Nathaniel Kwamina Howard (Autor)

Multiscale analysis of landscape data sets from northern Ghana: Wavelets and pattern metrics

Ecology and Development Series

No. 31, 2005

Nathaniel Kwamina Howard

Multiscale analysis of landscape data sets from northern Ghana: Wavelets and pattern metrics

Zentrum für Entwicklungsforschung
Center for Development Research
University of Bonn
ZEF Bonn

1 INTRODUCTION

1.1 Background

Spatial heterogeneity is ever-present at all scales and its formation and interactions with ecological processes are central to landscape ecology (Wu *et al*., 2000; Wu, 2004; Shen *et al*., 2004; Wu *et al*., 2002). In order to understand how landscapes affect and are affected by ecological processes, one must be able to quantify spatial heterogeneity and its scale dependence (i.e. how patterns change with scale). The scale dependence of spatial heterogeneity has long been recognized in both ecology and geography. There are two different but related connotations of spatial heterogeneity being scale dependent. The first implies that spatial heterogeneity exhibits various patterns at different scales, or patterns have distinctive "operational" scales (Lam and Quattrochi, 1992) at which they can be best characterized. This connotation is consistent with the concept of characteristic scale and hierarchy that have appeared in ecological literature since the 1980s (Allen and Starr, 1982; Allen *et al*., 1984; O'Neil *et al*., 1986; Urban *et al*., 1987; Wu and Loucks, 1995; Wu, 1999). The second connotation means the dependence of observed spatial heterogeneity on the scale of observation and analysis – often discussed in terms of scale effects on image classification and spatial analysis (Wu, 2004).

Recent studies have shown that an important and universal characteristic of spatial heterogeneity is its scale multiplicity in space (e.g., Miller 1978, Kolasa and Pickett, 1991; Wu and Loucks, 1995; Cullinan *et al*., 1997; Werner, 1999). The scale multiplicity of landscapes has important ecological implications: (1) landscapes may be hierarchically structured; (2) landscapes exhibit distinctive spatial patterns at different scales which may be caused by different processes, and thus the scale of observation significantly influences what is to be observed; (3) understanding landscape functioning requires a multiple-scale characterization of spatial pattern and processes, and single-scale descriptions are highly likely to be partial and misleading; and (4) models developed at one particular scale are not likely to apply at other scales, thus we need to either link models developed at different scales, or develop multiple-scaled or hierarchically structured models.

The process of relating the different observations across scales (or scaling) is a fundamental challenge in both theory and practice in all earth sciences. In particular, scaling is essential for addressing a wide range of ecological and environmental issues concerning biodiversity loss and global change in part because most ecological studies to date have been carried out at very local scales in both time and space (van Gardingen *et al*., 1997; Wu, 1999). Scaling is often a difficult task due primarily to landscape heterogeneity and nonlinearity, and understanding the scale multiplicity in pattern and process is a key to the success of scaling (Wu, 1999). See Chapter 2 for comprehensive discussion of scaling. This study employs two approaches to multiscale analysis of landscape pattern: the direct and indirect approaches. Specifically, we employ wavelets and landscape metrics as methods for detecting and describing multiple-scale or hierarchical structures in landscapes from northern Ghana.

1.2 Motivation

In order to quantify the multiple-scale characteristics of landscapes, a multiscale or hierarchical method must be employed. By definition, a hierarchical method is multiple-scale. However, a multiple-scale method may not necessarily be hierarchical in the sense of a nested hierarchy (Wu 1999). There are two general approaches to multiscale analyses: (1) the direct approach which involves inherent multiple-scale methods, and (2) the indirect approach which involves repeated use of single-scale methods at different scales. Commonly used multiscale methods in landscape ecology include semivariance analysis (Robertson and Gross, 1994; Burrough, 1995), spectral analysis (Platt and Denman, 1975; Ripley, 1978), fractal analysis (Krummel *et al*., 1987; Milne, 1991; Nikora *et al*., 1999), lacunarity analysis (Plotnick *et al*., 1993; Henebry and Kux, 1995), blocking quadrat variance analysis (Greig-Smith, 1983; Dale, 1999), scale variance analysis (Townshend and Justice, 1988, 1990; Wu *et al*., 2000) and wavelet analysis (Bradshaw and Spies, 1992; Saunders *et al*., 1998; Brunsell and Gillies, 2003; Hu *et al*., 1998; Kumar and Foufoula-Georgiou, 1993a,b). The mathematical formulation or processes of each of these methods involve multiple-scale components, and are therefore either hierarchical or multiscaled. The indirect approach to multiscale analyses, on the other hand, involves methods that are designed for single-scale analysis. Appropriate methods are used to estimate a wide variety of landscape metrics (e.g., diversity, contagion, edge density, relative richness) as well as statistical measures (e.g., mean, variance, variance-mean ratio, and coefficient of variation). The scale multiplicity in the indirect approach is realized when a landscape data set is resampled at different scales according to grain size or extent, and then the landscape metrics or statistical measures computed for the resampled data at the different scales. A common way to resample data is to systematically aggregate the original fine resolution data set to produce a hierarchically nested data set.

There are two related, yet distinct goals for conducting a multiscale analysis of an ecological landscape. The first goal involves characterizing the multiple-scale structure of a landscape, while the second involves detecting or identifying "scale breaks" or hierarchical levels in a landscape. In both cases, the researcher obtains a better understanding of how spatial heterogeneity changes with scale. However, a description of landscape pattern at different scales may be necessary or desirable even if scale breaks do not exist or the landscape is not hierarchical. On the other hand, scale breaks often lead to the identification of characteristic scales of patterns which may frequently facilitate understanding underlying processes. Thus, one may view the two goals as complementing each other. This is one of the researcher’s motivations for employing both approaches to multiscale analysis of landscape data sets.

Recent research (e.g. Bradshaw and Spies, 1992; Kumar and Foufoula-Georgiou, 1993a, 1993b; Hu *et al*., 1998; Saunders *et al*., 1998; Brunsell and Gillies, 2003) suggests that wavelet transforms are powerful tools for analyzing the scaling behavior of remotely sensed and other geophysical data sets. Like Fourier transforms, wavelet transforms are series of expansions of a function using orthonormal basis. The rational and motivation for choosing wavelets over other inherent multiscale methods lies in the fact that wavelet transforms possess the following remarkable and unique properties (among others) that make them most attractive for this research. Wavelet transforms are based on multi-resolution analysis. In other words, wavelet multiresolution decomposition allows the separation of functions into multiresolution components: large-scale and small-scale components. This property allows for the separate study of both large-scale behavior and small-scale behavior. Wavelets are localized in both time/space and scale/frequency domains. They have compact support (they are zero everywhere outside the domain of finite size) which enables their localization in time or space. Also, the wavelet basis are dilates and translates of a "mother wavelet" which enable their localization in frequency or scale such that the size of the support is proportional to the "size of the feature" it represents. There is small support for high-frequency features and large support for low-frequency features. These properties allow for zooming into the irregularities of a function and characterize them locally. Furthermore, fluctuations at different scales can be obtained due to the multiscale transform properties of wavelets. Another property of wavelets which is useful for this research is that, two-dimensional wavelet transforms enable the decomposition of a process into spatially oriented frequency components. Thus, features with dominant frequencies in different directions are extracted as separate components. This property is exploited to study the anisotropic behavior of our data.

Scale effects have been studied using landscape metrics in ecology, remote sensing, and geography in the past two decades (Meentemeyer and Box, 1987; Turner *et al*., 1989, 2001; Bian and Walsh, 1993; Moody and Woodcock, 1994; Benson and Mackenzie, 1995; Wickham and Riitters, 1995; Jelinski and Wu, 1996; O'Neill *et al*., 1996; Qi and Wu, 1996; Wu *et al*., 2002). Scale effects on spatial pattern analysis may be observed in each of the following three situations: (1) changing the size of the smallest observable measurement (grain) within the landscape data only, (2) changing the size of the study area (extent) only, and (3) changing both the grain size and extent. In the first situation, scale effects may occur as a result of the effect of changed grain size as well as the method employed to effect the change. The extent may also be changed in different ways: e.g. by carving out from the center of a map or by starting from one corner and moving in along a diagonal. Studies have shed new light on the problems of scale effects in pattern analysis as well as the multiscale nature of spatial heterogeneity. However, most studies considered only a few landscape metrics over a narrow range of scales. Also, the landscape data sets used in all of these studies emanated from Europe and North America. In this study, the researcher will consider several commonly used landscape metrics over a very wide range of scales. It is also the researcher's belief that differences in composition and configuration of landscape data sets could affect the outcome. The researcher, therefore, wishes to investigate the scaling relations exhibited by the landscape data from northern Ghana and compare the results with those from related studies.

1.3 Objectives

The main objective of this research is to employ direct and indirect approaches to multiscale analysis of landscape data from northern Ghana. In particular, we shall use the wavelet transform as a direct approach to detecting and describing the multiple-scale nature of landscape data sets from northern Ghana. In the indirect approach, several landscape metrics will be computed over a wide range of grain sizes (with different aggregation methods) and spatial extents (with different direction of analysis). Scaling relations would then be constructed for the landscape metrics whose change with grain size or extent is consistent among different landscape data sets.

The specific objectives include:

1. To investigate the land use and land cover maps for heteroscedasticity and proportional effect.
2. To determine the dominant scales of NDVI and DEM through wavelet-based analysis of variance.
3. To employ orthogonal wavelets in detecting and describing multiple-scale patterns in landscape data sets.
4. To investigate how commonly used landscape metrics change over broad ranges of grain sizes or spatial extents, and assess how these changes differ among distinctive landscapes.
5. To formulate general scaling relations for landscape metrics whose change with grain size or extent are consistent across landscapes.
6. To compare the effects of changing grain size and extent in respect of statistical correlations that exists among landscape metrics.

1.4 Organization of thesis

The entire thesis is partitioned into five broad chapters under the headings: 1. Introduction, 2. Literature Review, 3. Datasets and Methods, 4. Results and Discussion and 5. Summary and Conclusion.

The introduction chapter gives a brief background to the study – discusses what the problems are and the attempts that have been made at solving them. It also mentions the researcher’s motivation for outlining his research objectives and describes how he hopes to achieve them. Chapter 2 is a detailed review of the term scale and associated issues, the theory of wavelets, and a description of landscape pattern metrics. The chapter discusses the sources of ambiguity of the term scale and explains its meaning as used in this thesis. Relevant scaling issues are also mentioned and discussed. The chapter also describes the theories behind wavelet analysis, and highlights the strengths and weaknesses of other direct multiscaling methods. Finally, the chapter describes the 18 metrics selected for this study.

The source of the landscape data sets used in the research, the data sets, the problems associated with the data sets and how the problems are resolved are discussed in chapter 3. The chapter also discusses the theories behind the methods used in the various analyses and gives detailed descriptions of the important steps involved. Chapter 4 is on results and discussion. In this chapter, summaries of results of all the analyses conducted in this study are presented in the form of tables and/or graphs. The major findings in the study are then discussed in relation to result from similar and related research. Chapter 5 is the final chapter of this thesis. It summarizes all the major findings and discusses them concisely vis-à-vis the set objectives of the research. Conclusions that may be derived from the findings of the study are outlined. Recommendations are also made on issues that require further study.