Sensing Technologies and their Integration with Maps: Mapping Landscape Heterogeneity by Satellite Imagery

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Abstract Losses in biodiversity critically impact the ability of ecosystems to provide critical services ranging from carbon sequestration and food production to the maintenance of soil fertility. The maintenance of biodiversity is thus essential for human well-being and a sustainable future. Since landscape diversity often relates to species biodiversity, considering several ecological levels from species community diversity to genetic diversity, measuring landscape heterogeneity, is an efficient and relatively cheap way of providing biodiversity estimates over large geographical areas. In this study we will demonstrate the power of using remotely sensed data to estimate landscape heterogeneity and locate diversity hotspots, allowing effective management and conservation of the landscape.

1 Introduction

It is worth noting that the assessment of species diversity over relatively large areas is a challenging task. Compiling complete inventories has been hampered by the immense physical effort required for field estimates, and despite such effort, inaccurate estimates of diversity may result from changes in species composition through time.

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Yet it is critically important to assess and monitor changes in species diversity for effective conservation. Losses in biodiversity critically impact the capability of ecosystems to provide critical services ranging from carbon sequestration and food production to the maintenance of soil fertility (Cardinale et al. 2012). Thus the maintenance of biodiversity is essential for human well-being and a sustainable future (Naeem et al. 2009; Nagendra et al. 2013).

New approaches have been proposed to overcome these issues, using landscape heterogeneity measured by the spatial variation of remotely sensed spectral signal as a proxy for species diversity (see Rocchini et al. 2010 for a review). The heterogeneity of the Earth's surface is closely related to physical and ecological diversity (Nagendra and Gadgil 1999; Gillespie et al. 2008). Since landscape diversity often relates to species biodiversity considering several ecological levels from species community diversity to genetic diversity, measuring landscape heterogeneity is an efficient and relatively cheap way of providing biodiversity estimates over large geographical areas. Depending on the study objectives, species diversity can also be modelled at appropriate scales in time and space. This is true in light of the Spectral Variation Hypothesis (Palmer et al. 2002; Rocchini 2007), which assumes that the higher the habitat heterogeneity, the higher will be the species diversity therein. Depending on the scale and the habitat being considered, the Spectral Variation Hypothesis can be expected to hold true in many cases.

The availability of satellite-derived data with high spatial (IKONOS, Orbview-3, BGIS-2000 (Balls Global Imaging System-2000), RapidEye) and spectral resolution (CHRIS (Compact High Resolution Imaging Spectrometer), Hyperion, GLI (Global Imager), MERIS (Medium Resolution Imaging Spectrometer), and MODIS (Moderate Resolution Imaging Spectrometer)) together with long term programmes such as the Landsat programme makes it feasible to study all terrestrial regions of the globe up to a resolution of few meters.

Free and Open Source tools (allowing the access to the source code and its peer-review) for assessing landscape heterogeneity at different spatial scales and in different environmental conditions (e.g. different habitats with divergent entropy gradients) are under development (e.g. Rocchini et al. 2013). Such tools may help to identify biodiversity hotspots from remotely-sensed and/or geographical and/or climatic data, which could help to focus field-based campaigns in a more efficient way in terms of time and costs, based on the application of best-fit-based parameters at appropriate spatial scales.

2 Information theory applied to the quantification of landscape heterogeneity

The most popular metrics for entropy measurement are derived from information theory, which measures the disorder contained in a system (Margalef 1958). In particular, consider a universe of entities *u* (e.g. pixels in a satellite image), each of which can be represented as a tuple z(*u*)—s(*u*), where z(*u*) = property of the *u*th entity related to its s(*u*) spatial component (Goodchild et al. 1999).

Most measures of spectral diversity that have been proposed thus far are based on either i) the Shannon entropy index (Shannon 1948; see also Bolliger 2005; Ricotta 2005) $H' = -\sum p \times \ln(p)$ with $0 \leq H' \leq \ln(N)$, where p is the relative abundance of each spectral reflectance value (DN) and N is the total number of possible values, or ii) reversed dominance, derived from the Simpson Dominance index $D = \sum p^2$ with $0 \leq D \leq 1$ (Simpson 1949), as $1-D$ (Simpson Diversity index). Both H' and $1-D$ will increase if the DN values are equally distributed with no DN value being dominant with respect to the others.

However, Nagendra (2002) and Rocchini and Neteler (2012) reported several problems with entropy based metrics, that is, a single index of diversity was not useful for either distinguishing different ecological situations, or for discerning differences in richness or relative abundance. This is because areas differing in richness or relative abundances of reflectance values (DNs) may share similar Shannon index values. Instead, coupling such entropy- or reversed-dominance-based metrics with indices taking into account evenness would dramatically increase the information content of such metrics. Among these, the mostly widely used index is the Pielou evenness index $J = \frac{-\sum p \times \ln(p)}{\ln(N)}$ (Pielou 1969) with $0 \leq J \leq 1$, which takes into account the maximum diversity given the same number of DNs and thus can be rewritten as $J = \frac{H'}{H'_{max}}$ (see also Ricotta and Avena 2003 for a review).

As demonstrated by Ricotta and Avena (2003), each index increases/decreases in a different manner depending on the relative array of abundances being considered. Hence, one could under- or over-estimate entropy/diversity depending on the metric being used. Diversity cannot be reduced to single index information, since one can never capture all aspects of diversity in a single statistic (Gorelick 2006). As an example, Nagendra (2002), dealing with the Shannon H' index and the Simpson diversity index $1-D$, reports the case of discordant diversity patterns obtained by considering different indices. Such information may remain hidden if only one index is considered. Thus, following O'Neill et al. (1988) in a pioneer study on the landscape indices, a restricted set of non-redundant indices could reach significant aspects on the spatial patterns.

In this view, generalised entropy based algorithms for entropy calculation could provide a solution to such problems since they encompass a continuum of diversity measures by varying one of few parameters in their formula.

As an example, Rényi (1970) proposed a generalised entropy:

$$H_\alpha = \frac{1}{1-\alpha} \ln(\sum p^\alpha) \qquad (1)$$

where p=relative abundance of each spectral reflectance value (DN).

Such measure is extremely flexible and powerful since many popular diversity indices are simply special cases of H_α.

For instance, for α=0, $H_0 = \ln(N)$ namely the logarithm of richness (N=number of DN values) or the maximum Shannon entropy index (H_{max}) which is used as the denominator of the Pielou index, while for α=2, $H_2 = \ln \frac{1}{D}$ where D is the Simpson Dominance index. For α=1 the Rényi entropy is not defined and its derivation, H_1=Shannon's entropy H', is based on l'Hôpital's rule of calculus (Ricotta 2005).

While traditional metrics supply point descriptions of diversity, in Rényi's framework there is a continuum of possible diversity measures, which differ in their sensitivity to rare and abundant DNs, becoming increasingly regulated by the commonest DNs when increasing the values of α. This is why Rényi generalised entropy has been referred to as a "continuum of diversity measures" (Ricotta et al. 2003).

Implementing such algorithms into Open Source Software will help researchers to freely develop measures of landscape heterogeneity in an Open Source code space.

The aim of this study is to demonstrate the power of using remotely sensed data to estimate landscape heterogeneity and locate diversity hotspots over space, allowing effective management and conservation of the landscape. We will rely on the Rényi generalised entropy, based on the Free and Open Source Software GRASS GIS.

3 Open Source software philosophy for the calculation of landscape diversity metrics

The idea of Free and Open Source (FOSS) software has been around for almost as long as software has been developed (Neteler and Mitasova 2008).

The famous "four freedoms" paradigm, developed by Richard Stallman (1985) in his seminal work, proclaims i) the freedom to run the program for any purpose, ii) the freedom to study how the program works and adapt it to one's own needs, iii) the freedom to redistribute copies, and iv) the freedom to improve the program and release such improvements to the public. This guarantees that the whole community benefits from software development (also see Fogel 2009).

With the aim of calculating landscape metrics in GIS to ensure robust analysis output, particularly where complex algorithms are concerned (Neteler and Mitasova 2008), full access to the source code is crucial. There are well-known examples of FOSS in research fields such as statistics (e.g. R Language and Environment for Statistical Computing, R Development Core Team, 2013), while GIS scientists and more generally landscape ecologists may benefit from the powerful GIS named GRASS (Geographical Resources Analysis Support System, http://grass.osgeo.org, see Neteler et al. 2012), which includes more than 350 modules for managing and analysing geographical data. GRASS was originally created in 1982 by the U.S. Army Construction Engineering Research Laboratories, and is now one of the cutting-edge projects of the Open Source Geospatial Foundation (OSGeo, founded in 2006). Quoting Neteler and Mitasova (2008):

> The key development in recent GRASS history was the adoption of GNU GPL (General Public License, see http://www.gnu.org) in 1999. With this, GRASS embraced the Open Source philosophy, well known from the GNU/Linux development model, which stimulated its wide acceptance.

Adoption of the FOSS license changed the development process of GRASS with contributions to the source code becoming decentralised. The legal statements declared in the GPL are based on the aforementioned "four freedoms" paradigm (Stallman 1985; 1997) and allow the user to use the software's full range of capabilities, and to distribute, study and improve it.

Figure 19. 1 from Rocchini et al. (2013) represents an example of Rényi calculation (with $\alpha = 2$, relying on the *r.diversity* function of GRASS GIS (available at http://grasswiki.osgeo.org/wiki/AddOns/GRASS6), and the comparison with the Shannon, Simpson and Pielou diversity indices. Notice that the Simpson diversity index results in an emphasissmall differences in low-diversity areas (e.g. in homogeneous zones) since its formula contains a squared p, while logarithm-based indices (Shannon entropy, Pielou evenness, Rényi generalised entropy) enhance differences in sites with higher evenness (Nagendra, 2002).

4 A case study: mapping spatial heterogeneity in the Tadoba Andhari Tiger Reserve, India

The Tadoba Andhari Tiger Reserve (TATR) is a national park and wildlife sanctuary located in central India, in the eastern part of Maharashtra state. The protected area extends over 625 square kilometres, covering a landscape that is largely a matrix of dry tropical forests, interspersed with some grasslands, water bodies and a few small patches of riparian forest alongside streams. The park is drained by two main rivers. The southern section of the park is flat, giving way to gradually undulating topography as one moves northwards.

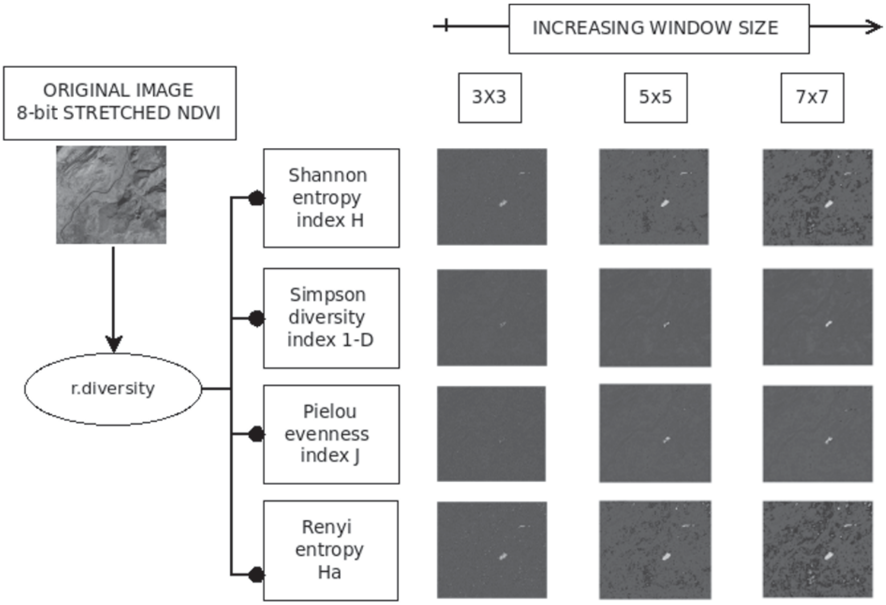

Fig. 19. 1 An example of the calculation of the Rényi generalised entropy with $\alpha = 2$ and the comparison with the Shannon, Simpson and Pielou indices, based on the *r.diversity* function of GRASS GIS applied to a Landsat Normalized Difference Vegetation Index (NDVI) map. Reproduced from Rocchini et al. (2013) under license permission number 3331820502202 from Elsevier Ltd. Refer to the main text for additional information.

There is a well-developed road network in the northeastern part of the reserve, which provides access to the forest for grazing and biomass extraction. To the north, south and east, the TATR has some protection from surrounding State controlled Reserve Forest and Protected Forest areas. Six villages are located within the boundaries of the park (one village has since been relocated outside the park), and there are two villages located on the periphery. In addition to the six interior villages, several other villages and communities access resources from the park. Nagendra et al. (2010a) individualised three main zones of human impact/pressure as reported in Figure 19. 2. These villages fulfil a large part of their fuel, fodder, timber and non-timber forest requirements from the park. The TATR also experiences substantial seasonal use from migrant herders, and is frequented by timber, bamboo and wildlife poachers. Thus, despite being located within a protected area, this dry tropical forest habitat is also subject to human disturbance due to grazing, fire and biomass extraction Figure 19. 2.

A Landsat ETM+ image, acquired on 29 October 2001 (path 144, row 046, spatial resolution 28.5 meters, band from 1 to 5 and 7. see Rocchini et al. 2009 and http://glcfapp.glcf.umd.edu:8080/esdi/ftp?id=268517)
covering the whole study area, was downloaded from the Global Land Cover Facil-

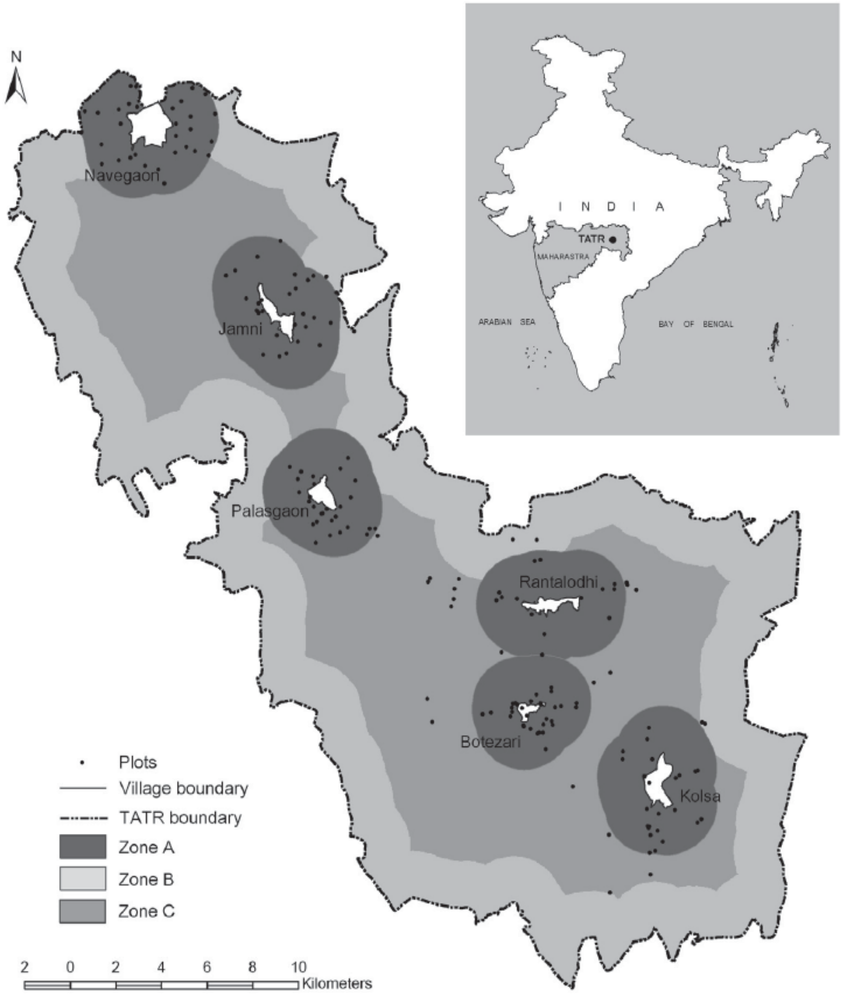

Fig. 19. 2 Map of the Tadoba Andhari Tiger Reserve (TATR, India), showing the villages in the park and three zones of human impact, from high (zone A, villages' surroundings) to low (zone C, dry tropical forest and grasslands) human disturbance, as defined in Nagendra et al. (2010a). The figure is reproduced from Nagendra et al. (2010a) under license permission number 3331821040245 from Elsevier Ltd.

ity site hosted by the University of Maryland (www.glcfapp.umiacs.umd.edu, Tucker et al. 2004 for major details).

A Principal Component Analysis (PCA) was performed on the image and the first component explaining 49.57% of the total variance was retained and rescaled to 16-bit to calculate the landscape heterogeneity by the *r.diversity* function in GRASS GIS.

Figure 19. 3 shows the results attained when relying on Rényi diversity with α=0 (related to richness) and α=2 (related to evenness). While Rényi diversity based on pure richness immediately saturated towards highest values (pixels being different from each other in a window of 3x3 pixels), this effect was not achieved when considerig evenness (Figure 19. 3) where the contrast between diverse and non-diverse areas is higher. It is worth noting that the highest diversity, considering overall evenness (α=2, i.e. contrast in the spectral signal) was found not only in the dry natural forest of the study area but also in the villages, as previously postulated by Nagendra et al. (2010a). Looking as an example at the location of the Navegaon village (Figure 19. 2, northern part) in the Rényi diversity index images (Figure 19. 3), this is one of the areas with highest landscape diversity over the whole area.

5 Discussion

The Tadoba Andhari Tiger Reserve (TATR) is an important tiger reserve in India, containing a large contiguous habitat of dry tropical forest that is very important for tigers as well as other large wildlife that is characteristic of the central Indian landscape. The landscape is also a very important source of human livelihood, with high densities of forest-dependent communities living in this region who harvest a wide range of forest products including timber, bamboo and non-timber forest products such as medicinal herbs (Nagendra et al. 2006). Hence, in addition to its biological significance, the maintenance of biological diversity has great social importance for livelihood sustainability. The forest dependent tribal populations living within the park are extremely dependent on the biodiversity in this forest for their daily livelihood, using as many as 19 different species of trees for timber and an even larger number of species for medicinal use through personal consumption, as well as for sale (Nagendra et al., 2010a). Depletion of biological diversity will create extreme problems for these communities.

Mapping and monitoring of biodiversity and forest heterogeneity in the TATR is thus very important for a better understanding of human impacts on ecology, given the importance of this large heterogeneous landscape for biodiversity. Such studies also provide a deeper understanding of human impacts on dry tropical forest, which represents a habitat type that is very important for biodiversity because of its biological richness as well as its vulnerability to human impact, yet which remains little studied in comparison to moist tropical and dry temperate forests (Feeley et al. 2005). As this research demonstrates, the villages in the interior of the park contain significant amounts of spatial heterogeneity which is believed to relate to biological diversity (Nagendra et al. 2010b). In particular, Navalgaon, a village that is located at the park gate with high levels of disturbance but which also provides access to the less disturbed park interior, has a significant diversity of habitats which relates to the intermediate disturbance hypothesis (Paine and Vadas 1969; Grime 1973; see also Catford et al. 2012 and references therein), which indicates that areas of intermediate disturbance are likely to have maximum diversity. This research thus points

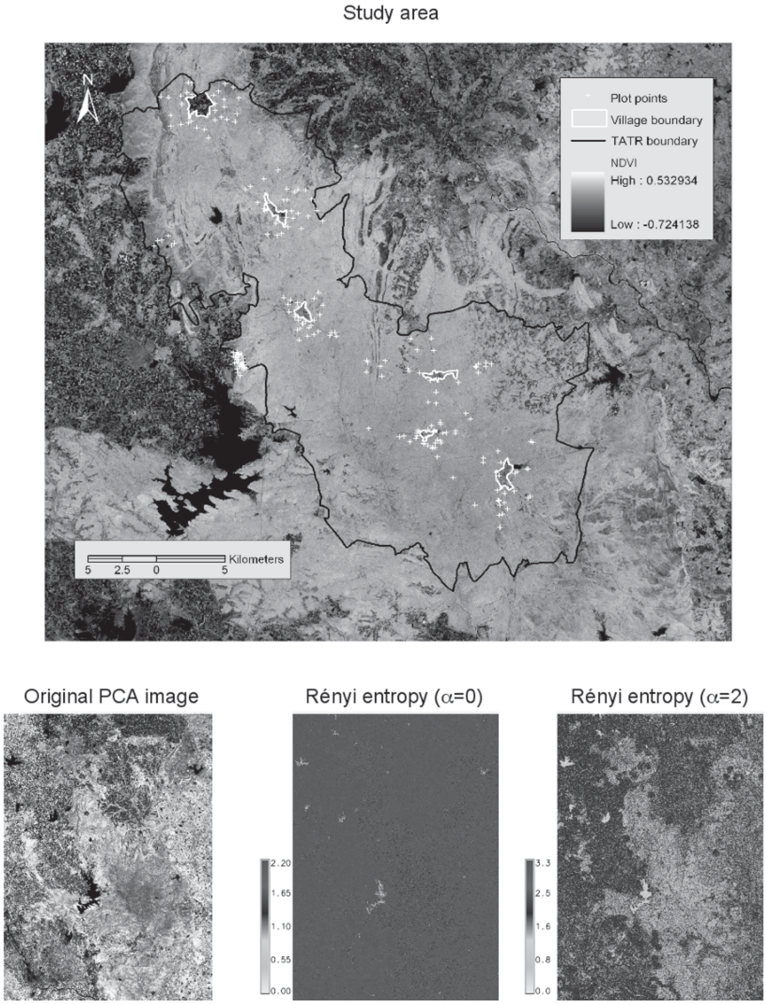

Fig. 19. 3 The Tadoba Andhari Tiger Reserve (TATR, NDVI image on top from Nagendra et al. 2010b, with village borders in white) and the calculation of the Rényi generalised entropy, measured from the first principal component of a Landsat ETM+. Rényi diversity based on pure richness immediately saturated towards highest values; this effect was not achieved when considering evenness where the contrast among diverse and non-diverse areas is higher. It is worth noting that the highest diversity was found not only in the dry natural forest of the study area but also in the villages. Refer to the main text for additional information.

to a need to go beyond the treatment of parks as monoliths requiring a standardized approach for management band monitoring across all areas(Nagendra et al. 2010a), towards a more sophisticated use of mapping approaches (e.g. Nagendra et al. 2013) to provide input for spatially directed monitoring and management based on the differences in heterogeneity and diversity across different areas of the park.

Despite efforts to demonstrate the relationship between remotely sensed- and species-diversity, there are still no useful tools available for managers and administrators responsible for environmental policy and landscape diversity, even though the maintenance of diversity is often a stated objective of these decision makers (Nagendra 2002). Strictly speaking, it is becoming increasingly important to develop means for rapidly and objectively forecasting species diversity in order to assess, with limited resources, the impacts of anthropogenic and natural disturbances on biodiversity.

Due to the difficulties of field-based data collection at wider spatial scales, we have demonstrated in this study how the use of remote sensing for estimating environmental heterogeneity as a proxy of diversity at different spatial scales represents a powerful tool since it allows an a-priori estimate of potential hotspots of diversity allowing an effective management and conservation of the landscape.

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Appendix 1:

Code used to calculate Rényi entropy in GRASS GIS 7.0

Import landsat bands

```
# freely available from http://glcfapp.glcf.umd.edu:8080/esdi/
# path of the used image: 144
# row of the used image: 046
# acquisition date: October 29th 2011
r.in.gdal in=/path/p144r046_7dt20011029.SR.b01.tif out=B1
r.in.gdal in=/path/p144r046_7dt20011029.SR.b02.tif out=B2
r.in.gdal in=/path/p144r046_7dt20011029.SR.b03.tif out=B3
r.in.gdal in=/path/p144r046_7dt20011029.SR.b04.tif out=B4
r.in.gdal in=/path/p144r046_7dt20011029.SR.b05.tif out=B5
r.in.gdal in=/path/p144r046_7dt20011029.SR.b07.tif out=B7
```

Set the region of analysis (optional)

```
g.region=B7 # all bands are overlapping each other
# image information
```

```
# projection: 1 (UTM)
# zone: 44
# datum: wgs84
# ellipsoid: wgs84
# north: 2292630
# south: 2194170
# west: 293250
# east: 362610
# nsres: 30
# ewres: 30
# rows: 3282
# cols: 2312
# cells: 7587984
```

Perform PCA to extract one single band with the highest information content

```
i.pca input=B1,B2,B3,B4,B5,B7 output_prefix=pc rescale=0,255  then store pc1
```

Perform Rényi entropy calculation

```
# code to produce entropy maps of Figure 19. 3
r.diversity input=pc.1 prefix=pc.1 size=3 method=renyi alpha=0
r.diversity input=pc.1 prefix=pc.1 size=3 method=renyi alpha=2
# the size equals the moving window size of analysis, in this case a 3x3
# alpha parameter is related to the Rényi formula (see the main text)
```

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