Comments

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 to truncated power laws (TPLs) were observed under high grazing pressures, leading to the hypothesis that such deviations could be used as indicators of approaching desertification in Mediterranean arid ecosystems (Kéfi et al. 2007a). We use here the same terminology as in Kéfi et al. (2007a) 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. This hypothesis now needs to be tested with additional field data, before it can be

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confidently used as a tool to monitor degradation in Mediterranean 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 found to be better described by a truncated power law (TPL) than by a power law. 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 should be used to monitor desertification. We argue in this comment that the analyses of ME09 do not allow them to draw such firm conclusions, for the following two reasons. First, because all of their sites were characterized by TPLs, the authors looked only at the scaling exponents γ of the TPLs to compare the degradation level of the sites. However, the exponent γ of the TPLs was not proven to vary with degradation in a consistent manner, and therefore the analyses of ME09 do not allow them to conclude that vegetation cover is better related to degradation than patch size distribution. Second, although the vegetation cover is often a simple, easy-to-use indicator of degradation, the authors do not take into account the increasing amount of theoretical literature that 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). Even though strict proofs of discontinuous transitions are difficult to obtain in the field (Scheffer et al. 2001, Schröder et al. 2005; but see, e.g., de Menocal et al. 2000, Foley et al. 2003), the high rate of irreversible degradation and the low restoration success of many dry degraded areas (e.g., Suding et al. 2004, Pueyo and Alados 2007, Sluiter and de Jong 2007, Pueyo et al. 2009) suggest that hysteresis commonly occurs in these ecosystems, which is one of the main components of discontinuous transitions (Beisner et al. 2003). When a discontinuous transition is about to occur, modeling studies have shown that the vegetation cover alone simply does not provide information on the proximity 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 TPLs 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 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. tenacissima* 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 a negative γ (i.e., a positive slope of the TPL) in the vast majority of their sites (22 of 29 sites listed in ME09: Table 1 and 7 of 8 sites illustrated in ME09: Fig. D1), in stark contrast to the positive γ (i.e., a negative slope of the TPL) observed by Kéfi et al. (2007a). A TPL with a negative γ 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). 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 (e.g., using aerial pictures or satellite images), 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 2005, Bauke 2007, White et al. 2008, Clauset et al. 2009). 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. 2009). 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-squares 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 straightforward and practical way of assessing the "health" of an arid ecosystem, there are cases where the cover may fail to predict desertification. 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). Desertification then occurs in sudden shifts, where ecosystems switch from an unknown vegetation cover to desert (e.g., de Menocal et al. 2000, Foley et al. 2003). In these cases, the vegetation cover would not be a suitable indicator of proximity to shifts and, therefore, other indicators need to be further developed so that they can be used in addition to the cover. The patch size distribution may, upon validation, be such a complementary indicator since it is hypothesized to work along both continuous and discontinuous transitions to desertification (Kéfi et al. 2007a). We would like to stress that we do not contend that the patch size distribution is a better indicator than the vegetation cover, and we do in fact support the continued use of the cover as a means of gauging an arid ecosystem's health. However, since the cover may not work in all cases (e.g., if the system is likely to undergo a discontinuous transition), we reiterate the need to explore additional (either alternative or complementary) indicators of degradation so

that more robust and reliable early-warning systems can be implemented.

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

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In a recent article published in this journal (Maestre and Escudero 2009), we report results from a study testing whether transitions from a vegetation patch size distribution characterized by a power law (PL) to another described by a truncated power law (TPL) function occur in areas closer to desertification. Two key results from our study, conducted in 29 *Stipa tenacissima* steppes located along a climatic gradient from central to southeast Spain, were that (1) deviations from a patch size distribution characterized by a PL are not directly related to desertification and (2) plant cover can be used more effectively than such distribution to track changes in "slow" soil variables (sensu Reynolds et al. 2007b) related to desertification processes, such as total N and P and organic C (e.g., Wang et al. 2008,

Zhao et al. 2009). Kéfi et al. (2010; KEAL10 hereafter) question the validity of these results by arguing that (1) our analyses were not fully appropriate to relate changes in the spatial pattern of vegetation to variations in desertification and (2) theoretical studies have shown that plant cover alone cannot be used to monitor desertification processes because this variable does not "provide information on the proximity to desertification." In this reply, we assess the suitability of our approach, discuss the different issues raised by KEAL10, and present additional reanalyses of our data to refute the major criticisms made by KEAL10 to our work.

Suitability of our approach

Our working hypothesis is based on Kéfi et al. (2007; KEAL07 hereafter), who put forward the idea that when the patch size distribution of vegetation passes from being characterized by a PL to another described by a TPL the system is under risk of "imminent" desertification. We aimed to test this hypothesis using an original and well suited dataset obtained in *S. tenacissima* steppes, which are also among the ecosystems studied by KEAL07 to validate their theoretical approach.

One of the main arguments of KEAL10 to criticize our work is that vegetation cover alone does not provide information on the proximity to desertification. However, the approach outlined in KEAL07 has the same problem, as it is a qualitative one that does not provide a quantitative distance to desertification. Despite we fully agree with KEAL10 on the latter issue, the title and abstract of KEAL07 include the word "imminent," giving the impression that the transition from a PL to a TPL distribution indicates that desertification is going to take place very soon, if not immediately. Similar interpretations were made in a comment accompanying the original paper (Solé 2007), as well as in posterior works referring to this article (e.g., Wagner 2007). We believe that the interpretation of the transitions between PL and TPL is crucial to calibrate the potential of the patch-size distribution of vegetation as an "early warning" system to monitor the onset of desertification. If the interpretation we make of the hypothesis put forward in KEAL07 (i.e., the transition from a PL to a TPL indicates that the system is under risk of imminent desertification) is not right, then we believe that these authors should have clearly specified how their work should be interpreted and their hypotheses tested.

Two major objections of KEAL10 to our work are related to (1) our use of the exponent of the TPL to assess how changes in the patch size distribution of vegetation were linked to surrogates of desertification processes and (2) the idea that, although TPL worked better than PL to describe the patch size distribution in all our study sites, it "does not appear to be the most appropriate model to use to fit the data." We believe

that these criticisms are not well founded for two main reasons. First, we had no intention to look for and fit the best model to the patch size distribution of vegetation found in our study sites; rather, as clearly stated in Maestre and Escudero (2009:1730), we just aimed to test the hypothesis put forward in KEAL07 using the same conceptual framework and analytical approach employed by these authors. Furthermore, in 24 of the 29 sites the TPL fitted to the data had R^2 values equal or higher than 0.90 (in all the 29 sites this value was higher than 0.80; see Maestre and Escudero 2009: Table 1), suggesting that this model may not be as bad as KEAL suggest, even if there are other models that could fit our data better. If the approach put forward by KEAL07 is a good candidate to monitor desertification processes worldwide, its framework should be widely applicable. If this is not the case, it should be clearly discussed under which circumstances this framework can be applied before it can be used to monitor such processes. Second, we used the exponent of the TPL (γ) as a single descriptor of the changes in the patch-size distribution of vegetation occurring along our study sites because it is a key parameter of this function, as γ provides information on how larger plant patches, which are key to maintain ecosystem structure/functioning in drylands (Bascompte and Rodríguez 2001, Maestre 2004, Maestre and Cortina 2004), are being lost from these sites (Kéfi et al. 2007). Our rationale for employing γ was very simple; if the patch-size distribution of vegetation is a key driver of ecosystem functioning/degradation, then γ could be a good candidate to explore how changes in this distribution relate to surrogates of desertification processes along the environmental gradient evaluated. In this direction, if γ is related to these surrogates, such a relationship would be helpful to connect recent theoretical work with observational approaches. Therefore, we do not believe that the use of γ per se invalidates our approach and analyses. As γ was not related as well as perennial plant cover to the different surrogates of desertification we evaluated, then we see nothing wrong with concluding that cover is a better descriptor of these surrogates than γ in the studied ecosystem.

A relevant point discussed by KEAL10 is the negative values of γ found in some of our studied sites. We are in full agreement with their observations, as this means that in the sites where this exponent is negative the patch-size distribution is biased towards the dominance of intermediate size classes. We also agree with KEAL10 on the likely prevalence of a dominant spatial scale in some of the studied sites, as regular patterns in the spatial distribution of *S. tenacissima*—largely determined by topography and the associated water fluxes—have previously been reported in steppes from Southeast Spain (Puigdefábregas et al. 1999, Maestre et al. 2005) and Algeria (Debouzie et al. 1996). Rather than being a drawback of our work, we believe that these issues

question again the universality of PL/TPL as a framework to describe the patch-size distribution of arid and semiarid vegetation. As discussed by KEAL10, there is an ample variety of possible vegetation structures—arising from different underlying mechanisms—that should be better known before we can use the spatial pattern of vegetation as a universal system to monitor desertification processes.

At this point in the discussion, we would like to stress that we do not know under which circumstances the patch size distribution of "well conserved" or "non desertified" ecosystems conforms to a PL function. A lack of large patches, which causes deviation from a patch-size distribution characterized by a PL, may be due to a large number of abiotic and biotic factors that are not necessarily linked to desertification processes. These include the dominant plant growth form (e.g., rhizomatous instead of caespitose grasses; Shiyomi et al. 2001), slope characteristics defining soil water availability and runoff dynamics (Puigdefábregas et al. 1999), or the presence of rock outcrops limiting the performance of plant patches (Ramírez and Bellot 2009), just to cite a few. In addition, the methodology used to determine plant patch size can also largely affect the results of fitting PL/TPL distributions. While this may seem straightforward, rules for how bunchgrasses are grouped into a "patch" in some grasslands or the inclusion of dead biomass from previous years' growth when assessing the size of shrub patches can have a large influence on the resulting patch size distribution. While these issues do not diminish the idea that there may be predictable changes in the structure of plant patches that can be used to predict/monitor the onset of desertification processes, knowing under which circumstances the patch size distribution of "well conserved" or "non desertified" ecosystems conforms to a PL function, and conducting a thorough evaluation of the methodology employed to characterize plant patch sizes, are important steps that need to be done before we can confidently use approaches such as that put forward by KEAL07.

We also agree with KEAL10 that γ does not capture all aspects of the TPL distribution, and that the behavior of the parameters of the TPL in relation to the functioning/degradation of the ecosystem is a topic that deserves more attention. To further contribute to this discussion, we have reanalyzed our data using S_c, the patch size above which the number of patches of a size S decreases faster than in a PL, highlighted by KEAL10 as a key parameter of the TPL. For doing this, we evaluated the relationships between S_c and the four components extracted from a principal component analysis conducted with our matrix of soil variables (see Maestre and Escudero 2009 for details) using linear and non-linear (logarithmic, hyperbolic, power and exponential) functions. We did not find any significant relationship between S_c and these components ($R^2 <$

0.04, $P > 0.34$ in all cases). These results suggest that S_c was not able to predict changes in the surrogates of desertification processes evaluated, and that the consideration of this parameter does not modify the conclusions of Maestre and Escudero (2009).

Concluding remarks

By questioning the validity of our analyses, KEAL10 implicitly argue that the conclusions of our work are not valid. We do not believe that they have presented convincing evidence to support this claim, and argue that their main criticisms are not well founded. However, we applaud the insightful discussions provided by KEAL10 on the technical and statistical issues surrounding the binning of data to fit PL and TPL functions, which will certainly be useful in guiding further research. We were completely aware of the complexity and limitations of the binning process to adjust PL/TPL models (see Maestre and Escudero 2009:1730), but, as highlighted already, our aim was to test the ideas put forward by KEAL07 using the same approach employed by these authors. We fully agree with KEAL10 on the need of additional research to overcome limitations of current approaches to use PL/TPL to characterize the patch size distribution of vegetation.

The search for accurate, easy-to-implement and to interpret indicators is a key issue in desertification research (Reynolds et al. 2007a). Our results by no means suggest that we need to discard the search for desertification indicators other than cover, nor that this variable can be used as a universal indicator of desertification that can be used everywhere and under all circumstances. Indeed, we would like to highlight that the use of cover as an "early warning" system for the onset of desertification still needs further research; not just because, as highlighted by KEAL10, arid and semiarid ecosystems may respond to external changes in an abrupt, rather than gradual, manner (a well-known feature of dryland desertification processes; Reynolds et al. 2007b, Verstraete et al. 2009), but mainly because we do not know for a given ecosystem which cover values determine the threshold at which these sudden changes may led to irreversible desertification. In addition, the complexity of vegetation structures that can be found in arid and semiarid ecosystems (Tongway et al. 2001, Whitford 2002), emphasizes the need for additional field studies conducted at large spatial scales and over a variety of vegetation types to further test the value of cover to monitor desertification processes. Current shortcomings to the use of cover can be partially offset by considering reference sites over which compare values of this and other vegetation attributes. In addition, shifts in species composition do not always imply important variations in total perennial cover. However, such shifts may promote dramatic changes in ecosystem structure

and functioning ultimately leading to the enhancement or reversal of desertification (Schlesinger et al. 1990, Maestre et al. 2009). In those ecosystems where this situation is likely to occur, care must be taken when interpreting total perennial cover alone; variations in this variable should be jointly studied with changes in the cover of the main plant functional types, which can also provide insights on the beginning of degradation processes (Jauffret and Lavorel 2003).

Another key issue that needs more discussion and additional research is the suite of variables that can be used to define if a given ecosystem is desertified or not, as this is crucial to meaningfully test the importance of potential indicators such as the patch size distribution of vegetation or total plant cover. Recent syntheses have emphasized the need of focusing on "slow" variables (e.g., soil fertility) for this purpose (Reynolds et al. 2007b). We think that the approach we followed is a reasonable first step in this direction, but do not consider that it provides a catch-all index of desertification that can be used in all circumstances. Additional research testing more "slow" biophysical variables over the full range of possible degradation conditions in multiple ecosystems is certainly needed. Whenever possible, we must integrate research on biophysical variables such as those described here with relevant socioeconomical variables (e.g., land use intensification, household capital wealth, demographic trends and migration), as this is a key step to better understand and monitor desertification processes (Reynolds et al. 2007b, Verstraete et al. 2009).

In closing, what we stated in our article, and maintain here, is that the use of the patch-size distribution of vegetation as a monitoring tool to assess the onset of desertification cannot be taken for granted, and that in the semiarid steppes studied perennial cover is a better predictor of changes in soil variables linked to desertification processes than γ. Whereas this does not invalidate the use of the patch-size distribution of vegetation as a potentially useful tool to monitor degradation processes, it questions the claims made by KEAL07 about its potential use as an "early warning" indicator for the onset of desertification. Indeed, this conclusion also emerges from KEAL10, and is reinforced with the discussion and new results presented here. We hope that our original article and these exchanges will foster much-needed theoretical and empirical studies to provide accurate, reliable, and cost-effective "early warning" systems for the onset of desertification, an important research topic with tremendous environmental and socio-economical implications.

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