Environmental Management. An Overview of Landscape Metrics.

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Abstract

Landscape ecology indicates its primary involvement as regards to the study of the various landscape patterns, their interactions and the way in which they formulate their alterations over time. Moreover, landscape ecology was founded on the grounds that the pattern and the interconnections of the various landscape elements, in other words the landscape structure, is the main factor decisive of the plethora of the ecological characteristics. According to the primary doctrine of management "what cannot be quantified, it cannot be managed", much effort and work has been conducted during the recent years in order to develop methods and processes suitable in the quantification of landscape structure, resulting in a bunch of metrics called landscape indicators. The present survey sets as its goal to review the major landscape indicators in existence today, their primary feats and caveats and their advantages and disadvantages, as well as any open field for further research possible. It mainly consists of three divisions. In the first, various concepts important for the comprehension of landscape structure and assessment are put forward. The second part mainly deals with the categorization of the most appraised landscape indicators in existence today and finally, the third part comments on their utilization in landscape management.

Keywords

Agri-Environmental Indicators, Landscape Metrics, Landscape Management, Landscape Ecology.

Introduction

The dynamic interactions among ecosystems take effect under the influence of the various ecological processes, the former also affecting the latter, in a bi-directional way. Recent policies and guidelines try to incorporate a landscape perspective for the plethora of efforts conducted to manage the land. Landscape ecology has emerged in the recent years as a way of thinking that might prove out to be useful in order to organize land management approaches. It focuses on three major landscape characteristics, namely structure, function and change. Landscape structure represents the spatial relationships among the various landscape elements, depicting the distribution of the landscape resources (i.e. energy, materials and species) in relation to the configuration of the landscape elements. Landscape function measures the interaction among the spatial elements, that is the flow of resources among the components of the landscape. Change on the other hand represents the alteration of the landscape structure and function over time. In addition, landscape ecology contemplates on the dynamics of spatial heterogeneity and its effects on ecological processes and it furthermore involves the application of the aforementioned principles in the formulation of solutions for real world problems.

The development of a concrete and widely accepted table of definitions is considered as essential by a plethora of researchers, due to the inconsistency regarding the analysis of landscape pattern throughout bibliography (Gustafson, 1998; Bogaert, 2003). The common descriptions among the various definitions of the term "landscape" include an area of land containing various patches, which is often described as a "mosaic of patches" or "landscape elements" (McGarigal and Marks, 1994). Other researchers impose a stress emphasizing on the interactions among various ecosystems. Thus, Forman and Godron (1986) defined landscape as a heterogeneous land area composed of a cluster of interacting ecosystems in a similarly repeated fashion. The definition of the term is dependent upon the context that drives the research or management. The size of the landscape also plays an important role, as regards to its definition. This leads to the conclusion that a landscape is defined by an interacting mosaic of patches relevant to the phenomenon under consideration at any scale.

Considerable confusion also arises among bibliographic references regarding the terms landscape metric and landscape indicator. These terms have been used throughout bibliography as illustrating more or less the same concept: a value, usually a number, conveying the quantitative approach towards an observed measurement. For the purpose of the present survey, however, their meaning is somewhat different. For one, landscape metrics are the basic statistical approach towards measuring a landscape characteristic, for instance fragmentation, complexity or diversity. Their combination or combined comparison may produce information on a higher level that could be environmentally exploited and which for this survey is called landscape indicator. An example of a landscape metric could be the Total Patch Area, while as an indicator we could refer to the Directional Leakiness Index. Furthermore, landscapes are composed of a mosaic of patches. A lot of different terms have been used in order to describe the patch of a landscape, including ecotope, biotope, landscape component, landscape element, landscape unit, landscape cell, geotope, facies, habitat and site. Their definition, size and shape heavily depend on the phenomenon under consideration. From the ecological point of view patches are discrete areas relating to spatial domain or periods relating to temporal domain comprised of relatively homogeneous environmental conditions. Their boundaries are defined by discontinuities in environmental character states and, regardless of the ecological phenomenon, they are dynamic and occur at multiple scales. Landscapes are typically composed of a wide variety of patches of different types, which comprise the various classes of the landscape. A class is a group of patches of the same type, either adjacent or dispersed. Of these classes, more often than not, one appears to dominate the landscape in size, it is the most extensive and most connected exerting a dominant influence on the landscape. This dominant class is called matrix and is incumbent upon the researcher to determine its existence and study.

The landscape ecological investigation or structural analysis is dependent upon spatial scale, which encompasses both extent and grain (Forman and Godron, 1986; Turner *et al*., 1989). Extent is the overall area of investigation whereas grain is the size of the individual unit of observation, which affects the resolution of the landscape. Research has already made it clear that different statements are obtained for different scales (Stein *et al.*, 2001). The term “context” helps describe the regional setting of the landscape, regardless of scale or definition, which may prohibit or encourage certain ecological processes. In this regard, landscape context is a function of the “openness” of the landscape (McGarigal and Marks, 1994) measuring the input and output of the materials and/or resources towards the landscape. Any landscape should be defined relatively to its context, as well as to its mosaic. On the other hand, landscape structure is a twofold function of composition and configuration, often referred to in the bibliography as landscape physiognomy or landscape pattern (Turner *et al.*, 1989). They characterize landscapes and can independently or in combination affect ecological processes and/or organisms. Landscape composition is associated with the variety or abundance of each class within the landscape but does not take under consideration the placement / location of patches within the mosaic, whereas landscape configuration refers to the physical distribution or spatial character of the patches within the landscape mosaic and is often viewed as a function of patch isolation or contagion. According to Gustafson (1998), composition is driven, quantified and described by three major parameters or properties, which are generated by simple counting algorithms. These properties of landscape composition are the number of classes in the map, the proportion of each class relative to the entire map and diversity. Landscape diversity encompasses two components: richness, and evenness, which refer to the number of classes and to the distribution of area among the various classes comprising the entire landscape respectively. Complementary to evenness is dominance, which illustrates the proportion of the map dominated by one – or a few – of the classes. Landscape spatial configuration is dual: a patch-based approach utilizes the description of spatial characteristics of individual patches, whereas the neighbourhood-based approach contemplates on the spatial relationships developed among neighbouring patches

Landscapes are dynamic systems, characterized by variability in structure, function and/or configuration not only spatial, but temporal as well, so that a lot of researchers have adopted the term “shifting mosaics” in order to better illustrate this alteration. Spatial heterogeneity illustratively describes the complexity and variability of a system property, such as any measurable entity of the landscape, in space and in time (Li and Reynolds, 1994). The complexity inherent in the ecological processes and functions, as well as the fact that the components of heterogeneity have not yet been standardized and defined concretely, render the quantification of spatial heterogeneity problematic. A lot of research work has been conducted towards the study and definition of mutually independent spatial pattern components. Li and Reynolds (1995), Riiters *et al.* (1995) and McGarigal and McComb (1995) research work conclusions on the identification of fundamental components comprising spatial pattern that are mutually independent, is summarized in the Table 1.

Materials and Methods

All methodologies developed in order to quantify landscape pattern aim to primarily produce samples and observations that are independent, on the grounds that the independence of observations forms the fundamental assumption for any statistical analysis. The primary data collection is provided by aerial photography, videography or satellite images in digital form, which are further processed to provide the fundamental data for evaluation. Gustafson (1998) reviews the basic types of analysis, concluding that two are the most prominent: Categorical map analysis and point-data analysis. The former involves representing heterogeneity by identifying relatively homogeneous patches on the map forming abrupt boundaries between them, whereas the latter is based on the grounds of the spatial continuity of the system property and analysis using geo-statistical techniques.

Categorical map analysis assumes the production of a thematic map in which system properties are represented either in vector or in raster form. The categorical approach represents a more simplified version of landscape heterogeneity compared to the point data approach, but is more relevant to ecological theory and, as such, more prone to easy and correct interpretive assumptions.

The next step to analysis is a way to capture and quantify landscape pattern variability and this is achieved via the use of landscape metrics, the development of which has seen a considerable boost over the last two decades. For the classification purposes of the indices, a two-dimensional approach is utilized. The first dimension encompasses characteristics of the landscape mosaic elements, i.e. patch, class and landscape metrics. On the other hand certain subject areas referring to the composition and the configuration of the mosaic are employed, resulting in a categorization including area and core area, density, size, edge, shape, nearest neighbour, diversity, contagion and interspersion metrics. For any given landscape mosaic, three groups of metrics relating to the characteristics of the mosaic can be defined. Metrics related to the various landscape elements are called patch metrics, whereas metrics referring to similar patches compose the class metrics and those having to do with the landscape as a whole comprise the landscape ones. Thus, landscape indicators exist in all the three levels of the landscape in focus. Patch metrics utilize mainly a computational basis and do not present a high interpretive value. Some species require suitable patches to use as habitat greater than a given threshold, so the size of each patch of the landscape becomes a decisive metric if we investigate the viable patches for a given species. The investigation of metrics regarding similar patches formulating a class in the landscape, comprise the class level of landscape metrics. Class indicators quantify the amount and distribution of each patch type in the landscape and thus they are considered as indices of fragmentation. Finally, landscape indicators measure and quantify the distribution and structure of the entire landscape and are primarily a measure of landscape biodiversity.

Gustafson (1998) introduced two general categories for indices; the composition and the spatial configuration indices. The former differ from the latter in that they do not require spatial information for their calculation. Composition indices encompass metrics used to quantify primarily the diversity, as well as the number of classes presented in the map and their proportion relative to the map. Examples of such indices widely used for the quantification of diversity at landscape level are the mosaic diversity index, the Shannon's, the Simpson's and the modified Simpson's diversity indices, accompanied by their richness and evenness counterparts. Recent trends in landscape ecology research show the speculation over the development of moving window indices for the quantification of spatial composition. A moving window is passed across the entire landscape map calculating an index value and representing it for each point. On the other hand, spatial configuration metrics are classified according to their scope of description and, as such, are either patch or neighbourhood based. Patch based metrics seek to quantify spatial characteristics of individual patches, whereas neighbourhood based ones aim towards the evaluation of the neighbouring properties using only pixel representations of system properties. Other approaches encompass statistical summaries of patches or classes comprised of mean, median, variance and frequency distributions. McGarigal and Marks, as well as the open source community, have accumulated a vast number of spatial configuration metrics and developed computer programmes for their calculation through their freely distributed programmes FRAGSTATS and Geographic Resources Analysis Support System (GRASS GIS) respectively (Baker and Cai, 1992). The documentation accompanying the offered packages is exhaustive as regards to the mathematical description and ecological interpretation of the accumulated spatial configuration metrics (http://grass.itc.it/ for GRASS GIS and http://www.umass.edu/landeco/research/fragstats/fragstats.html for FRAGSTATS).

Current Trends in Environmental Management.

The various environmental indicators are of a steeply increasing importance towards conveying environmental information to decision makers (Stein *et al.*, 2001; Onate *et al.*, 2000; Leitao and Ahern, 2002) and to facilitate policy design, while making it possible to inform the general public. The primary purpose of the metrics' existence is to quantify landscape patterns. On the other hand, ecological processes are measured via response variables, such as survival probability of populations. Landscape indicators are related to response variables via statistical methods and high correlation values indicate that the landscape indicator(s) in question provide information about landscape patterns with particular importance to an ecological process.

The current knowledge over landscape indicators is the result of the accumulated research work conducted over the past two decades by a plethora of researchers. Recent research work has made it possible to quantify the proneness of a landscape to retain or to lose resources (Bastin *et al.*, 2002). The researchers tested the performance of four indicators, namely the landscape leakiness index, the weighted mean patch size, the lacunarity index and the proximity index towards measuring the potential of landscape resource retention. Research work conducted in different directions has also implemented environmental indicators towards modeling the landscape complexity (Papadimitriou, 2002) or designing sustainable rural development (Schultink, 2000; Leitao and Ahern, 2002) or even developing criteria to evaluate the environmental implications of intensive agricultural practices (Ares *et al*., 2001; Dramstad *et al*., 2001), or land quality. They have also been used as a means to monitor landscape change as a standalone ecological process or in combination with desertification development (Lausch and Herzog, 2002).

Although landscape indicators have been widely used towards quantifying ecological phenomena and processes with positive, even admirable in certain cases, results, there are some major problems associated with the generalization of their use. The first major obstruct seems to be that despite their increased use, there seems to be no agreement towards the development of a holistic system for the measurement of landscape pattern. (Bogaert, 2003). Many commonly used indicators provide redundant information over spatial patterns (O'Neill *et al*., 1988; Riiters *et al*., 1995; Giles and Trani, 1999) and factor analysis techniques have been developed in order to reduce redundancy (McGarigal and McComb, 1995; Riiters *et al*., 1995). As a result, the problem of metric abundance stands as the major issue of debate on the correlation of many indices (Bogaert, 2003; Gustafson, 1998). Indicatively, we have accumulated and present in Table 2 certain metrics measured by various versions of the freely distributed program Fragstats, which are reported to have been partially, or absolutely redundant. It should be taken under consideration that most of these metrics have been dropped in the final version of the program (http://www.innovativegis.com/products/fragstatsarc/manual/manmetrics.htm).

The redundancy of the metrics is underlined by their high – or even perfect in some cases – correlation. This fact stems from their inherent characteristic to quantify a similar or identical aspect of landscape structure; in other words, they represent the same amount of information either in quantity or in quality. In the most of these cases, only one metric should be used. Another aspect of redundancy falls under the category 'empirical' and is associated mainly with the statistical correlation of certain patterns among different landscapes. According to McGarigal and Marks (1994), the 'empirical' redundancy of metrics, when correctly and holistically interpreted, can develop our knowledge of the ecological processes dominant in certain landscapes, while this is not the case regarding the aforementioned 'inherent' redundancy. Other researchers (Li and Reynolds, 1994; Riiters *et al*., 1995; Bogaert, 2003) consider that the problem of metric abundance origins in a deeper disaccord among the scientific community regarding the measurement of the landscape patterns and propose as solutions either the definition of independent components of spatial pattern (see above) in order to develop relevant independent metrics for their measurement, or the use of factor and multivariate analysis. Furthermore, certain landscape indicators provide ambiguous information regarding spatial patterns (Gustafson and Parker, 1992) and are sensitive to the spatial resolution (scale) of the landscape (Turner *et al*., 1991; Baker and Cai, 1992; Leduc *et al*., 1994; Qi and Wu, 1996; Nikora *et al*., 1999)

Conclusions

Summarizing, four milestones have been identified in the course of the present survey to be crucial for the successful application of landscape metrics to the quantification of landscape pattern in the line of environmental management.

- Careful layout of the research to be conducted as a preliminary step. The phenomenon of interest should be well defined topologically, ecologically, as well as spatio-temporally and as regards to the landscape characteristics best fit to represent its full potential and function. The grain and extent of the landscape for the best modeling of the phenomenon under consideration should be elected within the limits of this step.
- Selection of the best set of indicators. Probably the most elemental and decisive step towards a successful research is the selection of a suitable set of metrics, proportional to the phenomenon under investigation. Due to the fact that there is a stunning number of metrics available and considering the problem of redundancy, one is confronted with the difficult task of metric selection already from the early steps of his research. For example, the Shannon's diversity index has been widely criticized as conveying misleading results in the cases where richness falls below 100. In the most cases, a preliminary factor analysis is essential in order to identify a suitable set of metrics (Riiters *et al*., 1995; Herzog and Lausch, 2001; Lausch and Herzog, 2002)
- Scaling issues are of primary importance due to the fact that results referring to a metric vary according to scale. Scaling upwards decisively affects spatio-temporal variability, which could be an advantage in the cases when the interest is focused at the recognition of a general pattern, but could be proved out to be fatal when research is conducted for observing spatio-temporal extremes, as the small scale heterogeneity has already been eliminated by the scaling process (Stein *et al*., 2001). A good research planning could be of decisive help here as regards to the phenomenon under investigation.

- Proper interpretation of the results and conclusions. It is essential to understand what a metric actually measures in relation to the phenomenon under investigation. No matter how elaborate the layout of a research, the work will never conclude right unless the interpretation of the results is proper. Gustafson (1998) stresses out this point underlying for one the potential of a metric to produce misleading results and pose interpretive difficulties. Certain indices, such as contagion, may produce results inherent with subtleties that should be taken under consideration. On the other hand, all of the diversity metrics, the proximity index, patch cohesion and edge metrics pose often insoluble interpretation problems because they are constructed so as to measure several aspects of pattern simultaneously. To overcome the problem, the researcher should carefully observe the behavior of the metric as changes occur in the pattern, while she has a profound understanding of the construction of the metric in question. Patch based metrics are often summarized calculating their mean or variance, but this could cause interpretation problems in the cases where a statistically significant number of patches tend to be of smaller sizes. Gustafson (1998) suggests using area-weighted means or medians as better estimates of central tendency.

Perhaps the most challenging problem posed for future research is the ability to identify the appropriate scale for the application and, furthermore, to be able to correctly extrapolate findings across various scales. The debate also falls under the development of indices which capture heterogeneity in a single or very few value(s), as opposed to the development of a suite of metrics each one of which measures a single component of spatial heterogeneity. Furthermore, future work on the effects of the methods used to characterize spatial heterogeneity should be conducted and possible limitations of the current categorical map analysis, such as the "homogeneity" of conditions inside patches which is never the case in the real world, could be alleviated.

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TABLES

Table 1: Fundamental independent components of spatial heterogeneity.

Li and Reynolds (1995)	Compositional Components	Number of classes. Proportion of each class.
	Spatial Components	Spatial arrangement of classes. Patch shape. Contrast between neighboring classes.
Riiters *et al.* (1995)	Pixel distribution and adjacencies	Average patch compaction. Overall image texture.
	Fractal components	Average patch shape. Patch – perimeter scaling.
		Number of classes.
McGarigal and McComb (1995)		Patch shape and edge contrast. Patch density. Patch size

Table 2: Redundancy of landscape metrics.

Redundant Metrics	Level	Significance	Notes
- Mean Patch Size - Patch Density	Landscape	Absolute	They are both a function of the NP and TLA at landscape level.
- Patch Size Standard Deviation - Patch Density	Landscape	Partial	This redundancy is affected by the type of variation.
- Total Edge - Edge Density	Landscape	Absolute	The indices are identical when the landscapes are of identical size, namely they have the same TLA.
- Total Edge Contrast Index - Mean Edge Contrast Index - Area-weighted Mean Edge Contrast Index	Class	Partial	
- Core Area Density - Mean Core Area	Landscape	Absolute	They are both based on TLA at landscape level.
- Relative Patch Richness - Patch Richness	Landscape	Absolute	If the landscapes under investigation are similar in area and the maximum possible number of classes is held constant the metrics may also be partially redundant with Patch Richness Density.