The Official Journal of the International Association for Landscape Ecology, Chapter Germany (IALE-D)
Landscape Online
International Peer-Review Free-Access Online

Received: 09.07.2007 Received in revision: 23.01.2008 Accepted: 24.01.2008 Published: 19.02.2008

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Hoechstetter, S., Walz, U., Dang, L.H., Thinh, N.X. 2008
Effects of topography and surface roughness in analyses of landscape structure – A proposal to modify the existing set of landscape metrics
Landscape Online 3, 1-14. **DOI:10.3097/LO.200803**

Effects of topography and surface roughness in analyses of landscape structure – A proposal to modify the existing set of landscape metrics

Hoechstetter, S.*, Walz, U., Dang, L.H., Thinh, N.X.

Leibniz Institute of Ecological and Regional Development (IOER), Weberplatz 1, D-01217 Dresden, Germany
E-mail: s.hoechstetter@ioer.de , u.walz@ioer.de , s2980966@inf.tu-dresden.de , ng.thinh@ioer.de

* Corresponding author

Abstract

Topography and relief variability play a key role in ecosystem functioning and structuring. However, the most commonly used concept to relate pattern to process in landscape ecology, the so-called patch-corridor-matrix model, perceives the landscape as a planimetric surface. As a consequence, landscape metrics, used as numerical descriptors of the spatial arrangement of landscape mosaics, generally do not allow for the examination of terrain characteristics and may even produce erroneous results, especially in mountainous areas. This brief methodological study provides basic approaches to include relief properties into large-scale landscape analyses, including the calculation of standard landscape metrics on the basis of "true" surface geometries and the application of roughness parameters derived from surface metrology. The methods are tested for their explanatory power using neutral landscapes and simulated elevation models. The results reveal that area and distance metrics possess a high sensitivity to terrain complexity, while the values of shape metrics change only slightly when surface geometries are considered for their calculation. In summary, the proposed methods prove to be a valuable extension of the existing set of metrics mainly in "rough" landscape sections, allowing for a more realistic assessment of the spatial structure

Keywords:

patch-corridor-matrix model, neutral landscapes, digital elevation models, relief, roughness parameters

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1. Introduction – The "3D-issue" in landscape ecology

"3D" has become a frequently-used term in many fields of science, even in ecology. 3D-visualisation and 3D-graphics have undergone enormous advancements in the recent years. Realistic visualisations of landscapes or cities are gaining importance in spatial planning processes, for example when the impact of construction projects is to be clarified or when the dynamics of landscape change over time are to be demonstrated. Also "3D-GIS" is beginning to emerge. However, "3D-analysis" in landscape ecology and the examination of "3D-patterns" are still somewhat neglected, even though elevation and land surface features can be regarded as key elements in many ecological processes. Thus, from a landscape ecological perspective, there is a need for 3D-analysis in terms of the examination and characterisation of the topography of landscapes and specific terrain features.

Previous publications have tried to highlight the necessity to incorporate aspects of the third dimension into large-scale landscape analyses. Many authors have pointed out that topography is a factor which may play a key role in ecosystem functioning and structuring, and which in many cases is not sufficiently taken into account. The connection between surface characteristics and both the species richness and composition in vascular plants (as shown in Burnett et al. 1998; Davis & Goetz 1990; Sebastiá 2004) is a well-known fact that has frequently been used for the design of biodiversity distribution models (e.g. Bolstad et al. 1998). The impact of relief on the differentiation of an ecosystem as a whole and on particular ecological functions such as soil moisture, temperature distribution, the balance of solar irradiation, or microclimate has been described in detail as well (Bailey 2004; Oke 1978; Swanson et al. 1988).

Bearing these well-studied links between terrain features and ecological processes in mind, one fact appears to be noteworthy: So far, the well-established patch-corridor-matrix model – as suggested by Forman (1995) – does not explicitly consider the third dimension in its approach to describe the spatial arrangement of landscapes. It is generally accepted that the acknowledgement of the "effect of pattern on process" (Turner 1989) constitutes the self-conception of modern landscape ecology. But the established use of landscape metrics for the characterisation of geometric and spatial properties of categorical map patterns (McGarigal 2002) holds a view of the land as a "planimetric" surface – aspects of three-dimensional patterns (topography, elevation) have not yet expanded into this concept (see also Blaschke & Drăguţ 2003).

A large number of landscape metrics has been described in detail and used for several purposes, including spatial planning or ecological modelling. A lot of user-friendly software products for the computation of such metrics on the basis of either vector or raster data are available, e.g. FRAGSTATS (McGarigal & Marks 1995), Leap II (Schnekenburger et al. 1997) or V-LATE (Lang & Tiede 2003). But information about 3D-features like surface roughness, landform, or relief variability within landscape elements ("patches") cannot be made accessible using these measures. Moreover, one may even yield erroneous results from the calculation of landscape metrics, since the basic geometries (area, perimeter) of patches and distances between them are generally underestimated in planimetric observations by neglecting the underlying relief. These discrepancies between the patch-corridor-matrix model and the actual conditions within landscapes can be regarded as a major drawback of the concept, especially in mountainous regions or in areas exhibiting a complex terrain. Figure 1 provides a visual representation of the effects that relief may have on the parameter output of common groups of landscape metrics. For example, it is apparent that for area or distance metrics, a definite tendency towards higher values can be expected when surface complexity is taken into account.

Geomorphology offers a large set of parameters to describe the land surface and to classify the georelief (see Dikau & Schmidt 1999; Evans 1972; Pike 2000; Wilson & Gallant 2000). However, measures of cur-

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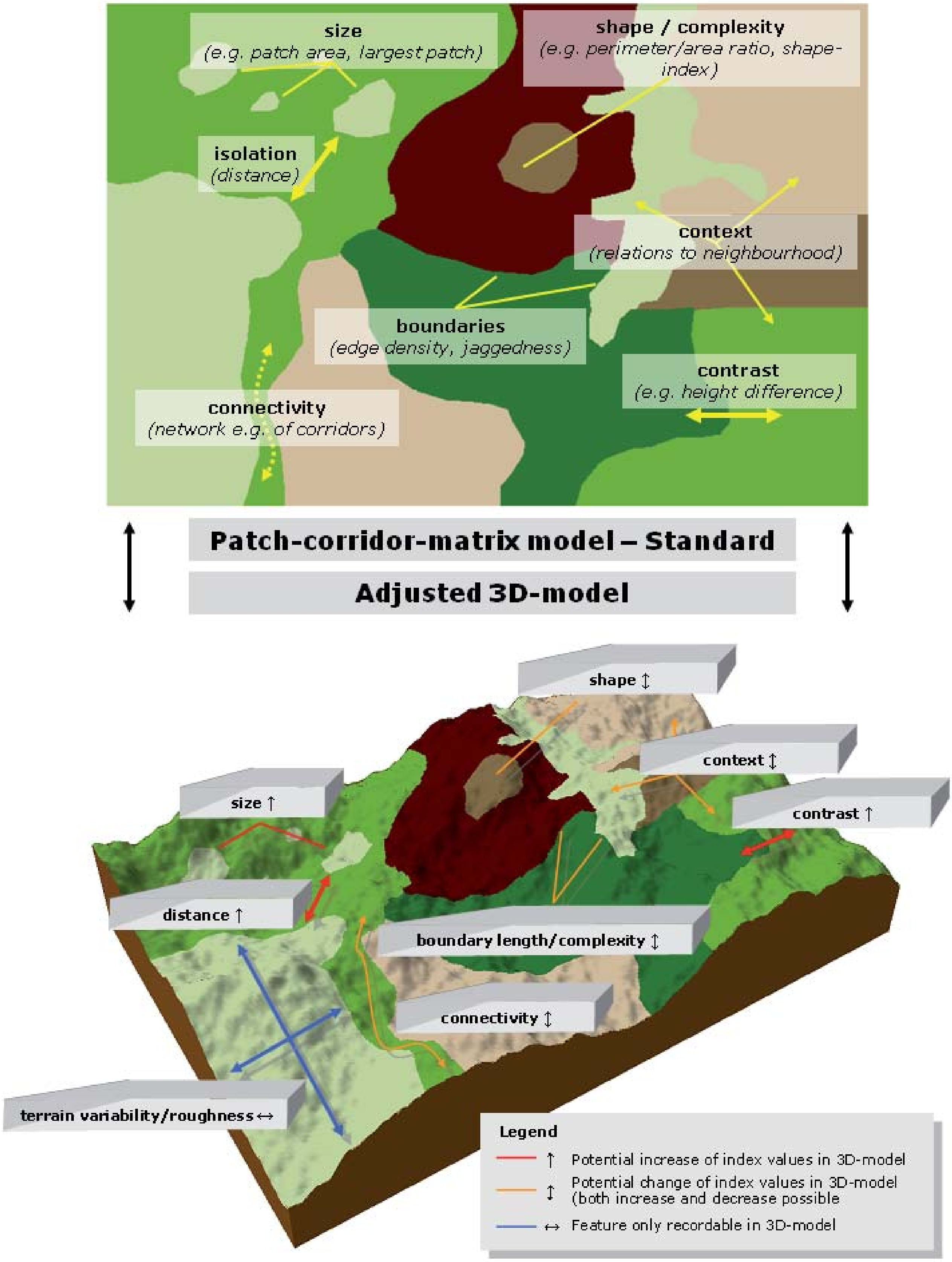

Figure 1: Common landscape metrics groups used in the patch-corridor-matrix model and the effects of underlying terrain (upper part redrawn according to Wiens et al. 1993).

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vature, aspect, slope, or combined parameters such as wetness indices are only of limited use when one tries to characterise the spatial pattern of landscapes using categorical maps. These measures in general relate to catchment areas and discrete landform elements, rather than to the "patches" that common landscape metrics are applied to; a compatibility between these approaches cannot be taken for granted in every case.

Other techniques to incorporate surface features into landscape analyses have been proposed. For example, Beasom (1983) has suggested a simple method for assessing land surface ruggedness based on the intersections of sample points and contour lines. More elaborate proposals to include topographic characteristics into analyses of landscape pattern and of vegetation distributions have been made by Dorner et al. (2002). Simple moving-window algorithms for estimations of the "concavity/convexity" of raster pixels in digital elevation models (DEM) have been developed by McNab (1992) and Blaszczynski (1997). While an application of these approaches for special case studies and particular thematic contexts may be very valuable, integration into the patch-corridor-matrix model has not been achieved yet.

Meanwhile, the technological progress in the field of remote sensing has led to a rapid improvement in the quality of DEMs. Especially LiDAR ("light detection and ranging") measurements provide high-resolution elevation data of the land surface. They can accurately estimate attributes of vegetation structure and should therefore be of particular interest to landscape ecologists (Lefsky et al. 2002). First attempts to derive 3D-landscape metrics from LiDAR data have already been made earlier (e.g. Blaschke et al. 2004).

All these notes on the "3D-issue" in landscape ecology and the shortcomings in the analysis of important surface features mark the starting point for the study at hand. The main purpose of this paper is to present some basic principles on how to solve the problem, based on the recognition of the discrete land unit as a central concept in landscape ecological hypotheses (Zonneveld 1989). The term "3D" is used in this context, even though digital elevation models actually refer to a "2.5D" representation of the real world, with one z-value associated with each x,y-coordinate. In most cases, however, DEMs can be considered as sufficient to provide an approximation of the true surface conditions.

This methodically oriented article attempts to reveal and quantify the effects that the variability and roughness of the land surface may have on the parameter values of common landscape metrics and tries to present a few suitable workarounds for this issue. These include modification algorithms for common landscape metrics as well as the introduction of alternative measures to capture surface roughness. These methods are mainly exemplified using neutral landscape models.

2. Methods – Considering terrain characteristics in the patch-corridor-matrix model

Two basic approaches for the first steps towards 3D-analysis of landscape structure are proposed in this paper: The first one comprises different correction algorithms for standard area, shape and distance metrics. The second one is based on the aggregation of height information in the form of simple "surface roughness" parameters.

2.1 Adjusting standard landscape metrics

The simplest and most obvious approach to incorporate the third dimension into landscape analyses is to adjust the existing set of metrics and to mitigate the source of error associated with the planimetric projection of slopes. Such techniques have been proposed earlier by Dorner et al. (2002), who suggested to compute the true surface area of each raster cell in a DEM by the quotient *projected area/cos(slope)* and to approximate the true distances between adjacent cells by simple application of the Pythagorean Theorem using

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Euclidean distance and differences in elevation. However, a systematic integration into calculation algorithms of landscape metrics was not presented.

In this paper, a more detailed approach is chosen to calculate true surface area, based on the findings of Jenness (2004). The technique is based on a moving window algorithm and estimates the true surface area for each grid cell using a triangulation method (Figure 2). Each of the triangles is located in three-dimensional space and connects the focal cell with the centre points of adjacent cells. The lengths of the triangle sides and the area of each triangle can easily be calculated by means of the Pythagorean Theorem. The eight resulting triangles are summed up to produce the total surface area of the underlying cell. This method is preferred since it can be expected to provide more accurate results; in contrast to the approach mentioned above, all eight neighbours of the pixel of interest are included in the calculation, instead of only the one defining the slope angle.

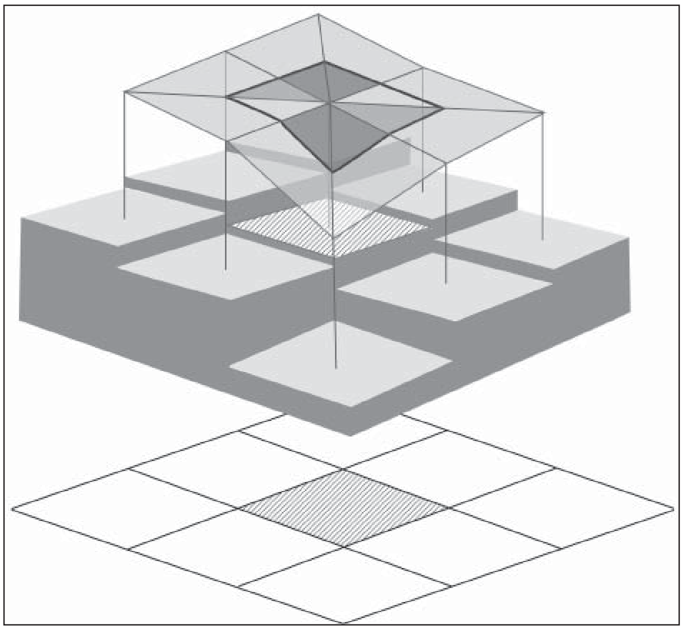

Figure 2: Method to determine true surface area and true surface perimeter of patches. True surface area of the focal raster cell is obtained by adding the eight shaded triangles, true surface perimeter by summation of the eight bold line segments (figure redrawn according to Jenness 2004).

Additional computation steps have to be conducted to obtain the true surface area not only for each raster pixel but for each patch in a landscape in order to include these new geometry values into the calculation of common landscape metrics. A raster file containing the patch structure of the concerning land mosaic is overlaid with the corresponding elevation model. Then surface area values of the pixels representing each patch are summed up. Equal resolution and extent of the patch file and the elevation model are presumed. Jenness' method is also adapted in order to calculate realistic surface perimeters of each patch. This is done by simply adding up the line segments forming the surface edge of the raster pixels (see bold lines in Figure 2) in case they are part of the patch boundary.

A more intricate procedure is needed for the calculation of the true surface distances between patches of the same class, that is the 3D-equivalent to the "Euclidean Nearest Neighbour" measure as used in the FRAGSTATS-set of metrics (see McGarigal et al. 2002). The question can be referred to as a so-called "shortest path problem", for which various solutions are described in literature, each of them having its assets and drawbacks (e.g. Cormen et al. 2001).

In the present case, a weighted graph *G(V, E)* is constructed, with each raster cell representing one vertex *V* and each connection line between the cells forming one edge *E* of the graph. The weight associated to every edge is calculated by using the Pythagorean Theorem to approximate the 3D-distance between centre points of adjacent raster cells. After these steps, a suitable algorithm needs to be applied to the graph in order to determine the shortest path between a border cell of the focal patch and the closest border cell of the closest patch of the same class. In the present case, a form of the Dijkstra-algorithm is chosen, as it is expected to provide good estimates for the shortest path (Chen 2003). This method is based on an undirected circular search procedure. Considering the problem, the vast computation effort becomes evident: for a 1000 x 1000 DEM, the constructed graph consists of $1*10^6$ vertices, aggregated to form a number of "nodes" (defined by the patches present), and approx. $4*10^6$ edges. This implies that a trade-off bet-

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Table 1: Selected standard metrics, calculated using both 2D- and 3D-geometries.

Landscape metrics	Formula
Mean patch area (a)	-
Mean patch perimeter (p)	-
Mean distance to nearest patch of same class (dist)	-
Mean Perimeter-Area Ratio (PARA)	$PARA = \frac{p}{a}$
Mean Fractal Dimension Index (FRAC)	$FRAC = \frac{2 * \ln(0.25 * p)}{\ln a}$
Mean Shape Index (SHAPE)	$SHAPE = \frac{0.25*p}{\sqrt{a}}$

ween computation time and calculation results has to be made, with the Dijkstra-method providing an acceptable compromise between these two factors. On the basis of these true surface geometries, a number of basic landscape metrics can be calculated and be compared to their planimetric 2D-equivalents. These metrics are listed in Table 1.

2.2 *Characterising surface roughness*

As outlined in the first chapter, surface roughness may be a critical issue in assessing a number of ecological functions, notably climatic conditions or erosion processes. Therefore, simple and straightforward measures to capture roughness characteristics are needed to help improve the accuracy of landscape analyses. The most self-evident approach in this context may be to simply calculate the ratio of true surface area (as described in the previous section) and planimetric area. This may provide a first estimate of the overall deviation of the patch surface from a perfect 2D-plane. Completely plane patches consequently result in an area ratio-value of 1.

Other concepts for the characterisation of surface features such as roughness are provided by surface metrology (Stout et al. 1993). This scientific field deals with the characterisation of manufactured surfaces (for example optic lenses) on a microscopic scale. When these measures are transferred to a larger scale, they may be applicable to ecological problems and analyses of landscape structure as well. The index "Average Surface Roughness" (*Ra*) appears to be the most-frequently used parameter from this set and at the same time the one with the least computation effort. *Ra* is usually calculated as the mean absolute departure of a patch's elevation values from the mean plane. Unlike the 3D/2D-area ratio, this index is not dimensionless but maintains the units of the DEM. Therefore, it can be considered as an absolute measure of surface roughness. A modification of *Ra* is *Rq*, the "Root-Mean-Square Deviation of the Surface", which is a standardised version of the former. These and other measures for the characterisation of the land surface using surface metrology-indices are given in Table 2, even though not all of them are explicitly covered in detail in this study. *Ra* and *Rq* were chosen for this study since they are widely-used in disciplines like materials science and are rather easily interpretable.

The implementation of the methods described was carried out using both the MATLAB package (MathWorks 2005) and an ArcGIS-extension programmed in C# using the .NET-environment and the ArcObjects class libraries (ESRI 2005).

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2.3 Case study using neutral landscape models

At this point, a couple of questions may arise: Is it actually necessary to include elevation and topography respectively into analyses of landscape structure? Is there any significant difference at all between the 2D- and 3D-forms of landscape metrics? Do simple roughness parameters tell us anything about the relief variability? And, which may even be the most important one: is the additional computation effort worth being carried out?

In order to help answering these questions and to make valid statements about the relevance, sensitivity and explanatory power of the proposed methods, the above mentioned indices were applied to a set of neutral land-

Table 2: Examples of some simple indices to derive information about surface characteristics and their calculation formulae (Precision Devices 1998).

Surface Index	**Description**	**Formula**
Average Surface Roughness (Ra) *	Approximates surface roughness by calculating the mean absolute departure of the elevation values from the mean plane.	$Ra = \frac{1}{N}\sum_{n=1}^{N}\lvert h_n \rvert$ N = Number of pixels in concerning patch; h_n = difference of elevation between the n^{th} pixel in concerning patch and the mean value
Root-Mean-Square Deviation of the Surface (Rq) *	Modification of Ra; used as an equivalent to the sample standard deviation in statistics.	$Rq = \sqrt{\frac{1}{N}\sum_{n=1}^{N} h_n^{\ 2}}$
Tenpoint-Height of Surface (Sz)	Defined as the average value of the absolute heights of the five highest peaks and the depths of the five deepest pits or valleys within the one patch.	$Sz = \frac{\sum_{i=1}^{5}\lvert h_{pi}\rvert + \sum_{i=1}^{5}\lvert h_{vi}\rvert}{5}$ h_{pi} = height of the i^{th} peak in concerning patch, h_{vi} = height of the i^{th} valley in concerning patch
Density of Summits (Sds)	Number of summits within one patch, which relies on the eight nearest neighbour summit definition.	$Sds = \frac{S}{a}$ S = Number of summits defined on an eight nearest neighbour rule, a = patch area
Skewness of Topography Height Distribution (Ssk)	Measure of the asymmetry of surface deviations around the mean plane; for a Gaussian surface, the skewness is zero.	$Ssk = \frac{1}{NRq^{3}}\sum_{n=1}^{N} h_n^{\ 3}$
Kurtosis of Topography Height Distribution (Sku)	Measure of the “peakedness” or “sharpness” of the surface height distribution; A centrally distributed surface has a kurtosis value larger than 3 whereas the kurtosis of a well spread distribution is smaller than 3.	$Sku = \frac{1}{NRq^{4}}\sum_{n=1}^{N} h_n^{\ 4}$

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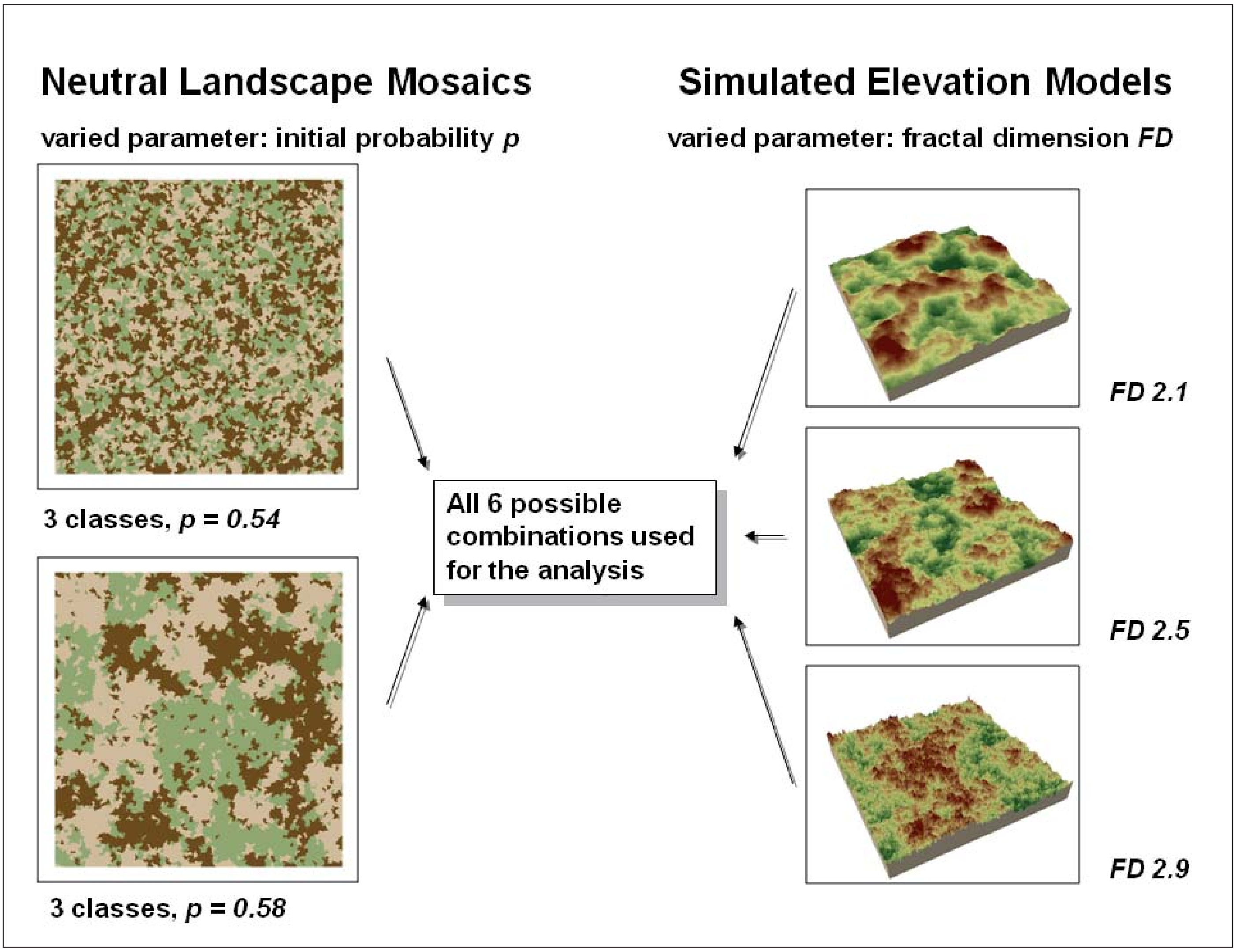

Figure 3: Combinations of neutral landscape models and simulated DEMs.

scape models and simulated DEMs. Neutral landscape models have proved to be a valuable means for the representation of realistic conditions or for the reflection of extreme states of landscape systems (Gardner & Urban 2007; Gardner et al. 1987; Li et al. 2004). This turned out to be useful, as neutral landscapes allow to mirror landscape sections of different structuring, whereas simulated elevation models may reflect variable heterogeneity of the underlying terrain.

In the given case, the software Simmap (Saura & Martínez-Millán 2000) was used to create landscapes with an extent of 1000 x 1000 raster cells (with an assigned horizontal resolution of 1 x 1 m) and three land use classes of equal surface percentages. The initial probability *p* was altered to produce two different types of landscape structuring. Similarly, the programme Landserf (Wood 2005) was applied to produce elevation models of various relief variabilities. More precisely, the parameter "fractal dimension" (*FD*) was altered to yield three DEMs of increasing "roughness". Details about the test landscapes and the DEMs can be derived from Figure 3.

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3. Results – The effect of topography on selected landscape metrics

The six land mosaic/elevation model-combinations were subject to 3D-landscape analysis according to the outlined techniques. The arithmetic mean of the index values was calculated for all the patches present in the landscapes in order to illustrate the effect of the underlying relief in the examined situations (planimetric conditions as well as DEMs with fractal dimension 2.1, 2.5 and 2.9 respectively). The results are displayed in the diagrams in Figure 4.

Some fundamental findings can be noted. For the mean patch area and mean patch perimeter, there is a clear trend towards higher values for increasing relief variability. This holds true for both the highly fragmented landscape ($p = 0.54$) as well as for the mosaic dominated by fewer and larger patches ($p = 0.58$). The differences between the planimetric case and each of the three simulated DEMs prove to be significant when compared using a t-test for paired samples. As expected, a clear dependence of the values on the terrain variability and the ability of the applied methods to capture this effect can be demonstrated.

For the distance measure "Nearest Neighbour", a similar effect is evident. There is a clear increase for the mean distance between nearest neighbours of the same class when the relief is becoming "rougher" and more variable.

For the group of the shape metrics, the findings are not as clear and not as easily interpretable. For the Fractal Dimension (*FRAC*), the differences between the 2D-version and its 3D-equivalent applied to the three DEMs are rather low and almost neglectable, while still slightly increasing with terrain roughness. Perimeter-Area Ratio (*PARA*) shows its typical size-dependency (McGarigal et al. 2002), and therefore this index has to be carefully interpreted due to the growing mean patch size with increasing terrain roughness. Thus, a definite statement about the effects of terrain on the output of this parameter can hardly be made. All in all, this parameter appears to be largely independent of terrain roughness. As the Shape Index (*SHAPE*) corrects for the size problem of the Perimeter-Area Ratio index, it may be the most interesting one to have a closer look at within the group of the shape metrics. The differences of the mean Shape Index for the four relief situations examined seem to be rather small for the 2D-case and the first two elevation models with an abrupt rise for the most variable elevation model. This again is the case for both of the landscape mosaics considered. Of course, this rise is up to a certain extent proportional to the increase in mean patch area (see above), as *SHAPE* tends to increase with growing area, even if perimeter increases for the same factor at the same time. This can be derived from the calculation formula for *SHAPE*.

Finally, the two simple roughness parameters calculated, Average Surface Roughness (*Ra*) and Root-Mean-Square Deviation of the Surface (*Rq*), were applied to the test landscapes. The results indicate a clear dependency of the parameter outputs on the underlying relief with a very similar behaviour of the two indices and similar outputs for the two different landscape mosaics.

4. Discussion – On the relevance of the proposed methods

This short methodological examination is supposed to clarify the effect of topography and surface roughness on a few common landscape metrics. Moreover, some both simple and fundamental approaches to consider these effects are presented.

Patch area and perimeter exhibit a strong connectedness to the variability of the underlying terrain. The effects may not be as distinct under real-world conditions. But the simulated landscape models and DEMs clearly demonstrate that a consideration of landscape

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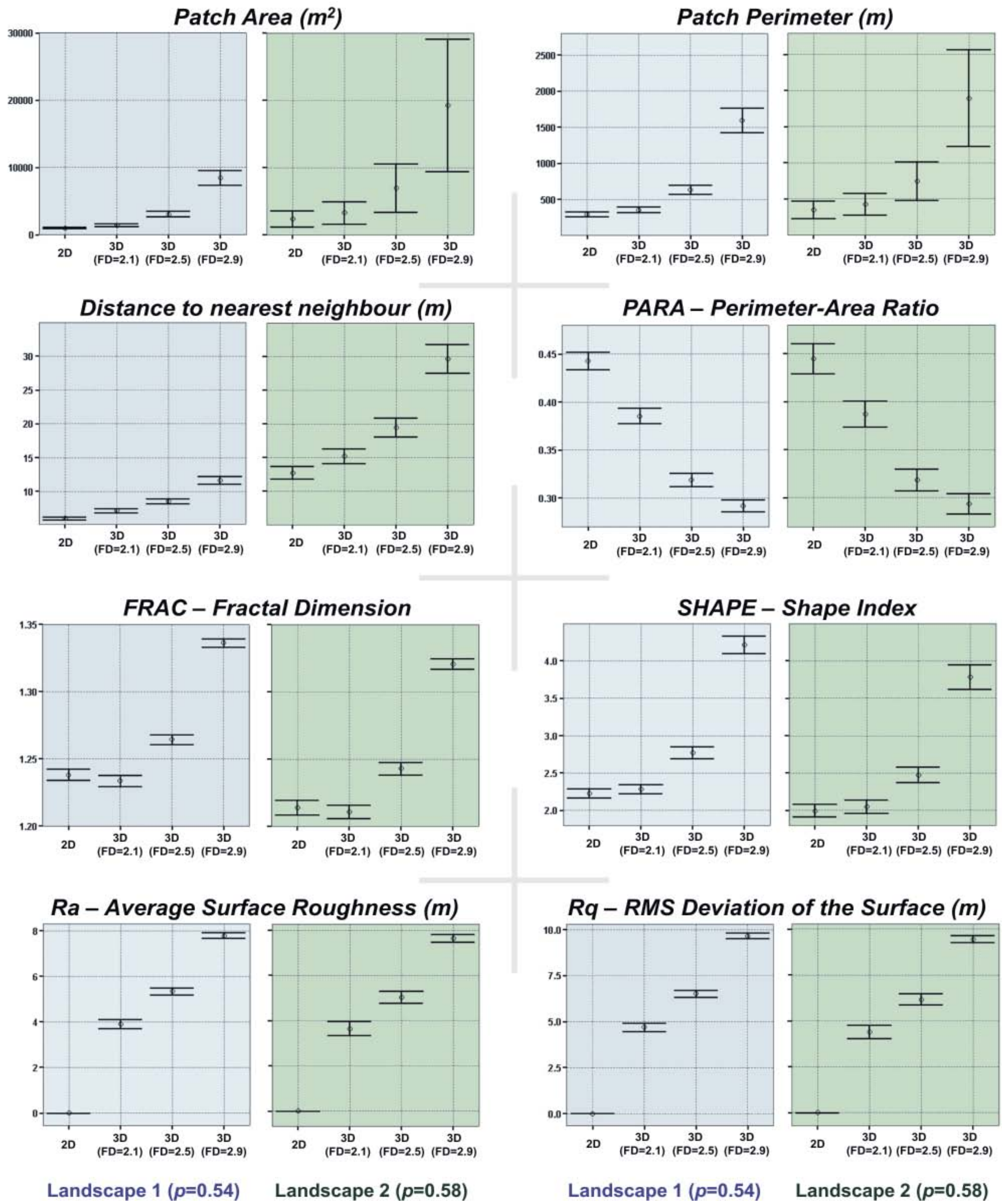

Figure 4: Diagrams displaying the arithmetic means and 95 %-confidence intervals around the mean value for the selected indices; each index was calculated for the two test landscapes (displayed in blue and green respectively) combined with each of the three elevation models as well as the planimetric case.

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mosaics as purely planimetric surfaces and their characterisation using 2D-landscape metrics may not be sufficient in every case, especially when terrain is highly variable. When one tries to characterise landscapes in these cases, the application of corrected metrics as proposed in this paper may be advisable.

The same holds true for distance measures. These metrics may have a critical relevance e.g. in species-centred habitat analyses. As can be seen from the results presented here, the effect of the relief on the "true" surface distances between patches should not be neglected in rough terrain. This effect may be exaggerated by the application of the simulated landscapes, even if the purpose is to reveal the fundamental relationship between distance and topography and to provide a technique to improve the calculation of such distance measures.

Statements regarding shape indices like *PARA*, *FRAC* or *SHAPE* are not as concise. These metrics do react to the terrain, but absolute differences between the examined relief situations tend to be low and the trend is not as obvious for all of these measures as is the case for area, perimeter and distance measures. One reason for this may be the simple fact that in the calculation algorithms for these metrics, parameters of the patch geometries appear both above and below the fraction line. Therefore, when dividing for example 3D-perimeter by 3D-area (both having larger values compared to their 2D-equivalents), the differences between the 2D- and the 3D-approach may simply level out to a certain extent.

Finally, the results reveal that the analysis of surface roughness may serve as a valuable instrument to provide highly condensed information about the topographic characteristics of patches. As both *Ra* and *Rq* are closely connected to the initial roughness parameter of the respective DEMs (i.e. their fractal dimension *FD*), they can be regarded as a good extension of common landscape metrics towards the third spatial dimension, especially as their calculation algorithms are rather straight-forward and can be easily integrated into the patch-corridor-matrix model of landscapes. Moreover, the results from these parameters are easily interpretable.

To assess the influence of landscape configuration and patch structuring on the metrics output, the two chosen mosaics with an initial probability p were supposed to serve as a representation of different structural conditions. It turns out that the general trends in index behaviour for increasing fractal dimension of the underlying relief are generally the same. The distance to the nearest neighbour in the same class tends to be larger for $p = 0.58$, because on average larger patches of other classes have to be crossed. This indicates that the application of the correction algorithm for distance calculations may be particularly valuable in coarse-grained landscapes with large relief variability. Aside from these findings, preliminary studies carried out applying the proposed methods to real-world data have shown that large patches in general lead to some mitigation of terrain effects on landscape metrics, as often landscape elements comprise both "flat" and "rough" areas. This circumstance is not reflected to the same degree by the relatively homogeneous simulated elevation models used in this study, where the quantification of terrain roughness rather than general landscape configuration was the main focus.

The results suggest that the proposed methods may exhibit a large potential for many ecological problems. Since especially measures for habitat area and habitat isolation or fragmentation are key variables in many species-centred analyses, the usage of correction algorithms for these geometries appears to offer the possibility of improved results (for examples dealing with these measures see Bennett 2003; Fahrig 1997; Krauss et al. 2005; van Dorp & Opdam 1987).

5. Conclusions and outlook

The findings presented in this paper indicate that the patch-corridor-matrix model as the prevailing concept to perceive and describe landscapes may not suffice in cases where topographic and morphologic features of the land surface need to be taken into account. As topography plays a crucial role in many eco-

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logical processes, simple methods and techniques for its assessment are needed.

We propose some straightforward approaches that enable landscape ecologists to account for the effects of relief and landform in their analyses. The suggested framework for the adjustment of standard landscape metrics, thus converting them to 3D-metrics, may be applied to all indices using the basic geometries of patches (i.e. their area and perimeter as well as the distances between them) as input parameters. In this way, more realistic results can be achieved. This may especially hold true for examinations where habitat area or isolation play an important role.

The presented indices derived from surface metrology can serve as analysis tools for the overall variability of altitude values within patches, as one has to keep in mind that patches in reality cannot be regarded as spatially homogeneous, but rather possess their specific "within-patch-heterogeneity".

Future work has to concentrate on the refinement and improvement of the methods as well as on their testing under real-world conditions in order to gain more insight in their applicability and sensitivity. Especially the specific impacts of different topographic regions (high mountains/low mountain ranges/lowland etc.) have to be examined. In this regard, potential fields of application have been compiled by Walz et al. (2007).

From our point of view, the search for alternative landscape concepts should also be emphasised in future theoretical and methodological work. McGarigal & Cushman (2005) have coined the term "gradient concept" in this context, pointing out that the patch-corridor-matrix model can be regarded as an oversimplification of realistic conditions, as it acts on the assumption of the landscape as a composite of flat and homogeneous "puzzle pieces", divided by sharp and clearly defined boundaries. Obviously, this cannot be taken for granted in every case. This notion was also formulated by Blaschke & Drăguţ (2003) or Ernoult et al. (2003). Fuzzy approaches (Drăguţ & Blaschke 2006) or spectral and wavelet analysis (Couteron et al. 2006; Saunders et al. 2005) have been proposed as attempts at a solution. Further techniques to resolve the shortcomings of the patch-corridor-matrix model are needed, with the paper at hand as one approach to the problem.

Acknowledgements

This project (*Landschaftsstrukturmaße zur Analyse der raum-zeitlichen Dimensionen (4-D-Indizes))* is funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG).

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