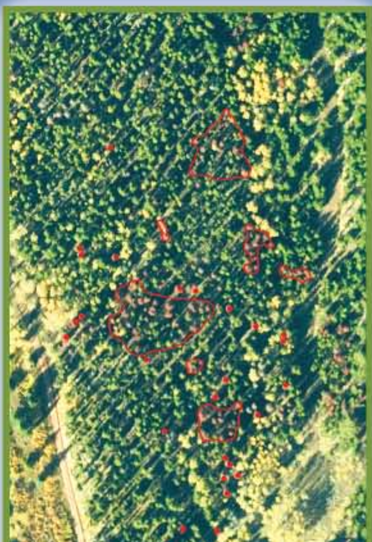
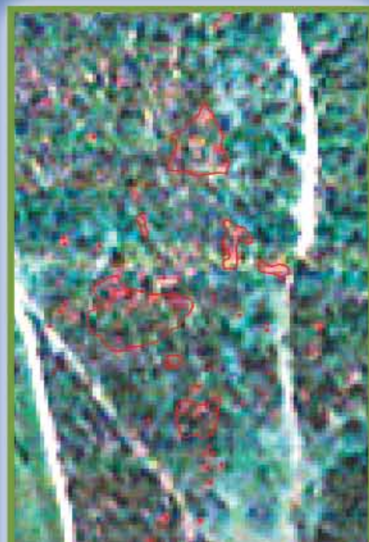
Understanding Forest Disturbance and Spatial Pattern

Remote Sensing and GIS Approaches





Edited by

Michael A. Wulder
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Taylor & Francis
Taylor & Francis Group
Boca Raton London New York

CRC is an imprint of the Taylor & Francis Group,
an informa business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8493-3425-X (Hardcover)
International Standard Book Number-13: 978-0-8493-3425-2 (Hardcover)

Library of Congress Cataloging-in-Publication Data

Wulder, Michael A.
Understanding forest disturbance and spatial pattern : remote sensing and GIS approaches / author / editors, Michael Wulder and Steven E. Franklin.
p. cm.
Includes bibliographical references and index.
ISBN 0-8493-3425-X (alk. paper)
1. Forests and forestry--Remote sensing. 2. Geographic information systems. I. Franklin, Steven E. II. Title.

SD387.R4W85 2006
634.9--dc22 2006007999

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To Yoka and John

M.A.W.

For Barb

S.E.F.

Preface

This book was conceived as a contribution to the increasingly urgent need in the scientific and resource management communities to develop greater understanding of forest disturbance as a means to aid in the resolution of complex forest management planning issues worldwide. It is our view that, in the past decade, the capability to use remotely sensed data for the generation of forest disturbance products is increasingly well understood and, consequently, more widely available. The "how-to" questions that have preoccupied geospatial analysts and practicing resource management professionals are now less critical. Rather, clarification is sought on the wider ecological meaning of the spatial patterns associated with disturbance and what can and should be done with the copious and diverse information that is generated by remote sensing and geographical information system (GIS) approaches. In addition, questions are emerging regarding how forest practices should be changed (if at all) to accommodate the new perspectives generated by geospatial technologies. For example, the use of landscape metrics to characterize landscape pattern from remotely sensed map products enables unprecedented opportunities for improved forest management and sustainable stewardship. Landscape metrics provide a synoptic and systematic means to understand the implications of disturbance processes, including issues such as altered habitat and forest fragmentation. However, the appropriate application and insightful interpretation of landscape metrics are only in their infancy, as are the emerging disciplines of landscape ecology and conservation biology, both of which owe a portion of their growth and potential to developments in the fields of remote sensing and GIS.

We perceived an opportunity to present in this book a sequence of topics that would take the reader from a general biological or landscape ecological context of forest disturbance, to remote sensing and GIS technological approaches, through to pattern description and analysis, with compelling applied examples of integration and synthesis. The chapters for this volume were invited, peer reviewed, revised, and edited; the authors and reviewers adhered to the strictest standards and highest quality criteria in this process. The issues discussed here address both natural and human-caused forest change and include factors such as biological components, monitoring approaches, scale, and pattern analysis. In this book, our goal was to consider forest disturbance and spatial pattern from an ecological point of view within the context of structure, function, pattern, and change. Remotely sensed and GIS data are now the data sources of choice for those whose responsibility it is to capture, document, and understand landscape pattern and forest disturbance. A discussion of the concepts of pattern characterization, which is an area of research and application we expect will continue to grow in importance and significance to resource managers, highlights the challenges in this emerging area of research, and although significant progress has been made, clearly much remains to be done. We conclude this book with a final chapter in which we provide a summary and description of the thematic issues related to detection and mapping of forest disturbances with remotely sensed and GIS data. Over the course of the book, we attempt to illustrate how the elements presented from ecological underpinnings, data considerations, change detection method, and pattern analysis, combine as a problem-solving, information-generating approach. It is our hope that the materials presented will stimulate discussion and provide guidance for those who are interested, or faced with similar challenges, in capturing and characterizing forest disturbance and pattern.

ACKNOWLEDGMENTS

We acknowledge the important financial and administrative support from the Canadian Forest Service, the University of Saskatchewan, and the Natural Sciences and Engineering Research Council of Canada, without which this book would not have been possible. Sincere thanks are likewise extended to the many authors and reviewers for their enthusiastic participation in this project. Any contribution that this volume will make in advancing the understanding of spatial pattern and forest disturbance through remote sensing and GIS approaches is largely a result of their effort and commitment. A special thank you is offered to Jill Jurgensen and the staff and editors at Taylor & Francis for their superb assistance in bringing the source manuscript to fruition in this book publication. David Seemann and Joanne White of the Canadian Forest Service are thanked for support and assistance with the production of the book manuscript. To our many collaborators and colleagues, we are appreciative and indebted for your insights and constructive engagement on so many aspects of research, development, and communications. Finally, and especially, to our families, we express our sincere thanks for love, understanding, and continued support.

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About the Editors

Michael A. Wulder received his B.Sc. (1995) degree from the University of Calgary and his M.E.S. (1996) and Ph.D. (1998) degrees from the Faculty of Environmental Studies at the University of Waterloo. On graduation, Dr. Wulder joined the Canadian Forest Service, Pacific Forestry Centre, in Victoria, British Columbia, as a Research Scientist. He has served on the executive committee of the Canadian Remote Sensing Society since 2003, was co-chair of the 22nd Canadian Symposium on Remote Sensing in 2000, and co-edited the ensuing special issue of the *Canadian Journal of Remote Sensing* (December 2001). He has also co-chaired international workshops on light detection and ranging (LIDAR) remote sensing of forests in Canada and Australia (which also resulted in a special issue of the *Canadian Journal of Remote Sensing* in October 2003). In 2000, he assumed the lead role in the Land Cover component of the Earth Observation for Sustainable Development of forests program, funded by the Canadian Space Agency and the Canadian Forest Service. A land cover map of the forested area of Canada is nearing completion based on this effort. Dr. Wulder's research interests focus on the application of remote sensing and GIS technologies to address issues of forest structure and function. Dr. Wulder's major research publications include the book *Remote Sensing of Forest Environments: Concepts and Case Studies* (2003, KAP) and a forthcoming book entitled *Monitoring of Large Area Forest Cover and Dynamics* (2007, Taylor and Francis). He has produced more than 60 refereed articles in leading journals from the fields of remote sensing, forestry, environmental science, and geographical information systems. Dr. Wulder is an adjunct professor in the Department of Geography at the University of Victoria and the Department of Forest Resources Management of the University of British Columbia.

Steven E. Franklin received his B.E.S. (1980), M.A. (1982), and Ph.D. (1985) degrees from the Faculty of Environmental Studies at the University of Waterloo following earlier studies in the School of Forestry at Lakehead University in Thunder Bay, Ontario. Dr. Franklin taught remote sensing and geographical information system courses at Memorial University of Newfoundland (1985–1988) and the University of Calgary (1988–2003) before joining the University of Saskatchewan in 2003 as Vice-President Research and Professor of Geography. He has served as associate editor of both the *Canadian Journal of Forest Research* (2000–2003) and the *Canadian Journal of Remote Sensing* (1991–1996) and has served on the editorial board of the journal *Computers and Geosciences* (1993–1996). Dr. Franklin is a Fellow of the Canadian Aeronautics and Space Institute and has served on the executive of the Canadian Remote Sensing Society, including two years as chair. His major publications include more than 100 journal articles in a wide range of remote sensing and environmental journals and the books *Remote Sensing for Sustainable Forest Management* (2001, Lewis/CRC) and *Remote Sensing of Forest Environments: Concepts and Case Studies* (2003, KAP). Dr. Franklin has supervised more than 30 graduate students and postdoctoral fellows in an environmental remote sensing research program, with applications in forest ecology and wildlife management, largely funded by the Natural Sciences and Engineering Research Council of Canada.

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1 Introduction: Structure, Function, and Change of Forest Landscapes

Julia Linke, Matthew G. Betts, Michael B. Lavigne, and Steven E. Franklin

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INTRODUCTION

Forests are inherently dynamic in space and time. Their composition and distribution can change not only through continuous, subtle, and slow forest development and succession, but also through discontinuous, occasional, and sudden natural disturbances (Botkin, 1990; Oliver and Larson, 1996; Spies, 1997). In addition to natural processes, human activities and disturbances are the source of much contemporary forest change (Houghton, 1994; Meyer and Turner, 1994; Riitters et al., 2002). Such land cover change is widely considered the primary cause of biodiversity decline and species endangerment (Hansen et al., 2001). Monitoring natural and human-caused land cover and forest changes, disturbance processes, and spatial pattern is relevant for the conservation of forest landscapes and their inhabitants (Balmford et al., 2003). In recent years, international political momentum dedicated to conservation of biodiversity and sustainable development has increased (Table 1.1).

Biodiversity conservation and sustainable forest management require the collection of new kinds of forest and land cover information to complement traditional forest databases, model outputs, and field observations. Remote sensing and geographical information systems (GISs) have emerged as key geospatial tools — together with models of all kinds and descriptions — to satisfy increasing information needs of resource managers (Franklin, 2001). But, these are more than tools — they represent essentially new *approaches* to forest disturbance and spatial pattern mapping and analysis because they enable new ways of viewing disturbances and landscapes, which in turn influence our understanding and management practices. Critical developments in the use of remote sensing and GIS approaches include the ability to map biophysical (e.g., Iverson et al., 1989), biochemical (e.g., Roberts et al., 2003), and disturbance (e.g., Gong and Xu, 2003) characteristics of forest landscapes over a wide range of spatial scales and time intervals (Quattrochi and Pellier, 1991; Turner et al., 2003).

This introductory chapter provides a brief landscape ecological foundation for the importance of detecting and monitoring forest disturbances and changes in forest landscape patterns. We discuss monitoring and scale considerations and then describe basic stand and landscape dynamics of interest to resource managers. We introduce landscape metrics, which are then more completely reviewed by Gergel (Chapter 7, this volume). We emphasize a developing understanding of pattern/process reciprocity in forested landscapes, which is then highlighted by several case studies of different disturbance patterns in widely differing forest environments. Immediately following this introduction is background material on pertinent remote sensing and GIS data selection, methods, and applications issues in support of forest pattern analysis and change detection (Chapter 2). This material leads naturally to the suite of illustrative examples of remote sensing and GIS approaches in forest harvest pattern detection (Chapter 3), forest insect defoliation mapping (Chapter 4), monitoring fire disturbance (Chapter 5), and the role of GIS in forest disturbance and change mapping (Chapter 6). Subsequent chapters in this book present specific aspects of spatial pattern analysis, including remote sensing considerations (Chapter 7) and a detailed remote sensing/GIS/pattern analysis case study (Chapter 8) designed to aid in understanding critical resource management issues. Each of these chapters has been selected as a representative perspective on developing remote sensing and GIS approaches, which are increasingly recognized, in combination with field data and modeling methods, as the only feasible way to monitor landscape change over large areas with sufficient spatial detail to allow comparison of resultant patterns of different management or natural disturbance regimes.

TABLE 1.1
Selected National Programs on the Conservation of Biological Diversity and Sustainable Management of Earth Resources Developed Since the Rio Earth Summit, the United Nations Conference on Environment and Development (UNCED), in 1992

Program	Initiation Year and Organization	Vision	Web Site Address
Convention on Biological Diversity (CBD)	1992, United Nations Environment Programme	International treaty to pursue the conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources, including by appropriate access to genetic resources and by appropriate transfer of relevant technologies, taking into account all rights over those resources and to technologies, and by appropriate funding	http://www.biodiv.org/default.shtml
The Montreal Process	1994, Inter-Governmental Organization of Forestry Agencies	A working group for the development of criteria and indicators that provide member countries with a common definition of what characterizes sustainable management of temperate and boreal forests	http://www.mpci.org/home_e.html
Pan-European Biological and Landscape Diversity Strategy	1994, Council of Europe	The principal aim of the strategy is to find a consistent response to the decline of biological and landscape diversity in Europe and to ensure the sustainability of the natural environment	http://www.coe.int/t/e/Cultural_Co-operation/Environment/Nature_and_biological_diversity/Biodiversity/default.asp#TopOfPage
Kyoto Protocol	1997, United Nations Framework Convention on Climate Change	Convention on Climate Change sets an overall framework for intergovernmental efforts to tackle the challenge posed by climate change with the Kyoto Protocol committing parties to individual, legally binding targets to limit or reduce their greenhouse emissions	http://unfccc.int/2860.php

Continued.

TABLE 1.1 ***(Continued)***
Selected National Programs on the Conservation of Biological Diversity and Sustainable Management of Earth Resources Developed Since the Rio Earth Summit, the United Nations Conference on Environment and Development (UNCED), in 1992

Program	Initiation Year and Organization	Vision	Web Site Address
Earth Observation for Sustainable Development of Forests (EOSD)	1999, Canadian Forest Service and Canadian Space Agency	Research and applications program to develop a forest measuring and monitoring system that responds to key policy drivers related to climate change and to report on sustainable forest development of Canada's forest both nationally and internationally; space-based earth observation technologies are used to create products for forest inventory, forest carbon accounting, monitoring sustainable development, and landscape management	http://eosd.cfs.nrcan.gc.ca/
Earth System Science Partnership (ESSP)	2001, DIVERSITAS, International Geosphere-Biosphere Programme (IGBP), International Human Dimensions Programme on Global Environmental Change (IHDP), World Climate Research Programme (WCRP)	The ESSP brings together researchers from diverse fields and from across the globe to undertake an integrated study of the Earth system: its structure and functioning; the changes occurring to the system; and the implications of those changes for global sustainability	http://www.essp.org/
Millennium Ecosystem Assessment (MA)	2001, United Nations	International work program designed to meet the needs of decision makers and the public for scientific information concerning the consequences of ecosystem change for human well-being and options for responding to those changes	http://www.millenniumassessment.org// en/index.aspx

LANDSCAPE ECOLOGY

The traditional focus of forest ecology, management, and planning has been primarily on separate landscape elements such as homogeneous forest stands or habitat patches. The importance of interactions among different elements in a landscape was noted in the early 1980s (Forman, 1981), coincident with the need for forest management strategies to consider landscape structure as a requirement for long-term conservation of biodiversity (Noss, 1983; Risser et al., 1984). It has since become generally accepted that the structure of the landscape influences the ecological processes and functions that are operating within it (Haines-Young and Chopping, 1996). The discipline of *landscape ecology* is now widely recognized as a distinct perspective in resource management and ecological science.

The central goal of landscape ecology is the investigation of the reciprocal effects and interactions of landscape patterns and ecological processes (Turner, 1989). Fundamental to such investigation is the awareness that landscape observation is scale dependent, spatially and temporally, with different landscape patterns and processes discernible from different points of view and time that are specific to the organism (e.g., trees vs. earthworms) or the abiotic process (e.g., carbon gas fluxes) under study (Perera and Euler, 2000). A brief overview of general scale considerations is included in this introductory section; Coops et al. (Chapter 2, this volume) present concrete spatial data selection issues related to scale.

Landscape Structure, Function, and Change

When studying the ecology of landscapes, at least three basic elements must be considered and understood: structure, function, and change (Forman, 1995; M. Turner, 1989). Landscape *structure* generally refers to the distribution of energy, material, and species. The spatial relationships of landscape elements are characterized as landscape pattern in two ways (McGarigal and Marks, 1995; Remmel and Csillag, 2003). First, the simple number and amount of different spatial elements within a landscape is generally defined as landscape composition, and this measure is generally considered to be spatially implicit. Second, the arrangement, position, shape, and orientation of spatial elements within a landscape are generally defined as landscape configuration, which is a spatially explicit measure. Within the framework of this book, this meaning of landscape pattern is used to ensure that both the amount and arrangement of spatial elements of interest are included. In contrast, some studies equate landscape pattern strictly with configuration and treat composition as a second landscape characteristic unrelated to pattern (e.g., Martin and McComb, 2002; Miller et al., 2004).

A landscape can be defined as a spatially complex, heterogeneous mosaic in which homogeneous spatial elements or patches are repeated in similar form over an area bounded by the spatial scale at which ecological processes occur (Urban et al., 1987). For example, juvenile dispersal distance has been used to estimate the spatial extent of landscapes in forest birds (Villard et al., 1995); in another example, a third-order watershed could be the appropriate landscape for consideration of water flow and quality (Betts et al., 2002). Mosaic patterns exist at all spatial scales from submicroscopic to the planet and universe and the type, size, shape, boundary, and arrangement of landscape elements across this mosaic influence a variety of ecological functions.

Landscape *function* generally refers to the flow of energy, materials, and species and the interactions between the mosaic elements (Forman, 1995). Examples range from fundamental abiotic processes, such as cycling of water, carbon, and minerals (Waring and Running, 1998), to biotic processes, including forest succession (Oliver and Larson, 1996), and the dispersal and gene flow of wildlife (e.g., Hansson, 1991). Such biotic and abiotic flows are determined by the landscape structures present, and in turn, landscape structure is created and changed by these flows. The main processes or flows generating landscape structure formation and landscape *change* over time can be considered as natural and anthropogenic disturbances (e.g., wildfire, insect infestation, harvesting); biotic processes (e.g., succession, birth, death, and dispersal); and environmental conditions (e.g., soil quality, terrain, climate) (Levin, 1978). An overview of some of these processes in the forest environment is presented in a subsequent section of this chapter and in later chapters discussing specific disturbance processes.

Forest Management

The goals of forest management have expanded in recent decades to include values leading to the implementation of different strategies based on concepts of sustained yield, multiple use, and more recently, ecosystem management. Ecosystem management includes the balancing ecological and social (economic and noneconomic) forest values in the context of increasing population growth, resource use, pollution, and the rate and extent of ecosystem alteration (Kimmins, 2004). Concepts of natural disturbance emulation encompass the idea of trying to arrange changes in forests due to human disturbance to more closely approximate those induced by natural processes (Attiwill, 1994; Hunter, 1990). This is an acknowledgment of disturbances as one of the fundamental processes and drivers of landscape structure and functioning at all spatial and temporal scales in the field of landscape ecology (Turner, 1987). Principles of landscape ecology help to make this forest management approach a viable management option by providing a higher-level context for forest management practices (Crow and Perera, 2004).

Emulating natural disturbance aims to guide local forest management by mimicking the natural range of spatial and temporal variation in landscape- and stand-level forest landscape structures created by past natural disturbances in the given location (Bergeron et al., 1999; Hunter, 1999; Kimmins, 2004). The presettlement landscape allowing for natural dynamism is thought to be the ideal condition against which contemporary landscape diversity and composition ought to be evaluated (Noss, 1983; Seymour and Hunter, 1999). The natural disturbance approach builds on the underlying assumption that forest ecosystems, long-term forest stability, and biodiversity will be sustained if the forest structures created by natural disturbances are maintained since they reflect the same conditions under which these ecosystems have evolved (Bunnell, 1995; Engelmark et al., 1993; Hunter, 1990). For example, Hudak et al. (Chapter 8, this volume) provide a case study perspective of forest harvest and fire disturbance patterns in an area where both disturbances are known to have occurred.

Consideration of the ecological effects of spatial patterns created by forest harvesting is important for the management regime (Franklin and Forman, 1987), and the patterns and processes in landscapes created by natural disturbances generally display greater variation in time and space than traditional silviculture and forest management (Seymour et al., 2002). Disturbance regimes can be described by a variety of characteristics; however, the main components include magnitude, timing, and spatial distribution (Seymour and Hunter, 1999), and each of these will have an impact on the stand- (or patch-) and landscape-level of the forest ecosystem. Magnitude generally describes the intensity or the physical force of the disturbance or the severity of the effect of the disturbance on the landscape element or organism (Seymour and Hunter, 1999; Turner et al., 2001). Timing of a disturbance mainly specifies the frequency, which is often expressed not only as the return interval between disturbances, but also as the duration and seasonality of a disturbance type (Seymour and Hunter, 1999). The spatial distribution of a disturbance refers to the extent, shape, and arrangement of disturbance patches (Seymour and Hunter, 1999).

A review by Seymour et al. (2002) of disturbance regimes in northeastern North America contrasts the differences in aspects of these three main characteristics (magnitude, timing, and spatial distribution) by comparing wildfire with pathogens and insect herbivory. In the investigated cases, wildfires were of stand-replacing magnitude, with a return interval of 806 to 9000 years and a disturbance patch size distribution ranging between 2 and more than 80,000 ha, while pathogens and insect herbivory disturbance was of a magnitude to create smaller canopy gaps, with a return interval and patch size distribution ranging between 50 and 200 years and between 0.0004 and 0.1135 ha, respectively (Seymour et al., 2002; Figure 1.1).

While the natural disturbance approach may be an ecologically sound premise, its constraints and limitations also need to be considered. Some issues to address in the future include (a) society's reluctance to accept this paradigm in ecosystems that experience disturbances that are very large, severe, and frequent; (b) whether past disturbance regime effects will be rendered inapplicable in the future due to long-term climatic variation, invasion of nonnative species, air pollution, human-induced climate change (Kimmins, 2004); and (c) the difficulty in obtaining and interpreting historic disturbance data for adequate conclusions about the natural disturbance characteristics (Appleton and Keeton, 1999).

SCALE

Every organism is an "observer" of the environment, and every observer looks at the world through a filter, imposing a perceptual bias that influences the recognition of natural systems (Levin, 1992). Science, in general, can be seen as a product of the way the world is seen, constrained by the space and time within which humans inhabit the world (Church, 1996). There is little doubt that ecologists' perceptions have been revolutionized through availability of satellite imagery; for example:

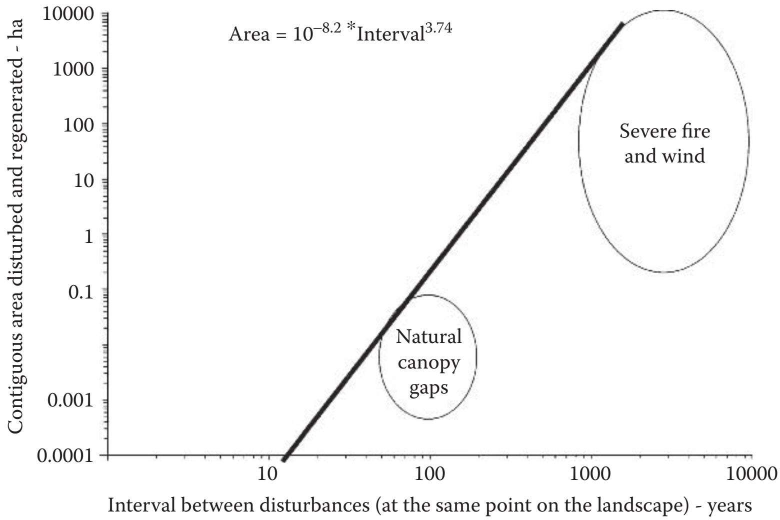

FIGURE 1.1 Boundaries of natural variation in studies of disturbance in northeastern North American forests. The hand-fitted diagonal boundary line defines the upper limits on these disturbance parameters in combination, all of which fall in the lower right of the diagram. Upper limits of the area and return interval of severe fires and windstorms were truncated at 10^4 Ha and 10^4 years, respectively. (Adapted from Seymour et al., 2002.)

- "Images from satellites have revolutionized our perception and approaches to understanding landscapes and regions" (Forman, 1995: p. 35)
- "More than any other factor, it was this perspective provided by satellite imagery that changed the … manager's views about the main threats to the panda's survival" (Mackinnon and de Wulf, 1994, p. 130)

Scale is a strong determinant of viewing, and interpreting the environment and the interest in scale-related research is rapidly increasing (Schneider, 1994). Scale is often understood simply as dimensions of time and space, but has been defined in various more complex ways; for example, Church (1996) considered scale as a relative measure set by the resolution of measurements. Schneider (1994, p.3) defined scale as "the resolution within the range of a measured quantity." Common to all scientific definitions of scale, however, is a recognition of the temporal and spatial dimensions (Lillesand and Kiefer, 2000; Wiens, 1989).

Spatial Scale

In ecology, spatial scale is usually considered as the product of *grain* and *extent* (Forman, 1995; Wiens, 1989), which, in remote sensing, relate to *resolution* (pixel size) and *area of coverage,* respectively (Lillesand and Kiefer, 2000). A remote sensing scientist will typically define spatial scale as a proportion, a ratio of length on a map to actual length. Small scale, therefore, suggests that a large area is covered; in other words, the difference between actual and mapping size is great (coarse spatial detail). An ecologist's typical definition of spatial scale is the level or degree of spatial resolution and spatial extent perceived or considered. Ecologists understand a small-scale study to encompass a small area with fine spatial detail. Overall extent and grain define the upper and lower limits of resolution of a study; they are analogous to the overall size of a sieve and its mesh size (Wiens, 1989). The spatial scale at which measurements or observations are taken influences the recognition of spatial patterns and underlying processes of the environment and of the organisms under study (Wiens, 1989); this has been called *intrinsic* scale, which may determine the type of spatial patterns observed. "The intrinsic scale is a property of the ecological process of interest, for example, tree fall, competition, stomatal control, or microclimate feedbacks, and it is governed in part by the size of the individual organisms (or events) and in part by the range of their interactions with their environment" (Malingreau and Belward, 1992, p. 2291). Others (e.g., Hunsaker et al., 2001) have been keen to understand the *uncertainty* associated with spatial data at different scales.

Remotely sensed imagery is an optimal way to collect spatial data across multiple nested or hierarchical scales; imagery can provide synoptic coverage over large areas, enabling investigations at the landscape scale, or more detailed imagery can be collected representing smaller areas, most practically through some form of sampling framework. As always, limitations exist in the quantities of spatial resolution and area of coverage that can be obtained. Spatial resolution of imagery depends on the sensor spectral sensitivity, and the instantaneous field of view, while the area of coverage depends on the satellite or airborne altitude (swath width) and the instrument total field of view (Lillesand and Kiefer, 2000; Richards and Jia, 1999). Landsat satellites typically cover an area of 185 × 185 km with a sensor spatial resolution or pixel size of 30 × 30 m for most of the spectral bands; other satellites carrying Advanced Very High Resolution Radiometer (AVHHR) sensors cover an area of 2394 × 2394 km with a spatial resolution of approximately 1.1 km. More details on these fundamental concepts are presented in Chapter 2 of this volume.

Temporal Scale

Temporal scale refers to the frequency with which an observation is made (Lillesand and Kiefer, 2000), but similar to the spatial scale, it is made up of two components; the temporal resolution and the temporal extent. The key to temporal scale is change over time, and this pattern or trend may change with hours, days, months, years, or centuries. Depending on the research question and the object under study, the temporal scale of the investigation can be very different. For each source of imagery, the temporal resolution — a sensor-specific component of scale — must be quantified. Satellites passing frequently over the same area translates into a higher temporal resolution for a given sensor package; for example, the temporal resolution is 24 days for Indian Resource Satellite (IRS)–P2 satellites (Richards and Jia, 1999), but 1 day for satellites carrying the AVHRR (Malingreau and Belward, 1992). In addition, the original start of data collection for different sensor packages determines the maximum possible temporal extent of any earth observation study. Operable satellites launched many years ago translate into a higher temporal extent; for example, the

IRS-P2 satellite was launched in October 1994 (Richards and Jia, 1999), while AVHRR satellites were launched in several National Oceanic and Atmospheric Administration series between June 1979 and May 1991. Clearly, the ability to monitor frequent landscape changes at the temporal scale desired (e.g., daily) may be limited by the temporal resolution and extent of a given satellite platform.

Research Design and Interpretation

Understanding the effect of scale on the detection and understanding of patterns and causal mechanisms is one step toward the development of common ecological theories within scales (Wiens, 1989). There is no single proper scale at which all sampling ought to be undertaken (Levin, 1992; Wiens, 1989), and there are no simple rules to select automatically the appropriate scales of attention (Meentemeyer, 1989). Ecological structure, function, and change are dependent on spatial and temporal scale (Turner, 1989). The identification of the appropriate scale to use will depend on the organism or phenomenon under investigation. A species- or phenomenon-centered approach, with recognition of its intrinsic scale to the identification of structure, is most relevant in the research design and analysis of forest landscapes.

Arbitrary scale choices can be avoided by analyzing the variance of measurements across many scales using techniques such as the nearest neighbor method (Davis et al., 2000), semivariance analysis (Meisel and Turner, 1998), and several other univariate (spatial correlograms and spectral analysis) and multivariate methods (Mantel test and Mantel correlogram; Legendre and Fortin, 1989). Statistical approaches are typically based on the observation that variance increases as transitions are approached in hierarchical systems (O'Neill et al., 1986). Peaks of unusually high variance indicate scales at which the between-group differences are especially large, which suggest the representation of the scale of natural aggregation or patchiness of vegetation (Greig-Smith, 1952) or organisms; this is sometimes referred to as the boundary of a scale domain (Wiens, 1989). A method of identifying the appropriate scale of remotely sensed imagery uses a high spatial resolution image characterized statistically and then subsequently collapsed to successively coarser spatial resolutions while calculating local variance (Woodcock and Strahler, 1987). The image resolution at which local variance is highest can be deemed the appropriate remote sensing scale in relation to the structural components of the ground.

PROCESSES GENERATE PATTERNS

Remote sensing of terrestrial ecosystems in support of resource management involves identifying ecosystems and their biological, ecological, and physical characteristics (Franklin, 2001). The definition of an ecosystem and the relevant characteristics vary with the resource managed and the issue under consideration. Therefore, the expectations that ecologists might have of remote sensing will vary; for example, species composition and the physical arrangement of the vegetation can be remotely sensed and used to describe or infer ecosystem attributes using straightforward methods and readily available data. Advances in remote sensing technology continue to expand the capacity to monitor changes of interest in ecosystems and resource management (Wulder et al., 2004). Forest ecosystems change over time because the trees must grow to survive, due to competition among trees, interactions among trophic levels, and large-scale disturbances. Certain aspects of the current state of ecosystem dynamism can be inferred from individual, remotely sensed images, and other aspects can only be assessed using a time series of images. In this section, we provide ecological background on the remote sensing of ecosystem attributes with special attention to the dynamic nature of these ecosystem attributes, the landscape structure, and composition.

Forest Stand Dynamics

Current understanding of patterns and processes of stand development have been fully described by Oliver and Larson (1996). Their synthesis is useful as a basis for understanding the potential contributions of remote sensing. *Disturbance*, meaning the death of trees that frees growing space, is fundamentally important for stand development. Oliver and Larson (1996) distinguished between autogenic and allogenic forms of disturbance; *autogenic* processes cause death of individual trees for reasons that are particular to the tree and ecosystem, and *allogenic* forms of disturbance arise outside of the affected trees or ecosystem. For ease of explaining the processes involved in stand dynamics and the stand structures that result, Oliver and Larson first described long-term stand development following a major disturbance, including autogenic processes responsible for death of trees, and then incorporated the impacts allogenic forms of disturbance imposed on this underlying pattern of stand development. Oliver and Larson pointed out that stand development has been investigated from two perspectives, one based on describing stand structures and the other based on understanding stand developmental processes. The latter approach has great value to resource management because it leads to greater capacity for predicting changes to stands over time. Individual remotely sensed images may be well suited to the stand structural approach to understanding stand dynamics, while stand development typically requires multitemporal resolution imagery. Ecological knowledge must be used to interpret the remotely sensed images to ensure maximum information extraction occurs from available remotely sensed data (Graetz, 1990).

Forest ecosystems pass through four stages during the course of stand development (Figure 1.2). The period immediately following a major disturbance is the stand initiation stage. During this stage, the important process in stand dynamics is the establishment of a cohort of vegetation. New vegetation becomes established when the preexisting vegetation is killed; the number of species and the number of plants that establish themselves and grow to fill the unoccupied growing space depends on the ecoclimatic zone, site capacity to supply essential materials (nutrients and water), and the relative amount of growing space that is made available and the manner in which it is made available. The period of recruitment ends when the community of trees first comes to fully occupy the available growing space. At this time, the ecosystem enters the stem exclusion stage. Competition among established trees is the dominant process affecting ecosystem development and structure during the stem exclusion stage. Inherent differences among species affect the course of competition and consequently the stand structures that develop. Virtually no growing

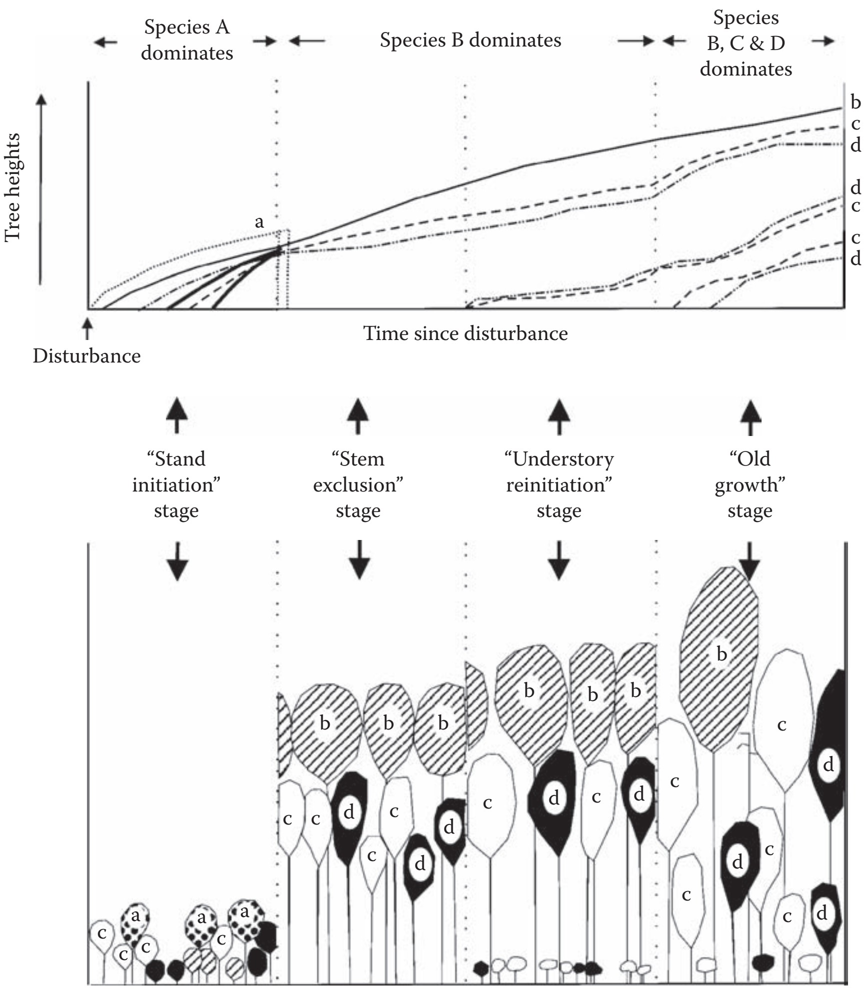

FIGURE 1.2 Schematic stages of stand development following major disturbances. All trees forming the forest start soon after the disturbance; however, the dominant tree type changes as stem number decreases and vertical stratification of species progresses. The height attained and the time lapsed during each stage vary with species, disturbance, and site. (Adapted from Oliver and Larson, 1996.)

space becomes available for the establishment of additional trees as the result of density-dependent mortality (competition). At about the time that the height growth of successful competitors becomes negligible, these trees begin losing their ability to maintain their "grip" on the growing space. This diminished capacity might be abetted by disease or the activities of insects commonly found in the ecosystem and eventually some trees die.

Species that have been less successful in competing in previous years may now expand to fill the vacated growing space and consequently come to dominate the overstory. However, if some of the growing space that comes available is captured by