

INTRODUCTION

COPYRIGHTED MATERIAL

1

CHARACTERIZING, MEASURING, ANALYZING, AND MODELING SCALE IN REMOTE SENSING: AN OVERVIEW

QIHAO WENG

1.1 SCALE ISSUES IN REMOTE SENSING

Scale is a fundamental and crucial issue in remote sensing studies and image analysis. The University Consortium for Geographic Information Science (UCGIS) identified it as a main research priority area (1996). Scale influences the examination of landscape patterns in a region. The change of scale is relevant to the issues of data aggregation, information transfer, and the identification of appropriate scales for analysis (Krönert et al., 2001; Wu and Hobbs, 2002). Extrapolation of information across spatial scales is a needed research task (Turner, 1990). It is suggested that spatial characteristics could be transferred across scales under specific conditions (Allen et al., 1987). Therefore, we need to know how the information is transferred from a fine scale to a broad scale (Krönert et al., 2001). In remote sensing studies, use of data from various satellite sensors may result in different research results, since they usually have different spatial resolutions. Therefore, it is significant to examine changes in spatial configuration of any landscape pattern as a result of using different spatial resolutions of satellite imagery. Moreover, it is always necessary to find the optimal scale for a study in which the environmental processes operate. Theories, methods, and models for multiscaling are crucial to understand the heterogeneity of landscapes (Wu and Qi, 2000; Wu and Hobbs, 2002). Methods and techniques are important for the examination of spatial arrangements at a wide range of spatial scales. Regionalization

describes a transition from one scale to another, and upscaling or downscaling is an essential protocol in the transition (Krönert et al., 2001).

Characterized by irregularity and scale independence, fractals are recognized as a suitable method to capture the self-similarity property of the spatial structure of interest (Zhao, 2001). Self-similarity represents invariance with respect to scale. In geoscience, the property of self-similarity is often interpreted as scale independence (Clarke, 1986). However, most environmental phenomena are not pure fractals at all scales. Rather, they only exhibit a certain degree of self-similarity within limited regions and over limited ranges of scale, which is measurable by using statistics such as spatial auto-covariances. The underlying principle of fractals is to use strict or statistical self-similarity to determine the fractal dimension (FD) of an object/surface, which is often used as an indicator of the degree of irregularity or complexity of objects. When fractals are applied to remote sensing, an image is viewed as a complex “hilly terrain surface” whose elevations are represented by the digital numbers. Consequently, FDs are readily computable and can be used to denote how complicated the “image surfaces” are. Remote sensing studies assume that spatial complexity directly results from spatial processes operating at various levels, and higher FD occurs at the scale where more processes operate. With FDs, the spatial processes that occurred at different scales are measurable and comparable. Compared to other geospatial algorithms in image analysis such as landscape metrics, fractals offer a better benefit in that they can be directly applied to raw images without the need for classification or land cover feature identification, in addition to their sound mathematic bases. Therefore, it is not surprising to see a growing number of researches utilize fractals in remote sensing image analysis (De Jong and Burrough, 1995; Emerson et al., 1999, 2005; Lam, 1990; Lam and De Cola, 1993; Myint, 2003; Qiu et al., 1999; Read and Lam, 2002; Weng, 2003). Fractal-derived texture images have also been used as additional layers in image classification (Myint, 2003).

Spatial resolution has been another focus in remote sensing studies. It is necessary to estimate the capability of remote sensing data in landscape mapping since the application of remote sensing may be limited by its spatial resolution (Aplin, 2006; Buyantuyev and Wu, 2007; Ludwig et al., 2007). Imagery with finer resolution contains greater amount of spatial information, which, in turn, enables the characterization of smaller features better. The proportion of mixed pixels is expected to increase as spatial resolution becomes coarser (Aplin, 2006). Stefanov and Netzband (2005) identified weak positive and negative correlations between the normalized vegetation index (NDVI) and landscape structure at three different resolutions (250, 500, and 1000 m) when they examined the capability of the Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI data in the assessment of arid landscape characteristics in Phoenix. Asner et al. (2003) examined the significance of subpixel estimates of biophysical structure with the help of high-resolution remote sensing imagery and found a strong correlation between the senescent and unmixed green vegetation cover values in a deforested area. Agam et al. (2007) sharpened the coarse-resolution thermal imagery to finer resolution imagery based on the analysis of the relationship between vegetation index and land surface temperature. The results

showed that the vegetation index–based sharpening method provided an effective way to improve the spatial resolution of thermal imagery.

Adaptive choice of spatial and categorical scales in landscape mapping was demonstrated by Ju et al. (2005). They provided a data-adaptive choice of spatial scale varying by location jointed with categorical scale by the assistance of a statistical finite mixture method. Buyantuyev and Wu (2007) systematically analyzed the effects of thematic resolution on landscape pattern analysis. Two problems need to be considered in landscape mapping: the multiplicity of classification schemes and the level of detail of a particular classification. They found that the thematic resolution had obvious effects on most of the landscape metrics, which indicated that changing thematic resolution may significantly affect the detection of landscape changes. However, an increase in spatial resolution may not lead to a better observation since objects may be oversampled and their features may vary and be confusing (Hsieh et al., 2001; Aplin and Atkinson, 2004). Although coarse resolution may include fewer features, imagery with too fine resolution for a specific purpose can be degraded in the process of image resampling (Ju et al., 2005). Remote sensing data may not be always be sufficient when specific problems were addressed at specific scales and on-ground assessment may be needed, since coarser imagery cannot provide sufficient information about the location and connectivity in specific areas (Ludwig et al., 2007).

Substantial researches have previously been conducted on scale-related issues in remote sensing studies, as discussed above. This book intends to revisit and reexamine the scale and related issues. It will also address how new frontiers in Earth observation technology since 1999—such as very high resolution, hyperspectral, lidar sensing, and their synergy with existing technologies and advances in remote sensing imaging science such as object-oriented image analysis, data fusion, and artificial neural networks—have impacted the understanding of this basic but pivotal issue. The scale-related issues will be examined from three interrelated perspectives: in landscape properties, patterns, and processes. These examinations are preceded by a theoretical exploration of the scale issue by a group of authorities in the field of remote sensing. The concluding section prospects emerging trends in remote sensing over the next decade(s) and their relationship with scale.

1.2 CHARACTERIZING, MEASURING, ANALYZING, AND MODELING SCALE

This book consists of 5 parts and 14 chapters, in addition to this introductory chapter. Part I focuses on theoretical aspects of scale and scaling. Part II deals with the estimation and measurement of vegetation parameters and ecosystems across various spatial and temporal scales. Part III examines the effect of scaling on image segmentation and object extraction from remotely sensed imagery. Part IV exemplifies with case studies on the scale and scaling issues in land cover analysis and in land–atmosphere interactions. Finally, Part V addresses how new frontiers in Earth observation technology, such as hyperspectral and lidar sensing, have impacted the understanding of the scale issue.

Three chapters are included in Part I. In Chapter 2, Ehlers and Klonus examine data fusion results of remote sensing imagery with various spatial scales. The scales are thought to relate to the ground sampling distances (GSDs) of the respective sensors. They find that for electro-optical sensors GSD or scale ratios of 1:10 (e.g., IKONOS and SPOT-5 fusion) can still produce acceptable results if the fusion method is based on a spectral characteristic-preserving technique such as the Ehlers fusion. Using radar images as a substitute for high-resolution panchromatic data is possible, but only for scale ratios between 1:6 and 1:20 due to the limited feature recognition in radar images. In Chapter 3, Quattrochi and Luvall revisit an article published in *Landscape Ecology* in 1999 by them and examine the direct or indirect uses of thermal infrared (TIR) remote sensing data to analyze landscape biophysical characteristics to offer insights on how these data can be used more robustly for furthering the understanding and modeling of landscape ecological processes. In Chapter 4, Weng discusses some important scale-related issues in urban remote sensing. The requirements for mapping three interrelated entities or substances in the urban space (i.e., material, land cover, and land use) and their relationships are first examined. Then, the relationship between spatial resolution and the fabric of urban landscapes is assessed. Next, the operational scale/optimal scale for the studies of land surface temperature are reviewed. Finally, the issue of scale dependency of urban phenomena is discussed via reviewing two case studies, one on land surface temperature (LST) variability across multiple census levels and the other on multiscale residential population estimation modeling.

Part II also contains three chapters. Vegetation indices can be used to separate landscape components into bare soil, water, and vegetation and, if calibrated with ground data, to quantify biophysical variables such as leaf area index and fractional cover and physiological variables such as evapotranspiration and photosynthesis. In Chapter 5, Glenn, Nagler, and Huete use a case study approach to show how remotely sensed vegetation indices collected at different scales can be used in vegetation change detection studies. The primary sensor systems discussed are digital phenocams, Landsat and MODIS, which cover a wide range of spatial (1 cm–250 m) and temporal (15 min–16 days) resolutions/scales. Sources of error and uncertainty associated with both ground and remote sensing measurements in change studies are also discussed. In Chapter 6, Wang and Zhang combine plot data and Thematic Mapped (TM) images to map above-ground forest carbon at a 990-m pixel resolution in Lin-An, Zhejiang Province, China, by using two upscaling methods: point simple cokriging point cosimulation and point simple cokriging block cosimulation. Their results suggest that both methods perform well in scaling up the spatial data as well as in revealing the propagation of input data uncertainties from a finer spatial resolution to a coarser one. The output uncertainties reflect the spatial variability of the estimation accuracy caused by the locations of the input data and the values themselves. In Chapter 7, Yuhong He intends to bridge the gap in spatial scales through estimating grassland chlorophyll contents from leaf to landscape level using a simple yet effective canopy integration method. Using data collected in a heterogeneous tall grassland located at Ontario, Canada, Yuhong's study first scales leaf level chlorophyll measurements to canopy and landscape levels and then investigates the

relationships between a chlorophyll spectral index and vegetation chlorophyll contents at the leaf, canopy, and landscape scales. Significant relationships are found at all three scales, suggesting that it is feasible to accurately estimate chlorophyll contents using both ground and space remote sensing data.

In remote sensing, image segmentation has a longer history and has its roots in industrial image processing but was not used extensively in the geospatial community in the 1980s and 1990s (Blaschke, 2010). Object-oriented image analysis has been increasingly used in remote sensing applications due to the advent of high-spatial-resolution image data and the emergence of commercial software such as eCognition (Benz et al., 2004; Wang et al., 2004). In the process of creating objects, a scale determines the occurrence or absence of an object class. Thus, the issue of scale and scaling are fundamental considerations in the extraction, representation, modeling, and analyses of image objects (Hay et al., 2002; Tzotsos et al., 2011).

The three chapters in Part III focus on discussion of these issues. In Chapter 8, Hay introduces a novel geo-object-based framework that integrates hierarchy theory and linear scale space (SS) for automatically visualizing and modeling landscape scale domains over multiple scales. Specifically, this chapter describes a three-tier hierarchical methodology for automatically delineating the dominant structural components within 200 different multiscale representations of a complex agro-forested landscape. By considering scale-space events as critical domain thresholds, Hay further defines a new scale-domain topology that may improve querying and analysis of this complex multiscale scene. Finally, Hay shows how to spatially model and visualize the hierarchical structure of dominant geo-objects within a scene as “scale-domain manifolds” and suggests that they may be considered as a multiscale extension to the hierarchical scaling ladder as defined in the hierarchical patch dynamics paradigm. Chapter 9 by Tzotsos, Karantzalos, and Argialas introduces a multiscale object-oriented image analysis framework which incorporates a region-merging segmentation algorithm enhanced by advanced edge features and nonlinear scale-space filtering. Initially, edge and line features are extracted from remote sensing imagery at several scales using scale-space representations. These features are then used by the enhanced segmentation algorithm as constraints in the growth of image objects at various scales. Through iterative pairwise object merging, the final segmentation can be achieved. Image objects are then computed at various scales and passed on to a kernel-based learning machine for classification. This image classification framework was tested on very high resolution imagery acquired by various airborne and spaceborne panchromatic, multi-spectral, hyperspectral, and microwave sensors, and promising experimental results were achieved. Chapter 10, by Im, Quackenbush, Li, and Fang, provides a review of recent publications on object-based image analysis (OBIA) focusing on determination of optimum scales for image segmentation and the related trends. Selecting optimum scale is often challenging, since (1) there is no standardized method to identify the optimality and (2) scales in most segmentation algorithms are arbitrarily selected. The authors suggest that there should be transferable guidelines regarding segmentation scales to facilitate the generalization of OBIA in remote sensing applications, to enable efficient comparison of different OBIA approaches, and to select optimum scales for the multitude of different image components.

Part IV introduces three case studies on the scale and scaling issues in analysis of land cover, landscape metrics, and biophysical parameters. Chapter 11 by Liu and Weng assesses the effect of scaling on the relationship between landscape pattern and land surface temperature with a case study in Indianapolis, Indiana. A set of spatial resolutions were compared by using a landscape metric space. They find that the spatial resolution of 90 m is the optimal scale to study the relationship and think that it is the operational scale of the urban thermal landscape in Indianapolis. In Chapter 12, Liang and Weng provide an evaluation of the effectiveness of the triangular prism fractal algorithm for characterizing urban landscape in Indianapolis based on eight satellite images acquired by five different sensors: Landsat Multispectral Scanner, Landsat Thematic Mapper, Landsat Enhanced Thematic Mapper Plus, Advanced Spaceborne Thermal Emission and Reflection, and IKONOS. Fractal dimensions computed from the selected original, classified, and resampled images are compared and analyzed. The potential of fractal measurement in the studies of landscape pattern characterization and the scale/resolution issues are further assessed. Chapter 13 by Hong and Zhang provides important insights into the spatiotemporal scales of remotely sensed precipitation. This chapter first overviews the precipitation measurement methods—both traditional rain gauge and advanced remote sensing measurements; then develops an uncertainty analysis framework that can systematically quantify the remote sensing precipitation estimation error as a function of space, time, and intensity; and finally assesses the spatiotemporal scale-based error propagation in remote sensing precipitation estimates into hydrological prediction.

The last part of this book looks at how new frontiers in Earth observation technology have transformed our understanding of this foremost issue in remote sensing. Chapter 14 examines lidar data processing, whereas Chapter 15 explores hyperspectral remote sensing for land cover mapping. Digital terrain models (DTMs) are basic products required for a number of applications and decision making. Nowadays, high-spatial-resolution DTMs are primarily produced through airborne laser scanners (ALSs). However, the ALS does not directly deliver DTMs; rather it delivers a dense point cloud that embeds both terrain elevation and height of natural and human-made features. Hence, discrimination of above-ground objects from terrain is a basic processing step. This processing step is termed ground filtering and has proved especially difficult for large areas of varied terrain characteristics. In Chapter 14, Silvan-Cárdenas and Wang revise and extend a filtering method based on a multiscale signal decomposition termed the multiscale Hermite transform (MHT). The formal basis of the latter is presented in the context of scale-space theory, a theory for representing spatial signals. Through the unique properties of the MHT, namely local spatial rotation and scale-space shifting, the original filtering algorithm was extended to incorporate higher order coefficients in the multiscale erosion operation. Additionally, a linear interpolation was incorporated through a truncated Taylor expansion which allowed improving the ground filtering performance along sloppy terrain areas. Practical considerations in the operation of the algorithm are discussed and illustrated with examples. In Chapter 15, Petropoulos, Manevski, and Carlson assess the potential of hyperspectral remote sensing systems for improving discrimination among similar land cover classes at different scales. The chapter provides first

an overview of the current state of the art in the use of field spectroradiometry in examining the spectral discrimination between different land cover targets. In this framework, techniques employed today and linked with the most important scale factors are critically reviewed and examples of recent related studies and spectral libraries are provided. Then, it focuses on the use of hyperspectral remote sensing for obtaining land use/cover mapping from space. An overview of the different satellite sensors and techniques employed is furnished, providing examples taken from recent studies. The chapter closes by highlighting the main challenges that need to be addressed in the future towards a more precise estimation of land cover from spectral information acquired from hyperspectral sensing systems at variant spatial scales.

REFERENCES

- Agam, N., Kustas, W. P., Anderson, M. C., Li, F., and Neale, C. M. U. 2007. A vegetation index based technique for spatial sharpening of thermal imagery. *Remote Sensing of Environment* 107(4):545–558.
- Allen, T. F. H., O'Neill, R. V., and Hoekstra, T. W. 1987. Interlevel relations in ecological research and management: Some working principles from hierarchy. *Journal of Applied Systems Analysis* 14:63–79.
- Aplin P. 2006. On scales and dynamics in observing the environment. *International Journal of Remote Sensing* 27(11):2123–2140.
- Aplin, P., and Atkinson, P. M. 2004. Predicting missing field boundaries to increase per-field classification accuracy. *Photogrammetric Engineering and Remote Sensing* 70:141–149.
- Asner, G. P., Bustamante, M. M. C., and Townsend, A. R. 2003. Scale dependence of biophysical structure in deforested areas bordering the Tapajos National Forest, Central Amazon. *Remote Sensing of Environment* 87(4):507–520.
- Benz, U. C., Hofmann, P., Willhauck, G., Lingenfelder, I., and Heynen, M. 2004. Multi-resolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information. *ISPRS Journal of Photogrammetry & Remote Sensing* 58:239–258.
- Blaschke, T. 2010. Object based image analysis for remote sensing. *ISPRS Journal of Photogrammetry and Remote Sensing* 65(1):2–16.
- Buyantuyev, A., and Wu, J. 2007. Effects of thematic resolution on landscape pattern analysis. *Landscape Ecology* 22(1):7–13.
- Clarke, K. C. 1986. Computation of the fractal dimension of topographic surfaces using the triangular prism surface area method. *Computers and Geosciences* 12:713–722.
- De Jong, S. M., and Burrough, P. A. 1995. A fractal approach to the classification of Mediterranean vegetation types in remotely sensed images. *Photogrammetric Engineering and Remote Sensing* 61:1041–1053.
- Emerson, C. W., Lam, N. S. N., and Quattrochi, D. A. 1999. Multiscale fractal analysis of image texture and pattern. *Photogrammetric Engineering and Remote Sensing* 65:51–61.
- Emerson, C. W., Lam, N. S. N., and Quattrochi, D. A. 2005. A comparison of local variance, fractal dimension, and Moran's I as aids to multispectral image classification. *International Journal of Remote Sensing* 26:1575–1588.

- Hay, G. J., Dube, P., Bouchard, A., and Marceau, D. J. 2002. A scale-space primer for exploring and quantifying complex landscapes. *Ecological Modelling* 153(1–2):2–49.
- Hsieh, P. F., Lee, L. C., and Chen, N. Y. 2001. Effect of spatial resolution on classification errors of pure and mixed pixels in remote sensing. *IEEE Transactions on Geoscience and Remote Sensing* 39(12):2657–2663.
- Ju, J. C., Gopal, S., and Kolaczyk, E. D. 2005. On the choice of spatial and categorical scale in remote sensing land-cover classification. *Remote Sensing of Environment* 96(1):62–77.
- Krönert, R., Steinhardt, U., and Volk, M. 2001. *Landscape Balance and Landscape Assessment*. New York: Springer.
- Lam, N. S. N. 1990. Description and measurement of Landsat TM images using fractals. *Photogrammetric Engineering and Remote Sensing* 56:187–195.
- Lam, N. S. N., and De Cola, L. 1993. *Fractals in Geography*. Englewood Cliffs, NJ: Prentice Hall.
- Ludwig, J., Bastin, G., Wallace, J., and McVicar, T. 2007. Assessing landscape health by scaling with remote sensing: When is it not enough? *Landscape Ecology* 22(2):163–169.
- Myint, S. W. 2003. Fractal approaches in texture analysis and classification of remotely sensed data: Comparisons with spatial autocorrelation techniques and simple descriptive statistics. *International Journal of Remote Sensing* 24:1925–1987.
- Qiu, H.-L., Lam, N. S. N., Quattrochi, D. A., and Gamon, J. A. 1999. Fractal characterization of hyperspectral imagery. *Photogrammetric Engineering and Remote Sensing* 65:63–71.
- Read, J. M., and Lam, N. S. N. 2002. Spatial methods for characterizing land cover and detecting land-cover changes for the tropics. *International Journal of Remote Sensing* 23:2457–2474.
- Stefanov, W. L., and Netzband, M. 2005. Assessment of ASTER land-cover and MODIS NDVI data at multiple scales for ecological characterization of an arid urban center. *Remote Sensing of Environment* 99(1–2):31–43.
- Turner, M. G. 1990. Spatial and temporal analysis of landscape patterns. *Landscape Ecology* 4(1):21–30.
- Tzotsos, A., Karantzalos, K., and Argialas, D. 2011. Object-based image analysis through nonlinear scale-space filtering. *ISPRS Journal of Photogrammetry and Remote Sensing* 66:2–16.
- Wang, L., Sousa, W. P., Gong, P., and Biging, G. S. 2004. Comparison of IKONOS and QuickBird images for mapping mangrove species on the Caribbean coast of Panama. *Remote Sensing of Environment* 91:432–440.
- Weng, Q. 2003. Fractal analysis of satellite-detected urban heat island effect. *Photogrammetric Engineering and Remote Sensing* 69:555–566.
- Wu, J., and Hobbs, R. 2002. Key issues and research priorities in landscape ecology: An idiosyncratic synthesis. *Landscape Ecology* 17:355–365.
- Wu, J., and Qi, Y. 2000. Dealing with scale in landscape analysis: An overview. *Geographic Information Sciences* 6(1):1–5.
- Zhao, W. 2001. Multiscale Analysis for Characterization of Remotely Sensed Images. Ph.D. Dissertation, Louisiana State University.