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Characterizing the canopy gap structure of a disturbed forest using the Fourier transform

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Abstract

Diseases and other small-scale disturbances alter spatial patterns of heterogeneity in forests by killing trees. Canopy gaps caused by tree death are a common feature of forests. Because gaps are caused by different disturbances acting at different times and places, operationally determining the locations of gap edges is often difficult. In this study, digital image analysis using aerial photos was used to formulate an operational definition of gaps and to compare spatial attributes of canopy gap structure in previously unharvested and harvested stands of ponderosa pine forests in the Black Hills of South Dakota. Fourier transforms of monochrome images of the study areas were edited to sequentially remove higher frequency spatial data implementing a type of moving window analysis where window sizes varied over a range of 1–1300 m^2. Boolean thresholds were chosen such that the mean gap size approximated the window size for each original image. Plots of mean gap size, mean fractal dimension, double log fractal dimension, and gap size density all versus window size showed distinct differences between treated and untreated plots.

Keywords: Spatial statistics; Forest gaps; Fourier analysis.

1. Introduction

A variety of small scale disturbances such as diseases, insects, small fires, and thinning are common causes of death of ponderosa pine (*Pinus ponderosa*) in the Black Hills, South Dakota (Lundquist, 1995). These disturbances directly impact the spatial heterogeneity of the forest mosaic by killing trees and creating canopy gaps, and thus indirectly affect propagation of other disturbances (e.g., Knight, 1987; Rykiel et al., 1988), redistribution of water and nutrients (e.g., Matson and Boone, 1984; Waring et al., 1987; Boone et al., 1988), and dynamics of plant and animal populations (e.g., Bennetts and Hawksworth, 1991; Lundquist et al., 1994, 1997). These gap structures link disturbances to various resources like aesthetic values, wildlife habitat, water production, recreation, and timber production, which are important to managers. To manage these resources requires a method of measuring and monitoring the changes in gap structure caused by diseases and other small-scale endemic disturbances.

Traditionally, disease impacts have been addressed from a timber production point of view with respect to outbreak conditions. Consequently, methods used to assess diseases have been based on timber metrics

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like volume of board feet of standing growing stock of saw-timber (Stark, 1987). These metrics have been useful for making timber production decisions, but they are less useful for making decisions about non-timber resources like wildlife habitat, recreation, wilderness, and aesthetic values. An alternative is metrics based on changes in spatial heterogeneity. Few studies of forest diseases are based on spatially referenced data (Jeger, 1988), and relatively little is known about their impact on spatial heterogeneity (Alexander, 1988). Undoubtedly diseases can have a major impact on the spatial heterogeneity of stand structure.

Because gaps occur at different times in the development of a forest, are caused by different agents of mortality, and because they can overlap in space, gaps are often difficult to delineate in the field. Disease caused gaps are especially difficult to distinguish because of their long life in the stand, their progressive spread in time and their affinity to interact with other mortality agents. Various gap definitions indicate a lack of standard measures for this phenomenon (Runkle, 1992). Identifying and quantifying small grain landscape features like canopy gaps using field methods is often imprecise or arbitrary, labor intensive and probably not practical for long term management or over large management areas. An operational definition of canopy gap that does not rely on personal judgment could be applied objectively to different forest stands and thus would be more precise and less arbitrary. The use of aerial photos could reduce the amount of labor required to obtain gap information and the application of objective criteria would allow automation with current computer technology, further reducing the labor required.

It may be possible to develop measurement and monitoring indices using aerial photos to classify differences between landscape features. McGarigal and Marks (1995) developed a computer code that calculates a wide variety of spatial metrics which have application to forest landscapes. The program uses Boolean landscape images; that is images that divide the landscape into regions of the existence and non-existence of landscape features such as trees. In the past such Boolean images have been obtained from labor intensive field surveys which limits the amount of data which is available. Alternatively such images have been constructed from artificial computer models (Hargis et al., 1997) which raises questions about their reality. Obtaining such images from aerial photos would allow a large number of analyses to be performed to test various hypotheses about the links between gap structure and gap causes. In addition, useful information may be available in the way the spatial metrics vary with spatial scale.

One method of discriminating features at different spatial scales uses low pass filters to average over selected spatial scales. One type of low pass filter is the moving window where the brightness of each pixel in an image is assigned the average brightness of pixels within a 'window' of pixels surrounding the pixel in question. It can be thought of as a mask that is displaced one pixel at a time. If the window size is the same as the pixel size, the image is not changed. As the size of the window increases, successively larger features are emphasized by averaging out features smaller than the window. By varying the window size, different spatial scales can be analyzed. The Fourier transform is a less intuitive technique that gives equivalent results. It analyzes the original image into a set of sine and cosine functions whose sum fits the brightness level at each pixel in the scene. The complete Fourier transform is equivalent to the single pixel window and contains the same information as the original image. Clear explanations of the Fourier transform may be found in Byerly (1893) and Wylie (1960). The transform is displayed in distance and brightness amplitude coordinates. By zeroing out higher spatial frequencies and performing the inverse transform, an image results which is averaged over the chosen spatial frequency and is equivalent to the averaging produced by a moving window. We chose the Fourier transform primarily for the practical reason that it is easy to implement with available commercial software and runs efficiently on a common personal computer. We found that its application was less labor intensive than a moving window filter. A comparison of Fig. 1A, C shows an example of the type of spatial smoothing obtained.

Our overall purpose in pursuing this type of study is to examine the usefulness of aerial photo methods for displaying the spatial distribution of canopy discontinuities caused by diseases in forest stands. We use canopy gaps to develop a method to consistently define differences in spatial stand structure between stands showing different levels of damage caused by a known disturbance. We specifically tested the possi-

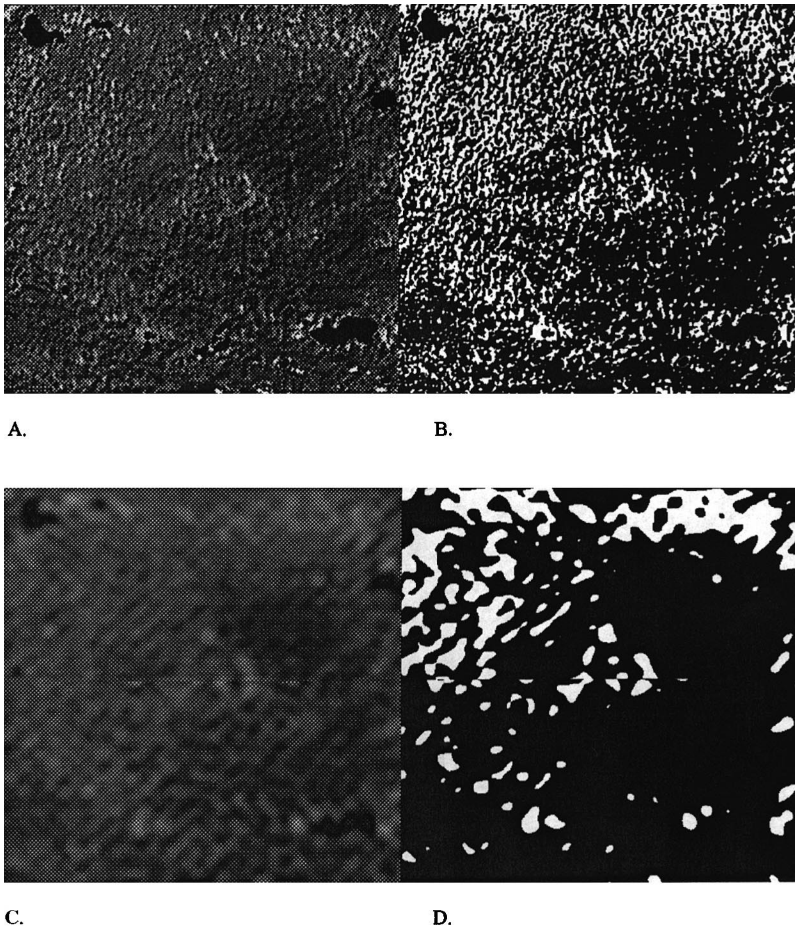

Fig. 1. A. Gray scale image at full resolution. Note masking of rocks. B. Boolean image of A. C. Fourier filter at 750 m^2. D. Boolean image of C.

bility that different optical intensity signatures might be used to signify canopy gaps using a previously unharvested stand. We then conducted a spatial analysis to compare this stand with a previously harvested stand to examine how some spatial metrics varied under these different conditions. Our overall aim is to identify spatial metrics that are sensitive enough to monitor changes in spatial stand structure caused by less intrusive agents, like diseases.

2. Methods

2.1. Study sites

This study was conducted in the Black Hills National Forest in southwestern South Dakota. Two sites composed mostly of mature ponderosa pine were used: (1) Upper Pine Creek Research Natural Area (UPC) and (2) Cameron Creek timber site. UPC represents a first order watershed and covers an area of 110 ha composed of previously unharvested forest. Three plots each from the UPC site of approximately 4 ha (UPC2, UPC3, and UPC5) were selected from five UPC plots for different aspects and slopes. The intention was to use them as replicates to determine the consistency of the metrics in unharvested plots with somewhat different landscape characteristics. UPC2 was located at the bottom and lower end of the drainage area, the east half of this plot sloped 20% to the north and rest of the plot encompassed a drainage bottom with a perennial stream. The drainage bottom sloped 0–7% with a northeast aspect. UPC3 was primarily a southeast facing slope of about 18% in the middle of the drainage area. UPC5 was located at the upper part of the drainage area where its slope varied from 13 to 21% with a northeast aspect. The Cameron Creek Timber Sale covers an area of 26 ha that had been intermediate thinned from a basal area of 110–80 in 1989. One plot was selected from the Cameron Creek area. This plot was primarily a uniform southeast facing slope of about 15%.

2.2. Analysis

The following procedure was used to generate values for various spatial statistics at increasingly larger spatial scales for each plot:

1. Aerial photos (1 : 14,800) of the two sites were taken at about noon and digitized using a Sony color video camera (DXC970MD). Image acquisition and processing was performed using ImagePro (Media Cybernetics, 1995). We used a color signature to mask out rocks, since these features were irrelevant to this study. Because of the high sun angle, no attempt was made to correct for shadows in this exploratory study. The color images were then converted to gray scale images for further processing.
2. Fourier transforms were applied, and edited to successively reject finer spatial information resulting in equivalent window sizes from about 1–1300 m^2. We then chose and applied a threshold level to convert the gray scale images to black and white Boolean images based on the observation that spaces between the trees were a lighter color than the trees. However, the gap size is also a function of the threshold level. For a uniform distribution of gap sizes, a 1–1 correspondence between the gap size and the window size should exist. Therefore, the threshold level in each case was chosen as a close approximation to

$$A_{\mathrm{gap}} = \left(\frac{\mathrm{Lag}}{2}\right)^2 + K \quad (1)$$

where A_{gap} is the mean gap area. Lag is spatial cutoff frequency for the low pass Fourier filter and the term (Lag/2)^2 represents the effective area of the bright half of the moving window (Sommerfeld et al., 1994). K is related to the minimum gap size for the particular landscape. Linear regressions of the mean gap area versus window area aided in judging the best threshold level for each image. Some judgment was involved because the distributions were not necessarily uniform.

An example of the process is shown in Fig. 1. A shows the initial gray scale image with the rocks masked in black. The difficulty of determining gap sizes on this image is clear. B shows the Boolean image derived from A. C. shows a low pass Fourier analysis of A with an equivalent window size of 750 m^2 and D shows its Boolean image. It is seen that this process results in gap images that are clearly defined.
3. Determine the gap areas and their perimeters using ImagePro.
4. Calculate the mean gap area, mean fractal dimension, double log fractal dimension, and gap frequencies for various window sizes.

Calculate the mean gap size using ImagePro software.

Calculate the mean gap fractal dimension (MFGD), as,

$$\mathrm{MGFD}_i = \frac{\sum_{j=1}^{n} \left(2 \ln p_{ij} / \ln a_{ij}\right)}{n_i}$$

where p_{ij} is the perimeter length of gap j for window area i, a_{ij} is the area of gap j for window area i, and n_i is the total number of gaps for effective window area i within the total image. The MGFD is larger for more complex shapes which have relatively long borders for their area. See McGarigal and Marks (1995) for a more complete explanation.

Double log fractal dimension (DLFD), calculated as,

$$\mathrm{DLFD}_i = \frac{2\left(n_i \sum_{j=1}^{n} (\ln p_{ij})^2\right) - 2\left(\sum_{j=1}^{n} \ln p_{ij}\right)^2}{\left[n_{ij} \sum_{j=1}^{n} (\ln p_{ij})(\ln a_{ij})\right] - \left[\left(\sum_{j=1}^{n} \ln p_{ij}\right)\left(\sum_{j=1}^{n} \ln a_{ij}\right)\right]}$$

The DLFD relates to the way the complexity of the gaps change with scale. (McGarigal and Marks, 1995).

Gap size density. The number of gaps corresponding to each window size per total area. This is calculated by subtracting the gap count of the next larger window area from the count of each window area and dividing by the total plot area.

5. Compare and contrast some spatial statistics for UPC and Cameron areas. The above spatial variables were compared and contrasted to define how stand manipulations altered spatial heterogeneity (Fig. 2).

3. Results

Fig. 2 shows metrics which were selected as representative of differences between UPC and Cameron. The main selection criterion, however, was that the

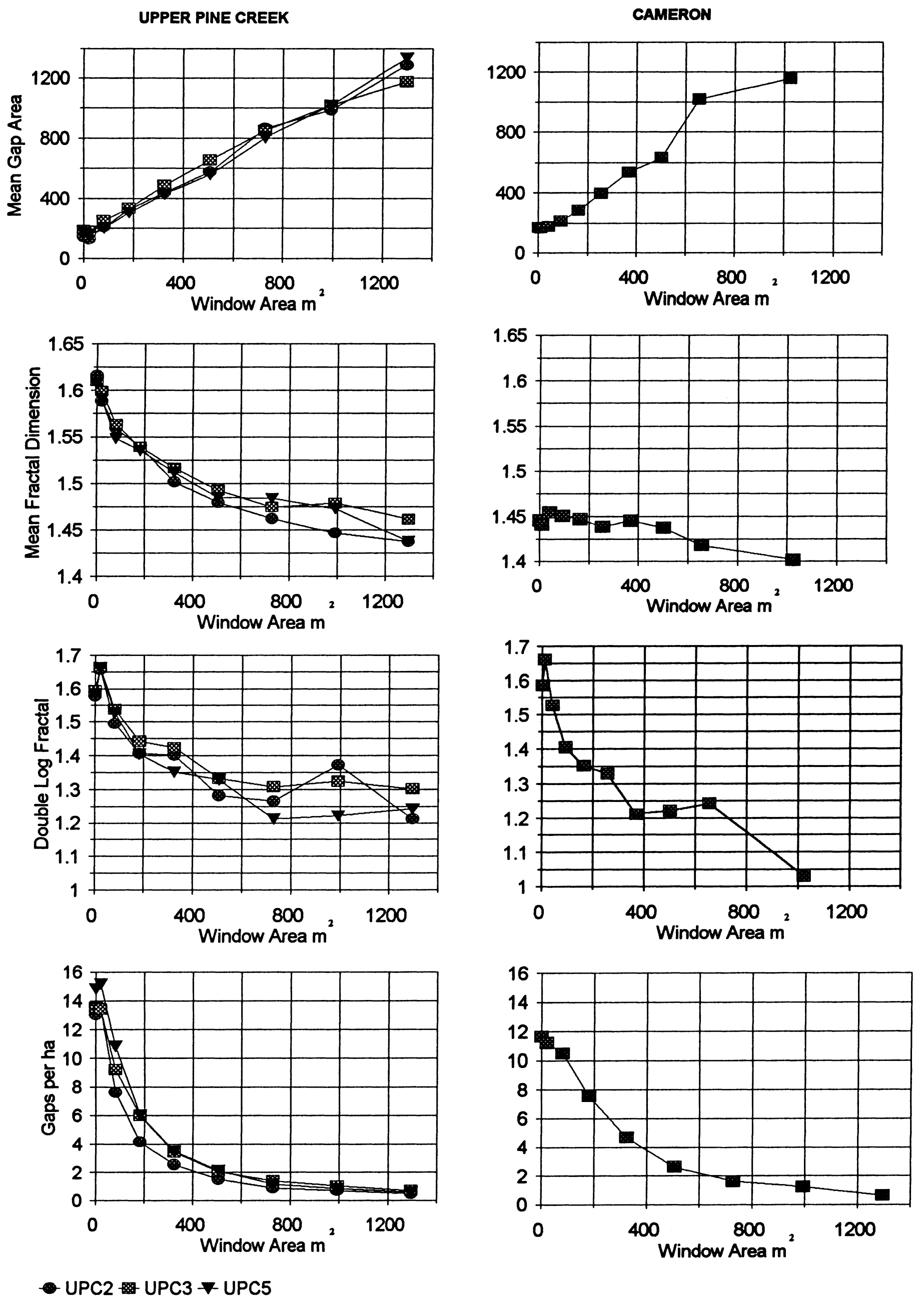

Fig. 2. Selected metrics versus window area for the unharvested (UPC) and harvested (Cameron) study sites.

parameters used in their calculation were available from ImagePro. Thus, the calculations could be performed in a spreadsheet and it was not necessary to implement the full analysis program of McGarigal and Marks (1995) for this exploratory study. Mean gap area for all plots at both sites increased approximately linearly in the range 1–1300 m^2 with increasing effective window area (Fig. 2A). Trends were similar for both unharvested and harvested sites, except that the distribution was more uniform in the upper range in UPC. Cameron had fewer gaps within the interval 500–600 m^2. This probably occurred because of the thinning protocol. All plots in UPC showed similar trends indicating that they were similar with respect to the metrics presented in Fig. 2.

For UPC, mean fractal dimension shows a decreasing trend with increasing lag interval, which indicates that the increasing window size smoothes the gap perimeter, an artifact of the low pass filtering (Fig. 2B). In contrast, Cameron showed little change in mean fractal dimension values with changing interval, indicating that all size gaps have relatively smooth edges. UPC showed higher values for all except the highest lag intervals indicating more complexly shaped gaps.

Double fractal dimension values (Fig. 2C) show a general decreasing trend with increasing lag interval for both sites, but the patterns within this trend differed between UPC and Cameron. UPC shows a peak of relatively high values at 10 m, and a plateau starting at about 50 m. All UPC plots showed similar trends except some plots showed weak peaks at 35 and/or 63 m. All values were lower for Cameron than for UPC except at the lower window areas. Gaps per size class showed that UPC had greater numbers of gaps in the 10–45 m lag intervals (Fig. 2D).

4. Discussion

Diseases and other small-scale disturbances alter spatial patterns of heterogeneity in forests by killing trees. Because gaps are caused by different disturbances acting at different times and places, operationally determining the locations, sizes, and shapes of gaps is often difficult. In this prototype study, digital image analysis using aerial photos and a Fourier transform was examined for its potential use in operationally defining gaps. We examine what might be considered two extremes — unharvested wilderness plots with some variation in landscape parameters and a uniformly thinned stand. The former represents a reference condition, which managers would use to assess the impacts of small-scale disturbances. Based on the results the hypothesis that the chosen metrics were sensitive to the known disturbance was verified. This allows us to further hypothesize that this method is an objective method of characterizing and defining spatial discontinuities in canopy stand structure. Testing of this hypothesis will require more extensive analysis of a wider range of landscapes and is beyond the scope of our preliminary test.

Spatial heterogeneity has several meanings, and can be measured in many ways. In this study, we used the definition of Li and Reynolds (1995), complexity and/or variability of a system property in space and/or time, and specifically focused on canopy gaps. The extent to which gap characteristics depend on cause of tree mortality is not well known. In this study, we examine what might be considered two extremes — unharvested research natural area and a uniformly thinned stand. The results indicate that the statistics we examined were all able to detect and quantify differences in some spatial characteristics. Further studies would be necessary to relate these characteristics to aethetic values, wildlife habitat, water production, recreation, timber production, and other management objectives that might be impacted by small-scale disturbances.

Lundquist (1995) examined several ponderosa pine stands in the Black Hills that represented a gradient of harvest intensities using 4 ha plots. In that study, harvesting was found to affect the small grain stand structure in various ways. Lundquist's study was based on intense field sampling using optical densiometers over a 10 m grid of 4 ha plots. This method is time consuming and expensive and operationally impractical for a forest manager. Aerial photo methods overcome many of these problems. Results of the present study suggest that aerial photos can be used to characterize and assess small-scale spatial stand structure if adequate threshold filters are used. This study showed that harvesting decreased the frequency of gaps in certain size ranges, and decreased the complexity of gap shapes at all gap sizes. This study also indicates that harvesting may be scale dependent. The double log fractal dimension, for example, suggests that a fine-scale pattern within the general trends may be observable by examining a range of spatial scales. St-Onge and Cavayas (1997) mention that future management needs will involve very high resolution digital imagery, and that using these data will require 'radically different image processing approaches a single pixel will no more represent the averaged signal reflected by a number of trees, but will only characterize a small part of a tree crown or of other objects found in the forest.'

A decrease in complexity of the gap shapes as indicated by the difference in MGFD and DLFD in Fig. 2 is what would be expected from a thinning treatment. The result of this study for gap size density, however, seems to present counterintuitive results. The total number of gaps is smaller in the thinned plot than in the unthinned plots. The Fourier transform emphasizes brightness amplitude differences at the chosen scale. Thinning tends to produce a regular spacing of trees. In the case of perfectly regular spacing, e.g. trees on grid nodes, the Fourier transform would find no gaps at spacings larger than the grid dimension. This phenomenon would explain the seemingly anomalous effect of reducing the number of gaps by removing trees. The results show that the techniques applied in this study are sensitive to such changes.

5. Conclusions

Tree diseases are major drivers of forest diversity. Silviculturists often try to control stand structure and composition by mimicking natural small-scale disturbances. To manage, manipulate, or mimic disturbances effectively, we must be able to adequately measure them and their impact on the ecosystem.

We have presented a case study which shows that low pass analyses, implemented with two-dimensional Fourier analyses, identifies spatial features which are closely related to a known artificial cause, thinning. We have proposed an operational definition of a forest gap based on differences in optical intensity in aerial photos of forest stands. Using this definition we have evaluated mean gap area, mean fractal dimension, mean double log fractal dimension, and gap density. Not surprisingly, the four metrics indicate a simplification of the gap shapes and distributions with thinning. We speculate that spatial features identified with this method can be related to endemic natural causes like diseases. If a limited number of window sizes could be shown to be diagnostic, the technique could be very useful. However, for the examples shown, no single window area is diagnostic of the differences between UPC and Cameron.

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