



Vegetation cluster-size distribution, dynamics and resilience indicators in African semi-arid ecosystems from high-resolution satellite data

Utsav Biswas and Vishwesh Guttal

Indian Institute of Science, Centre for Ecological Sciences, Bengaluru, India (utsavbiswas@iisc.ac.in)

Semi-arid ecosystems cover around one-third of the Earth's terrestrial surface and support over 1.2 billion people. These are water-limited landscapes that are vulnerable to climate variability and various anthropogenic pressures. An important feature of these ecosystems is the emergence of distinct spatial patterns. Such patterns result from processes of self-organisation that are driven by local plant-plant interactions and water redistribution.

Predictions from theoretical models and computer simulations show that these vegetation patterns exhibit specific statistical properties, notably in their cluster-size distributions. Healthy ecosystems are predicted to have underlying power-law distributions (having the form: $N(x) \sim x^{-\beta}$ where β is the power-law exponent), characterised by the presence of vegetation clusters of all sizes, including large, connected patches. As ecosystems degrade, theory predicts a progressive truncation of the power-law distribution, with large clusters fragmenting into smaller ones. This has been proposed as a potential early warning signal of ecosystem collapse.

Although extensive theoretical work on self-organised vegetation patterns has been conducted, empirical validation remains critically limited. Most studies examine spatial gradients at a single moment using a space-for-time approach, but only a few have repeatedly monitored the same ecosystem over many years to determine whether the way clusters change over time aligns with what theory predicts. There are no studies at high spatial resolution (~ 1 m) that also cover landscape-level scales (>1 km²) that have been conducted so far. Our study addresses this gap by analysing multi-year, high-resolution satellite data (~ 1 m) from the study sites in the African semi-arid region. We have examined six sites in the African drylands, utilising high-resolution data from the WorldView-2 satellite, to derive NDVI, binarize vegetation via Otsu thresholding, and extract underlying vegetation cluster-size distributions. Using the `spatialwarnings` and `powerLaw` packages, we fit power-law, truncated power-law, and exponential models to quantify spatial structure and evaluate the power-law exponent β as an indicator of fragmentation and resilience. Temporal analysis examines how vegetation clusters have changed at each location over a few years.

Looking at the underlying vegetation cluster-size distributions, we found that some sites have $2 < \beta < 3$ (where β is the exponent of the power-law fit to the cluster-size distribution), indicating little fragmentation and a balanced mix of small & large clusters, while one site showed a highly

fragmented system. Additional insights can be gained by examining how the clusters have evolved over time at a landscape level. Together, these analyses provide a novel approach to studying semi-arid ecosystems from anywhere in the world, utilising satellite imagery, and to make a quantitative assessment of their health in terms of fragmentation and resilience. This approach provides a scalable framework that can be applied globally to identify vulnerable dryland sites and prioritise those that require conservation and management interventions.