Africa – Part 1: Image analysis and characterization of spatial patterns

Data: Satellite imagery of four sites in the semi-arid environs of Kruger National Park, South Africa, for the years 1983, 2000, 2003, 2006. Each site has two treatments; annual burn (called **burnt**) and **control** where fire was supressed.

Characterization of spatial patterns: The spatial vegetation patterns for each treatment were characterized with three metrics.

1. Patch size distributions
2. Distribution of distances to nearest neighbouring patch for each patch
3. Overall vegetation density (proportion of vegetation)

Questions:

1. Which probability distribution (amongst **power law**, **exponential**, **log-normal** and **power law with an exponential cut-off**) best captures the patch size distributions.
2. Which probability distribution best captures inter patch distances?
3. How can we mechanistically explain the underlying distributions?

Methods: MLE estimators to fit the distributions, as underlined in Clauset et al 2009.

Results:

1. We observed a **log-normal** distribution of patch sizes across all years and in both the burnt and control plots. Only one treatment (**Numbi 1983, burnt**) showed a clear power law fit.
2. Inter patch distances followed a **power law with an exponential cut-off** for almost all treatments. However, the exponential cut-offs were very low and the fits approximated exponential distributions. As the exponential fits performed almost equally well, the distributions were considered to be **exponential**.

Discussion:

We have little mechanistic understanding of how these patterns arise. Log-normal distributions, however, have rarely been associated with vegetation patch sizes in semi-arid regions and we show that these might in fact be prevalent in certain ecosystems. Patch sizes, therefore, are not scale free and the dynamics of such a system are still unknown.

We have also devised a new metric (distribution of inter patch distances) which, along with patch size distributions, can be used to uniquely identify vegetation patterns at any site. The importance of a second metric will be demonstrated in the next part.

It is interesting that the shape of these patterns remained consistent across the years and for both burnt and control plots. As each treatment now has unique parameter values from the distributions (**Shape** and **Scale** for log-normal (patch size), **Rate** for exponential (inter patch distance) and vegetation **Density**), how do they (4 variables) change across the years and what are the differences between burnt and control plots?

What do these variables **represent physically**?

Log-normal variables: I have understood that **Scale** is a measure of the centre of the data. With patch sizes, increasing scale potentially means that the median patch is becoming larger. **Shape** is a measure of the spread of the data, which indicates a fatter tail and the presence of larger patches and higher variance as it increases.

Exponential variable: An increase in **Rate** should indicate that nearest neighbour patches are becoming closer and that few patches are at large distances from their nearest neighbours.

Vegetation density: An increase in **Density** represents an increase in the proportion of the plot occupied by vegetation.

Africa – Part 2: Variation **across years** and between **burnt** and **control** plots

As the years are unevenly spread out, some measure of seasonality will have to be incorporated to test this.

Questions:

1. How do the four variables **change across years** at each site and how is this different between burnt and control plots? Can an environmental variable be used to explain this variation?
2. How are these **variables correlated**? Does the nature of this relationship change when plots are annually burnt?

Premise: Fire is an integral part of the system and these ecosystems are poised at a critical self-organized stable state. With no burning, as in the control plots, the ecosystem will have to shift towards an alternate state of organization. Fire and a characteristic spatial pattern are critical to maintaining the ecosystem in its incipient stage.

Hypotheses Q 1): Difficult to make predictions without environmental variables.

1. Density
2. For the **control** plots, density can be expected to increase (if it is below what the system can sustain) even with constant or slightly reduced rainfall.
3. Alternatively, in a water limited system, perhaps more vegetation cannot be supported beyond a threshold and only an increase in rainfall can cause densities to increase. As mentioned earlier, the system might become unstable with fluctuations in density until a new stable state is achieved.
4. For the **burnt** plots, the system may already be at a self-organized state to maintain density levels (assuming fire is an integral part of the system). Barring drastic changes in rainfall, density can be expected to remain relatively constant with corresponding changes in the other variables to nullify the changes in water availability.
5. Shape and scale of log-normal (patch sizes)
6. For the **control** plots, **Shape** (spread) will increase over the years as the large patches will continue to increase in size. Only a period of poor rainfall will cause this to reduce.

**Scale** (centre) will decrease as nothing now inhibits the formation of several small patches.

1. For the **burnt** plots, **Shape** will increase at a slower rate as large patches will continue to grow in size.

**Scale** in this case can be expected to increase over the years as new patches will find it difficult to establish. Average patch size is likely to increase.

1. Rate of exponential (inter patch distances)
2. Difficult to make predictions without environmental variables.

Hypotheses Q 2): Better predictions but unfortunately influenced by results although I tried hard to remain objective.

1. For the **control** plots, I would expect the characteristic patterns of self-organization to be lost with the only dynamic being growth and a movement towards an alternate stable state. **Densities** therefore can be expected to change but can be expected to only **weakly influence patch size distributions**. However, inter patch distances will invariably be affected by increasing density. **Rate**, therefore, will be **positively correlated** with **density**.

Rate for inter patch distances will be a function of patch size distributions because, as mentioned previously, growth of patches and establishment of new patches will be the only dynamic. Both **shape** and **scale** will be **positively correlated** with **rate** as both an increase in the central tendency as well as the variance will cause inter patch distances to reduce.

1. For the **burnt** plots, directed self-organization will be required to maintain densities in what is a more stressed system. Both patch size distributions as well as inter patch distances are likely to be highly sensitive to changes in density. It is difficult to speculate about the nature of these correlations except that as in the case of the control plots, I would expect **rate** to be **positively correlated** with **density**.

More indicative is the prediction that patch size distributions and inter patch distances will organize independent of each other and that shape and scale will also vary independently. This will imply very strong self-organization of vegetation in the burnt plots.

Results: Variation across years

Vegetation density remains relatively constant for the burnt sites across the years but changes haphazardly in the control sites. This is in keeping with the hypotheses. Scale of patch size distributions does not follow any consistent trend in the burnt sites but does so in the controls. The other two variables follow similar trends in the burnt and control plots.

All trends effectively reverse between 2003 and 2006 but the reason is unknown.

Results: Correlations between variables



Rate increases as a function of density as expected in both burnt and control plots. The strength of the relationship is stronger in the burnt plots. Shape and scale are strongly positively correlated with density in the burnt plots but appear to be unrelated in the control plots.

As hypothesized, all variables are independent in the burnt plots but are highly correlated in the control plots. Shape is negatively correlated with rate but scale is positively correlated with rate although I expected a positive correlation in both cases.

In summary, the spatial patterns are linked with density in the burnt plots but patch size distributions are independent of density in the control plots. Also, in the burnt plots, the three other variables are independent unlike the strong inter-dependence observed in the control plots.

Discussion and additional thoughts:

I cannot comment on the trends of all variables across the years but it is apparent that the system has been affected by some strong environmental change. However, the trends with vegetation density suggest that the burnt ecosystems were relatively stable and were able to maintain constant vegetation cover over the years. The system was possibly already adapted to annual fires. In the control plots, vegetation cover seems to fluctuate and the system appears quite unstable. Moreover, the strong relationship of patch sizes and inter patch distances with vegetation cover in burnt plots indicates that the vegetation self-organizes characteristically at different stable vegetation densities but that the nature of organization is determined by the densities themselves.

Although both burnt and control have same distribution, it is interesting that burnt plots are more stable than the control plots (veg. density vs shape plots). In a sense, burnt plots seem to neutralize the effects of other environmental drivers - which is an interesting result if we can get more solid evidence. Could grazing be some equivalent of fire? If so, can we say a certain level of disturbance causes stability (or at least, reduces variabilities and makes system less sensitive to other environmental factors) in semi-arid systems? Has any such phenomenon regularly observed in semi-arid ecosystems? The fact that scale vs shape has opposite trends for burnt and control plots is interesting. It seems control plots has lower shape (hence lower variability) for higher scale (hence, higher mean) and its reverse for the burnt plots.

The other three variables used to characterize spatial patterns are independent in the burnt plots which implies that all three are essential to describe the complex state of the ecosystem. This independence is absent in the control plots and any one variable is sufficient to describe the state of the system. This is possibly because of the breakdown of previously limiting processes or interactions on the ground and a reduction in the levels of stress.

Overall, I feel that the evidence for self-organization is strong in the burnt plots and an inability to reach a stable configuration is apparent in the absence of fire in the control plots.

Many aspects of this work still have to be understood.

Both log-normal and power-law are fat-tailed distributions. How are they qualitatively different? Can log-normal be thought of as "scale-free" for a limited range of scales whereas power-law is technically scale-free for all scales?

We need to understand the processes and interactions involved. The properties of the probability distributions are still not entirely clear. The relationships between the variables are also still unclear and the directionality of some of the relationships is difficult to understand.