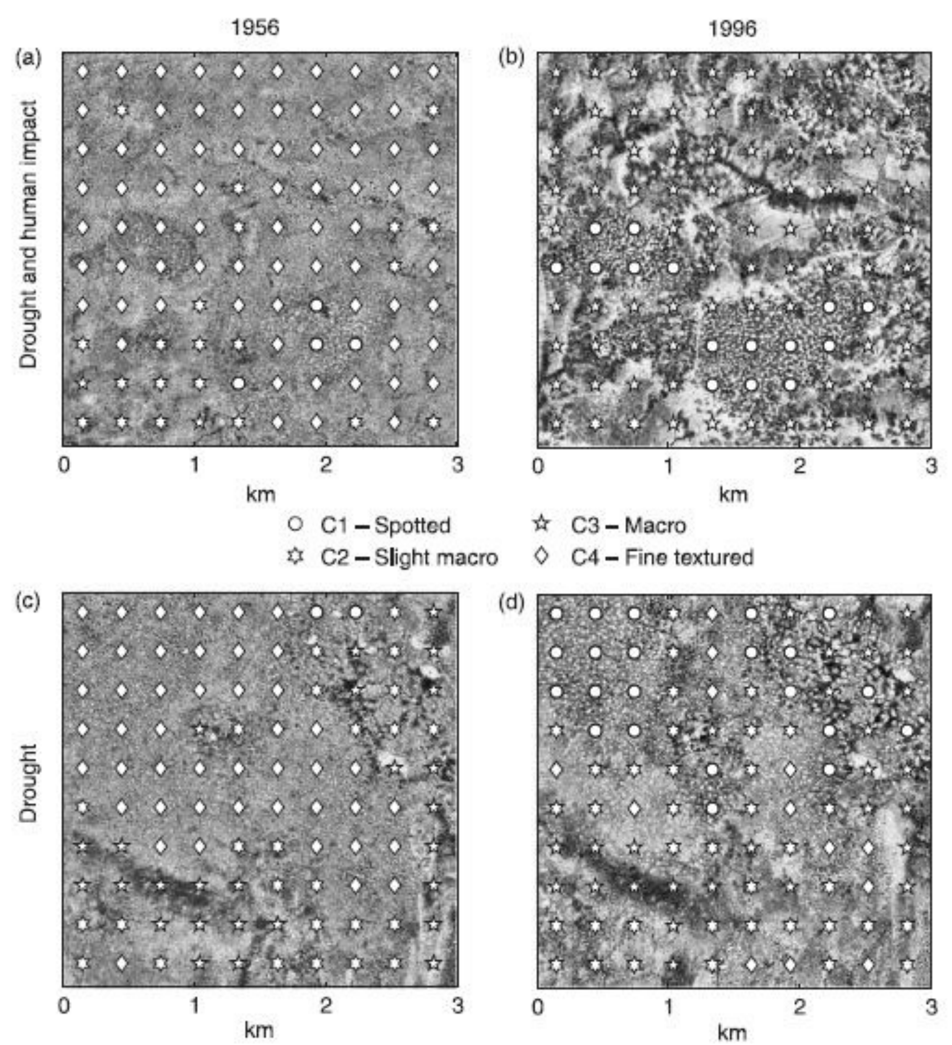


Fig. 6 Maps of land-cover patterns illustrating the temporal dynamics in two particular square areas of 3000 m on a side: (a,b) outside the park, under human pressure; (c,d) in the park.

LOG-RATIO OF MEAN R-SPECTRA FOR THE 2 YEARS

- **In the park**, drought led to spotted patterns (20 cycles/km)
- **Outside park,** spots but also human-induced features at lower frequencies
- Second figure: focus on windows with spotted patterns, shot intensity of spotting patterns exacerbated by human activities

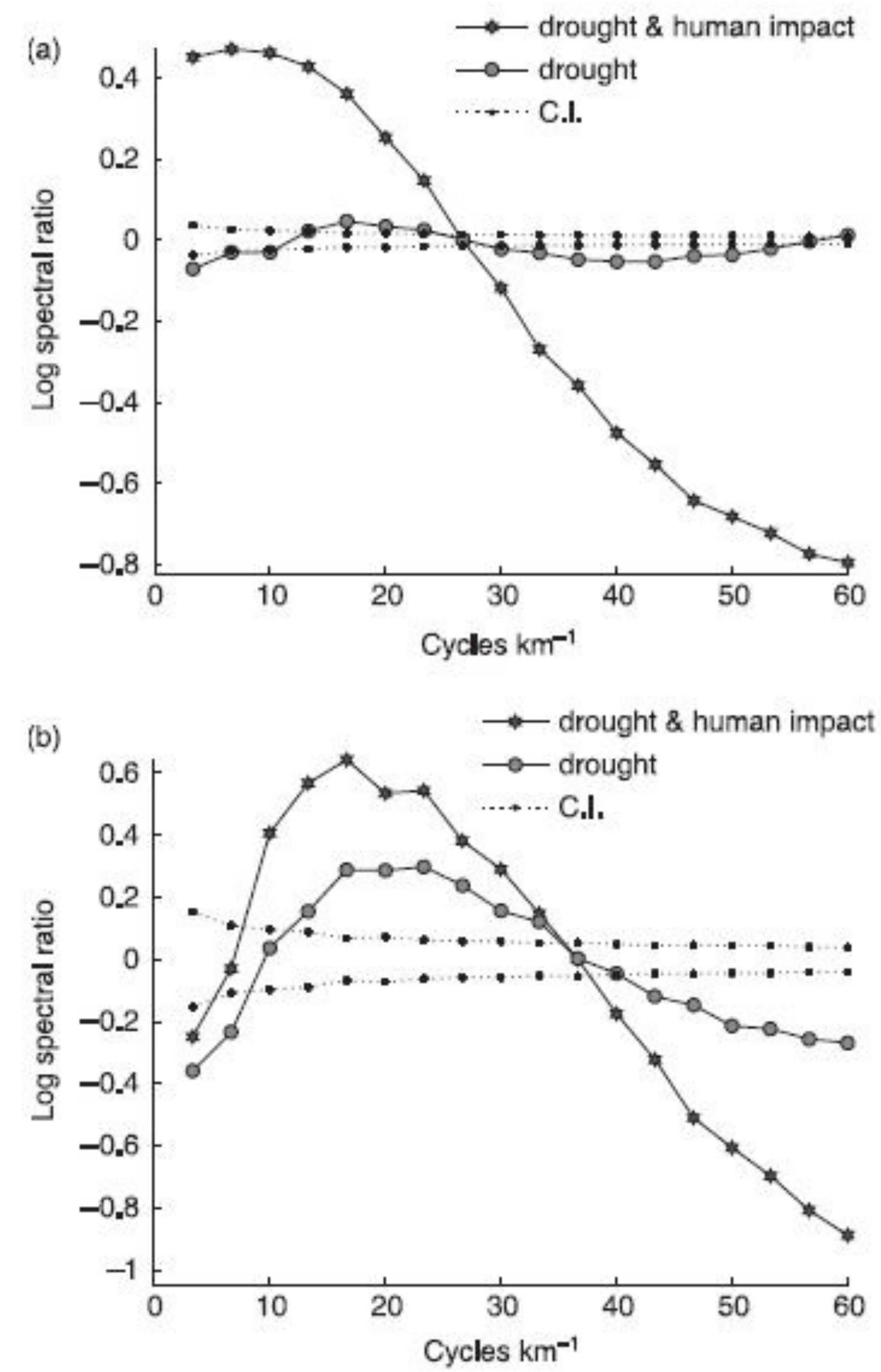


Fig. 7 Diachronic change in vegetation spatial patterns for protected (drought impact) vs. unprotected (drought + human impact) situations analysed using the log-ratios of mean 1996–56 Fourier r-spectra. The dashed lines represent the 95% confidence interval (CI) computed under the null hypothesis of absence of change between 1956 and 1996. (a) Log-ratios computed for all windows; (b) log-ratios computed for the windows classified as spotted in 1996.

ISOTROPY

- θ-spectra: factorial ANOVA on the Shannon entropy for spotted windows
- A significant decrease in entropy (less isotropic aspect) observed in the unprotected area
- **Labyrinthine**/banded periodic patterns

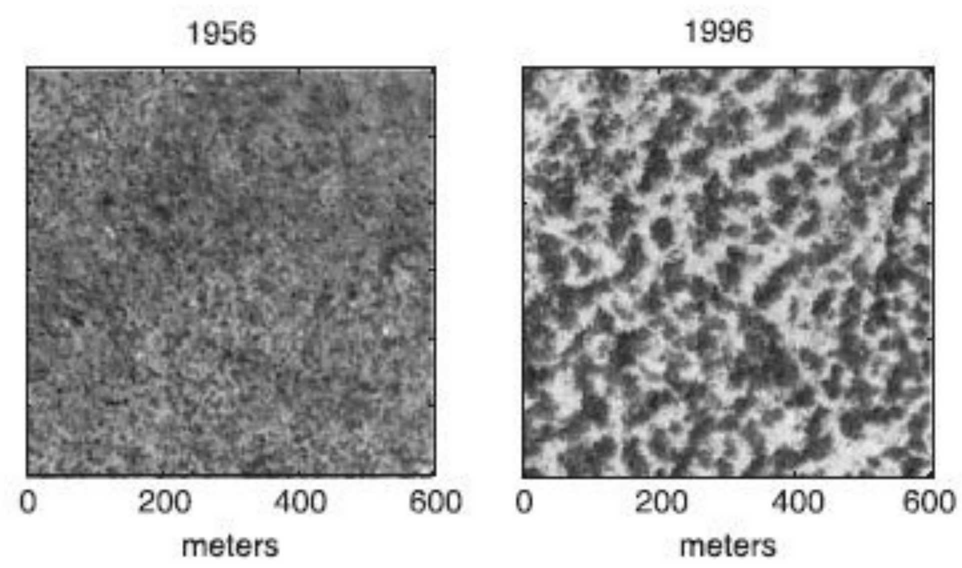


Fig. 8 Diachronic aspects of a reference area exemplifying an exceptional shift towards labyrinthine/banded pattern, i.e. the appearance of a dominant wavelength accompanied by a substantial loss of isotropy, with entropy figures of less than 2.8 in the banded parts of the right picture.

CONCLUSIONS

- A period of intense drought periods and general **decreasing rainfall** led to a systematic shift from homogeneous to periodic patterns (spots of bare ground).
- The patterns have a **dominant peak** around spatial frequencies of 20 cycles/km in the radial spectrum.
- Periodic patterns can form **even in absence of pre-existing spatial heterogeneity** (thus 2nd class of models more accurate).
- Strongest patterning dynamics occurred outside the park, hence interaction between **human activities and drought** may trigger periodic patterns.
- Sequence of patterns under increasing stress is predicted to be **spots of bare ground, labyrinths/bands, and spots of vegetation.**
- Impact: studies on **interactions between climate and land cover**; spatial patterns in the extension of bare ground are known to influence atmospheric energy and water budget in a nonlinear way.