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.
REMOTE SENSED DATA

- Aerial photographs turned to greyscale: bright 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 $\theta$-spectrum
- r-spectrum: partition of the image variance across spatial frequencies
- $\theta$-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
Periodograms and spectra
Couteron 2002

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 $\beta$, a WN with $\sigma = 0.1\beta$, and a linear trend of amplitude $\beta$. 
- 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.

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.
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.
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

- $\theta$-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.
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.