MEASURING CONNECTIVITY – A NEW APPROACH FOR THE GEOMETRIZATION OF THE LANDSCAPE AND FOR THE ENHANCEMENT OF COST-EFFECTIVENESS IN LANDUSE PLANNING

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Abstract
The study aims to introduce a new method and approach for measuring the diversity of connectivity with the help of the landscape geometrization, in order to create a new variable useful in landscape metrics and to decrease the costs of landscape planning if its main goal is the enhancement of connectivity. Using induction we identify the landscape elements with geometric elements, calculating the theoretical maximum line, section, intersection point (node) number and compare these values of the idealistic landscape to the values of the real landscape.

Keywords: connectivity, diversity, geometrization of landscapes, node, patch, corridor

1. Introduction

This study focuses on two major aims. First, by working out a simple (but far not concise and fully elaborated) method for the geometrization of the landscape (that hopefully may induce further debates), we intend to broaden the instruments of landscape ecology (landscape metrics) by introducing a new (and probably independent) index of diversity for connectivity that can be compared to other diversity indexes (Shannon-, Simpson-diversity index, Kininmoth et al. 2003, Mezősi and Fejes, 2004a). Then, by applying theoretical considerations and results in practice, the method may help landscape planning to reduce the costs, offering a way to enhance connectivity and free migration of species and, if it is desirable, fragmentation induced by human activity can decrease species number (a deer needs 500 ha to subsist) and enhanced connectivity can increase density (Harrison and Bruna, 1999, Debinski and Holt, 2000, Vos et al. 2001).

The structure of the study shows the above mentioned duality. The first part deals with the possibilities and limits of the elaborated method. The second, experimental part describes how the method may work in the reality: based on several small study areas we tried to simplify real landscapes by identifying their exact geometry and define new corridors, ecotons in order to increase connectivity.

Among the main tasks of landscape ecology the examination and measurement (qualitative and quantitative as well) of impacts, loadability, stability, elasticity, the dynamics of landscapes (Lóczy in Kerényi, 2007) and the extraction and identification of parameters can be found referring to them (Lóczy, 2002; Mezősi and Fejes 2004b; Túri and Szabó, 2008). Furthermore, in our opinion it should give a helping hand for landscape planning as well (Báldi, 1998).

Connectivity in landscapes can be interpreted by using pure geometry as well beside the existing interpretations (i.e. Jaeger 2000; Kininmoth et al. 2003) – the first part of this study focuses on the elaboration of such method. The approach produces new parameters that – beside porosity – can characterise the connectivity of landscapes and the potential mobility/expansion of species, too, and can be grouped together with the indexes of diversity. Migration is an important factor in the determination of the different diversity levels (thus "the value" and the naturality of landscapes). The rate and the method of the expansion/getaway of species are influenced by the connectivity of the landscape elements (beside the abundance of barriers) (Báldi, 1998, Saura and Torné, 2009). Although numerous indexes exist regarding diversity measurements, referring to different phenomena (i.e Harary-index, CCP, LCP, see: Jordan et al. 2003) due to GIS methods but not all these variables are considered independent (McGarigal and Marks, 1994, Ritters et al. 1995, Szabó and Csorba, 2009). Our method and its physical content differs from those in use, however, it does not mean that a Principal Component Analysis would consider it as an independent variable.

2. Methods

The mathematical model is based on the fact that patches can be considered plane surfaces; ecotons and corridors can be interpreted as the boundary (direct) lines of plane surfaces. The curved lines are also interpreted here as direct lines. Existing real landscapes units can be transformed using abstraction and geometrization, thus mathematical laws can be applied on them.

Thus, the potential of species movement based on connectivity can be measured by:

A, the number of direct (intersecting) lines (which refers to the 'order' of the landscape unit). Intersecting lines create intersection points, sections and plane surfaces.

B, the number of the created plane surfaces,

C, the number of intersection points and sections,

D, the cumulative number of the spreading directions measured from the intersection points,

E, the number of the routes to reach an intersection point from another one (graph theory).

Knowing the number of direct lines, the maximum number of surface planes, intersection points and sections can be calculated using the equations discussed later in this paper. The possible (theoretical) maximum values can be compared to the real values measured in the existing landscape unit. Full induction – applied in mathematics – was used to prove the relevance of the statements regarding geometry.

Before getting acquainted with the method, the elements of the model like landscape unit, intersection points, direct lines should be defined and interpreted, and the limits and the constraints of the method should be discussed.

3. Discussion of the theoretical background

3.1. The theoretical background of the model and the role of the introduced variable among diversity indexes

Our model is apt only for measuring connectivity and gamma-diversity,[1] therefore we do not intend to deal with the problems of minimum area of patches, minimum population (Vos et al. 2001), SLOSS, distances, fragmentation (Rutledge, 2003) and other complications with which other indexes do so: the new parameters are to characterise porosity and potential mobility (which connectivity may refer to). In the following, in order to separate it from other parameters of diversity, we introduce the discussed definition as ”*potential mobility*” or ”*diversity of connectivity*” and do not use the term as Kininmoth et al. (2003) did.

The different parameters related to diversity do not give reliable results if it is applied alone: comprehensive approach is necessary to select proper or independent variables (Szabó and Csorba 2009), and our method is intended to enhance the instruments of measuring diversity. The elaborated method does not distinguish between patch types (forest, meadow, ploughland etc.). This can also affect diversity, and the results cannot be extrapolated to all species at the same time on the same landscape unit (species-dependent model), i.e. corridors sometimes can be considered barriers for different species (Báldi, 1998).

[1] According to the law of *structure and functioning*, heterogeneous landscapes can be characterised by the largest biomass product, porosity and diversity. Some monocultures may produce large biomass amounts, but are extremely vulnerable to any changes. For this, see the ratio of biomass-production and species number, biomass-production and patch number.
According to the law of *structure and diversity*, the ecoton is the unit within the landscape where the greatest species-diversity and biomass-production can be measured. This means that the species mobility might be great along patches as well, and this reflects to corridor number, patch number and thus, connectivity.

For the model it is indifferent whether the patches are parts of the matrix or the patches of different land use, thus we can measure greater potential species migration or connectivity in a homogeneous landscape (i.e. arable land) where smaller parcels are surrounded with bushes, then on a landscape of diverse land use.

However, ecotons usually function as buffer and mixture zones between different neighbouring patches and the direction of species and energy migration is usually perpendicular to the ecoton itself, while corridors – contrary – ensure linear expansion between patches (and the movement is parallel with the corridor). Our model can not make difference between them since we are convinced that parallel movements occur in the ecotons as well. This leads us to several different interpretation of the landscape types (see Fig. 6A-C) but each can translated to the language of mathematics and these differences are irrelevant from this aspect.

3.2. The applied mathematical model for the geometrization of landscapes

Any plane (the landscape, matrix without pattern are considered planes) can be dissected by lines (ecotons, corridors, barriers) to several plane surfaces (patches, pattern of landscape). The number of these patches depends on the number of line-shaped elements in a landscape unit, and whether the lines are parallel or dissect each other. These also determine the number of intersection points, patches and sections.

It is evident that supposing parallel lines, the connection between ecotons (corridors, barriers) will be zero mathematically, and the number of patches also remains reduced: **n** parallel lines create **n+1** plane surfaces (Fig. 1). Between these plane surfaces (i.e. parcels of a ploughland) any connection can be realized only through routes *perpendicular* to the lines, thus the latter can be barriers as well, leading to minimised connectivity (certainly this may be a goal of landscape planning as well).

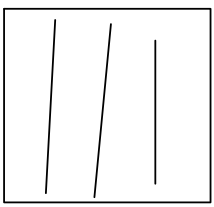

Fig. 1. Plane dissected by parallel lines

In the cases of the lines intersecting each other, more plane surfaces, intersection points and sections are created. Based on full induction applied in mathematics, we can conclude that in the case of 2 lines 4 plane surfaces, in the case of 3 lines 7 plane surfaces, in the case of 4 lines 11 plane surfaces and in the case of 5 lines 16 plane surfaces are realized, resulting in the following equation (Fig. 2):

n lines create maximum **n×(n+1)/2+1** plane surfaces.

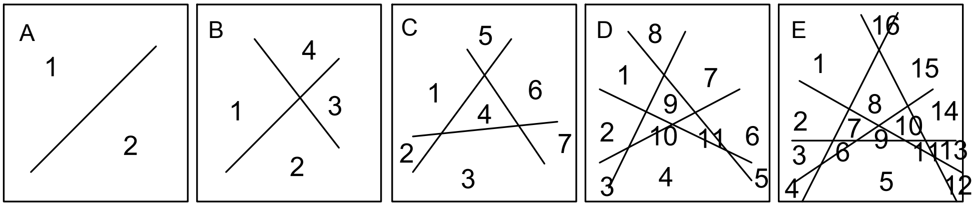

Fig. 2 A-E: Relationship between the number of lines and the maximum number of plane surfaces

The more lines occur in the unit area the greater the maximum patch number might be, and the size of patches decreases while patch number increases – so patch density (porosity) increases as well. Thus, the method is equivalent with the porosity if *different* landscapes with the *same unit areas* are compared.

At first sight it also seems evident that the more intersection points are created the more considerable number of directions of movement occurs, making species and energy migration possible. However, there are certain limits: 3 lines can intersect each other at the same point, thus we have 6 directions but only one intersection point, while if the 3 lines intersect each other at 3 points, 12 possible directions (4 as average) are created. In the following we consider intersection points as elements with at least 3 possible directions where the species can spread. (Diffusion into 2 directions is possible at any point of a linear element). This phenomenon is important to be emphasized since there are points where only 2 directions are possible. (These are not real intersection points usually occurring on curved lines and *loops* as linear elements of the landscapes). There is a great difference in the geometry of the real landscape and the abstract landscape after geometrization. The enumeration of lines and intersection points need to be paid attention to.

In the case of 2 lines the *maximum number of intersection points* (*nodes*) reaches 1 in the case of 3 lines the maximum number of intersection points is 3 and in the case of 4 lines this number is 6. Based on full induction,

n lines create maximum **n×(n-1)/2** intersection points

and multiplying it by 4, the equation gives the maximum number of directions:

n×(n-1)*2 (see *Fig. 3*)

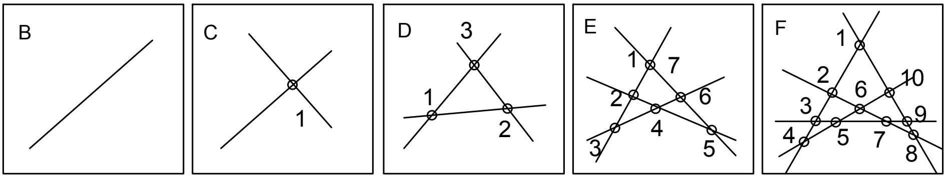

Fig. 3 A-F: Relationship between the number of lines and the maximum number of intersection points

The maximum number of direction can never be achieved if – within a unit area – more than 2 lines intersect each other at the same point. However, the number of directions may increase in that location, and if it happens, the number of directions remains under the possible maximum regarding the whole area.

Based on full induction we may conclude that

n lines create maximum $\mathbf{n^2}$ sections of linear elements (Fig. 4) - similarly to the concept of Jaeger (2000).

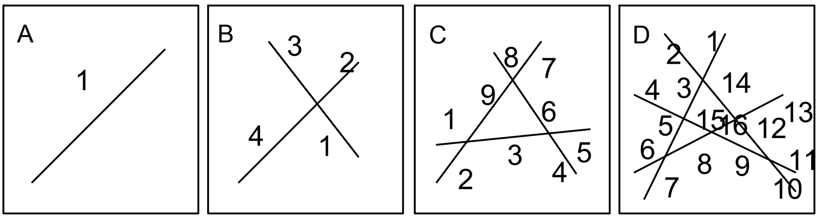

Fig. 4 A-D: Relationship between the number of lines and the maximum number of sections

This leads us to questions e. g. how we can get to one point from another by

A, using one section only once,

B, using one intersection point only once,

C, using the shortest route – a problem, which may be important for landscape planning issues as a possibility to reduce costs. This is definitely a problem of graph theory (Fig. 5) that is not investigated here since one equation cannot describe the features. For further details see: Cantwell and Forman (1993), Fejes (2004).

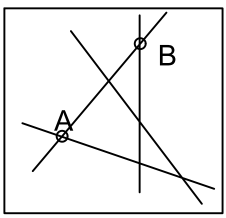

Fig. 5. Measuring the number of possible ways to get to B from A

These parameters mentioned above give us possibility to measure the diversity of connectivity of any landscape unit and *knowing only one element* (the number of lines) *the others can be calculated*. Before this, it is necessary to look through the different interpretations of the landscape and connectivity (the identification of plane surfaces, lines and intersection points with the elements of the landscape) and the method of the geometrization.

Connectivity can be interpreted in several ways e. g. on the level of corridors (Forman, 1995) but the connectivity of patches can also be interpreted especially with processes using software. The method is not sensitive to any of the interpretations; it can be used for all. Most of the authors consider nodes as patches (Fig 6A - a typical representative is a degrading forest, dissected into several smaller patches). A similar application based on graph theory is given by Saura and Pascual-Hortal (2007) in CS22.

If the unit area is totally covered by patches, the lines do not represent corridors but ecotons, the boundaries of the patches (plane surfaces). In this case all the patches can be the same (or different) (Fig. 6, centre and right). However, in most of the cases patches are connected by corridors and do not connect and communicate directly with each other. Fig. 6A shows a landscape unit where the intersection points are interpreted as patches without extension (different from the matrix) and lines represent corridors representing zones of communication while plane surfaces are considered as matrix dissected by corridors.

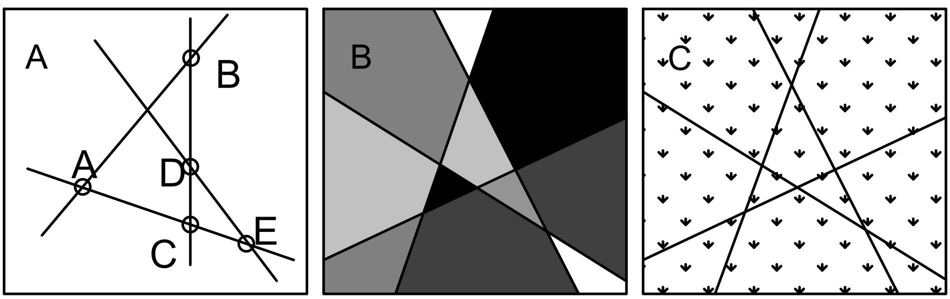

Fig. 6 A-C: Three different interpretations of patch-corridor / plane surface-line relations. On the left (Fig. 6A), intersection points (nodes) represent patches, lines represent corridors, plane surfaces represent the dissected matrix. See also the interpretation of Saura and Pascual-Hortal (2007), Saura and Torné (2009). A typical representative is a degrading forest, dissected into several smaller patches. In the centre (Fig. 6B), lines represent ecotons, corridors are missing, plane surfaces covering the whole area represent different patch-types. The picture on the right (Fig. 6C) shows the same situation without patches: the plane surfaces represent elements of the matrix dissected by corridors/barriers. Patch-type diversity is low while porosity and connectivity is greater. A typical example for the latter is an arable land dissected by roads or bushes used as delimitation of property.

Another interpretation problem to discuss is the geometrization of the landscape. The real pattern of the landscape is usually not as schematic as it appears to be in the simplified map after geometrization. As we have already mentioned, the number of lines determine other factors therefore it is enough to count the number of linear elements in the unit area. As the shape of patches often can be concave, the straight lines are rather curved thus the identification of linear elements may be problematic.

Fig. 7 shows an example for the geometrization of a landscape unit. By identifying the existing intersection points the landscape can be simplified. The *number of intersection points and patches has to remain constant after geometrization*. Here the concave patch can be reduced to a triangle with 3 intersection points (*thus manipulating the perimeter of ecotons* – another constraint of the method), and the 6 sections between intersection points originate from 3 intersecting lines.

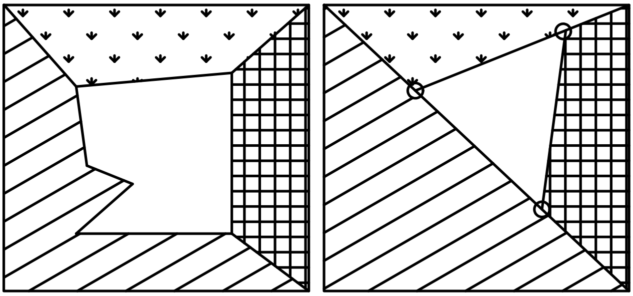

Fig. 7. The simplification of a real landscape (left) to geometric landscape (right)

Here, in the case of 3 lines, the theoretically possible maximum patch number is 3*(3+1)/2+1=7 while it is 4 on the picture therefore the diversity index is 4/7=0.57. The possible maximum number of intersection points is 3*(3-1)/2=3, the diversity index reaches the maximum. The potential maximum number of directions (of migration) is 12 while it is only 9 here, the diversity index is 0.75. The possible maximum number of patches is 9 but it is 6 here (0.67).

In the following we examine a larger area and set the rules of the geometrization of landscapes. In Fig. 8 one of the patches has only 2 intersection points, which means that it cannot be considered even a triangle in geometry. But since its boundaries are curved, it does exist in terms of the geometrization of a landscape and can be considered as diangle.

Generally the following advices can be given for the geometrization of a landscape:

1. The number of linear components should be reduced to the minimum. Intersection points may help to identify lines and do not mix lines up with sections. An intersection point shows at least 3 directions, which means at least 2 intersecting lines.
2. 2 identified neighbouring intersection points always fit on one line, even if it is curved or broken.
3. One line may contain more than 2 intersection points.
4. The original shape and perimeter of patches usually change during the process of geometrization. Simplification is necessary.
5. During simplification patch number and the number of intersection points should remain constant.
6. When calculating diversity indexes of connectivity, the basis of calculation is the number of lines from which the theoretical maximum of patch number, intersection number etc. can be calculated and be compared to the values measured on the simplified landscape unit.

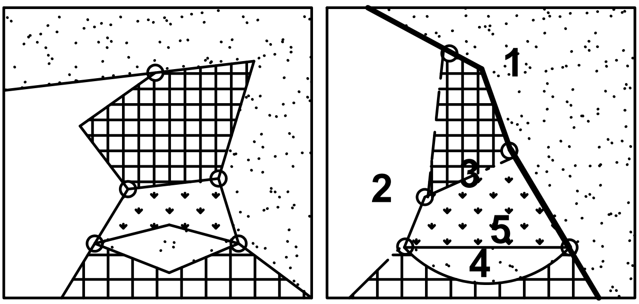

Fig. 8. An example for a mapped landscape unit (left) and its schematic version after geometrization (right). Note that the size of patches and the length of perimeter can change (as they are irrelevant from in terms of the examination) but patch number and intersection number remains constant.

The landscape unit in Fig. 8 can be characterised by the following connectivity diversity index (Table 1):

Table 1. Results of the geometrization of the landscape unit shown in Fig. 8

Properties	Theoretical maximum	Value measured on the schematised landscape	Index (ratio)
Number of lines	5	5	should be equal
Number of intersection points	10	5	0.5
Total number of possible directions	40	17	0.45
Patch number	16	6	0.36
Number of sections	25	10	0.40

To get an overall outlook on the meaning of these values, this investigation should be repeated many times on different landscape units, then the results should be compared to that of the beta- and gamma-diversity and reveal whether any correlation exist between them.

It is worth mentioning that the less line constitutes the landscape the easier to reach the theoretical maximums of number of intersection points, sections, etc. (Table 2). Therefore *it is futile to compare territories with the different number of lines* (that is a basic difference between beta-/gamma-diversity and the diversity of connectivity). The sample areas can only be compared to the theoretical maximum or – only if they contain lines near equal – to each other. This problem can be eliminated when *the extension of landscape units are the same: in this case they become comparable*. The difference in the number of lines on territorial units with the same extent can be interpreted itself as a value referring to the "order" of connectivity (Fig. 9).

Table 2. Results of the geometrization of the landscape unit shown in Fig. 7

Properties	Theoretical maximum	Real value measured on the schematised landscape	Index (ratio)
Number of lines	3	3	should be equal
Number of intersection points	3	2	0.66
Total number of directions	12	8	0.66
Patch number	7	6	0.85
Number of sections	9	7	0.77

In Fig. 9 the 2 sample areas are shown, compared to each other (as their territorial extension is considered equal) not to the theoretical maximum. On the left a 5th order landscape unit can be seen while on the right there is the landscape unit of the 3rd order. The patch type number is greater on the left but the patch number is less there (this brings us back to the porosity!) and the total number of potential escape directions is higher on the left again (17 vs. 12). However, it ranges up to the 45% of the theoretic maximum, while on the right it is 100%. The landscape on the left comprises more lines (5 vs. 3), sections (10 to 9) and intersection points (5 vs. 3) but the percentage values compared to the theoretical maximum are better in the case of the landscape unit on the right.

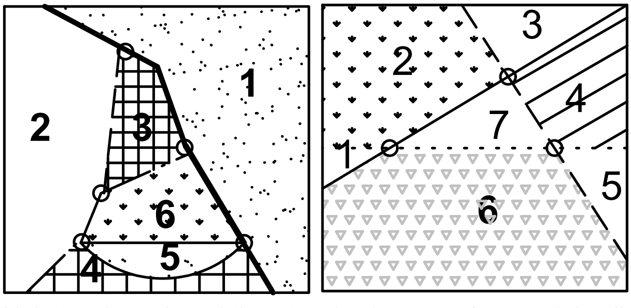

Fig. 9. A 5th (higher) order and a 3rd (lower) order (in terms of connectivity-diversity) landscape unit compared to each other (numbers represent patches)

4. Conclusions

Our method for measuring the diversity of connectivity can be used for
A, comparing landscape units with the same line numbers,
B, comparing landscape units where unit areas are equal while other parameters (number of lines) are different,
C, measuring the same landscape at different time horizons,
D, the 3 interpretation of patch-line relations,
E, optimizing the landscape planning,
F, comparing the diversity indexes.
In order to examine the applicability in practice we applied the method in a case study.

5. A case study: application in practice

Considering the criteria of application in practice, especially in landscape planning, 3 sample areas with 1 km^2 extent were chosen in the Tokaj-Hegyalja (N. Hungary) upland region for the examination. The parameters mentioned above were applied in the investigation.

One of the 3 sample areas was characterised by the lower level of diversity at first sight (Fig. 10) but there was not remarkable differences between the other two. From the further examination we concluded on that they were characterised by similar line numbers (25 vs. 24), however, the latter showed better values regarding not only the indices but the absolute numbers of directions, intersection points and plane surfaces. Therefore the latter was considered more diverse in terms of connectivity. Due to the high value of lines, the 11-15% percentage values seem to be low (*Table 3*) but the results show that greater percentage values should not be expected in Hungary. When we excluded isolated patches without connection, these values improved to 33%. However, the increase of connectivity-diversity means the decrease of patch numbers, thus porosity (and of course, the line numbers also decreased from 11 to 6, such as the order of the landscape connectivity).

Then, we examined how connectivity and connectedness can be improved without creating new lines. Two rules were set up to decrease costs in landscape planning.

1. It is easier to increase diversity by lengthening an existing section, intersecting the maximum amount of lines with it, creating many new intersection points and patches.

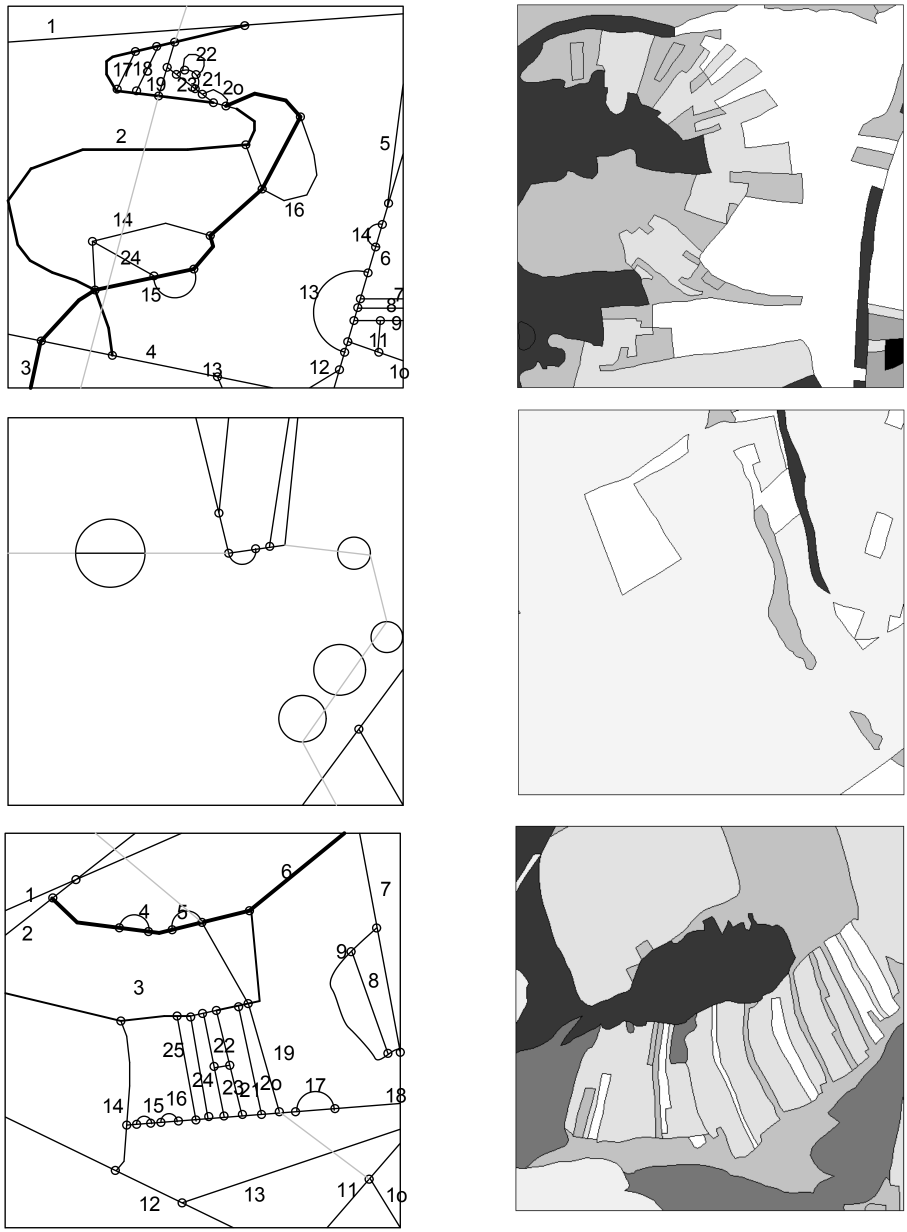

Fig. 10. The schematization of the 3 sample areas of 1 km^2 with different land-use in Tokaj-Hegyalja. The gray lines represent proposals for landscape planning to enhance the diversity of connectivity. Legend of land-use is not added since it is irrelevant from the point of view of the method.

2. This should happen within the shortest possible distances to reach low cost planning. This is another geometric problem but due to the limits of this paper we do not propose to deal with it.

3. It is also worth investigating whether natural processes tend to enhance connectivity by quick spreading, using stepping stones; or the opposite, the nature tends to increase patch size and reduce versatility and connectivity (as these are phenomena that can not cause only the migration of species but the spread of illnesses). It takes us to the question whether the connectivity is a value and whether it is useful, harmful or indifferent. Does the same process take place under natural circumstances and under artificial conditions (human interference) or not? It is also a good but unanswered question that to what extent the densification of intersection points (crossings on crossroads) can lead to the dominance of a certain patch type? Intersection points may grow and create patches by merging.

Table 3. Measuring the connectivity-diversity of 3 landscape units with different land-use, compared to the maximum values

Landscape unit	**1.**			**2a.** (isolated patches eliminated)			**2b.** (with isolated patches)			**3.**		
Properties	Measured	Theoretical maximum	%	Measured	Theoretical maximum	%	Measured	Theoretical maximum	%	Measured	Theoretical maximum	%
Number of lines (order)	*25*	*same*		6	*same*		11	*same*		*24*	*same*	
Patch number	*27*	*325*	*8*	7	22	30	12	67	18	*30*	*301*	*10*
Number of intersection points	*34*	*300*	*11,3*	5	15	33	5	55	9	*38*	*276*	*14*
Total number of directions	*103*	*1200*	*8,5*	15	60	25	15	22o	6,6	*120*	*1104*	*11*
Section number	*61*	*625*	*10*	11	36	30	16	121	13	*67*	*576*	*12*

As *Table 4* shows diversity of connectivity can be increased successfully only in the cases of landscapes with low line numbers (2a, 2b), especially if having isolated patches. In the cases of landscape unit 1 and 3 it is clearly observable that minimising costs (minimising increase in length) and maximising diversity may be controversial.

Table 4. Increasing the diversity of connectivity by connecting existing sections, without increasing line numbers

Landscape unit	**1.**			**2a.** (isolated patches eliminated)			**2b.** (with isolated patches)			**3.**		
Usefulness	Cost effective, but low enhancement of connectivity (decreasing line numbers)			Cost effective but not maximal enhancement of connectivity			Great enhancement of connectivity, low cost - efficiency			Great enhancement of connectivity, low cost - efficiency		
Properties	mea-sured	Theore-tical maximum	%	mea-sured	Theore-tical maximum	%	mea-sured	Theore-tical maximum	%	mea-sured	Theore-tical maximum	%
Number of lines (order)	*24*	*same*		6	*same*		11	*same*		*24*	*same*	
Patch number	*33*	*301*	*11*	8	22	36	21	67	31	*4o*	*301*	*13*
Number of intersection points	*37*	*276*	*13,4*	5	15	33	17	55	31	*46*	*276*	*17*
Total number of directions	*119*	*1104*	*11*	17	60	28	61	220	28	*154*	*1104*	*14*
Section number	*70*	*576*	*12*	12	36	33	35	121	29	*84*	*576*	*14,6*

Conclusion, final remarks

Summarising the results we can say that there are certain constraints in the application of the developed method, that may limit the applicability in practise (e. g. the geometrization takes time, reference units should be of the same extent, only landscapes of the same ‘order’ are comparable, beside tracing temporal changes), however, it cannot be challenged mathematically. An elaborate examination using more landscape units and a comparison with other indexes referring to diversity can answer the question whether it is worth using this index (for being independent variable, or it is just an other example for creative but futile brain-storming that increase the number of useless variables and articles. An advantage of the method is its flexibility, it can be used for 3 types of landscape interpretation (see *Fig. 6*), and its real physical content: it does measure connectivity).

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