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M.-S. Stupariu, I. Pătru-Stupariu & R. Cuculici
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Geometric approaches to computing 3D-landscape metrics

M.-S. Stupariu[1*], I. Pătru-Stupariu[2] & R. Cuculici[2]

[1] University of Bucharest, Faculty of Mathematics and Computer Science, Str. Academiei 14, 010014-Bucharest, Romania.

[2] University of Bucharest, Faculty of Geography, Bd. N. Balcescu 1, 010041-Bucharest, Romania.

* corresponding author stupariu@fmi.unibuc.ro

Abstract

The relationships between patterns and processes lie at the core of modern landscape ecology. These dependences can be quantified by using indices related to the patch-corridor-matrix model. This model conceptualizes landscapes as planar mosaics consisting of discrete patches. On the other hand, relief variability is a key factor for many ecological processes, and therefore these processes can be better modeled by integrating information concerning the third dimension of landscapes. This can be done by generating a triangle mesh which approximates the original terrain. The aim of this methodological paper is to introduce two new constructions of triangulations which replace a digital elevation model. These approximation methods are compared with the method which was already used in the computation of 3D-landscape metrics (firstly for parameterized surfaces and secondly for two landscape mosaics). The statistical analysis shows that all three methods are of almost equal sensitivity in reflecting the relationship between terrain ruggedness and the patches areas and perimeters. In particular, either of the methods can be used for approximating the real values of these basic metrics. However, the two methods introduced in this paper have the advantage of yielding continuous approximations of the terrain, and this fact could be useful for further developments.

Keywords

patch-corridor-matrix model, landscape metrics, relief, 3D-analysis, triangulation

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1 Introduction

It is a generally accepted fact that the study of the influence of spatial pattern on many processes that are ecologically important (Turner 1989) lies at the core of modern landscape ecology. The relationships between spatial patterns and ecological processes can be better understood by introducing indices which quantify the spatial heterogeneity (Turner 2005). The majority of these indices are related to the patch-corridor-matrix model, which conceptualizes landscapes as mosaics consisting of discrete patches (Forman & Godron 1986; Forman 1995; Turner et al. 2001). According to Forman & Godron (1986), any patch represents a non-linear surface area differing in appearance from its surroundings. More specifically, any patch is an area of relatively homogeneous environmental condition at a particular scale, while the patch boundaries represent abrupt discontinuity (Kotliar & Wiens 1990; Gustafson 1998; McGarigal 2002). A lot of landscape metrics were introduced, in order to quantify the composition and the spatial configuration of a patch mosaic (see e.g. Forman and Godron 1986; Gustafson 1998; Turner et al. 2001; McGarigal 2002; Botequilha Leitão et al. 2006). The landscape metrics have become a standard tool in the analysis of landscape pattern and ecological modeling. Several software packages were developed for their computation, using either vector or raster data, for example *r.le* (Baker & Cai, 1992), *FRAGSTATS* (McGarigal & Marks 1995 and McGarigal et al. 2002), *LEAP II* (Schnekenburger et al. 1997), *V-LATE* (Lang & Tiede 2003).

Despite its universality and its wide applicability, several limitations of the patch-corridor model were already pointed out in the literature, as for instance its discontinuity and its planimetric character. Hence, although most ecological attributes are inherently continuous in their variation, at least at some scale, (Wiens, 1989), the patch-corridor model does not accurately represent continuous spatial heterogeneity (McGarigal & Cushman 2005; McGarigal et al. 2009). As an alternative to the patch-corridor model, McGarigal & Cushman (2005) proposed the 'gradient model', based on continuity instead of discrete spatial heterogeneity and McGarigal et al. (2009) introduced the surface metrics for quantifying landscape gradients. Another limitation of the standard model is the fact that it is a two-dimensional one, ignoring the third dimension of landscapes. Hence, the necessity to add topographic aspects into the two-dimensionality of the patch-corridor concepts (Blaschke & Drăguţ 2003) or to include information related to 3D-features like surface roughness, landform or relief variability (Hoechstetter et al. 2008) was pointed out.

Let us now have a look at the necessity of accurately quantifying the third dimension of landscapes for other sciences. Relief variability is studied in the framework of geomorphometry, which is defined as the science of quantitative land-surface analysis (Pike et al. 2009). The development of geographic information systems made it possible to extract land-surface parameters and objects from digital elevation models and to use them for topographic quantification (Pike et al. 2009). Several topographic attributes (altitude, slope, aspect, profile curvature, contour curvature) are derived from the gridded matrix of elevation values (Huggett 2007). An introduction to this topic and further references can be found, for instance, in Pike (2000); Pike et al. (2009); Wilson & Gallant (2000). Moreover, using object-based image analysis, Drăguţ and Blaschke (2006) developed a methodology for automated classification of landform elements.

The relief variability and diversity are also key factors for many processes studied in hydrology, pedology or biodiversity. Hence, topography influences place-to-place variations in ecological factors, such as water availability and exposure to radiant solar energy (Bailey 2009). The organic world also depends on the irregularity in land surfaces. For instance, surface heterogeneity can decisively control the nature of vegetation and flora, and thereby the distribution of animals and other biota (Kruckeberg 2002). The vegetation pattern can be modeled by using digital terrain data (Davis & Goetz 1990) and indices that capture relationships between vegetation pattern and topography were introduced by Dorner et al. (2002). Moreover, a 3D landscape metrics metho-

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dology to modeling forest structure was developed by Blaschke et al. (2004). On the other hand, terrain is an important feature of the structural niche occupied by terrestrial species (Riley et al. 1999). Land surface ruggedness is a vital component of habitat for many wildlife species (Beasom et al. 1983) and its quantification is a necessary tool for animal habitat analysis (Sappington et al. 2007). Many applications of modern methodologies in wildlife conservation are described in the monograph Cushman & Huettmann (2010).

All these studies show the importance of the '3D-issue' in landscape ecology (Hoechstetter et al. 2008) and the necessity to develop adequate indices which capture terrain characteristics, by adapting the standard patch-corridor-matrix model. The basic ingredient of this two-dimensional model is the patch. In the raster format, any patch is a subset of the plane consisting of a union of squares (cells) satisfying certain properties. The triangulation method developed by Jenness (2004) made it possible to adjust the areas and the perimeters of the patches, taking into account the elevation of the grid cells, which was one of the categories described by Dorner et al. (2002). Moreover, using this method, Hoechstetter et al. (2008) showed that one can adjust the standard landscape metrics. Despite its usefulness for computation of standard landscape metrics, Jenness's method (Jenness 2004) presents some disadvantages, which are discussed in Section 2. Specifically, this model does not provide continuous objects and the length of a common border of two patches is not well defined, in the sense that it depends on the patch which is analyzed.

The purpose of this paper is to present two alternative methods of approximating terrains and to compare them with Jenness's method. The main advantage of these new triangulations of a digital elevation model is the fact that they eliminate the two limitations of Jenness's method mentioned above. In particular, they allow the replacement of each patch with a *continuous* three-dimensional triangle mesh. Therefore, this construction also satisfies the requirement to develop models based on continuous rather than discrete spatial heterogeneity (McGarigal & Cushman 2005). Although such a triangle mesh-patch is not constant from the point of view of the elevation, it still represents the abstractization of an ecologically homogeneous tract of land. Thus, it could be considered a land unit in the sense of Zonneveld (1989) and it could be the basic ingredient of a 3D patch-corridor-matrix model.

2 Methods – Generating triangle mesh approximations

The aim of this section is to describe three alternative constructions of triangle meshes which replace a digital elevation model and which represent a polyhedral approximation of a terrain. We first recall Jenness's method (Jenness 2004) and we then introduce two new triangulations of a digital elevation model. These methods could be used in the quantification of the third dimension of landscapes, particularly in the adaption of landscape metrics.

Consider a raster image in which each cell c has a particular value e_c associated with it, which represents the elevation (in meters) of the central point in that cell. The digital elevation model gives rise to a discontinuous surface consisting of squares (Figure 1).

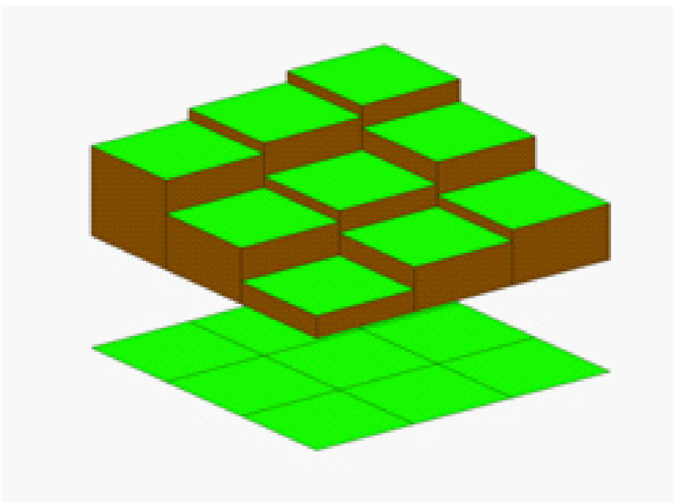
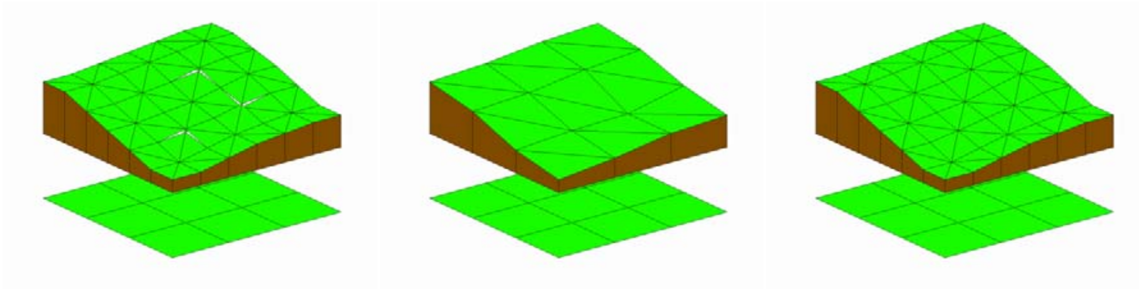


Figure 1. Sample digital elevation model (figure drawn according to Jenness 2004).



a b c

Figure 2. Polyhedral approximations of the original terrain.

A first method for generating a triangle mesh which approximates the original surface (hereafter referred as 'Method J') was proposed by Jenness (2004) and was already used by Hoechstetter et al. (2008) in order to adjust several landscape metrics (Figure 2a). Each cell c is replaced by eight triangles having as common vertex the center of the square. The other vertices correspond in the 2D-model to the vertices of the square c, respectively to the midpoints of its edges. Their elevations are induced by those of the adjacent cells. In fact, each adjacent cell c' induces a vertex v' having the elevation $e_{v'}=(e_c+e_{c'})/2$. For these triangles one can compute, using standard formulae, the area and the perimeter. These values can be used in the adjustment of standard metrics.

In the sequel we describe two alternative approaches. The main point of the construction is to associate an elevation to each node of the grid, obtained as the average value of the elevations of the adjacent cells. Thus, the elevation e_n of a node n is given by the formula

(1) $$e_n = \frac{\sum_{c \text{ adjacent to } n} e_c}{N_n},$$

where e_c is the elevation of a cell c and N_n is the number of cells adjacent to n. Usually, a node is adjacent to four pixels, that is $N_n = 4$, but this formula also integrates the case when the node is situated on the border of the grid. This construction yields a continuous (but in general not smooth) approximation of the initial surface, consisting of skew quadrilaterals. There is a one-to-one correspondence between the nodes of the original grid and the vertices of these quadrilaterals: each 2D-node (x_n, y_n) is replaced by a 3D one, namely (x_n, y_n, e_n). The first alternative approach (Figure 2b), hereafter called 'Method T_2', (Stupariu et al. 2009) consists in replacing each skew quadrilateral, say *ABCD*, by a union of two triangles. This is done by triangulating *ABCD* using the principle of Delaunay TIN for planar point sets (see e.g. de Berg et al. 2000). Hence, between the two possible triangulations (*ACB, ACD),* respectively *(BDA, BDC),* we choose the one that maximizes the minimum angle. Eventually, all these triangles yield a continuous triangle mesh which approximates the original terrain. The second alternative construction (Figure 2c), called hereafter 'Method T_8', gives rise to a fan consisting of eight triangles which replace each pixel. All these triangles have as common vertex the 3D-point (x_c, y_c, e_c) corresponding to the center of the pixel. The other vertices are the 3D-points (x_n, y_n, e_n) associated to the nodes of the cell and the 3D-points associated to the midpoints of the edges, whose elevations are again computed using formula (1). These triangles usually no longer give a triangulation of the skew quadrilateral which replaces the cell. In both constructions, each 2D-patch (a union of squares) is replaced by a 3D-patch (a triangle mesh) and its border is replaced by a continuous union of segments. Applying standard formulae from analytic geometry, one can easy compute for each 3D-patch the area and the perimeter. Further, one can also deduce several other metrics which can be expressed as function of these two basic landscape metrics.

These two alternative models own many of the advantages of Jenness's triangulation: neighborhood analysis, fast processing speed, consistent and comparable output, as well as some of its limitations: less accurate than TIN-based calculations (Jenness 2004).

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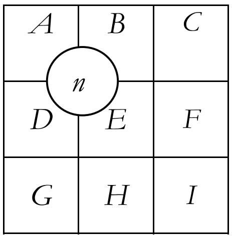
a



b

138	134	139
136	142	141
143	147	146

Figure 3. Grid consisting of nine cells and the corresponding elevations.

We claim that an advantage of Methods T_2 and T_8 is that they give rise to a *continuous* approximation of the true surface (in fact of any patch in the grid). By applying these methods, one can assign to each node a well-defined elevation and one can replace each edge with a line segment (Method T_2), respectively with the union of two line segments (Method T_8). Let us notice that, by using Method J, one gets some 'gaps' in the triangle mesh around some nodes (see Figure 2a), that is the triangulation provided by Method J is, in general, a *discontinuous* one.

This discontinuity can be proved rigorously as follows. Let's consider the grid in Figure 3a consisting of nine pixels. We apply Method J to the cells of this grid. When we analyze the pixel *E*, we compute the elevation $e_n=(e_E+e_A)/2$ for node *n*, while when cell *B* is processed, the same node will get the elevation given by the equality $e_n=(e_B+e_D)/2$. Usually, these values do not coincide and this shows that, in this model, the elevation of a node is no longer well-defined. Thus, the triangles which replace the corresponding pixels cannot be glued in order to get a continuous surface.

We also claim that Method J may sometimes induce inconsistencies in the computations of perimeters (especially when the differences between the elevations of the pixels are substantial). More precisely, the lengths of the edges are no longer defined, but they depend on the patch which is processed. In order to better understand these statements we analyze an explicit example. For simplicity, we will again take the grid in Figure 3a, consisting of 9 cells. We assume that the length of each square is equal to 10 and that the elevations are those given in Figure 3b. Suppose that the cells *B* and *E* (with elevations 134, respectively 142) are patches and let us compute the length of the common border of these patches, by using Methods T_8 and J. In model T_8, we first have to compute the elevations of nodes *n* and *n'*, which are the endpoints of this border, and the elevation of point *m,* which is the midpoint of the line segment [BE]. One has

$$e_n = \frac{e_A + e_B + e_D + e_E}{4} = 137.5, \quad e_{n'} = \frac{e_B + e_C + e_E + e_F}{4} = 139, \quad e_m = \frac{e_B + e_E}{2} = 138.$$

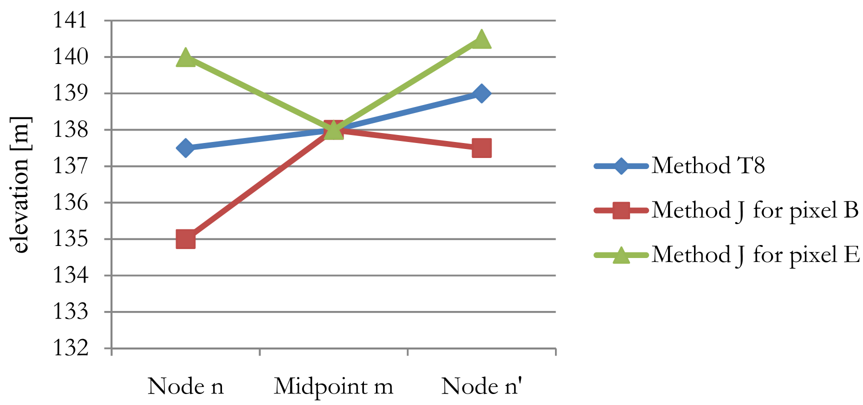


Figure 4. Elevations of the nodes and lengths of the common border.

Thus, in model T_8, the common border of the patches *B* and *E* is a union of line segments and has the length l ≈ 10.1239. Let us now apply Method J. As stated above, in this case the nodes *n* and *n'* no longer have a well-defined elevation, but their elevation depends on the pixel which is processed. Let us first analyze the pixel *B* with elevation 134. In this case, node *n* has the elevation $e_n = (e_B+e_D) / 2 = 135$ and node *n'* has the elevation $e_{n'} = (e_B+e_F) / 2 = 137.5$ (the elevation of *m* remains equal to 138). Hence, when pixel (patch) *B* is processed, the length of the border shared with *E* is $l_1 \approx 10.8559$. On the other hand, when pixel *E* is processed, the elevations of the nodes *n* and *n'* are equal to 140, respectively 140.5 and the length of the border shared with *B* is $l_2 \approx 10.9754$. The values provided by Method J are definitely larger than those provided by Method T_8. This difference arises because Method T_8 yields a 'better' averaging of the elevations of the nodes *n* and *n'* and the corresponding values are closer to the elevation of *m* (see Figure 4). By applying Method J, both patches (*B* and *E*) will have a well defined perimeter, but the length of the common border is not well defined, in the sense that it depends on the patch which is analyzed. Of course, usually the intersection of the borders of two patches consists of more than one such edge and such errors may cumulate or may annihilate each other, depending on the shape of the terrain. However, from this point of view, Method T_8 provides consistent lengths for the common borders of patches, in the sense that they do not depend on the patch which is processed. Analogous statements hold for Method T_2.

Another remark is that Methods T_8 and J are 'finer' than the Method T_2, since each cell is replaced by many triangles and one can hope to get a better approximation of the true area of the surface.

3 Results and Discussion

In this section we will apply and compare the methods described above: firstly on regular surfaces, for which quantitative indicators such as area are easy to compute, and secondly on grids corresponding to real terrains.

3.1 Approximation of parameterized surfaces

In order to better understand the behavior of the three models, we tested them on several standard parameterized surfaces: a parabolic cylinder, a parabolic hyperboloid and a real quartic (Zhou & Liu (2004) used similar techniques in a different context). Although it is clear that the surfaces occurring in the real situations are more complicated than these ones, we can carry out a first comparison of the methods described above. Moreover, for these surfaces, the true area can be well approximated using numerical methods. We considered the following explicit parameterizations:

$$\text{parabolic cylinder:} \quad f:[0,20]\times[0,20]\to\mathbf{R}^3,\ f(x,y)=\left(x,y,-\frac{y^2}{10}+4y\right),$$

$$\text{parabolic hyperboloid:} \quad f:[0,20]\times[0,20]\to\mathbf{R}^3,\ f(x,y)=\left(x,y,\frac{xy}{10}\right),$$

$$\text{quartic:} \quad f:[0,20]\times[0,20]\to\mathbf{R}^3,\ f(x,y)=\left(x,y,\frac{1}{10}\left(-\frac{x^2}{10}+2x\right)\left(-\frac{y^2}{10}+2y+2\right)\right).$$

We then created a grid consisting of 100 cells, each cell having the length equal to 2. For the center of each cell, which is a point of the form *(2m - 1, 2n-1)*, *m,n=1,…,10*, we computed the corresponding elevation, equal to *f(2m - 1, 2n-1*). To this raster we applied the three alternative methods described above, obtaining the corresponding areas. For the computations, we developed a *C++* application built with the *Microsoft Visual Studio* (Microsoft 2008) environment. On the other hand, using the *MATLAB* package (MathWorks 2008), we computed the true area for each of these surfaces. The results are synthesized in Table 1.

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Table 1. Polyhedral approximations of parametrized surfaces: comparative results.

	Parabolic cylinder	Parabolic hyperboloid	Quartic
2D-area	400.00	400.00	400.00
Method J	868.19	713.45	594.63
Method T_2	853.90	699.00	569.53
Method T_8	868.19	712.80	593.82
True area	929.36	744.63	660.43

The first conclusion is that all three methods are valid and, for all three surfaces considered, they provide better approximations of the true areas than the 2D-method. However, one should notice that Methods J and T_8 seem to be more accurate than Method T_2, providing values which are closer to the real area.

3.2 Case studies

We now apply these models of triangulation for two study areas situated in the Prahova Valley, in Romania. The first sample area is located in the sub-mountainous region of the valley, while the second one is situated in its mountainous sector. Ortophotoplans and topographic maps containing contour lines at scale 1:5,000 were digitized and the vector files were transformed, using the *ArcGIS* 3D Analyst TIN Creation tools (ESRI 2008), into a TIN surface. Using the Spatial Analyst extension of *ArcGIS*, a DEM (with a cell size of 5m) was created. The files were exported in ASCII format and the data were analyzed using a C++ application built with the *Microsoft Visual Studio* environment.

In Table 2 we included the 2D-area, the surface area (computed with the Surface Analysis extension of *ArcGIS*), as well as the areas provided by the three alternative triangulations of the raster image. As expected, the differences between the 2D-area and the approximations of the true 3D-area (quantified in Table 2 by the ratios between the 3D-approximation and the 2D-value) are greater in the case of the mountainous landscape, where terrain roughness becomes more significant. The Methods T_8 and J again provide close results and these values are greater than the value obtained applying Method T_2. It is interesting to notice that the TIN area is closer to that provided by Method T_2. However, it is difficult to evaluate which one of these values is closer to the true surface area of the terrain.

Table 2. Area estimations and ratios between the 3D-approximation and the 2D-value in the case of the two test landscapes (surface areas are expressed in m^2).

	Cornu (sub-mountainous)		Sinaia (mountainous)	
	Area	Ratio	Area	Ratio
2D	1.666E+07	1.000	5.732E+07	1.000
Method T_2	1.702E+07	1.022	6.301E+07	1.099
Method T_8	1.710E+07	1.026	6.342E+07	1.106
Method J	1.712E+07	1.028	6.350E+07	1.108
Surface area	1.702E+07	1.022	6.315E+07	1.102

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Table 3. Statistics for three basic metrics, computed for the two test landscape mosaics.

		Cornu (sub-mountainous)				Sinaia (mountainous)			
		Min	**Mean**	**Max**	**Mean of ratios**	**Min**	**Mean**	**Max**	**Mean of ratios**
AREA *(m^2)*	2D	25.000	1.200E+05	2.611E+06	1.000	25.000	5.259E+05	2.801E+07	1.000
	T_2	25.085	1.225E+05	2.700E+06	1.014	25.000	5.781E+05	3.083E+07	1.044
	T_8	25.367	1.230E+05	2.714E+06	1.018	25.000	5.818E+05	3.103E+07	1.049
	J	25.406	1.231E+05	2.717E+06	1.019	25.000	5.826E+05	3.107E+07	1.050
PERIM *(m)*	2D	20.000	2.505E+03	3.260E+04	1.000	20.000	2.697E+03	9.022E+04	1.000
	T_2	20.034	2.524E+03	3.300E+04	1.006	20.000	2.790E+03	9.498E+04	1.022
	T_8	20.053	2.528E+03	3.306E+04	1.008	20.000	2.796E+03	9.525E+04	1.024
	J	20.096	2.534E+03	3.310E+04	1.009	20.000	2.809E+03	9.643E+04	1.025
SHAPE	2D	1.000	1.951	5.578	1.000	1.000	1.695	4.262	1.000
	T_2	1.000	1.950	5.582	0.999	1.000	1.697	4.277	1.001
	T_8	1.000	1.949	5.581	0.999	1.000	1.696	4.275	1.001
	J	1.000	1.951	5.583	0.999	1.000	1.698	4.325	1.001

In order to better understand the behavior at patch level of the alternative 3D-models, we conducted a comparative statistic analysis - similar to the one presented by Hoechstetter et al. (2006). We computed the minimum, mean and maximum values at patch level (see Table 3) in the case of three landscape metrics: *AREA*, *PERIM* and *SHAPE*. For the latter one, we used the formula *SHAPE = 0.25 * PERIM / sqrt(AREA)*. Comparing the results obtained for the two study areas, we conclude that, at least for these two examples, all three methods correctly reflect the relief variability dependence of *AREA* and *PERIM,* in the sense that the 'discrepancies' between the 3D-values and the 2D-values are greater in the mountainous area than in the sub-mountainous one. The computations also show that *SHAPE* is less dependent on this terrain complexity, fact already noticed by Hoechstetter et al. (2006). Another conclusion is that the 'hierarchy' of the methods noticed at landscape level seems to remain true at patch level. Hence, the values for *AREA* provided by Methods T_8 and J are close to each other and they are greater than the ones obtained using Method T_2. In the case of *PERIM*, the inequalities between the values provided by the three methods still remain true. One should notice that the mean and maximum values of *PERIM* in the mountainous region (see Table 3) confirm the existence of patches with great 'discrepancy' between the perimeters computed by using Method T_8 and those obtained with Method J. These discrepancies show that for

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terrains with an increased degree of variability, where the differences between the elevations of neighbor pixels in a DEM are substantial, the values provided by T_8 may be definitely lower than those provided by J (see the example and the comments in section 2). Nevertheless, as we will see later, such discrepancies occur only for few patches.

The inequalities between the values for *AREA* and *PERIM* provided by these methods (that is $AREA_{2D} < AREA_{T2} < AREA_{T8} < AREA_J$ and analogous for *PERIM*) are satisfied by the majority of the patches (more than 95%). We computed, for any patch and for each metric, the ratio between the value corresponding to a certain method and the 2D-value. Then, for each metric and each method, we computed the arithmetic mean of the ratios obtained for all patches (these average values of the ratios can also be found in Table 3). It is no surprise that the inequalities above remain true. One should notice that the values provided by Methods T_8 and J are close to each other, both for *AREA* and *PERIM*. In particular, this fact shows that, when using Methods T_8 and J, substantial differences between perimeters occur only for few patches. For each method and for each of the three metrics, the values of the ratios are normally distributed, in the sense that less than 5% of the values are outside the 95% confidence interval. We also notice that in the case of the mountainous region, for *AREA* there is a significant difference between the ratios at the landscape level (Table 2) and the average values of the ratios at patch level. This fact is explained by the existence of a huge compact patch (almost 50% of the surface) for which the ratio between the 3D-values and the 2D one is about 1.11 and by the existence of smaller patches, with ratios closer to one. If, instead of the arithmetic mean, one computes a weighted mean (with the weight of a patch given by its number of cells), then one obtains the values 1.099, 1.106 and 1.108 for methods T_2, T_8 and J, respectively. In particular, the analysis of these 3D-indices and their comparison brought additional information concerning the fragmentation degree of the mosaic.

4 Conclusion

This study reveals the fact that all three methods analyzed above are acceptable and could be used to compute the area, perimeter and several derived landscape metrics for patches of a landscape mosaic situated in the three-dimensional space. However, at least two fundamental questions arise. Are there any significant qualitative differences between these three techniques? Which method better approximates the real values?

The answer to the first question is affirmative. As shown above, Methods T_2 and T_8 eliminate two limitations of Method J: they provide continuous triangulations of the terrains and well-defined lengths for the common border of adjacent land cover patches. Continuous triangle meshes are widely used in visualization and computer graphics (see e.g. Hege & Polthier 2003) and similar techniques could be adapted in terrain modeling. On the other hand, patch edges play an important ecological role in the movement of plants, animals, people and nutrients across landscapes (Botequilha Leitão et al. 2006). The lengths of the common edges of patches are explicitly needed in the computation of the landscape metrics which quantify the contrast between adjacent patches. Hence, methods T_2 and T_8 could be useful in applications dealing with phenomena or processes related to patch edges and their functions.

Let us now discuss the second question stated above, which is concerned with the quantitative aspect of getting better approximations of the real values of areas and perimeters. The results obtained for parameterized surfaces indicate a certain 'hierarchy' of the three models, showing that, at least for the examples considered, Method J yields the best approximation of the true areas. One can also notice that the values provided by Method T_8 are close to those provided by Method J. Two problems still need to be analyzed, but they go beyond the scope of this paper. Is the 'hierarchy' of these three models valid for any parameterized surface? What happens with the approximations provided

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by these methods when the length of the cell goes to zero? One expects that all the methods provide values which converge to the true ones, but it is not clear which one of them converges faster. On the other hand, the hierarchy of the methods remained true for the two case studies considered (section 3.2). However, for real terrains it is impossible to indicate which one of the techniques approximates the real values better. We can only claim that, in the examples considered in this paper, Methods J and T_8 yield, with few exceptions, values which are close to each other. Corroborating this remark with the advantages of Method T_8 described above, we may conclude that, in some problems, Method T_8 could successfully replace Method J (from a computational point of view, the corresponding algorithms have the same complexity). However, further studies and applications of these methods are necessary in order to better understand the behavior, advantages and limitations of these methods.

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References

Bailey, R.G. 2009. Ecosystem geography. From ecoregions to sites. Springer, New York.

Baker, W.L. & Y. Cai 1992. The *r.le* programs for multiscale analysis of landscape structure using the GRASS geographical information system. Landscape Ecology 7, 291-302.

Beasom, S.L.; E.P. Wiggers & R.J. Giordono 1983. A technique for assessing land surface ruggedness. Journal of Wildlife Management 47, 1163-1166.

Blaschke, T. & L. Drăguţ 2003. Integration of GIS and object-based analysis to model and visualize landscapes. ISPRS workshop, 'Challenges in Geospatial Analysis, Integration and Visualization II' 2003 (Stuttgart, Germany), 18-23.

Blaschke, T.; D. Tiede & M. Heurich 2004. 3D-landscape metrics to modeling forest structure and diversity based on laser-scanning data. In: Thies, M.; B. Koch; H. Spiecker & H. Weinacker (eds.): Proceedings of the ISPRS working group VIII/2, 'Laser-Scanners for Forest and Landscape Assessment', International Society of Photogrammetry and Remote Sensing, 129-132.

Botequilha Leitão, A.; J. Miller; J. Ahern & K. McGarigal 2006. Measuring landscapes. Island Press, Washington.

Cushman, S. & F. Huettmann 2010. Spatial Complexity, Informatics, and Wildlife Conservation. Springer, New York.

Davis, F.W. & S. Goetz 1990. Modeling vegetation pattern using digital terrain data. Landscape Ecology 4, 69-80.

de Berg, M.; M van Kreveld; M. Overmars & O. Schwarzkopf 2000. Computational Geometry, Algorithms and Applications, Springer, New York.

Dorner, B.; K. Lertzman & J. Fall 2002. Landscape pattern in topographically complex landscapes: issues and techniques for analysis. Landscape Ecology 17, 729-743.

Drăguţ, L. & T. Blaschke 2006. Automated classification of landform elements using object-based image analysis. Geomorphology 81, 330-344.

ESRI 2008. *ArcGIS*. ESRI Inc., Redlands.

Forman, R.T.T. 1995. Land mosaics: The ecology of landscapes and regions. Cambridge University Press, Cambridge.

Forman, R.T.T. & M. Godron 1986. Landscape ecology. Wiley, New York.

Gustafson, E.J. 1998. Quantifying landscape spatial pattern: what is the state of the art? Ecosystems 1, 143-156.

Hege, H.C. & K. Polthier 2003. Visualization and Mathematics III. Springer, Berlin.

Hoechstetter, S.; N.X. Thinh & U. Walz 2006. 3D-indices for the analysis of spatial patterns of landscape structure. In: Kremers, H. & V. Tikunov (eds.): Proceedings InterCarto-InterGIS 12. International Conference on Geoinformation for Sustainable Development. Berlin, 108-118.

Hoechstetter, S.; U. Walz; L.H. Dang & N.X. Thinh 2008. Effects of topography and surface roughness in analyses of landscape structure – A proposal to modify the existing set of landscape metrics. Landscape Online 1, 1-14.

Huggett, R.G. 2007. Fundamentals of Geomorphology. Routledge, London.

Jenness, J.S. 2004. Calculating landscape surface area from digital elevation models. Wildlife Society Bulletin 32, 829-839.

Kotliar, N.B. & J.A. Wiens 1990. Multiple scales of patchiness and patch structure: a hierarchical framework for the study of heterogeneity. Oikos 59, 253-260.

Kruckeberg, A.R. 2002. Geology and plant life. The effects of landforms and rock types on plants. University of Washington Press, Washington.

Lang, S. & D. Tiede 2003. *V-LATE* Extension für *ArcGIS* – vektorbasiertes Tool zur quantitativen Landschaftsstrukturanalyse. In: ESRI Anwenderkonferenz. CDROM, Innsbruck.

MathWorks 2008. *MATLAB*. MathWorks Inc., Natick.

McGarigal, K. 2002. Landscape pattern metrics. In: El-Shaarawi, A.H. & W.W. Piegorsch (eds.): Encyclopedia of Environmetrics, 1135-1142. John Wiley & Sons, Chichester.

McGarigal, K. & S.A. Cushman 2005. The Gradient Concept of Landscape. In: Wiens, J. & M. Moss (eds.): Issues and Perspectives in Landscape Ecology, 112-119. Cambridge University Press, Cambridge.

McGarigal, K.; S.A. Cushman; M.C. Neel & E. Ene 2002. *FRAGSTATS*: spatial pattern analysis program for categorical maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. http://www.umass.edu/landeco/research/fragstats/fragstats.html (Access date: 30.11.2010).

McGarigal, K. & B.J. Marks 1995. *FRAGSTATS*: spatial pattern analysis program for quantifying landscape structure. General Technical Report PNW-GTR-351, USDA Forest Service, Pacific Northwest Research Station, Portland.

McGarigal, K.; S. Tagil & S.A. Cushman 2009. Surface metrics: an alternative to patch metrics for the quantification of landscape structure. Landscape Ecology 24, 433-450.

Microsoft 2008. *Microsoft Visual Studio*. Microsoft Inc., Redmond.

Pike, R.J. 2000. Geomorphometry - diversity in quantitative surface analysis. Progress in Physical Geography 24, 1-20.

Pike, R.J.; I.S. Evans & T. Hengl 2009. Geomorphometry: A Brief Guide. In: Hengl, T. & H. Reuter (eds.): Geomorphometry. Concepts, software, applications, 3-30. Elsevier, Amsterdam.

Riley, S.J.; S.D. De Gloria & R. Elliot 1999. A terrain ruggedness index that quantifies topographic heterogeneity. Intermountain Journal of Sciences 5, 1-4.

Sappington, J.M.; K.M. Longshore & D.B. Thompson 2007. Quantifying landscape ruggedness for animal habitat analysis: a case study using bighorn sheep in the Mojave Dessert. Journal of Wildlife Management 71, 1419-1426.

Schnekenburger, F.; A. Perera & D. Baldwin 1997. *LEAP II* – a landscape ecological analysis package for land use planners and managers. Forest Research Report 146, Ontario.

Stupariu, M.S.; I. Pătru-Stupariu & R. Cuculici 2009. Geometric techniques in quantifying landscape irregularities. In: Breuste, J.; M. Kozová & M. Finka (eds.): European Landscapes in Transformation: Challenges for Landscape Ecology and Management (Proceedings of the European IALE Conference 2009), 401.

Turner, M.G. 1989. Landscape ecology: the effect of pattern on process. Annual review of ecology and systematic 20, 171-197.

Turner, M.G.; R.H. Gardner & R.V. O'Neill 2001. Landscape ecology in theory and practice. Springer, New York.

 ISSN 1865-1542

Turner, M.G. 2005. Landscape ecology: what is the state of the science? Annual Review of Ecology, Evolution and Systematics 36, 319-344.

Wiens, J.A. 1989. Spatial scaling in ecology. Functional Ecology 3, 385-397.

Wilson, J.P. & J.C. Gallant 2000. Terrain analysis: Principles and applications. John Wiley & Sons, New York.

Zhou, Q. & X. Liu 2004. Analysis of errors of derived slope and aspect related to DEM data properties. Computers & Geosciences 30, 369-378.

Zonneveld, I.S. 1989. The land unit – A fundamental concept in landscape ecology, and its applications. Landscape Ecology 3, 67-86.

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