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The r.le programs for multiscale analysis of landscape structure using the GRASS geographical information system

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Abstract

Geographical information systems (GIS) are well suited to the spatial analysis of landscape data, but generally lack programs for calculating traditional measures of landscape structure (*e.g.*, fractal dimension). Stand-alone programs for calculating landscape structure measures do exist, but these programs do not enable the user to take advantage of GIS facilities for manipulating and analyzing landscape data. Moreover, these programs lack capabilities for analysis with sampling areas of different size (multiscale analysis) and also lack some needed measures of landscape structure (*e.g.*, texture).

We have developed the r.le programs for analyzing landscape structure using the GRASS GIS. The programs can be used to calculate over sixty measures of landscape structure (*e.g.*, distance, size, shape, fractal dimension, perimeters, diversity, texture, juxtaposition, edges) within sampling areas of several sizes simultaneously. Also possible are moving window analyses, which enable the production of new maps of the landscape structure within windows of a particular size. These new maps can then be used in other analyses with the GIS.

1. Introduction

Landscape ecology is concerned with analyzing the spatial structure of landscape elements and with the implications of this structure. The need for software to automate such analysis has been recognized (*e.g.*, Griffiths and Wooding 1988). Geographical information systems (GIS) are ideal for manipulating and analyzing spatial data, but, in part due to their broad scope, there is no GIS with adequate capabilities for computing traditional measures of landscape structure. Most GIS systems are limited to spatial data management and decision making support. Most recent GIS research has been on spatial database management, computer aided design (CAD), error analysis, and efficient techniques to manage both remotely sensed data and conventional map data in GIS (Berry 1987; Cowen 1988; Harlow 1989).

The spatial analysis associated with landscape ecology, however, is a GIS application that requires specific programs that are not generally available. For example, landscape ecological research places more and more emphasis on spatial analysis at different scales (Turner *et al* 1989), yet most GIS software has only limited capability for analysis at multiple scales. Moreover, it would be desirable to be able to analyze the relationship between a map of landscape structure (*e.g.*, juxtaposition or diversity) and maps of environment variables or land use. This would enable quantitative analysis of the potential sources of spatial variation in the structure of landscapes. This kind of analysis is ideal for integration within a GIS, but is difficult to complete using existing GIS programs. There is also a need for software that can be easily linked directly with spatial simulation models, so that changes in landscape structure can be monitored as a simulation runs (*e.g.*, Baker *et al.* 1991).

Some measures of landscape structure can be calculated using existing GIS software or stand-alone programs, but the measures that can be calculated are limited. Some landscape structure analysis can be done using existing GIS functions (Donovan *et al.* 1987; Hodgson *et al.* 1988; Johnson 1990; Johnston and Naiman 1990), but the set of available functions is incomplete and inefficient in most cases, and lacks flexibility. Some user-developed software is also available that has been widely used (Turner 1990), but this software lacks capabilities for multiscale analysis, lacks some needed measures (*e.g.*, texture measures), and is not integrated within a GIS.

With these problems in mind, we have developed a set of new programs for analyzing landscape structure. The set of programs is called "r.le," which stands for raster landscape ecological (spatial analysis package), and is specifically designed for the analysis of landscape structure within a GIS. The program includes a wide variety of measures of landscape structure. Sampling areas of various sizes can be defined by the user and used to obtain information on landscape structure at several scales simultaneously. This "multiscale" feature is new. It is possible to change other aspects of scale, such as the cell resolution (grain) or area of analysis (extent) in many GIS software packages, but not the size of sampling areas. The following sections describe the r.le programs and illustrate their use.

2. The GRASS GIS and the r.le programs

The Geographical Resource Analysis Support System (GRASS) is a public-domain geographical information system (USA-CERL 1991). GRASS is an integrated set of about 300 programs designed to provide digitizing, image processing, map production, and GIS analysis capabilities to the user. GRASS has programs for analyzing and manipulating both raster and vector data.

GRASS was chosen as the GIS system in which to embed the r.le programs for several reasons. First, the source code is available for all GRASS programs. Second, unlike most GIS packages, GRASS is fully programmable via user-written C code and an extensive library of GIS and spatial analysis functions. Third, new programs can easily be nested into the GRASS system. For example, the r.le programs have been designed to be simply new programs within the GRASS GIS. Fourth, a variety of other existing programs within GRASS are also useful for landscape ecological research. Finally, there are programs for conversion between GRASS and other GIS and image processing systems. GRASS runs under the UNIX operating system on many personal computers and workstations.

The current version of the r.le programs was developed for use on Sun workstations using the X windowing system. The sofware and documentation are in the public domain and can be downloaded from USA-CERL's ftp server (moon.cecer.army.mil, name = ftp) over the Internet network, or can be obtained from the senior author at minimal cost.

3. Overview of the r.le programs

The r.le programs were conceived for analyzing raster maps of landscapes containing patches having a particular value or "attribute." A variety of landscape data can be considered "patch" data. Patches may be disturbance patches, remnant patches, environmental resource patches, introduced patches, or simply patchy entities on a map (Forman and Godron 1986). Paches may have nominal or ordinal attributes, as in the case of landscape element types (Forman and Godron 1986), such as roads, dwellings, forest patches, grassland patches, hedgerows, or fields. Patches could also be the types identified by completing a classification of spectral data in a Landsat image, or in a scanned aerial photograph. Patches could also have interval or ratio attributes. For example, patches of different age occur in landscapes subject to disturbances (*e.g.*, fires, floods), where the age of the patch represents the time since it was last disturbed. Patch ages might also occur in an urban landscape where the patches represent buildings that are replaced or destroyed over time.

The r.le programs work directly with a variety of map layers that have been input and preprocessed in GRASS. Data from Landsat Multi-Spectral Scanner (MSS), Thematic Mapper (TM), or other satellites can be downloaded into GRASS using GRASS image processing programs. Data also can be input from a scanner or digitizer. It is possible to input almost any kind of pixel-based (raster format) data, in nearly any format into GRASS. Preprocessing capabilities of GRASS include programs to rectify imagery so that it matches a planimetric map and programs for classifying raw data into patch types.

There are some limitations, but also some advantages, to the exclusive use of raster format in the r.le programs. Some operations in the r.le programs (*e.g.*, measurement of texture) are only possible in raster format. Other operations (*e.g.*, measurement of patch edge) would be faster and potentially more precise in vector format. For maximum efficiency, then, it would be desirable to be able to convert the data from one format to another as the programs run. Vector-to-raster conversion is relatively fast and straightforward, but raster-to-vector conversion is difficult, prone to error, and time consuming (Piwowar *et al.* 1990). The GRASS raster-to-vector conversion program works well if there are large contiguous areas of similar cells, but fails when the raster contains many isolated pixels and small clusters. This was the major reason for implementing all measurements in raster format. Another limitation is that the raster "stairstep" representation of patch boundaries is imprecise for small patches. Moreover, the program still must determine what is or is not a patch, which may be ambiguous. Two of the r.le analysis programs (r.le.dist and r.le.patch) include a tracing module that scans the raster data and objectively identifies patches based on the contiguity of cell attributes. The tracing module is conservative in that isolated pixels touching a patch at a diagonal (bishop's pattern) are included in the patch rather than traced as a separate patch. An advantage of the exclusive use of the raster format is that the programs can complete the measurements with a single pass through the map, and are thus reasonably fast.

The r.le programs consist of a set of seven programs. The program r.le.setup is used to set up the sampling design (*e.g.*, size, shape, number, and location of sampling areas). The program r.le.show allows the user to check the sampling design. The program r.le.trace is a utility program used to display the boundaries of the patches identified by the r.le programs. Three analysis programs (r.le.dist, r.le.patch, r.le.tex) complete the measurements. A final program, r.le.null, is designed to generate a neutral map layer based on the theory of Gardner *et al.* (1987).

4. Setting up the sampling framework using r.le.setup, r.le.show, and r.le.trace

Information about the structure of the landscape is obtained by first overlaying a set of sampling areas on top of the map layer to be analyzed. The r.le programs can then be used to calculate specific landscape structure measures for the part of the map layer that corresponds to each sampling area.

There are four sampling strategies. First, the entire map layer may be the one (and only) sampling area (Fig. 1a). Second, if the map layer can be divided into meaningful geographical regions, then the regions themselves can be sampling areas (Fig. 1b). Third, sampling areas may be sampling units of fixed shape and size that are placed within the map layer as a whole (Fig. 1c). Finally, the sampling area may be a fixed shape and size that is moved systematically across the map as a moving window (Fig. 1d).

The program r.le.setup allows interactive design of the sampling framework, including design for simultaneous multiscale analysis. Regions, if used, can be drawn on the map layer using a mouse. Sampling units can be defined manually, by typing in size and shape parameter values, or graphically, using the mouse. Sampling units can be placed spatially into the landscape using the mouse, or using four standard geographical sampling methods

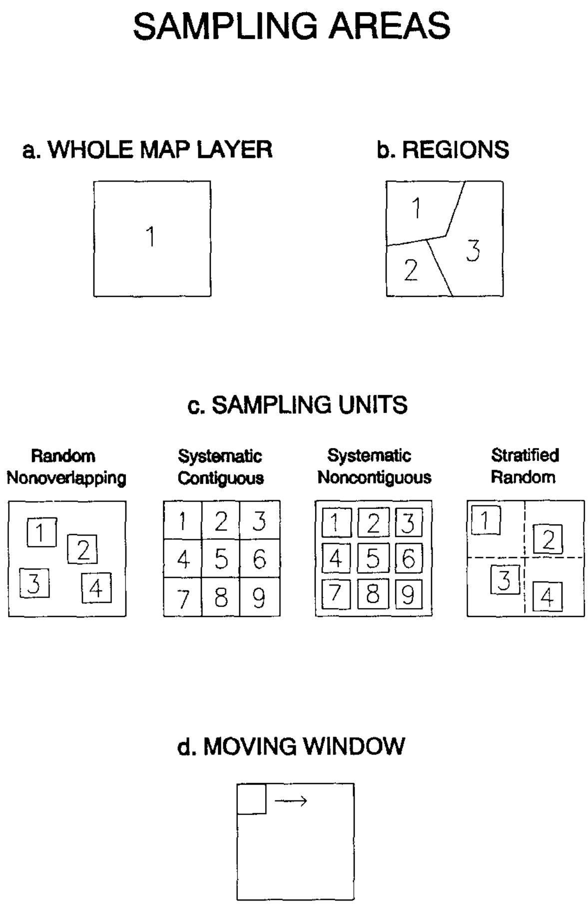


Fig. 1. Four sampling strategies (*i.e.*, sampling areas) available in the r.le programs: (a) the whole map layer; (b) regions; (c) sampling units; four standard methods of spatially allocating sampling units (Dixon and Leach 1978) are also illustrated; and (d) a moving window or a sampling unit of fixed size and shape that is moved pixel-by-pixel across the map layer, producing a new map.

(Fig. 1c). The user can choose the number of sampling units as well. Finally, sampling units with up to 15 different sizes can be defined for a single analysis, enabling simultaneous multiscale analysis of the landscape structure of a single map layer. This sampling framework can be saved and then used to sample other map layers.

The moving window sampling method permits the user to create new maps of landscape structure from a map of patches. The moving window is a sampling area of fixed size and shape that is moved pixel-by-pixel across each row. While it is centered over a target pixel, one of a variety of measures of landscape structure, discussed in the next section, is calculated for the window area. The value of the chosen measure is then placed into a new map at the same location as the target pixel. The window is then moved to the right one pixel (and then down one row at the end of the row) and the process is repeated. This is an operation that has been described as a neighborhood characterizing operation by other authors (*e.g.*, Tomlin 1990), and some of the measures available for moving window analysis in the r.le programs are available in other software packages. In the r.le programs the size and shape of the window can be set manually or graphically (using a mouse) by the user. Shapes are constrained to be rectangular or square. Because the moving window method creates a new map which can contain only a single landscape measure, the measures that produce a distribution as output (*e.g.*, cover by group) use only the first "class" or "group" (see below) in the distribution. The user can use the r.le.setup program to define any class or group as the first class, however. After the creation of one or more maps of landscape structure, standard programs in GRASS can be used to analyze the relationship between the landscape structure layers and other map layers. For example, Mead *et al.* (1981) used the moving window technique to evaluate spatial variation in landscape structure in relation to wildlife.

The r.le.setup program can also be used to establish limits for classes and groups that can be used to report the results of analyses "by class" or "by group." The term "class" here refers to a subdivision of the range of values that a particular measure might take. For example, patch shapes can be calculated and reported "by class" if the limits of the shape index classes are defined using r.le.setup. It is also possible to calculate many measures "by group," where the group limits define a range of patch attributes specified using r.le. setup. For example, it is possible to calculate a histogram of patch ages, where age ranges have been merged into age "groups."

The programs r.le.show and r.le.trace allow the user to check the sampling design and tracing. The program r.le.show provides a visual check of the sampling units or moving window that were constructed using r.le.setup. The program r.le.trace displays the boundary of each patch and shows how the boundary was traced.

5. Computing landscape measures using r.le.dist, r.le.patch, and r.le.tex

The heart of the r.le programs are the programs r.le.dist, r.le.patch, and r.le.tex, which compute the landscape structure measurements. Each program and its measures are described briefly in the following sections.

5.1. r.le.dist

Distance can be measured and summarized in a variety of ways, depending on whether distance is measured: (1) from each patch in the sampling area or only from patches belonging to a specific group, (2) to all adjacent neighboring patches or only to the single nearest neighbor patch, and (3) regardless of the group of the neighbor or only to patches belonging to a specific group. There are four combinations of these choices (Fig. 2). Distance can also be measured from patch center to patch center, from center to edge, or from edge to edge. Although there are a total of twelve possibilities, two possibilities do not make sense (*e.g.*, from each patch to all adjacent neighbors using edge to edge distance would always be zero). The remaining ten methods of measuring distance are listed in Table 1.

Six standard statistics (*e.g.*, mean, standard deviation, and distribution) are used to summarize the distance data calculated for each sampling area (Table 1). The program outputs these measures for each sampling area, so that with many sampling areas and several scales of analysis, the output can be voluminous. Moreover, distance calculation is comparatively time-consuming.

5.2. r.le.patch

This program can be used to analyze patch attributes, as well as patch size, shape, fractal dimension, and perimeter (Table 2). The attribute measures include a mean and standard deviation measure for the attributes of each pixel, as well as the mean and standard deviation for the attributes of each patch. These first four attribute measures (Table 2) are only meaningful for interval/ratio patch attributes (*e.g.*, patch age). The set of six size measures are self-explanatory (Table 2).

There are three indices of patch shape. These are only three of the simplest indices of two-dimensional shape (Austin 1984):

1. Perimeter/area: The total length of the perimeter of each patch is divided by its area. This index varies with the size of the patch, even if shape is constant.
2. Corrected perimeter/area: The formula for this index for each patch is: $(.282 \times \text{perimeter})/(\text{area})^{1/2}$. This index corrects for the size problem of index 1. The index varies from a value of 0.0 for a circle to infinity for an infinitely long and narrow shape. It is 1.1 for a square.
3. Related circumscribing circle: This index compares the area of the patch to the area of the smallest circle that can circumscribe the patch. The formula for each patch is:

   $$\text{RCC} = \frac{2*(area/\pi)^{1/2}}{longest\text{-}axis}$$

   This index varies from 0.0 to 1.0 as the compactness of the shape approaches that of a circle. A square has the value 0.79789.

Each of these three indices can be used to calculate any of the six measures of patch shape for the sampling area (Table 2).

The fractal dimension, D, for the patches in a sampling area, is a measure of the complexity of the perimeter. The current version of r.le.patch implements only the perimeter-area interpretation of fractal dimension (Krummel *et al.* 1987). The formula for fractal dimension, *d*, is:

$$\text{d} = 2 * s$$

where s is the slope of the regression of the log of the patch perimeter versus the log of the patch area.

The perimeter of a patch is the distance around

Table 1. Measures that can be calculated by r.le.dist. CC = center-to-center distance, CE = center-to-edge distance, EE = edge-to-edge distance, gp = attribute group. The methods are illustrated in Fig. 2.

Measures:
- Mean distance
- Standard deviation distance
- Mean distance by gp
- Standard deviation distance by gp
- Number of distances in each distance class
- Number of distances in each distance class by gp

Methods:
- Each patch to all adjacent neighbors CC
- Each patch to all adjacent neighbors CE
- Each patch to nearest patch of same gp CC
- Each patch to nearest patch of same gp CE
- Each patch to nearest patch of same gp EE
- Each patch to nearest patch of different gp CC
- Each patch to nearest patch of different gp CE
- Patches of 1 gp to nearest of specific gp CC
- Patches of 1 gp to nearest of specific gp CE
- Patches of 1 gp to nearest of specific gp EE

the boundary, in pixel edges. The perimeter includes the edge of the sampling area when the edge of the sampling area intersects a patch. The perimeter is measured for each patch individually. Thus some boundaries between adjoining patches are measured twice. Edge measures, discussed later, do not duplicate count the perimeters. There are six self-explanatory measures available for perimeters (Table 2).

5.3. *r.le.tex*

This program can be used to analyze the diversity, texture, juxtaposition, and sum of the edges in the map layer (Table 3). There are four measures of the diversity of patch attributes within the sampling area.

1. Richness: This is simply the number of different patch attributes present in the sampling area.
2. Shannon index (H′): This is an index that combines richness and evenness. Its formula is:

$$H' = - \sum_{i=1}^{m} p_i * \ln(p_i)$$

Table 2. Measures that can be calculated by r.le.patch. gp = attribute group.

Attribute:
- Mean pixel attribute
- Standard deviation pixel attribute
- Mean patch attribute
- Standard deviation patch attribute
- Cover by gp
- Density by gp

Size:
- Mean patch size
- Standard deviation size
- Mean patch size by gp
- Standard deviation size by gp
- Number in each size class
- Number in each size class by gp

Shape:
- Indices:
  - Corrected perimeter/area
  - Perimeter/area
  - Related circumscribing circle
- Measures
  - Mean patch shape
  - Standard deviation shape
  - Mean patch shape by gp
  - Standard deviation shape by gp
  - Number in each shape class
  - Number in each shape class by gp

Fractal dimension
- Perimeter-area fractal dimension

Perimeter
- Sum of perimeters
- Sum of perimeters by gp
- Mean perimeter length
- Mean perimeter length by gp
- Standard deviation perimeter length
- Standard deviation perimeter length by gp

where p_i is the fraction of the sampling area occupied by attribute i, and m is the number of attributes in the sampling area.

3. Dominance: This index is related to the Shannon index, but emphasizes the deviation from evenness. The formula for dominance, D, is:

$$D = \ln(n) - H'$$

where n is the number of attributes in the sampling area. This index was first proposed and

Table 3. Measures that can be calculated by r.le.tex. gp = age/type group. The methods are illustrated in Fig. 3.

Diversity
Richness
Shannon
Dominance
Reciprocal Simpson's
Texture
Measures:
Contagion
Angular second moment
Inverse difference moment
Entropy
Contrast
Methods:
2-neighbor: horizontal (2N-H)
2-neighbor: 45 degrees (2N-45)
2-neighbor: vertical (2N-V)
2-neighbor: 135 degrees (2N-135)
4-neighbor: horizontal/vertical (4N-HV)
4-neighbor: diagonal (4N-DIAG)
8-neighbor (8N)
Juxtaposition
Mean juxtaposition
Standard deviation juxtaposition
Edge
Sum of edges

used by O'Neill *et al.* (1988).

4. Reciprocal Simpson's index (1/S): This index also combines richness and evenness. It is a measure of the probability of encountering two pixels with the same attribute when taking a random sample of two pixels. Its formula is:

$$1/S = 1/\sum_{i=1}^{m} p_i^2$$

where p_i is the fraction of the sampling area occupied by attribute i, and m is the total number of attributes within the sampling area.

Texture measures quantify the adjacency of similar attributes. They are in a sense simply local (neighborhood) measures of diversity. Most of the measures have been reviewed by Haralick *et al.* (1973), Haralick (1975), and Musick and Glover (1990). All of the measures require calculation of a grey-level co-occurrence matrix (GLCM), which is

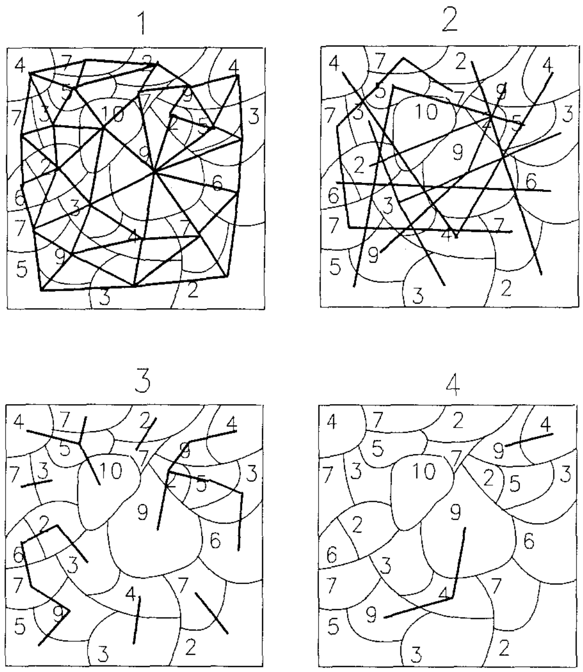


Fig. 2. Four possible methods to measure distance between patches: (1) from each patch in the sampling area to all the adjacent neighbors of each patch, (2) from each patch in the sampling area to the single nearest patch of the same group, (3) from each patch in the sampling area to the single nearest patch of a different group, and (4) from each patch of a specific group in the sampling area to the single nearest patch of a specific group. Only the center-to-center method of measuring distance is illustrated.

$m \times m$, where m is the number of attributes in the sampling area. The GLCM matrix contains entries, P_{ij}, which are the total number of times that attribute i is adjacent to attribute j. The total number of adjacencies is calculated by moving a 3×3 window through the sampling area pixel-by-pixel. The adjacencies for each pixel are determined by examining neighbors in the 3×3 window using one of seven methods (Fig. 3). There are five measures of texture that can be calculated using the seven methods:

1. Contagion: This measure quantifies the degree of clumping, and is a modification of the entropy measure (#4), so that it represents the deviation of the entropy measure from its possible maximum value. The formula for contagion, C, is:

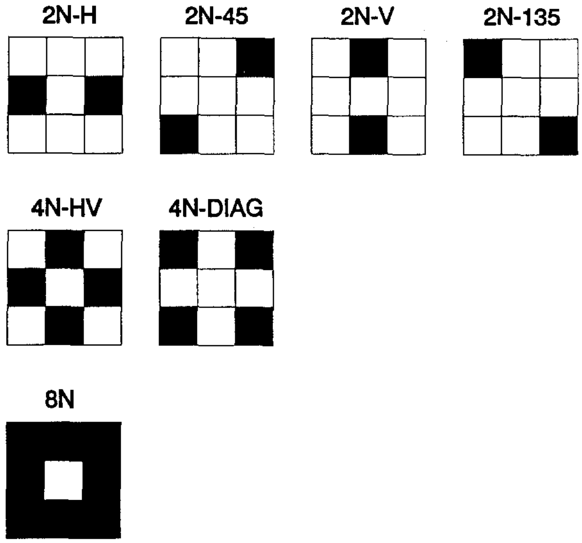


Fig. 3. Seven methods of measuring texture. The blackened squares are the pixels that enter into the calculation for each method. Each method uses some, or all of the eight pixels that are neighbors of the center pixel, allowing quantification of textures that have directional characteristics.

$$C = 2*\ln(m) - ENT$$

This measure was first used by O'Neill *et al.* (1988), although the formula given by these authors included a first term, $2m*\ln(m)$, that is not the maximum value for *ENT*.

2. Angular second moment: This is a measure of the homogeneity of the landscape. Larger values indicate more homogeneity. The formula for angular second moment, *ASM*, is:

$$\mathrm{ASM} = \sum_{i=1}^{m} \sum_{j=1}^{m} (P_{ij})^2$$

3. Inverse difference moment: The formula for inverse difference moment, *IDM*, is:

$$IDM = \sum_{i=1}^{m} \sum_{j=1}^{m} \frac{1}{1+(i-j)^2} P_{ij}$$

4. Entropy: Entropy is a maximum when all pixels of attribute i are as far apart from one another as possible. The formula for entropy, *ENT*, is:

$$ENT = - \sum_{i=1}^{m} \sum_{j=1}^{m} P_{ij} * \ln(P_{ij})$$

5. Contrast: This is a measure of the contrast or amount of local variation present in the landscape. The formula for contrast, *CON*, is:

$$CON = \sum_{i=1}^{m} \sum_{j=1}^{m} [(i-j)^2 * P_{ij}]$$

Juxtaposition is a measure of the weighted length of edges surrounding a center pixel. Two adjoining attributes that are different make an edge. Juxtaposition was described and used by Mead *et al.* (1981) and Heinen and Cross (1983) to quantify potential wildlife habitat. The r.le.tex program calculates the juxtaposition for each pixel in the sampling area by examining the attributes in the 8 neighboring cells. Weights are assigned by the user to different types of edges. The required weighting matrix ($m \times m$, where m is the number of attributes in the map layer) must be created by the user. This weighting matrix contains real numbers (w_{ij}) explained below. Diagonal neighbors get a quantity ranking (q) of 1.0, while horizontal and vertical neighbors get a ranking of 2.0. The juxtaposition for a center cell surrounded by eight neighbors, is then given by:

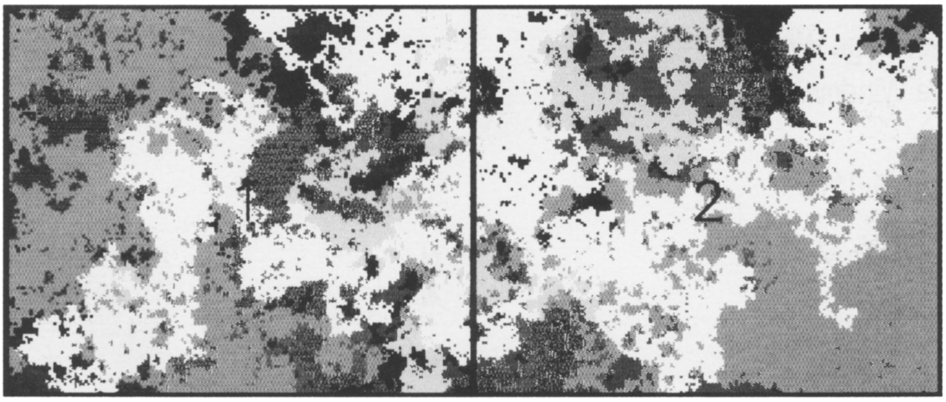
$$J = \sum_{n=1}^{8} \frac{q_n * w_{ij}}{12}$$

where q_n is 2.0 if cell n is horizontally or vertically adjacent and is 1.0 if cell n is diagonal, and w_{ij} is a number between -1.0 and $+1.0$ which indicates the relative "quality" or weight to be given to edges between attributes m_i and m_j. The mean and standard deviation of juxtaposition values are then calculated.

Edge is the length of patch boundary, but in summing edge for all the patches in a sampling area shared edges are counted only once. The sum of the edges is the total length of all the edges, counted only once, of all the patches in the sampling area.

6. Examples of the use of the r.le programs

An analysis of a single map layer that was produced from a simulation model of disturbances in landscapes (Baker *et al.* 1991) is used to illustrate the multiscale capabilities of the r.le programs. The map, which is a 150 row $\times$ 360 column raster (54,000 total pixels) contains several hundred



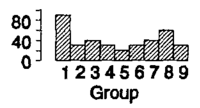
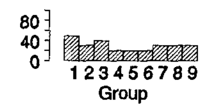
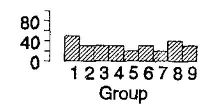
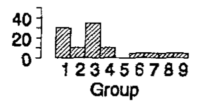
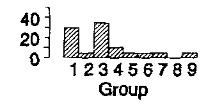
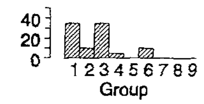
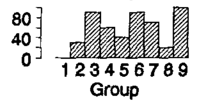
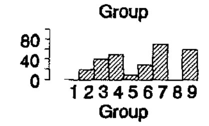
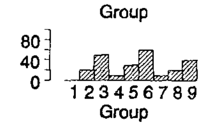
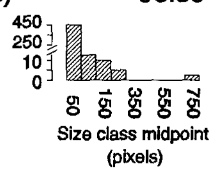
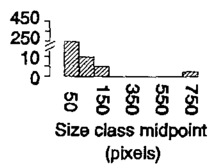
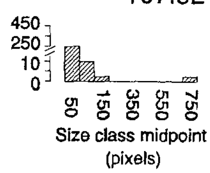
	Scale 1-unit 1	Scale 2-unit 1	Scale 2-unit 2
r.le.dist			
Mean distance (pixels)	43.30	31.20	33.39
Stand. dev. distance	44.99	25.94	29.05
Mean dist. by gp (pixels)			
r.le.patch			
Mean patch age gp	5.72	5.77	5.50
Cover by gp (%)			
Density by gp			
Mean patch size (pixels)	96.83	84.74	107.92
No. in ea. size class			
Fractal dimension	1.36	1.37	1.37
Mean perim. length (pixels)	56.88	53.73	58.38
r.le.tex			
Shannon diversity	1.71	1.70	1.62
Dominance	.49	.49	.57
Contagion	1.73	1.70	1.92
Angular second moment	.16	.15	.18
Inverse difference moment	.79	.78	.81
Contrast	3.70	4.30	3.08

Fig. 4. An example of a multiscale analysis of a map using the r.le programs. The map contains patches differing in age (represented as a gray scale). The sampling framework for analyzing the map consists of two scales. Two sampling units are numbered in black. Scale 1 has one sampling unit (the whole map with the two sampling units merged). Scale 2 has the two sampling units (the two halves of the map). The results of the analysis are presented for sixteen measures of landscape structure.

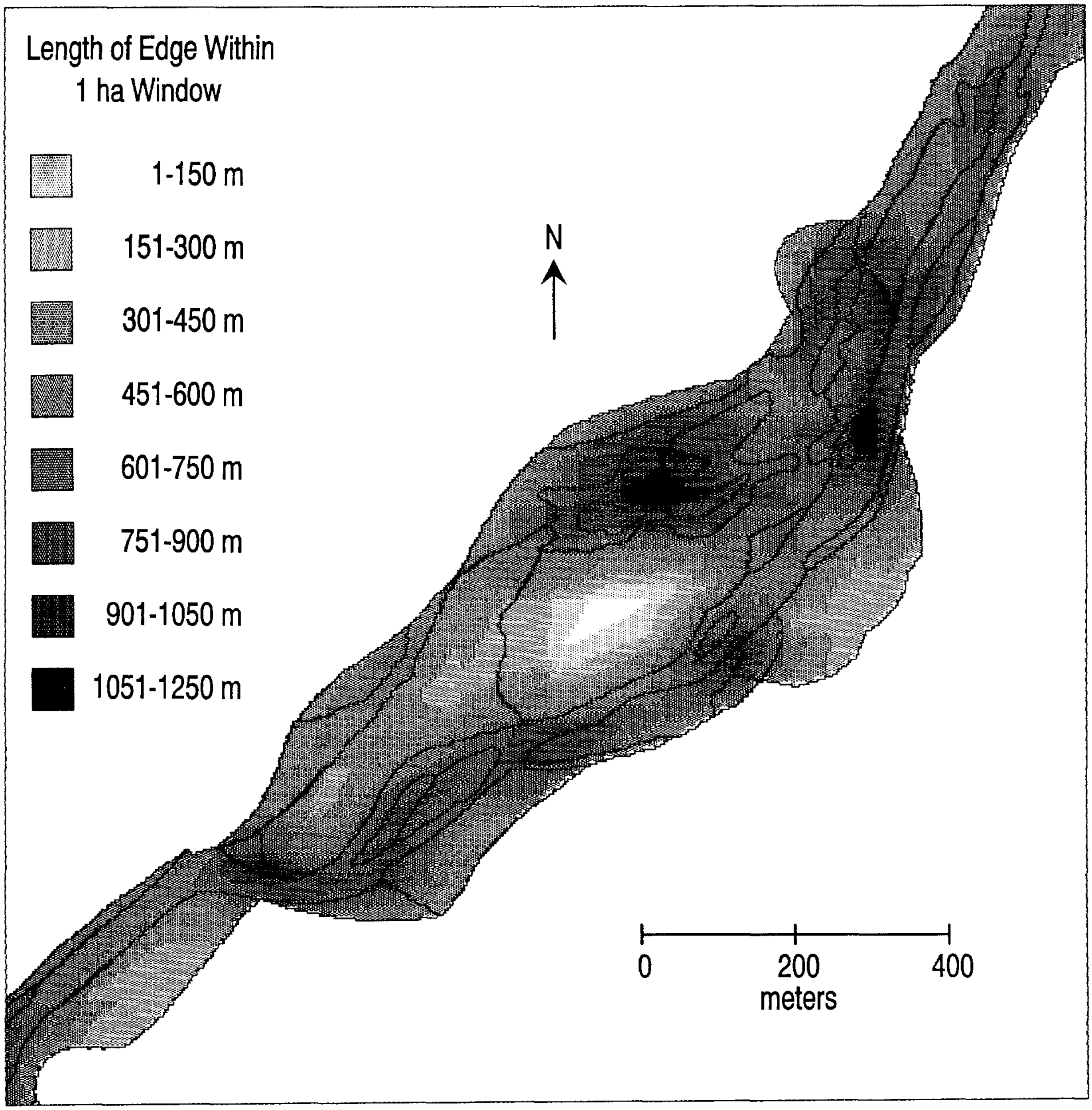


Fig. 5. An example of a moving window analysis of a map using the r.le programs. The map is of a reach of the Animas River in southwestern Colorado. Black lines indicate the boundaries of patches, produced by past floods, that were mapped in the field using aerial photographs. The moving window (100 m × 100 m = 1 ha) was used to compute the total length of edge within a window centered on each pixel (10 m resolution).

patches, each of whose attribute is one of nine 50-year wide age groups representing the length of time since last disturbance (Fig. 4). A simple multi-scale analysis was completed in which scale 1 has a single sampling unit (the whole map), and scale 2 contains two sampling units (the two halves of the whole map). Sixteen measures of landscape structure were calculated using the r.le.dist, r.le.patch, and r.le.tex programs (Fig. 4).

The programs completed the analysis of the 54,000 pixel landscape relatively quickly. On a Sun Sparcstation 1 running at 12.5 MIPS the r.le.dist program took 34 seconds, the r.le.patch program took 1 minute and 36 seconds, and the r.le.tex program took 6 seconds. The r.le.dist and r.le.patch programs require more time because the boundaries of the patches must be traced prior to the actual calculations.

The analysis suggests that the two halves of the map and the whole map do differ in structure based on some measures, but are similar in terms of other measures (Fig. 4). Mean patch size, perimeter length, contagion, and contrast differ between the two halves, and for these measures neither half is quite like the whole map. This kind of analysis, in combination with multivariate analysis, could be used to determine which measures distinguish landscapes and which scale of analysis is most appropriate.

An analysis of a map of a river reach illustrates the moving window capability of the program (Fig. 5). The r.le.tex "sum of edges" option was chosen. The program completed the analysis and produced the map in about four hours for a 450 × 400 pixel map. For a species sensitive to edge and with an ecological neighborhood of 1 ha, this map illustrates the value of each pixel in the landscape as potential habitat. Maps such as this one can be used as potential predictors in building quantitative landscape-based models of species habitat.

7. Discussion

There is an increasing need for software for computing standard measures of landscape structure. Monitoring efforts at the landscape scale are expanding (Hunsaker *et al.* 1990). Ecological studies more often now have a spatial component and include landscape-scale parameters (Forman and Godron 1986).

The availability of geographical information systems has facilitated more sophisticated analysis of wildlife habitat (Haslett 1990) and focussed attention on the importance of appropriately scaled analyses (Wiens 1989). The r.le programs make possible the production of GIS maps of landscape structure scaled to species' ecological neighborhoods (Addicott *et al.* 1987). It is also possible to use the r.le programs to produce maps, with several neighborhood sizes, that could then be used to test which neighborhood size best explains species distribution in a landscape.

The r.le programs can be used to compute about 60 different measures of landscape structure at up to 15 scales in as many as several hundred sampling units simultaneously. The potential data volume is large. Undoubtedly, some or many of these measures may be highly correlated, and some scales may not contain unique information. Certainly one of the remaining problems for landscape ecologists is to determine which measures are redundant and which set of measures is essential to span the ways that landscapes vary across several spatial scales. New combinations of measures, that contain the essential or most meaningful information, may be needed. Principal components analysis can be used to reduce the data volume and identify unique combinations of measures in individual applications (Baker, unpublished data), but this approach makes comparison between study areas difficult. Landscape ecologists may need to develop standardized synthetic measures, perhaps modelled after measures used in remote sensing, such as the normalized difference vegetation index (Goward *et al.* 1985).

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