Is the patch size distribution of vegetation a suitable indicator of desertification processes?: Comment

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With ongoing climate change, the search for indicators of imminent ecosystem shifts is attracting increasing attention (e.g. Scheffer et al. 2009). Recently, the spatial organization of ecosystems has been suggested as a good candidate for such an indicator in spatially structured ecosystems (Rietkerk et al. 2004, Kéfi et al. 2007a, Guttal and Jayaprakash 2009). Arid ecosystems are well-known for the spatial organization of their vegetation cover, which is often characterized by clumps of vegetation in an otherwise bare soil matrix. Two recent studies revealed that the distribution of the vegetation patch size can be described by a power law over a wide range of environmental conditions in arid ecosystems (Kéfi et al. 2007a, Scanlon et al. 2007). Furthermore, deviations from power laws were observed under high grazing pressures, leading to the hypothesis that such deviations could be used as indicators of approaching desertification in arid ecosystems (Kéfi et al. 2007a). This hypothesis now needs to be validated with additional field data, before it can be confidently used as a tool to monitor degradation in arid ecosystems.

In a recent study, Maestre and Escudero (2009) (hereafter referred to as ME09) aimed to test this hypothesis with data from 29 steppes located on a rainfall gradient in southeast Spain. In all of their sites, the patch size distribution was best described by a truncated power law (TPL)[1]. Relating the scaling exponents of these TPLs to soil variables, the authors concluded that 1) the patch size distribution was not directly related to desertification but rather that 2) vegetation cover could be used to monitor desertification. We argue in this comment that the analyses of ME09 do not allow them to draw these conclusions, for the following two reasons. First, because all of their sites were characterized by TPLs, the authors looked only

1 We use here the same terminology as in Kéfi et al. (2007) and Maestre and Escudero (2009), where a TPL refers to a power law with exponential cutoff, i.e. such that $N(S)=CS^{-\gamma}\exp(-S/S_c)$ with N the number of patches of size S, C a constant, γ the scaling exponent (positive) and S_c the patch size above which N decreases faster than in a power law (positive).

at the scaling exponents γ of these TPLs to compare the degradation level of the sites. However, γ was not proven to vary with degradation in a consistent manner, and therefore the analyses of ME09 do not allow them to conclude whether vegetation cover is better related to degradation than patch size distribution. Second, although the vegetation cover is often a simple and efficient indicator of degradation, the authors do not take into account the increasing amount of literature that strongly suggests vegetation cover in arid ecosystems is likely to respond in a discontinuous way to gradual, external changes (Rietkerk et al. 1996, Lejeune et al. 1999, Scheffer et al. 2001, von Hardenberg et al. 2001, Kéfi et al. 2007b). In these cases, the vegetation cover alone simply does not provide information on the actual distance to desertification.

The categorization proposed by Kéfi et al. (2007a) is a qualitative one in that it does not provide a quantifiable distance to extinction: a shift (in time) from a pure power law to a TPL suggests that an ecosystem is degrading and approaching the desertification threshold. The sites studied by ME09 are all described by TPLs. Among sites characterized by similar patch size distributions, Kéfi et al. (2007a) do not propose any criteria to distinguish among sites of varying degradation; currently, such criteria are sorely lacking. In an attempt to compare the degradation levels of their 29 sites, ME09 investigated changes in the scaling exponent γ of the TPL among the different sites. This was not part of the hypothesis formulated by Kéfi et al. (2007a). It is an interesting approach, but it implicitly assumes that γ varies consistently with the level of stress, which has not been proven to be the case. In fact, in the data analyzed by Kéfi et al. (2007a), there does not appear to be any consistent variation of γ among sites characterized by different stress levels (i.e. grazing pressures). For example, with increasing grazing pressure (from medium to high) the absolute value γ of the TPL decreases in the data

3

from Spain but increases in the data from Morocco and Greece (see Fig. 1 in Kéfi et al. (2007a)). The lack of a clear relationship between γ and the stress level could very well explain why ME09 find that γ is not related to the perennial cover. It is noteworthy that this result is in agreement with previous studies on steppes dominated by *Stipa tenacissima* in the arid Mediterranean region. For example, it has been shown that the spatial distribution of *S. tenaccisima* is not clearly related with its abundance (see Table 1 in Alados et al. (2006)). Furthermore, the exponent γ alone does not provide a complete description of the shape of the TPL; the location of the cutoff, S_c, cannot be ignored. Indeed, the latter describes where the deviation from power law behavior begins, and it is this deviation which was proposed to be linked to the level of degradation in Kéfi et al. (2007a). Thus, we doubt whether γ is the correct parameter to investigate. Further theoretical and empirical work is needed in order to identify the parameters which are best correlated to the stress level and which therefore should be monitored.

Another concern regarding the analysis of ME09 is that, when fitting TPLs to their data, they find negative power law exponents in the vast majority of their sites (22/29 sites listed in ME09 Table 1 and 7/8 sites illustrated in ME09 Fig. D1), in stark contrast to the positive power law exponents observed by Kéfi et al. (2007a). A TPL with a negative power law exponent can be understood as follows: the number of patches N(S) actually increases with size S until some intermediate path size is reached, at which point N(S) begins to decrease. Thus, in ME09's distributions, it is common for smaller patches to be less abundant than patches of intermediate size. For this reason, a TPL does not appear to be the most appropriate model to use to fit the data. The distributions found by ME09 actually suggest the presence of a dominant spatial scale, contrary to the scale invariance observed by Kefi et al. (2007a).

4

Indeed, some arid areas are characterized by regular vegetation patterns (Rietkerk and van de Koppel 2008), where patch size distributions do not follow power laws but instead reflect a characteristic patch size (or a range of patch sizes). Manor and Shnerb (2008) developed a promising model which can reproduce both the irregular patterns described by power law distributions and the regular patterns characterized by a dominant spatial scale. They showed how the relative strength of competition and facilitation can drive the type of pattern that emerges; strong facilitation favors irregular pattern formation while strong competition favors regular patterns. In systems characterized by regular patterns, it has been suggested that the shape of the patterns can be used to gauge the level of degradation, with spot patterns being the last to occur before desertification (Rietkerk et al. 2004). Further research is needed to determine if these findings can indeed be applied to the sites studies by ME09. More generally, what is currently lacking is a robust way of characterizing the spatial organization of ecosystems, since, depending on the type of patterns (which emerge from different underlying ecological mechanisms), the indicators that need to be monitored may vary.

Before patch size distributions can be used as a monitoring tool in systems characterized by irregular patterns, many technical issues need to be addressed and further tests need to be conducted in the field. From a practical point-of-view, the patch size distribution is indeed a more complicated tool than the vegetation cover. Among others, there are issues with the binning of the data and the fitting of the mathematical functions.

Traditionally, data is binned when visualizing frequency distributions (Newman 2006, Bauke 2007, White et al. 2008, Clauset et al. *In press*). When the data are binned into bins of equal sizes (so-called linear binning), the right-hand side of the distribution is often noisy: the largest elements are rare, and, therefore, each bin contains only a few elements which creates large variations in bin counts among bins (Newman 2005, Bauke 2007). This is a concern when dealing with patch size distributions, since we are especially interested in the behavior of the putative power law in the area around the largest, i.e. the rarest, patches. To decrease the noise in the right-hand tail of the distribution, logarithmic binning is typically employed, where the bins in the tail of distribution receive more elements than with linear binning. Various techniques have been proposed to estimate the optimum bin size (e.g. Sturges' rule, Scott's rule, and the Freedman-Diaconis rule); all strive to achieve a reasonable balance between the number of bins and the number of elements in each bin. However, these techniques do not always yield consistent results, which makes the choice of binning fairly arbitrary. A better way of plotting the data is to use the cumulative distribution function, which does not involve the binning of the data (Newman 2005, Bauke 2007, White et al. 2008).

After binning the data, a linear fitting of the log-log transformed data is typically performed using least squares regression (Newman 2005, Bauke 2007, White et al. 2008, Clauset et al. *In press*). Fitting methods based on binning and least squares regression are widely used in ecology and in other fields to fit models to data and to estimate the scaling exponents of frequency distributions. White et al. (2008) recently demonstrated that such methods give biased results and therefore cannot be relied upon. While these biases are dangerous with regards to estimating the scaling exponent of a distribution, binned-based methods can also lead to differences in the determination of which distribution best fits the data. For example, a data set that is best described by a power law using a given bin size could be best described by a TPL when using a different bin size.

Independently of the way the data are plotted, a reliable alternative to least square linear regression is to use fitting methods based on maximum likelihood estimation (MLE) to extract the scaling exponent of the frequency distribution (e.g. Goldstein et al. 2004). White et al. (2008) showed that MLE is the single most accurate method for estimating the scaling exponents of frequency distributions. Currently, MLE is available for the pure power law distribution (Goldstein et al. 2004, Newmann 2005, Bauke 2007) but not for the TPL distribution as defined here, which limits the application of MLE to this particular case for now, but is a promising line of future research.

In conclusion, although looking at the vegetation cover is still the most obvious and practical way of assessing the "health" of an arid ecosystem, there are notable cases where the cover fails to predict desertification. Desertification can occur in sudden shifts, where ecosystems switch from an unknown vegetation cover to desert. Theoretical studies increasingly suggest that ecosystems which include facilitation may respond to gradual external changes in an abrupt, rather than gradual manner (e.g. Lejeune et al. 1999, Scheffer et al. 2001, von Hardenberg et al. 2001, Rietkerk et al. 2004, Kéfi et al. 2007b). In these cases, the vegetation cover is not an appropriate indicator of proximity to shifts and, therefore, other potential indicators (e.g. the patch size distribution) need to be further developed so that they can be used in addition to the cover. In the meantime, we advocate the continued but cautious use of the cover as a means to gauge an arid ecosystem's health, but reiterate the need to explore more robust techniques before a reliable early-warning system can be implemented.

7

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8

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9

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 10