Quantitative approaches to landscape spatial planning: clues from landscape ecology

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Abstract

Quantitative approaches to analyse and interpret landscape spatial patterns have developed rapidly during the last decade. The landscape ecological paradigm, based on a foundation of island bio-geography and meta-population dynamic theories, has emerged as a conceptual basis for incorporating such approaches to sustainable landscape planning and development. In this paper we describe two approaches to landscape pattern analysis that originate in landscape ecology: landscape pattern indices (i.e. landscape metrics) and cost-surface modelling. Landscape pattern indices quantify the composition and configuration of ecosystems across a landscape (e.g., patch size, shape, nearest-neighbor distance; proximity index; etc.) thus allowing quantitative comparison between different landscapes or within the same landscape at different times. Cost-surface modelling evaluates potential pathways between landscape elements (e.g., habitat patches) thus allowing quantitative estimation of landscape connectivity and/or fragmentation. The two approaches are described in terms of data requirements, GIS-based algorithms, and results interpretation. The approaches are then compared for applicability to landscape planning and we discuss the validity of approaches for different planning objectives. The two approaches are illustrated with examples on rural landscapes from Canada and Italy and the resulting quantities compared for implications to landscape planning. We conclude with practical advice for professionals seeking to incorporate quantitative approaches to sustainable landscape planning and development.
Keywords: spatial planning, landscape ecology, sustainable development, GIS.

1 Introduction

As a basic foundation of the landscape ecological theory, the study of landscape pattern has acquired relevance in the process of planning and developing sustainable landscapes. Quantifying the spatial distribution of landscape elements (i.e., patches and corridors) is a way to determine the degree of fragmentation and spatial heterogeneity of landscape mosaics, Gustafson [1]. Landscapes are heterogeneous systems composed of clusters of interacting ecosystems that vary in size, shape and spatial distribution, Forman [2]. Interactions among landscape elements are commonly described in terms of energy flows, nutrient cycling, and flora/fauna dispersal, which in turn determine the survival of species population and the persistence of the landscape in a "steady state" over time, Turner *et al* [3]. The ability to quantify landscape spatial patterns is therefore a prerequisite to predict landscape functions and changes, McGarigal and Marks [4], and to achieve sustainability in landscape spatial planning and development. Through pattern analysis, planners may gain additional information and knowledge on the: (1) composition and spatial configuration of the landscape as it currently appears; (2) transformation of landscape elements in response to ecological and social factors; and (3) evolution of the landscape under different planning and development strategies (i.e., alternative landscapes or landscape scenarios). For example, spatial attributes such as habitat area and structure, land uses, vegetation pattern, and distance between habitat patches may help planners to develop more ecologically sound plans and decisions. Starting from these considerations, in this paper we describe two basic approaches to landscape pattern analysis as part of a unique framework that originates in landscape ecology: landscape pattern indices (i.e. landscape metrics) and cost-surface modelling. Landscape pattern indices quantify the composition and configuration of ecosystems across a landscape (e.g., patch size, shape, nearest-neighbor distance; proximity of patches; etc.), thus allowing quantitative comparison between different landscapes or within the same landscape at different times. Cost-surface modelling evaluates the spatial configuration of landscape elements (e.g., habitat patches) allowing a quantitative estimation of landscape connectivity and fragmentation. The two approaches are described in terms of data requirements, GIS-based algorithms, and results interpretation. The approaches are then compared for applicability to landscape planning and we discuss the validity of approaches for different planning objectives. The two approaches are illustrated with examples on rural landscapes from Canada and Italy and the resulting quantities compared for implications to landscape planning. We conclude with practical advice for professionals seeking to incorporate quantitative approaches to sustainable landscape planning and development.

2 Landscape pattern analysis

The analysis of the landscape pattern generally involves the adoption of quantitative approaches and methods along with dedicated tools based on geographical information systems (GIS) and remote sensing (RS) technologies. Once spatial information on landscapes have been made available and/or derived from remotely sensed data, pattern analysis can take place considering each landscape unit (e.g., land-cover type) as part of a discrete patch mosaic: each patch is intended as a structural element of the landscape bounded by other patches that may be more or less similar. Landscape units are then subject to further analysis and computation aimed at determining quantitative measures of landscape composition and spatial configuration. In general, landscape composition refers to the relative amount of landscape units within the landscape mosaic, whereas landscape configuration refers to the spatial arrangement, location, and functional connectivity of landscape units. A basic scheme of the procedure for analysing landscape patterns is illustrated in fig. 1.

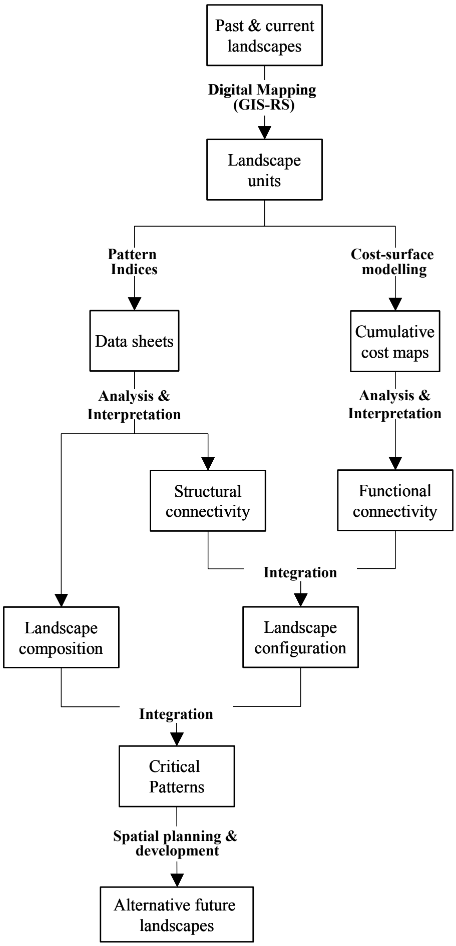

Figure 1: Basic scheme of the procedure for the analysis of landscape patterns.

The analysis of landscape pattern is therefore a complex process of understanding the critical patterns of the landscape and their reciprocal interrelationship and interdependency. As a consequence, performing pattern analysis requires a full integration between the expanding technology (GIS-RS) and the theory in landscape ecology that lies behind numbers and algorithms. This integration could be achieved combining two basic approaches that originate in landscape ecology: landscape pattern indices and cost-surface modelling. These approaches to landscape pattern analysis have to be integrated in a unique-holistic framework, figure 1, while defining the “future” of the landscape through the acts of planning, designing and alteration of patch patterns.

2.1 Landscape pattern indices

In the pattern:process relationship, landscape pattern has been commonly described by the use of indices that quantify the elements of a landscape (composition) and how the elements are spatially arranged (configuration), [1]. Landscape pattern indices are calculated on digital map data. Spatial data, most often in a GIS, is classified for an ecological property of interest and measured with selected landscape pattern indices. Two immediate issues arise: the landscape classification system used, and the landscape pattern indices applied. Landscape classification for design and planning purposes usually yields land cover types with descriptive labels for human purposes: “road”, “park”, “orchard”, “field”, “forest”, ”lake”, etc. While these labels may be entirely adequate for communicating a spatial design concept to stakeholders, they are not very useful for quantifying ecological consequences of plans or designs, Corry and Nassauer [5]. Landscape classification for ecological purposes requires that broadly-described land cover types be re-classified as, for example, habitat quality or units of landscape for some target guild or species. Even small changes in management, such as changes in farm tillage from conventional to minimum tillage, have implications for ecological outcomes such as carbon sequestration, runoff, soil loss, and habitat, Nassauer [6]. Indices commonly applied in landscape pattern analysis are myriad. In current versions of FRAGSTATS (a very popular index-calculating software), there are hundreds of indices available that can apply to a single patch, to all patches of a particular type, or to every patch in the landscape, [4]. It is imperative that indices be carefully selected because of a hypothesized relationship with an ecological property, Wu [7]. Applying dozens of indices and sifting through results to find an index which confirms the investigators’ suspicion is not a valid use of landscape pattern analysis, [1]. Landscape pattern indices range from very simple measures (such as number of patches, or area of a class of land covers) to complex (such as edge contrast, or interspersion and juxtaposition of patch types). These metrics are applicable to either raster or vector spatial data. Some indices are applicable only to one data type (e.g., contagion cannot be calculated on vector data), and values can differ for an index calculated for the same landscape represented as either vector or raster data. If raster data are used (more indices apply to raster data than vector data) individual polygon identities should be preserved such that neighbouring, contiguous patches remain distinct, [5]. That is, if patches begin to blend together, index values become difficult to interpret because of how patches are connected through the landscape and measured as a single large patch with a net-like shape. Table 1 lists a small number of landscape pattern indices and how they are calculated. For a fuller description of how landscape pattern indices are computed on spatial data, including formulae and interpretation, see [4].

Table 1: Sample landscape metrics, algorithms and meaning. Modified from [4].

Index	Algorithm	Description	Implications in landscape planning and development
Percentage of landscape	$P_i = \frac{\sum_{j=i}^{n} a_{ij}}{A}$	Percentage of landscape equals the sum of the area of a particular class (a_{ij}), as a proportion of the landscape area (A)	For ecologically-functional land cover classes, higher percentages are better; for disturbed or hostile land cover classes, lower percentages are better
Mean patch size	$MPS_i = \frac{\sum_{j=i}^{n} a_{ij}}{n_i}$	Mean patch size is the sum of all patch areas of a particular class (a_{ij}), divided by the number of patches in that class (n_i)	For ecologically-functional land cover classes, larger mean patch size values are better; for disturbed or hostile land cover classes, lower mean patch size values are better
Aggregation index	$AI = \left[\frac{g_{ii}}{g_{ii}(\max)}\right] \cdot 100$	Aggregation index calculates the number of like adjacencies (joins) between pixels of patch type (g_{ii}) as a portion of the maximum number of like adjacencies for a particular class	For functional classes, increased aggregation is better; for disturbed or hostile land cover classes, less aggregation is better
Modified Simpson's evenness index	$MSIEI = \frac{-\ln \sum_{i=1}^{m} P_i^2}{\ln m} \cdot 100$	The modified Simpson's evenness index is the proportional abundance of each patch type (P_i) relative to the maximum possible diversity for that number of patch types (m)	For highly fragmented landscapes, greater evenness is better than less evenness (implying that the landscape is more heterogeneous)

Landscape pattern index values are reported by FRAGSTATS in separate text files or data sheets for the individual patch, land cover class, or landscape level indices. Indices differ in their range (some are range-limited, while others are not) and units (some are unit-less, while others may be reported as percentages or in map units). Interpreting indices with different units or ranges can be difficult, and as mentioned, determining an ecologically-significant change in index values is challenging. Landscape pattern indices may be best interpreted by relating the change in pattern to some beginning or "baseline" condition. This condition may be the current or *status quo* landscape, and index values for alternative plans or designs can be relative to that baseline condition. Interpreting values relative to the baseline eliminates the difficulty of units and ranges, but does not resolve the issue of ecological significance. The landscape pattern index values can be useful to quantify how alternative landscapes compare to a baseline, and possibly rank alternatives for changes in landscape pattern that are desirable – if not ecologically significant. The missing connection for landscape pattern indices, as with many quantities, is determining if in fact a change in pattern will have a positive ecological outcome. The structural aspects of pattern are much more easily quantified than the functional aspects of pattern. However, landscape pattern indices are useful tools for comparing alternative patterns, though their value for inferring ecological function is questionable, [3, 5]. Landscape pattern index values are easily tested for statistical significance, which is part of their appeal. A statistically-significant change in index values, however, does not necessarily equate to an ecologically-significant difference in landscape patterns, [1, 3]. More empirical research is needed to identify the relevance of changes in landscape pattern and the difference in measures of landscape composition and configuration, Wu and Hobbs [8]. Of particular interest for planning and design applications is, finally, the issue of "scale". In terms of spatial analysis, "scale" refers to the extent and resolution of a study area. Changes in either, or comparisons among different extents or resolutions, affects landscape pattern index values, [3], Li and Wu [9]. Planning and design decisions often apply at resolutions from several to a few metres – towns, farms, highways, to walkways, roadsides, hedgerows. This challenges landscape pattern indices to be able to discriminate large, often poor-quality habitat patches, from very fine-scale bits of relatively-high biodiversity, Corry and Nassauer [10].

2.2 Cost-surface modelling

One of the basic principles in landscape ecology is that large and heterogeneous habitat patches and networks of habitat connections support higher level of species diversity by increasing the probability of interbreeding among species populations, Peck [11]. Under a planning perspective, habitat connections are essential elements to be investigated in order to ensure a balance between human and animal/plant needs. Dealing with organisms in the landscape (i.e., functional connectivity) implies broadening the common approach of planners to landscape assessment: from a mere site approach (object of planning) to more spatially explicit models and methods: landscape planners must be able to determine potential pathways among habitat patches and compare alternative patterns as consequence of alternative plans and decisions. As part of the landscape pattern analysis, the cost-surface modelling approach can be used to derive quantitative information on the spatial configuration (isolation *vs*. connectivity) of landscape elements, in absence of direct species movement observations. In applicative terms, this approach involves the adoption of a simple algorithm called: 'least-cost', Adriaensen *et al* [12] or 'least-resistance path algorithm' (*lrp-alg*), Lafortezza *et al* [13]. The algorithm requires 'gridded' landscapes in which patches are identified by a contiguous group of cells of the same mapped category, [3]. Specifically, two grid-layers are needed to run the algorithm: (1) a *source grid* that defines the source and destination patches (e.g., habitat patches from which species are expected to emigrate) and a *cost grid* (or friction layer) that assigns an impedance in some uniform unit measurement system that depicts the 'cost' involved in moving through any particular cell (as part of the intervening landscape matrix grid cells). In the *cost grid*, the numerical value assigned to each cell is assumed to represent the 'cost' *per* unit-distance of passing through the cell, where a unit-distance corresponds to the cell width, ESRI [14]. In landscape planning applications, the 'cost' may represent the degree to which landscape elements facilitate or impede movement of species across the landscape, considering the behavioural aspects of a focal species and/or a group of species, Taylor *et al* [15]. These values are preferably based on empirical data, or else on expert appreciation and assessment, Chardon *et al* [16]. Over the two input data, the 'least-resistance path algorithm' calculates, for each cell, the minimal cost (i.e., least cost) to reach a given patch from a source cell or set of source cells, Verbeylen *et al* [17]. The outcome of the cost-surface modelling is a *cumulative cost grid*: for any vertical or horizontal movement from cell A_i to cell A_{i+1} the cumulative cost, $CC(A_{i+1})$, is computed as the cost to reach cell A_i, $C(A_i)$, plus the average cost to move from cell A_i to cell A_{i+1} multiplied by the cell size (d), fig.2:

$$CC(A_{i+1}) = C(A_i) + d \cdot \left[\frac{C(A_i) + C(A_{i+1})}{2}\right] \tag{1}$$

$$CC(A_{i+1}) = C(A_i) + d \cdot \frac{\sqrt{2} \cdot [C(A_i) + C(A_{i+1})]}{2} \tag{2}$$

In the case of diagonal directions, eqn (2), the cost is multiplied by the square root of two to compensate the longer distance, [12]. The cumulative cost is thought to be the 'effective geographical distance' between landscape elements, [17]. The use of the cost-surface modelling approach in landscape planning and development is therefore a way to quantify the functional connectivity between habitat patches (landscape metrics are indeed indicators of structural connectivity) and to predict species dispersal in the landscape. In addiction, this methodological approach can be used to develop several alternative future developments (landscape scenarios) for a given landscape, each one corresponding to a different planning strategy and/or decision.

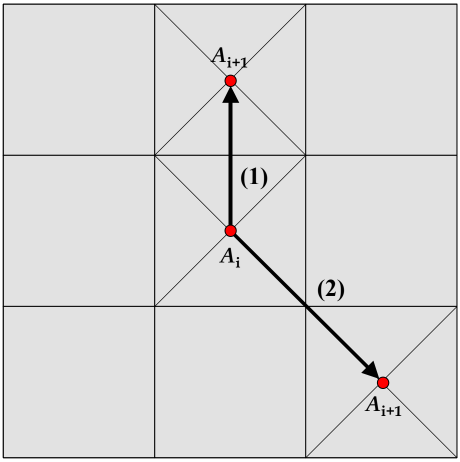

Figure 2: Exemplificative scheme of the cost-surface modelling: (1) vertical and horizontal directions; (2) diagonal directions (see text for corresponding equations).

2.3 Pattern analysis in landscape spatial planning and development

As above mentioned, the co-use of pattern indices and cost-surface modelling may augment the understanding of landscape patterns and processes. The two approaches must be seen as complementary processes within the same unique framework, fig.1, which considers the clues from landscape ecology as foundational. Pattern indices provide information on the structural features of the landscape mosaic (physical composition and configuration) without explicit reference to ecological functions: landscape elements are thought of as independent elements in a landscape matrix, primarily with relationships only within a single land cover type. Cost-surface modelling considers the matrix in between habitat patches as an important factor affecting species movement and therefore the functional connectivity of the landscape. The integration of these quantitative approaches in the process of planning and development sustainable landscapes represents a key challenge for landscape ecologists. Especially in the case of highly fragmented landscapes, this integration may help planners in determining the amount of habitat remnants (e.g., forest fragments) and their reciprocal arrangement from a species perspective. A common task in landscape planning is indeed the allocation of new elements (introduced patches) in patchy mosaics: planners identify optimal positions for new housing developments, industrial sites, recreational areas, forest plantations, etc. Besides the consideration of economic and social factors (e.g., distance from main roads, water and soil availability, etc.), the plan must contain solutions that strengthen ecological processes inside and/or outside new patches. New patches have to be planned, designed and developed using quantitative information coming from the analysis of landscape pattern. The general composition of the landscape context indicates the variety and abundance of patch types along with the average size, shape and proximity distance among patches (as a measure of the structural connectivity). The configuration of the landscape describes the spatial character of patches based upon species-specific resistance values of the intervening matrix (as a measure of the functional connectivity). As a consequence, planners can acquire a better knowledge on “what has to be planned” and “how to plan” in order to meet the target of sustainability. Another recurrent objective in landscape planning is the creation of alternative future landscapes in response to land-reorganization projects, like brownfield sites rehabilitation, [13]. Planners have to build alternative options for their plans and decisions, thus recommending the one that best fits specified criteria and/or constraints. The analysis of landscape pattern may provide, in quantitative way, useful insights for predicting the effect of each option on the surrounding landscape elements: enhancement of landscape connectivity/fragmentation; modification of the general pattern of existing patches and corridors, etc. An example of the complementary use of pattern indices and cost-surface modelling as been recently proposed by Lafortezza and Brown [18] for the development of a new golf course in the rural Mediterranean landscape of Apulia, Southern Italy. New patches of Mediterranean vegetation have been planned and designed within the recreational area, considering: (1) the *pattern* of the neighbouring fragments of natural vegetation, expressed in terms of number of patches, average size, shape, and core area; (2) the *spatial arrangement* and *functional connectivity* of Mediterranean scrublands and pine/oak plantations with undergrowth in relation to the behavioural aspects of species like the Hermann’s tortoise (*Testudo hermanni*). Another application of the pattern analysis in landscape planning and development has been described by Corry and Nassauer [10]. Indices were applied to ecological landscape planning alternatives for highly-fragmented Corn Belt agriculture watersheds (Iowa, USA). Corry and Nassauer [5], tested the applicability of landscape pattern indices for judging alterative landscape design and management across small watersheds (56-87 km^2). Using a small set of landscape pattern indices, results showed that not all indices ranked alternatives similarly for amount of habitat, heterogeneity, landscape connectivity, and landscape grain size. That is, while an index might imply that an alternative landscape may be better connected, another index might imply reduced landscape heterogeneity. When compared to spatially-explicit population models (small mammals) applied to the same alternative landscapes, indices did not validly imply ecological consequences. However, indices were reported to be adequate measures of changes in landscape pattern, and useful for judging alternatives for their pattern consequences, [5].

3 Conclusion

Planning for sustainable landscapes is a complex task that necessarily requires the adoption of quantitative approaches and methods that originate in landscape ecology. In this paper, we described two emerging procedures to investigate landscape patterns as part of a unique and holistic landscape ecological framework. Landscape pattern indices and cost-surface modelling represent 'two facets of the same medal': from one side, there is a need to determine the physical or *structural* characteristics of patches considered as discrete entities in themselves (e.g., woodlands, wetlands, prairies, grasslands, etc.); from the other side, it is critical to analyse the *functional* joinings or connections between target patches (e.g., habitat patches) in relation to one or more species of interest. Combining structure and function of landscape elements, landscape planners may strength their plans and decisions with new insights and ecological considerations. In practice, professionals seeking to incorporate such principles in their works can find in the proposed quantitative approaches two valid methods to: (1) appreciate the inherent heterogeneity of patches that surround the object of planning and development (patches typified by a fine-grain texture are likely to concentrate relatively high diversity in small areas); (2) estimate whether the shape of surrounding patches is regular or not (for a given size, a rounded shape ensures less points of interaction with the adjacent patches than an elongated or convoluted shape); (3) identify the appropriate size and shape of new green patches (larger and irregular patches of vegetation tend to support more suitable habitats for a wide range of species, and are more likely to be intercepted and colonized by dispersing species); and (4) determine the optimal location of the patch/patches being introduced through the analysis of the high-permeability pathways assessed in the *cumulative cost grid* (patches located along potential pathways are likely to facilitate or impede movement of species, acting as conduits or barriers). Despite the prominent value added by pattern measurement to landscape planning and development, it is important to note that quantitative measures must be tested in the field before extensively used. For example, monitoring protocol and indicators could be established to analyse long-term data collected in the study area and to weigh comparative applications at multiple scale of resolution (from coarse-to-fine scale). The definition of validation procedures of pattern indices and cost-surface modelling might be a productive topic to focus further study. Having a clear indication of the meaning of each quantity will certainly help to bridge the gap existing between fundamental theories (conveyed by academics and researchers) and final applications of principles (exerted by professional planners) in the field of sustainable planning and development. Planners and designers should continue to seek suitable quantitative tools for objectively judging the outcomes of planning. Landscape pattern indices and cost-surface models have revealed to be suitable, applicable tools that can be capably applied by planners and designers. Quantities that describe the structural pattern (composition and configuration) and functional connectivity of alternative plans or designs can be useful to infer ecological consequences. While it is questionable to use landscape pattern indices to imply an ecological consequence, index values can quantify the differences in landscape pattern. Alternatively cost-surface modelling can yield better information about ecological consequences, but usually for a single or few species, [16, 17]. Both quantitative tools seem to be useful within a set of limitations. The limitations do not fatally diminish the value of either tool for landscape ecological planning. In fact these tools have been legitimately promoted for improving applications of planning and design, Botequilha Leitão and Ahern [19]. In order to achieve more ecologically functional future landscapes, tools that quantify the structural complexity and functional implications of alternative plans are needed. Landscape pattern indices and cost-surface models are promising tools that have only begun to be developed and tested for landscape planning. Used wisely, and with full knowledge of the usefulness of each, these tools can lead landscape planning to more desirable outcomes.

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