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Quantifying landscape structure: a review of landscape indices and their application to forested landscapes

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Abstract: An important assumption of many environmental decisions is that some patterns or combinations of land cover are optimal or more preferable to others. Management plans frequently seek to change the structure of a landscape to realise particular management goals, because it is recognized that the spatial arrangement of elements in a land cover mosaic control the ecological processes which operate within it. This study reviews some of the tools available to those who need to describe and understand the spatial structure of landscapes. In particular, it examines the way in which quantitative measures, or indices, can be used and what contribution they might make to the management of forested landscapes in the UK. The paper discusses the way in which the different landscape indices can be used to assess the spatial implications of the various design guidelines that have been proposd to promote sustainable forms of forestry. It is concluded that while progress has been made in the development of a range of landscape pattern measures, and in our understanding of the factors constraining their use, there is a pressing need for further research into the relationship between landscape pattern and ecological process.

Key words: landscape indices; landscape structure; forest design; landscape ecology; sustainable forestry.

I Introduction

An underlying assumption of many environmental decisions is that some patterns or combinations of land cover are optimal or more desirable than others. Management plans frequently seek to change the structure of a landscape to realize particular goals, because it is assumed that the spatial arrangement of elements in a land-cover mosaic controls the ecological processes which operate within it. This review considers some of the tools available to those who need to describe and understand the spatial structure of landscapes. In particular, it examines the way in which quantitative measures, or indices, can be used and what contribution they might make to the management of forested landscapes in the UK.

Landscape indices are important because it is now widely recognized that modern, economic forestry has to take account of its wider environmental impact. The need for forest enterprises to promote the conservation of biodiversity and sustainable forms of development is, for example, an important element of recent rural policy (HMSO, 1994; 1995). Major environmental issues facing commercial forestry included problems associated with

- the potentially deleterious effects of fragmentation on biodiversity in lowland broadleaved forests, as a result land-cover change in rural areas;
- the loss of habitat through commercial planting, because many woodlands have been sited inappropriately, often on areas of previously semi-natural vegetation such as open heath or former broadleaved woodlands; and
- the reduction in habitat quality as a result of the preponderance of even-aged tree species over a large proportion of planted areas, especially, for example, in the Scottish Uplands.

Solutions to these problems may, in the case of existing plantations, require programmes of habitat restoration or other types of mitigation measures to counter the most extreme effects of forestry on biodiversity. In the case of new planting, solutions may require the development of novel types of design which pay attention to the landscape and conservation context.

Although the goals of sustainable forestry are fairly clear, the development of practical means for achieving them are still problematic. Kirby and Rush (1994), for example, have considered strategies to ensure the integration of nature conservation into forestry, and conclude that the task requires not only the development of targets for the area and character of different forest types but also specification of the ways in which the performance against these targets can be monitored. In the case of fragmentation, they conclude that it is essential that '. . . various measures of woodland fragmentation need to be developed and then converted into targets for different landscapes zones' (Kirby and Rush, 1994: 8). Baskent and Jordan (1995) also argue for the use of descriptive summary indices of landscape structure in forest landscape management. They assert:

> . . . a quantitative basis for measuring spatial structure is a prerequisite to implementing forest landscape management. Without such [a basis], structural objectives cannot be established nor can the understanding of spatial dynamics necessary to achieve structural objectives be mastered (Baskent and Jordan, 1995: 1830).

Unfortunately, the use of such indices and other quantitative measures which express different aspects of forest and landscape structure is as yet not well established; their refinement is an important task for the research community. In order to make progress with this task, this review aims primarily to clarify the issues involved. It will consider the recent literature on landscape, the different approaches to index construction and the issues affecting their use.

II Measuring landscape structure

1 Guidelines for forest design

A number of guidelines for operation and design of commercial forestry have been developed in recent years (HMSO, 1994; Kirby and Rush, 1994). Many have been derived from current research in landscape ecology and forestry planning (Selman and Doar, 1991; 1992; Selman, 1993; Forman, 1995a; Fry, 1996; Ratcliffe and Peterken, 1995), and necessitate the provision of some means of quantifying elements of landscape structure (composition and configuration).

An early and influential contribution in the area of forest design was Harris (1984), with later contributions by Forman and Godron (1986), Saunders *et al.* (1991) and Spellerberg and Sawyer (1993). Such ideas have been culminated in the guidelines published by the Forestry Commission (HMSO, 1989; 1990; 1992). For forested landscapes in general in the UK it is suggested (Watkins, 1991; 1993; HMSO, 1989; 1990; 1992; 1994; Kirby and Rush, 1994) that designers should seek to

- promote a diverse age structure;
- promote a diverse physical structure;
- increase forest cover overall by significant amount;
- promote large contiguous wooded area (e.g., patches);
- promote 'curvey' edges for edge habitat (e.g., pheasant/deer);
- promote nongeometric shapes inside forests (e.g., edges, rides);
- promote some open spaces within forests (e.g., increase amenity and aesthetic value);
- promote connection of ancient woods with new (e.g., for ancient species dispersal);
- promote compact shapes (i.e., maximize interior habitat area); and
- avoid planting on semi-natural habitats.

For lowlands in particular, designs should attempt to

- retain all current broadleaved woodland;
- avoid clearance of broadleaved woodland for agriculture;
- increase area of broadleaved woodland by planting on agricultural land;
- increase area of broadleaved woodland by natural colonization;
- increase area of broadleaved woodland by replacement of conifers;
- conserve ancient semi-natural broadleaved woodlands; and
- maintain open spaces in woodland for communities of special conservation value.

While in the uplands designs should aim to

- increase tree species diversity;
- increase proportion of native species;
- increase open spaces inside forests;
- follow landform in design (shape, margins, open spaces, patterns of species); and
- create habitats to increase wildlife diversity.

It is not the purpose of this study to review the ecological merits of such guidelines critically, but rather to ask 'how can they [the design goals] be measured quantitatively so that progress towards them can be monitored?' (cf., Kirby and Rush, 1994; Baskent and Jordan, 1995). To do so requires consideration of the various landscape indices reported in the landscape ecological literature.

2 Landscape indices

In the late 1980s and early 1990s a number of studies explored the utility of landscape metrics in landscape analysis (Turner *et al.*, 1989; Turner, 1990; Cullinan and Thomas, 1992; Gustafson and Parker, 1992). One of the first studies, O'Neill *et al.* (1988), presented just three measures – dominance, contagion and shape. Turner *et al.* (1989) also presented a study based on the same three indices but in 1990 went on to present a FORTRAN program, SPAN (spatial analysis), to calculate a much wider range of measures. These included: patch size and perimeter; patch type proportion; patch perimeter fractal dimension; simple edge contrast; and patch type adjacency – in addition to the three indices used in the previous study. Gustafson and Parker (1992) expanded SPAN routines in their HISA (Habitat Island Spatial Analysis) to include proximity, patch elongation, linearity, interior (core) area and edge area.

As a result of these early studies, a large number of landscape indices may now be found in the literature. Perhaps the most comprehensive set of indices to be found in a single program is provided by FRAGSTATS Version 2 (McGarigal and Marks, 1994). FRAGSTATS provides spatial statistics and metrics at the patch, class and landscape levels. Following Baskent and Jordan (1995), most of the landscape metrics and indices available can be classified into areal, lineal and topological measures for different scales of investigation:

- *Areal indices* provide measures of landscape or patch size, shape and interior or core area.
- *Linear indices* provide measures of boundary length, width and shape at the patch level, as well as connectivity and circuitry at the landscape level.
- *Topological indices* provide measures of the spatial relationships between landscape elements, in terms of dispersion, spatial association, interspersion, isolation and connectivity. Many of the landscape- and class-level statistics such as those provided by FRAGSTATS are topological measures, since they convey *spatial* information for one class derived from the relationships between patches of the target class and all others within a neighbourhood of a specified extent.

Although the division into areal, lineal and topological indices is useful in that it provides a conceptual framework, for practical purposes a simpler division would be to use the following categories (Table 1):

- area
- edge
- shape
- core area
- nearest-neighbour
- diversity
- contagion and interspersion.

A large number of studies examine the utility of landscape indices and metrics. In general the indices are used to quantify landscape structure in terms of landscape configuration and landscape composition. The information is then used either to make inferences about the operation of particular ecological processes within the landscape mosaic or as a basis for evaluating the conservation value of particular structural patterns. Two examples illustrate these different uses.

The early study by Franklin and Forman (1987) illustrates how inferences about specific process might be made on the basis of differences in landscape structure as portrayed by various landscape indices. These authors used a range of indices measuring patch size, edge length and patch configuration to explore the effects of imposing management on 'primeval' forested landscapes in North America. They used a simple patch-corridor-matrix-type model to explore the effects of the different management regimes used on federal lands in the western USA, and concluded that the probability of disturbance owing to fire or wind and other biotic factors was highly sensitive to structural changes in the landscape mosaic, as expressed by the different indices. Figure 1 shows how the different cutting regimes differ in average patch size and border length for a given level of forest area cut. Franklin and Forman (1987) argue that an understanding of the way in which these different regimes affect structure is essential if management goals are to be achieved effectively. For example, if the area of clear-cut is to be minimized to prevent wind throw then checkerboard and network patterns are preferable.

In contrast to the study by Franklin and Forman (1987), Baalman and Kirby (1995) used a range of indices in the analysis of the potential conservation value of forest patches and the effects of fragmentation in English lowland and Cumbrian landscapes. They used indices based on measures of interwood distances and the proportion of linear features (i.e., corridors) in 1 km^2 squares to assess 'wildlife friendliness' at the landscape scale, together with measures of the area of semi-natural habitat per square, the number of intersections between lines drawn across the middle of the 1 km × 1 km cell and linear features, and the number of intersections between the lines and roads. This approach had the merit of assessing the effects of barriers on habitat quality and the general permeability of a landscape to the movement of a wide range of species. The authors suggest (Baalman and Kirby, 1995: 11) that the simple measures investigated provide crude yet robust indicators which are 'likely to be as useful as anything else as measures of how landscapes differ in these respects', that is in terms of measuring the degree of isolation of semi-natural habitat patches.

III Landscape indices – methodological issues

Our review of the use of landscape indices to the analysis and description of landscape structure suggests a number of overlapping methodological issues affecting their use and interpretation. These issues are discussed below.

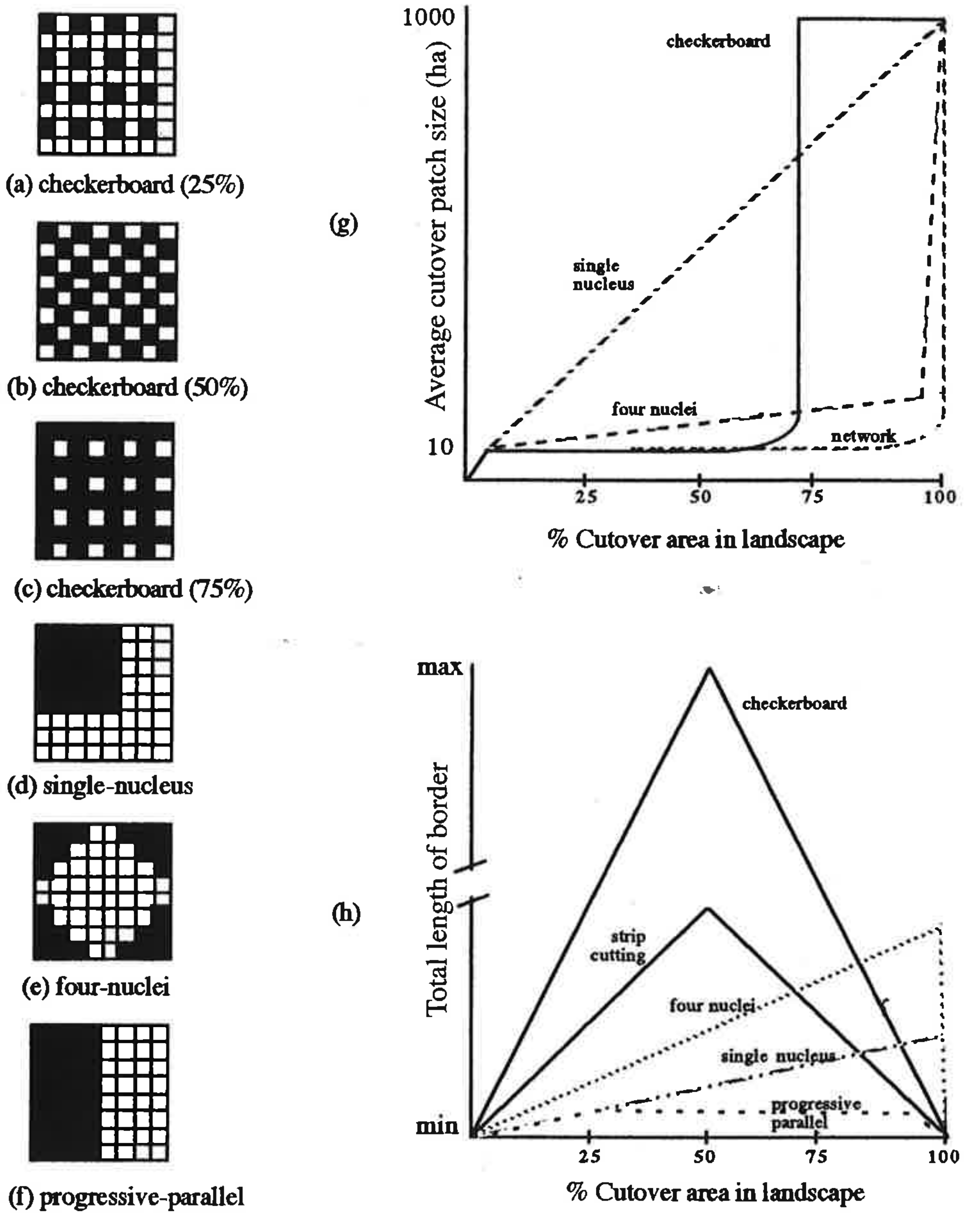
1 Uniqueness

Forman (1995a) has recently provided a detailed review of the spatial characteristics of different land mosaics and has suggested that the ideal shape index should, for example,

- be easy to calculate;
- work over the whole domain of interest;
- unambiguously and quantitatively differentiate between different shapes; and
- permit the shape to be drawn based on knowledge of the index number alone.

Unfortunately, he concluded that no such ideal indices exist. Certainly no single index can, for example, unambiguously differentiate all shapes; a particular shape index number can usually result from a wide variety of shapes. A similar criticism could probably be levelled at most other landscape indices (Baskent and Jordan, 1995).

Musick and Grover (1991: 79) also note the problem of uniqueness and suggest its



(a) checkerboard (25%)

(b) checkerboard (50%)

(c) checkerboard (75%)

(d) single-nucleus

(e) four-nuclei

(f) progressive-parallel

Figure 1 Effects of cutting regimes on patch size and border length: (a)–(f) clear-cutting patterns; (g) average patch size vs. % cutover; (h) total length of forest border vs. % cutover
Source: After Franklin and Forman (1987)

Table 1 Descriptions and broad definitions of selected indices

Index type	Index description/definition
Area metrics	
Total landscape area (ha)	total area of landscape (defined as total area minus 'background')
Largest patch index (%)	percentage of landscape accounted for by largest patch
No. patches	no. of disjunct patches in the landscape
Patch density (*n*/100 ha)	no. of patches per 100 ha
Mean patch size (ha)	average patch size
Patch size SD (ha)	patch size standard deviation (ha; absolute variability)
Patch size CV	patch size standard deviation in terms of average patch size; % variation (relative)
Permeability	area of unsuitable patches (for transmission) divided by total area
Dominance	extent to which one/a few patch types dominate a landscape (from information theory)
Edge metrics	
Total edge (m)	total length of all edges; may or may not include landscape boundary
Edge density (m/ha)	length of edge per hectare
Contrast-weighted ED (m/ha)	length of edge per hectare, weighted by edge contrast weights
Total edge contrast index (%)	sum of edge lengths, multiplied by contrast weight, divided by total edge × 100
Mean edge contrast index (%)	sum of patch edge segments × contrast weight/total patch perimeter/no. patches × 100
Area-weighted MECI (%)	sum of (sum of patch edge segments × contrast weight/total patch perimeter × patch area/landscape area)
Isolation	% edge adjoining similar patch types
Shape metrics	
Landscape shape index	ratio of sum of edge lengths to total area (measured against square or circle standard)
Mean shape index	sum of patch perimeter/square root of patch area, adjusted by constant/no. of patches
Area-weighted MSI	sum of patch perimeter/square root of patch area, adjusted by constant × patch area/total area
2 × log fractal dimension	departure of landscape mosaic from Euclidean geometry (how plane-filling shape is)
Mean patch fractal dimension	mean fractal dimension for all patches
Area-weighted mean patch FD	mean fractal dimension adjusted for proportion of total area
Elongation	diagonal of smallest enclosing box divided by average main skeleton width
Deformity	sum of (main skeleton length/skeleton depth) / (area × number of skeleton pieces)
Core area metrics	
Total core area (ha)	area of interior habitat, defined by specified edge buffer width
No. core areas (*n*)	no. of core areas (may be more or less than no. of patches)
Core area density (*n*/100 ha)	no. of core areas per 100 ha
Mean core per patch (ha)	average amount of core area per patch (ha)
Core area SD1 (ha)	standard deviation of core area per patch (ha; absolute variability)
Core area CV1 (%)	standard deviation of core area per patch in terms of the average; % variation (relative)
Mean area per disjunct core (ha)	average core area when no. of core areas is denominator (rather than no. of patches)

Table 1 Continued

Index type	Index description/definition
Disjunct CASD	disjunct equivalent of core area SD1
Disjunct CACV	disjunct equivalent of core area CV1
Total core area index (%)	percentage of landscape which is interior habitat (core)
Mean core area index (%)	average percentage of a patch which is core area
Nearest-neighbour metrics	
Mean nearest-neighbour distance (m)	average distance to nearest patch of same patch type
NN standard deviation	standard deviation of mean nearest-neighbour distance (absolute variability)
NN coefficient of variation	standard deviation in terms of mean nearest-neighbour distance (relative variability)
Mean proximity index	average proximity of patches to similar patches within specified distance
Diversity, richness and evenness metrics	
Shannon's diversity index	richness and evenness index based on information theory
Simpson's diversity index	sum of the proportional abundance of patch type; probability that two patches are similar
Modified Simpson's diversity	Simpson's diversity index modified to belong to information-theory class
Patch richness (%)	no. of patch types in the landscape
Patch richness density (*n*/100 ha)	no. of patch types in the landscape per hectare
Relative patch richness (%)	patch richness as % of maximum potential patch richness (user defined)
Shannon's evenness	observed Simpson's diversity divided by maximum value for the no. of patch types
Simpson's evenness	observed Shannon's diversity divided by maximum value for the no. of patch types
Modified Simpson's evenness	observed modified Shannon's diversity divided by maximum for the no. of patch types
Interspersion/juxtaposition, contagion and configuration metrics	
Interspersion/juxtaposition	observed interspersion divided by maximum interspersion for the no. of patch types
Interspersion 2	no. of stand attribute changes in adjacent stands/total no. of adjacent stands
Contagion index (%)	observed contagion divided by maximum contagion for no. of patch types (cell based)
Dispersion	degree of fragmentation/complexity of patch boundaries, based on nearest-neighbour
Association	concentration of spatially distributed attribute variable, based on specified focal distance
Connectivity and circuitry	
Connectivity	network model; no. of links in net over maximum possible no. of links
Circuitry	network model; no. of circuits in net over maximum possible no. of circuits
Spatial autocorrelation	
Spatial autocorrelation	patch type spatial correlation; patch type distribution (concentrated, dispersed, random)

Source: O'Neill *et al.*, 1988; Selman and Doar, 1992; McGarigal and Marks, 1994; Baskent and Jordan, 1995.

significance depends on the context in which the indices are being used. They suggest that a pattern index that did not distinguish between two dissimilar landscape mosaics might be judged as unsatisfactory in a practical context, whereas from the descriptive or interpretative perspective the conclusion that the two patterns were 'structurally equivalent' might be useful. Unfortunately the question is not so easily resolved, because in both cases the decision depends on an understanding of the relationships between the index and the underlying set of ecological or environmental process. The situation can be illustrated by reference to Figure 2.

Figure 2 shows the trends in three shape indices calculated by the authors using FRAGSTATS for a forest plantation in the Highland Region of Scotland. They have been calculated for the existing forest layout, and the various stages in the evolution towards some 'desired future condition' as set out by a set of design proposals. A key design goal in the scheme was to restructure forest interior by diversifying stand ages and the reshaping of forest blocks. The indices apparently show contradictory trends, in that the mean shape index increases in value, while the fractal shape measures, such as the double-log fractal dimension and the area-weighted mean patch fractal dimension, show little change. All the indices purport to measure the departure of the shape of the forest blocks from a simple geometric shape (usually a circle or a square).

When different forest designs are being compared the structural equivalence of different spatial patterns is often a significant issue in deciding between design options. If a particular pattern measure is unable to differentiate different design options then it may well be that there is little advantage of one proposal over the other, *providing the basis of the index is understood*. The problem of uniqueness can only be overcome is such knowledge is available. Unfortunately this is rarely the case. As Fry (1996) notes, our understanding of the links between landscape and process is generally weak.

2 Index sensitivity

Quite apart from our lack of understanding of the links between pattern and process, the general sensitivity of indices to changing patterns is also poorly understood (Riitters *et al.*, 1995). It is certainly a problem which is overlooked by those who seek to characterize landscape structure by such quantitative measures.

The problem can be illustrated by reference to a study undertaken by Selman and Doar (1992) to evaluate the utility of areal and topological indices in planning areas of farm forestry. The work was based on a topological GIS model which allowed restructuring of the landscape, in this case an area adjacent to Cumbernauld, Strathclyde, with new woodland allocated on the basis of a number of important constraints. Two maps of the potential future state of the landscape were created with 5% and 30% woodland cover, respectively, and landscape metrics for average wood area, wood shape, boundary proximity, connectivity and circuitry were calculated for both the current situation and the two future scenarios. The test results showed that although the areal indices compiled were potentially useful indicators which allow, for example, estimates of the overall provision of interior habitat by the landscapes, the lineal measures of connectivity and circuitry employed were not sufficiently sensitive to the parameters under investigation (Figure 3). The reasons given for this include the properties of the indices themselves and the difficulty of deciding what constitutes an effective connecting link, since the degree to which a hedgerow, scrub row, tree row, fence, wall

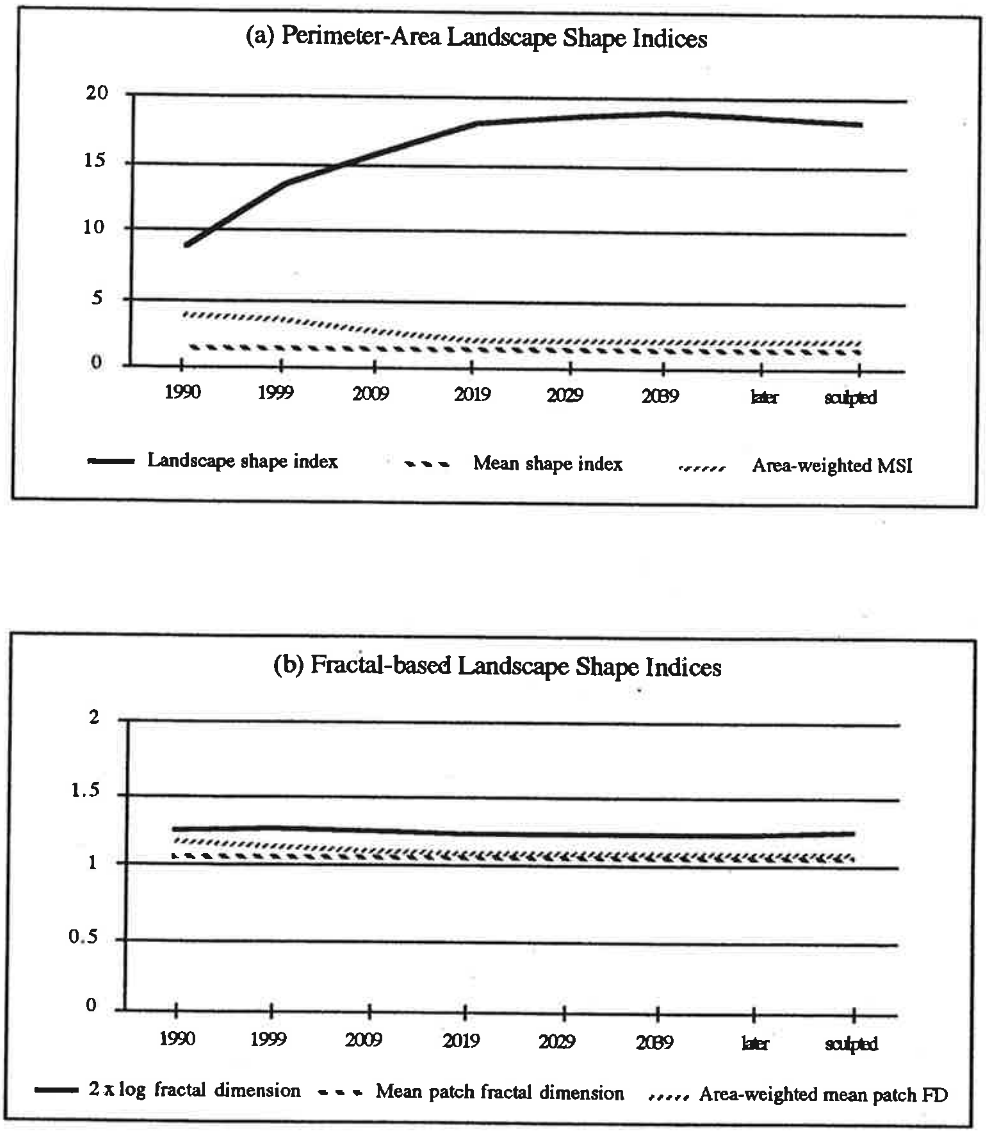


Figure 2 Shape metrics for a forested landscape of *c.* 1500 ha in the Highland Region of Scotland using 12.5 m cell size: (a) landscape shape index, mean shape index and area-weighted mean shape index; (b) double log fractal dimension, mean patch fractal dimension and area-weighted mean patch fractal dimension. Later means post-2039; sculpted means following a further degree of sculpting of forest edges

or ditch may be considered a link depends on how well it functions as a link; that is, physical connectedness does not automatically imply functional connectivity.

The issue of index insensitivity is further illustrated by the study of Hulshoff (1995), which considered the applicability of the range of indices used in North America to the analysis of landscape pattern in Dutch landscapes. The selected indices described

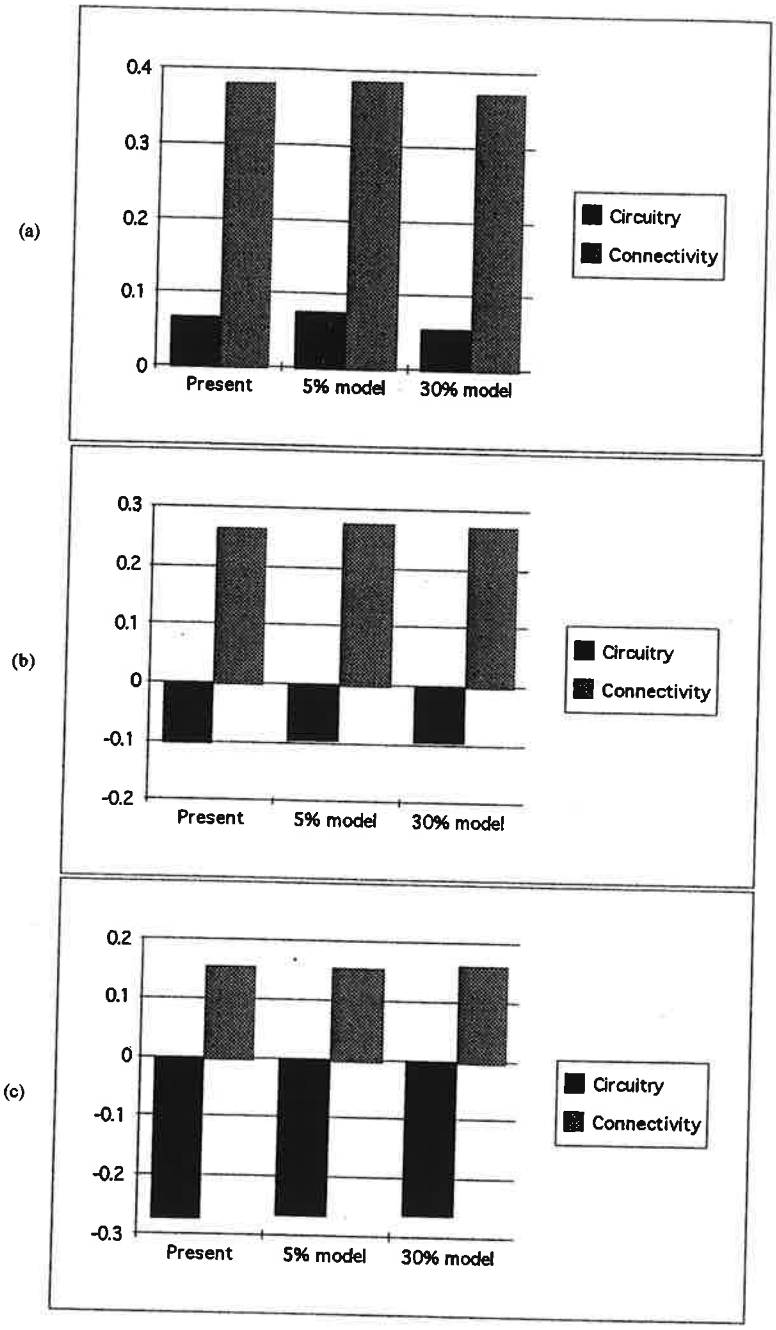


Figure 3 Sensitivity of circuitry and connectivity measures to changing landscape configuration and method: (a) considering all boundaries; (b) considering only wooded boundaries; (c) considering only intact wooded boundaries
Source: After Selman and Doar (1992)

pattern (proportion of each land-cover type, patch number, mean patch size and dominance) and patch shape; the rate of change over time for each cover type was also examined. The study employed raster land-cover data at 200 m × 200 m resolution for the period 1845–1982 for the Veluwe region of The Netherlands.

Hulshoff (1995) found that not all the indices considered were appropriate for the analysis of the Dutch landscape. The dominance index, for example, did not seem sensitive enough to describe the observed changes in land cover. She also found that interpretation of the two shape indices was ambiguous and that they measured fundamentally different aspects of form. Moreover, no index properly reflected the changing geographical position of patches so that they were probably of limited value in the study of landscape dynamics. It was considered that the indices had to be interpreted in combination with each other; the most useful indices were found to be the proportion of each land use, the number of patches and their mean size. However, further work was required to develop new indices, particularly those which described changing geographical position.

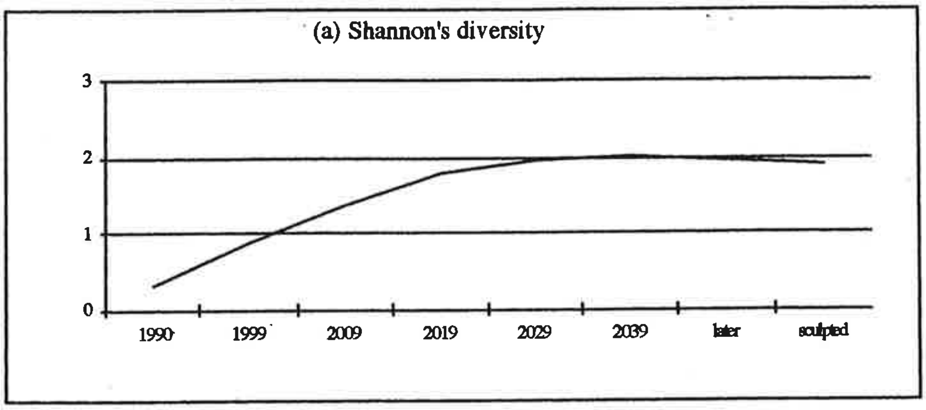
3 Index selection and redundancy

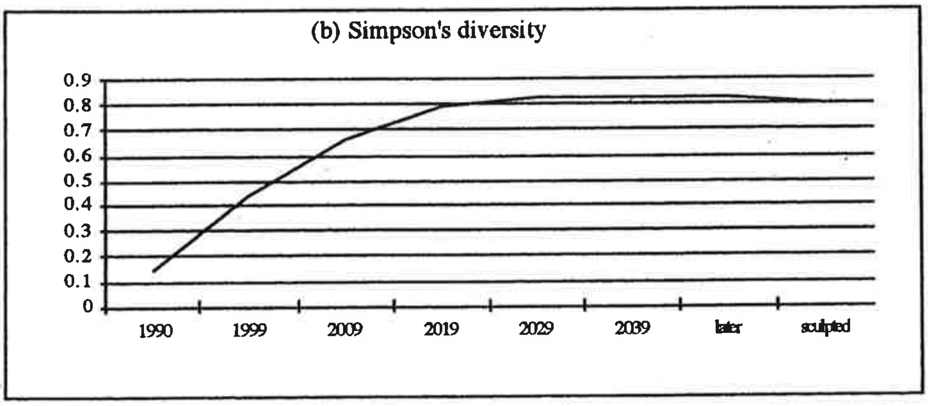
As noted above, a large number of landscape indices have been developed and when one is confronted with the task of using them to describe a particular landscape, the choice of which measures to use often seems overwhelming. Although the choice of indices must always depend on the context of the particular study, it is clear that there is a good deal of redundancy and duplication in indices available. The redundancy problem is illustrated in Figure 4, which shows the trends in three diversity measures over time for the same forest restructuring scheme described above. All indices show an increase in diversity up to 2019, after which little change in structural diversity occurs.

Patterns such as those shown in Figure 4 lead one to ask whether it is possible to identify a minimum set of indices by which a landscape could most efficiently be described. The recent study by Riitters *et al.* (1995) suggests how progress in this area might be achieved. The aim of that study was to choose a set of landscape metrics for monitoring landscape condition in terms of pattern and structure. Fifty-five indices were calculated for 85 maps of land use and cover in the USA. It was found that the initial set of 55 indices could be reduced to 26, and that the first six factors extracted explained 87% of the total variation. The factors were interpreted as composite measures of

- average patch compaction;
- overall image texture;
- average patch shape;
- patch perimeter-area scaling;
- number of attribute classes; and
- and large patch-area scaling.

It should be noted that the terms given above are not direct measures, since their meaning is derived from an examination of component loadings; these terms are simply convenient labels. The interpretation of the factors was determined by examining the loadings to see which metrics were most highly correlated with each factor. For example, the first factor, 'average patch compaction', is thus called because it is most highly correlated with measures of patch compaction (average perimeter-area ratio,


(a) Shannon's diversity


(b) Simpson's diversity

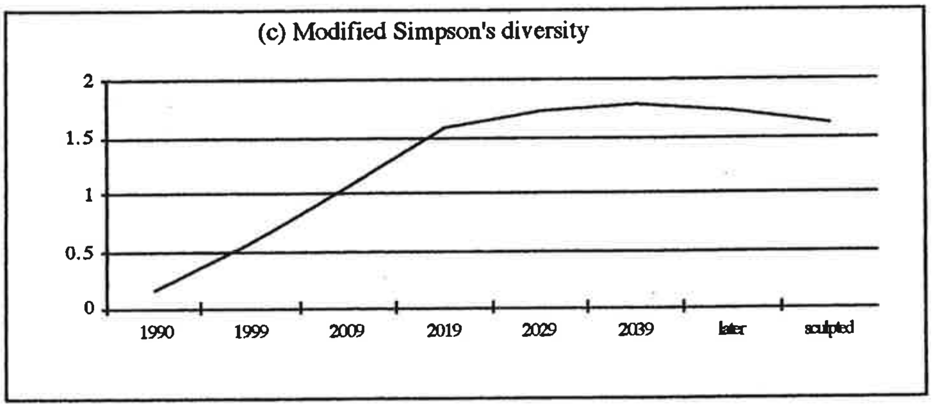

(c) Modified Simpson's diversity

Figure 4 Diversity metrics for a forested landscape of *c.* 1500 ha in the Highland Region of Scotland using 12.5 m cell size: (a) Shannon's diversity; (b) Simpson's diversity; (c) modified Simpson's diversity average adjusted area-perimeter ratio, average radius of gyration) and large patch texture (average large patch lacunarity), while the fourth and sixth factors are most highly correlated with perimeter-area fractal measures and a fractal estimator of patch mass, respectively.

Riitters *et al.* (1995) suggest that it is possible to derive a subset of metrics which could be regarded as surrogates for a more extensive set by choosing the single metric with the highest loading on each factor, provided that the loading is high for this single factor and low for all other factors. In this analysis, Riitters *et al.* (1995) propose that their first five factors could be adequately represented by five univariate metrics:

- Average patch perimeter-area ratio.
- The Shannon contagion index.
- Average patch area normalized to the area of a square with the same perimeter.
- Patch perimeter-area scaling (where perimeter is measured as the number of cells enclosing a patch).
- The number of attribute classes.

Although other dimensions of pattern could probably be identified if patterns were analysed at either different scales or in other landscapes, the work of Riitters *et al.* (1995) shows that factor analysis can be a useful tool in helping identify an efficient set of landscape descriptors. These workers conclude, however, that while such tools can show which metrics are best at measuring particular sorts of pattern, these methods cannot be used to help decide whether property is worth measuring at all. 'The answer to that question', they suggest, 'depends on the goals of the analysis' (Riitters *et al.*, 1995: 32). Once again, we are confronted by our lack of understanding of the link between landscape pattern and process.

4 Edges

Musick and Grover (1991) note that when a landscape is represented by qualitatively different elements such as forest or agricultural land, edges are simply the locations where different types join. In these circumstances the calculation of indices describing patch shape, size and juxtaposition is relatively easy. When the landscape is represented as a continuum of the amount or intensity of some value such as tree density or level of spectral reflectance, the definition of discrete objects is more problematic. To deal with such situations they describe a range of textural measures derived from the image processing literature which can be used to derive indices of landscape pattern (e.g., lacunarity or 'gappiness').

In the image processing literature, texture refers to the spatial variation in brightness values within a region of an image or across the image as a whole; it may be analysed in terms of such properties as uniformity, coarseness, regularity, frequency and linearity, all of which may be relevant in the analysis of landscape structure. When faced with the analysis of continuous change in some landscape variables, Musick and Grover (1991) suggest that one solution is to assume that an edge is a point where the local gradient exceeds some threshold.

The approach outlined by Musick and Grover (1991) assumes that some suitable threshold can identified. Clearly the decision as to what that threshold is may be difficult because different species may respond to the landscape in different ways (Risser *et al.*, 1984); an area that is heterogeneous for one species may be uniform for another.

Musick and Grover (1991) argue that it may be desirable on theoretical grounds to analyse continuous data in terms of gradients rather than as discrete units, but that statistical tests may be applied to determine which model best fits the data. In their study they investigate the properties of several homogeneity measures and describe how their calculation may be varied to extract information on different aspects of pattern, including the directionality and spacing of repeating patterns.

The implications of the work of Musick and Grover (1991) are that many landscape indices can be applied only where there is good reason to assume that the landscape can be represented adequately by discrete units – that is they conform to the patch-corridor-matrix model described by Foreman (1995a). In cases where this assumption may not hold (that is, where edges dividing discrete patches are not well defined or where a continuous data model is necessary), it is still possible to derive measures of landscape pattern if these are based on statistical rather than structural approaches, but such an approach may render results more difficult to interpret. Musick and Grover describe two such measures from Haralick (1973), originally developed in the context of image processing: the Angular Second Moment (ASM) and the Inverse Difference Moment (IDM). Both indices are based on adjacency between neighbouring cells, rather than patches, and both are measures of homogeneity; ASM is an inverse measure of interspersion, while IDM is a measure of the shallowness of local gradients in continuous surfaces.

5 Nonspatial statistical effects

A number of nonspatial statistical effects may be observed for many landscape indices. These include the effects of quantization levels, contrast levels and degree of aggregation of the basic input data. The effect of quantization levels on texture measures is not difficult to comprehend; for example, reducing the number of quantization levels from 1024 to 256 in a cell-based raster map will clearly result in a far greater likelihood of neighbouring cells having identical values, affecting measures such as Haralick's ASM (Haralick, 1973). Contrast is another property of an image which may impact on measures of texture since it is a nonspatial property, that is, it does not depend on the locations of the data cells. The spatial structure or pattern of an image may not vary with changing contrast levels, although certain indices will, requiring that the data be transformed, for example, by equal probability quantization or histogram equalization. The effects of aggregation are apparent in many landscape indices which depend on patch counts as the denominator, including all first-order statistics such as means; many of the landscape indices provided by FRAGSTATS show this dependency and are thus sensitive to data set artefacts, such as point 'noise', where a thematic digital map has slivers and gaps as a result of poor digitizing and poor consistency checking.

Musick and Grover (1991) suggest that the sensitivity of landscape pattern indices to nonspatial statistical properties should be considered in comparing the results from different indices and in generalizing from the results obtained with a particular index. While the sensitivity of a particular index to these properties can sometimes be assessed in advance (for example, where the measure is an average for all patches), this is less straightforward for some of the more sophisticated indices.

6 Topographic and boundary effects

The selection of an appropriate boundary within which the analysis of landscape pattern is to be made is important because it is evident that results are often sensitive to decisions about the study area. Some landscapes may be clearly defined, when for example a watershed is being considered, but in other situations the precise boundary of the study area may be difficult to delimit. This may be because the landscape is embedded in a large area which is heterogeneous and fragmented at large scales but more homogeneous at small scales; in these cases it may be necessary to define the landscape boundary by reference to the underlying soils or geology, or to anthropogenic barriers such as motorways.

The effects of choice of boundary are rarely considered in the literature, however, even in those cases where topographic effects may be important, and where the effects of relief in defining discrete landscape units can easily be determined. In spite of the planimetric map views employed by most landscape analysis and GIS, the effects of topography may be incorporated into an analysis to some extent without true three-dimensional representation and display; for example, digital elevation maps may be used to construct slope maps and these in turn used to derive landform maps showing areas of concavity and convexity. Landform maps may be used to compare variability in landform with variability in a 'landscape' (i.e., land-cover map) and thus provide a first-order indication of how far a landscape design conforms to the underlying topography; this type of analysis may be important for upland forest landscape design in Great Britain.

7 Scale

Studies into the way landscape analysis is affected by scale considerations are perhaps the most numerous in the literature. Not only is it recognized that the nature of the pattern detected in a landscape is dependent on scale (Forman and Godron, 1986; McGarigal and Marks, 1994) but also that '. . . parameters and processes important at one scale are frequently not important or predictive at another scale, and information is often lost as spatial data are considered at coarser scales of resolution' (Turner, 1990: 22). The problem of data loss is forcefully illustrated by the recent study by Fuller and Brown (1994) who investigated the effect of translating the ITE *Land cover map of Great Britain (LCMGB)* into its CORINE equivalent. The translation is not simply one of converting cover classes from one system to another but of changing the resolution of the data. According to the CORINE methodology, the minimum mappable area is 25 ha. By contrast, for the *LCMGB* a minimum unit of 0.125 ha was used. If one followed the CORINE mapping methodology many small patches would be eliminated from the cover map, and their area would be severely underestimated in the final representation of land cover. In the pilot study undertaken in Yorkshire, for example, these authors showed that in comparing estimates from the *LCMGB* with a classification of the same imagery based on the CORINE standard, only 35% of the original woodland cover and 5% of the rough grassland pixels were retained using the larger minimum mapping unit.

The loss of detail in the CORINE representation compared to the *LCMGB* would clearly have a profound effect on landscape metrics calculated for the same area from these different data sources. More importantly such differences might profoundly affect the conclusions one might draw about the conservation status of such landscapes. The effects of scale on the calculation of landscape indices is among the most profound of all those reviewed, so much so that it has led Aspinall (1996) to observe that, in the case of diversity measures, one can obtain almost any answer by changing the taxonomic and geographical resolution of the input data.

The effect of scale on the level detail observed in a land-cover mosaic is usually described in relation to the concept of 'grain'. The grain of a landscape mosaic is defined as the size of the individual units of observation of the landscape elements, e.g., the smallest element possible in a raster data model. The smaller the grain size, the higher the image resolution. Since it is usually impossible to define the most appropriate scale at the outset of a study – because the resolution at which the phenomena of interest operate and are operated on may not be immediately apparent – the best practice is to adopt the highest resolution available. This is particularly important where the measurement of edge length and patch shape is concerned; scale is likely to have significant effect on these metrics, especially but not exclusively where raster maps are used, since what is represented as a convoluted, irregular edge at large scales may easily become a straight edge at smaller scales. In addition, there can be severe aliasing effects ('staircasing') on the representation of edges in raster maps if the resolution chosen is too coarse, with a potentially significant loss of measurement precision. The choice of the grain element of scale also has important implications for core area indices, diversity indices and all indices dependent on patch count, since the loss of information associated with coarser resolutions also leads to the disappearance of patches.

Figure 5 illustrates some of the effects which a change in resolution has on landscape indices. The data relate to an area of lowland woodland in England, which is undergo-

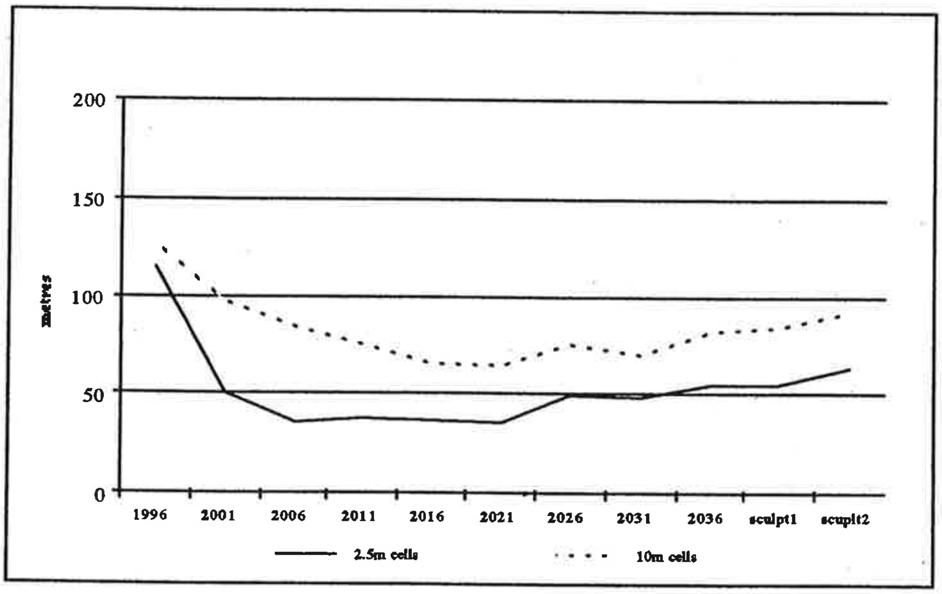


Figure 5 Mean nearest-neighbour distance calculated for an area of lowland woodland in England (*c.* 103 ha) for a potential restructuring programme, followed by differing levels of final sculpting of stand edges, using grain sizes of 2.5 m and 10 m

ing a restructuring programme involving the creation of a more diverse plantation in terms of composition and structure, with fewer geometric forms. Figure 5 shows the projected change over time for the mean nearest-neighbour distance, that is the average distance between stands of similar age within the woodland. The basic data for the area were available as a 2.5 m resolution raster. In order to simulate the effect of a change in resolution, the basic data were processed using the pixel thinning routine of the IDRISI GIS to give a degraded map at 10 m resolution. While the basic shape of the curve is maintained, the reduction in resolution both shifts the curve so that apparent distances are greater and reduces the range of values observed over the management cycle.

Benson and MacKenzie (1995) have made a more systematic study of the effects of spatial resolution using binary or 'two phase' maps of land and water (lakes) derived from three satellite sensors (SPOT HRV, Landsat Thematic Mapper and NOAA AVHRR), essentially representing two cell size classes: around 25 m and 1100 m. Like Turner *et al.* (1989) they also used majority rule aggregation to derive maps at a number of discrete scales and calculated a number of landscape indices including per cent water, number of lakes (patches), average lake area, lake perimter and fractal dimension, plus texture measures such as homogeneity, entropy and contrast. They report that almost all are sensitive to changes in grain to some degree (within the range 20–1100 m) but that in general texture measures based on counts of the transitions between cells of the two classes were the least sensitive of all the indices considered. Specifically, near-linear relationships were established between grain size and fractional class cover, mean class area, number of patches and mean patch perimeter, while two of the three texture indices used, homogeneity and entropy, did not vary significantly with increasing coarseness (4% and 9% variability over the range of grain sizes, respectively). The homogeneity texture index measures the extent to which there are few dominant greyscale transitions in an image, while entropy is a measure of the complexity of the image and is negatively related to homogeneity. The third texture measure, contrast, demonstrated variability of more than 600% over the range of grain sizes, although this index is usually applied to greyscale rather than binary images and is weighted by a coefficient which is intended to indicate the difference between two grey levels from a range of values.

It is important to note that increasing coarseness in terms of raster map cell size (grain) does not necessarily lead to the disappearance of rare patch types, as repeatedly stated by Turner *et al.* (1989) and Turner (1990), since a patch type may be rare in terms of patch representation or number – there may be only a single patch of a given type in a landscape – but may nevertheless occupy a significant proportion of a landscape. It appears that some authors define rarity in terms of the rapidity with which patch types are lost as grain size is increased; however, it is not *rare* patch types which are lost by decreasing the resolution of a data set but rather those represented by the least extensive and least compact patches (elongated and thin patches of small area will clearly disappear more rapidly with increasing spatial aggregation). This is why the relationship between landscape diversity and scale tends to be linear in real landscapes (Turner *et al.*, 1989); it is the distribution of shape as well as area over all patch types which determines the number of types apparent at any given degree of spatial aggregation.

Turner (1990) went on to review the development of methods to preserve information across scales and to quantify the loss of information with changes in scale. She

Table 2 Landscape indices in relation to forestry guidelines

Guidelines	Index class	Types of indices, crossreferenced to Table 1*
General forest landscape guidelines promote		
increases in forest cover overall by significant amount	areal	area, core area, shape
diverse age structure	lineal/topological	interspersion/juxtaposition, contagion, edge
diverse physical structure	lineal/topological	interspersion/juxtaposition, contagion, edge
diverse species composition	lineal/topological	interspersion/juxtaposition, contagion, edge
large contiguous wooded areas (i.e., patches)	areal/topological	area, core area, shape, contagion, interspersion/juxtaposition, edge
'curvy' edges for edge habitat (e.g., for pheasant/deer)	areal/lineal	shape, edge
nongeometric shapes inside forests (e.g., edges, rides)	areal/lineal	shape, edge
some open spaces within forests (increase amenity/aesthetic value)	areal/topological	area, core area, shape, contagion, interspersion/juxtaposition
connection of ancient woods with new (e.g., for ancient spp. dispersal)	lineal/topological	shape, interspersion/juxtaposition, contagion, edge, connectivity, circuitry
compact shapes (i.e., maximize interior habitat area)	areal/topological	area, core area, shape, contagion, interspersion/juxtaposition, edge
planting on non-natural habitats (i.e., avoiding semi-natural habitats)	areal	area, core area (class metrics only)
Guidelines for lowland broadleaf woodlands promote		
retention of broadleaf woodland (e.g., no clearance for agriculture)	lineal/topological	area, shape, interspersion/juxtaposition, contagion, edge
increase in area by natural regeneration	areal	area, core area, shape

increase in area by planting on agricultural land	areal	area, core area, shape
increase in area by replacement of conifers	areal	area, core area, shape
conservation of ancient semi-natural broadleaf woodlands	areal/topological	area, core area, shape, contagion, interspersion/juxtaposition
creation of open spaces for communities of special conservation value	lineal/topological	shape, interspersion/juxtaposition, contagion, edge, connectivity, circuitry
retention of open spaces for communities of special conservation value	lineal/topological	shape, interspersion/juxtaposition, contagion, edge, connectivity, circuitry
gradual rates of change	areal/topological/lineal	– all metrics –
a proportion of mature habit diversity of habitats	areal/topological	interspersion/juxtaposition, contagion, edge, core area
	lineal/topological	shape, interspersion/juxtaposition, contagion, edge, connectivity, circuitry
Guidelines for upland forested landscapes promote		
increase in species diversity	areal/topological	area, core area, shape, interspersion/juxtaposition, contagion, edge
increased proportion of native species	areal/topological	area, core area, shape, contagion, interspersion/juxtaposition
increased open spaces within forests	lineal/topological	shape, interspersion/juxtaposition, contagion, edge, connectivity, circuitry
unity of forest landscape with landform	topological	interspersion/juxtaposition, contagion

Note:
*These metrics and indices provide information related directly or indirectly to the guideline, e.g., the direction of change. For example, metrics relating to 'conservation of ancient semi-natural broadleaf woodlands' include not only those providing information on size, core area and shape but also contagion and interspersion, since it is generally recognized that natural colonization of adjoining areas by native species of ancient semi-natural woodland is highly dependent on proximity and connectivity with ancient sites (Kirby, 1993).

concluded (Turner, 1990: 28) that 'rules for extrapolating across spatial scales may be possible but scale must be defined and specified in terms of grain and extent'. King (1991) further demonstrated that grain and extent can be manipulated using the principles of hierarchy theory in order to derive quantitative methods for translating ecological models across spatial scales. However, these highly mathematical methods may not be easily accessible to those faced with design issues.

Cullinan Thomas (1992) carried out an extensive review of the techniques available for assessing different scales inherent in landscape ecological data sets, including tests of nonrandomness, estimation of patch size, spectral analysis, fractal dimension, variance ratio analysis and correlation analysis. They applied these techniques to three one-dimensional data sets composed of an independent Poisson random variable, a modified Poisson random variable (sine wave) and a 2050 m transect of percentage cover for *Agropyron spicatum*. The results are compared and discussed in terms of the relevance of each technique to questions in landscape ecological research, including examination of patch size and distribution; examination of spatial variation and correlation; estimation of spatial periodicity and lag; and detection of multiple scales in data sets. They argue that determination of the appropriate scales at which the ecological phenomena under investigation manifest themselves should be carried out prior to other analyses, since the aim is to make inferences about processes which potentially operate at multiple scales. However, they also point out that the realities of time and money often preclude such a preliminary study.

IV Landscape indices: implications for their use

As the search for more sustainable forms of commercial forestry illustrates, there is a need to link landscape design goals with an understanding of ecological principles (Selman and Doar, 1992; Fry and Herlin, 1995). Landscape indices have been proposed as a way of achieving this, because they potentially provide a means of describing the extent to which a landscape departs or conforms to a predefined design goal. However, such indices will be of value only if they can be used to measure important structural features which have clear ecological or environmental consequences. The development of such an understanding is likely to take some time, but a start can be made by relating the various design guidelines for forest, for example, to the different types of index (areal, lineal and topological) which can be used to measure how a landscape might change if these guidelines were implemented (see Table 2).

To the extent that Table 2 can be constructed it would seem that indices of landscape composition and configuration can potentially provide a way of quantifying important parameters for both the single wood, or stand level, and whole forest or landscape scale. However, our review of methodology issues suggests that these indices can be applied *only* where certain conditions are met. These conditions are summarized in Table 3.

It would appear that:

- The quantification and interpretation of simple areal characteristics such as mean patch area, largest patch, patch density, patch size variability, total edge, edge density and core area measures are rarely problematic, providing data are selected at an appropriate scale to depict the underlying resource in a reliable way.

- Shape is probably the most difficult characteristic to quantify adequately and so these indices should be used with caution. Indices based on perimeter-area ratios are insensitive to changes in morphology, while those based on fractal dimension require an adequate sample for the regressions involved. Measures employing medial axis transformations are optimal but are thus far computationally unwieldy and difficult to implement.
- Indices which measure edge characteristics, the character of interior habitat (core indices) and nearest-neighbour relationships are useful but results depend upon various weighting factors and parameters which have to be set by the user. Since there is little ecological information which can help the user decide on appropriate values, choice of parameter value is often arbitrary. As a result the results may be difficult to interpret and comparisons between areas difficult to make. In addition, these indices are particularly sensitive to grain size, that is size of the smallest patch that can be represented in the landscape.
- Core area metrics may employ a fixed value for defining interior habitat which may or may not have any ecological validity; again, this will depend on the edge width defined by the analyst. In addition, these metrics seem particularly sensitive to both grain size and to decisions about the matrix element in the landscape.
- Diversity, richness and evenness indices are sensitive both to the presence of rare patch types and to grain size, so that care must be exercised when defining the nature of the landscape mosaic which forms the object of study.

Providing indices are used with caution, therefore, then at the stand level, when a single plantation is the focus of the analysis, they can be a useful tool for optimizing restructuring programmes. Proposals can potentially be evaluated according to whether they open up the interior of woodlands, retain desirable interior habitat, increase the structural variation in terms of age and species distributions and promote nongeometric stand shapes. In particular, they potentially allow different designs to be compared in terms, say, of the way in which properties like core area, or path number and spacing change over time, with a view to evaluating the ecological impact of imposing the design on the existing woodland.

Indices may be used in a similar way when working at the scale of the whole landscape, although their potential value in these situations probably depends on whether they are being used in the context of upland or lowland forestry. Upland landscapes are often less complex than those of the lowlands, because landscape extent is usually more easily determined and there are fewer constraints at forest boundaries (i.e., fewer fixed patch types and impenetrable barriers). As a result, indices are likely to be easier to interpret than in the lowlands, where landscape is a patchwork of arable crops, woodlands, urban settlement, pasture and water bodies, with a network of linear features (rivers, roads, railways, hedgerows, power lines) superimposed on to it. These factors mean that indices are in general less sensitive to the lowland landscape characteristics. The degree of change which can be expected is likely to be subtle in quantitative terms so that their application using digital land-cover maps is less straightforward.

Whether indices are used at the stand or landscape level, a key assumption made in their use is that the ecological relationships mapped out in Table 2 do, however, apply. In any particular application this assumption must be considered critically. For while a set of indices might show that forest structure changes over space and time, we also need to know whether, say, a given change in edge length or average patch size will

Table 3 Landscape index dependencies and applicabilities 'at a glance'

Index	Dependent on/sensitive to	Applicability (cautions)
Total area	data format (raster/vector); scale (grain and extent); data quality*	landscape extent; basis for interlandscape comparisons and many other indices
Patch density, size and variability		
Largest patch index	data format (raster/vector); scale (grain and extent); data quality*	extent to which landscape is dominated by a patch type
No. patches	data quality*	landscape configuration (in conjunction with other metrics)
Patch density	patch count (no. patches)	landscape fragmentation
Mean patch size	patch count (no. patches)	landscape configuration (in conjunction with other metrics)
Patch size SD	patch count (no. patches); scale (grain and extent)	landscape configuration (in conjunction with other metrics)
Patch size CV	patch count (no. patches)	landscape configuration (in conjunction with other metrics)
Edge metrics		
Total edge	data format (raster/vector); grain and scale; proportion of boundary edge included as true edge	landscape configuration; edge effect (in conjunction with other metrics); landscape fragmentation
Edge density	fragmentation; scale/grain	landscape configuration; edge effect (in conjunction with other metrics); landscape fragmentation
Contrast-weighted ED	fragmentation; scale/grain; contrast weights	landscape configuration; edge effect (in conjunction with other metrics); landscape fragmentation
Total edge contrast index (%)	fragmentation; scale/grain; contrast weights	landscape configuration; edge effect (in conjunction with other metrics); landscape fragmentation
Mean edge contrast index (%)	fragmentation; scale/grain; contrast weights; patch count (no. patches)	landscape configuration; edge effect (in conjunction with other metrics); landscape fragmentation
Area-weighted MECI (%)	fragmentation; scale/grain; contrast weights; patch count (no. patches)	landscape configuration; edge effect (in conjunction with other metrics); landscape fragmentation

Shape metrics		
Landscape shape index	data format (raster/vector); boundary edge being true edge	departure from geometric shapes; assessment of edge effect (insensitive to changes in patch morphology); fragmentation
Mean shape index	data format (raster/vector); patch count (no. patches)	departure from geometric shapes; assessment of edge effect (insensitive to changes in patch morphology); fragmentation
Area-weighted MSI	sensitive to outliers (i.e., extremely large/small patches) and patch count/size distribution	departure from geometric shapes; assessment of edge effect (insensitive to changes in patch morphology); fragmentaton
2 × log fractal dimension	adequate sample size (employs regression)	departure from geometric shapes; assessment of edge effect (insensitive to changes in patch morphology); fragmentation
Mean patch fractal dimension	adequate sample size (employs regression); insensitive to changes in patch morphology	departure from geometric shapes; assessment of edge effect (insensitive to changes in patch morphology); fragmentation
Area-weighted mean patch FD	sensitive to outliers (i.e., extremely large/small patches); insensitive to changes in patch morphology	departure from geometric shapes; assessment of edge effect (insensitive to changes in patch morphology); fragmentation
Core area metrics		
Total core area (ha)	data format (raster/vector); scale/grain	assessment of interior habitat availability
No. core areas (*n*)	data format (raster/vector); scale/grain; data quality*; shape	assessment of interior habitat availability
Core area density (*n* 100 ha)	patch count; patch size; patch shape; edge width	assessment of interior habitat availability
Mean core per patch (ha)	patch count; patch definition; patch size; patch shape; edge width; grain and extent	assessment of interior habitat availability
Core area SD (ha)	patch count (uses no. of patches, not no. of core areas)	assessment of interior habitat availability/distribution
Core area CV (%)	patch count (uses no. of patches, not no. of core areas)	assessment of interior habitat availability/distribution
Mean area per disjunct core (ha)	patch count; patch definition; patch size; patch shape; edge width; grain and extent	assessment of interior habitat availability
Disjunct CA SD (ha)	as mean area (uses no. of core area, not no. of patches)	assessment of interior habitat availability/distribution
Disjunct CA CV (%)	as mean area (uses no. of core areas, not no. of patches)	assessment of interior habitat availability/distribution
Total core area index (%)	data format (raster/vector); grain and extent; data quality*; edge width; = % of landscape which is core area	assessment of interior habit availability
Mean core area index (%)	patch count; edge width	assessment of interior habitat availability

(continued)

Table 3 Landscape index dependencies and applicabilities 'at a glance' (continued)

Index	Dependent on/sensitive to	Applicability (cautions)
Nearest-neighbour metrics		
Mean NN distance (m)	patch count; extent; border definition	assessment of landscape fragmentation
NN standard deviation (m)	patch count	assessment of landscape fragmentation
NN coefficient of variation (%)	patch count	assessment of landscape fragmentation
Mean proximity index	patch count; extent; border definition; specified search radius	assessment of landscape fragmentation
Diversity metrics		
Shannon's diversity index	patch richness and distribution of area among patch types; rare patch types have a disproportionately large influence	combined measure of richness and evenness (value is relative)
Simpson's diversity index	probability index (of two patches being in same class); combined measure of richness and evenness	combined measure of richness and evenness (value has absolute and relative interpretations)
Modified Simpson's diversity index	information theory version of previous index; measure of richness and evenness	combined measure of richness and evenness (value is relative)
Patch richness (%)	rare patch types have a disproportionately large influence; scale is important (species-area bias); patch count	assessment of habitat richness (do not use for interlandscape comparisons)
Patch richness density (*n* 100 ha)	patch count; rare-patch bias; scale and species-area bias (this is patch richness standardized to a per-area basis)	assessment of habitat richness (better for interlandscape comparisons but still suffers from species-area bias)
Relative patch richness (%)	patch count; rare-patch bias; species-area bias; user-specified maximum potential richness	assessment of habitat richness
Shannon's evenness	patch count; patch type count; maximum no. of patch types	assessment of habitat type distribution
Simpson's evenness	patch count; patch type count; maximum no. of patch types	assessment of habitat type distribution
Modified Simpson's evenness	patch count; patch type count; maximum no. of patch types	assessment of habitat type distribution
Contagion and interspersion		
Interspersion/juxtaposition index	patch shape; edge length; dispersion; number of patches	assessment of spatial distribution of patch types
Contagion index (%)	cell size; patch type no./dispersion/interspersion; contiguity	assessment of aggregation/dispersion of patch types; landscape fragmentation

Note: *Data quality: raster images may contain spurious sliver polygons resulting from gaps or overlaps in vector data or owing to an inappropriate resolution in the rasterization process.

have any effect in ecological terms. It is unlikely that any putative relationship between a given index and some ecological property will be constant over time or space. For an index to be used effectively some kind of calibration study might be needed.

For example, we might conjecture that increasing forest edge length might be beneficial in terms of species diversity. For the index to be used effectively as a design tool, we would need to know by how much diversity would change for a given increase in length. Alternatively, when developing a particular forest design, we might ask by how much the population of some target organism might be expected to change by expanding the area of forest core habitat by a given amount. Answers to these types of questions are likely to be specific to particular types of location or environment. However, without such detailed information, it is clear that the blanket use of landscape indices for design purposes could well be misleading.

Our review of landscape indices suggests therefore, that while progress has been made in the development of a range of landscape pattern measures and in our understanding of the factors constraining their use, there is a pressing need for further research into the relationship between landscape pattern and process. In the context of forest design, Table 2 sets out something of a research agenda in this respect. An understanding of such relationships and how they change in different types of environment for different species or species groups is clearly fundamental to further progress in this general area.

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