The Economics of Forest Disturbances

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Editors

The Economics of Forest Disturbances

Wildfires, Storms, and Invasive Species

Springer

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FOREWORD

by Peter J. Roussopoulos, Director, Southern Research Station

The world and its ecosystems are repeatedly punctuated by natural disturbances, and human societies must learn to manage this reality. Often severe and unpredictable, dynamic natural forces disrupt human welfare and alter the structure and composition of natural systems. Over the past century, land management agencies within the United States have relied on science to improve the sustainable management of natural resources. Forest economics research can help advance this scientific basis by integrating knowledge of forest disturbance processes with their economic causes and consequences.

As the twenty-first century unfolds, people increasingly seek the goods and services provided by forest ecosystems, not only for wood supply, clean water, and leisure pursuits, but also to establish residential communities that are removed from the hustle and bustle of urban life. As vividly demonstrated during the past few years, Santa Ana winds can blow wildfires down from the mountains of California, incinerating homes as readily as vegetation in the canyons below. Hurricanes can flatten large swaths of forest land, while associated floods create havoc for urban and rural residents alike. Less dramatic, but more insidious, trees and forest stands are succumbing to exotic insects and diseases, causing economic losses to private property values (including timber) as well as scenic and recreation values. As human demands on public and private forests expand, science-based solutions need to be identified so that social needs can be balanced with the vagaries of forest disturbance processes.

Forest economics and allied disciplines can help provide solutions to natural resource management problems by linking policy questions to valuation frameworks. Utilizing the insights from biological, sociological, physical, and atmospheric sciences, economists can add value to forest policy decisions by identifying the trade-offs implicit in alternative policy scenarios. And, as economists are ever cognizant of the importance of budget constraints in making decisions, economic analysis provides insights into the efficient allocation of scarce resources to satisfy the needs of society.

Given the preponderance of natural disturbances currently affecting forests and human communities, *The Economics of Forest Disturbances: Wildfires, Storms, and Invasive Species* is a timely book. Its impact derives both from its presentation of a unifying framework for conducting economic analyses and through its careful explanations of the latest research advances. It is my hope that this book will contribute to an appreciation for the scientific issues raised by the study of forest disturbances and the techniques used by resource economists to understand them. Furthermore, I hope that these chapters stimulate new thinking about the means by which landowners, communities, and governments may become more efficient and effective stewards of the forests they treasure.

PREFACE

As Hurricane Ivan bore down upon the cozy mountain setting of Asheville, North Carolina in late September, 2004, a dedicated team of resource economists gathered to pool their knowledge about the measurement and management of forest based disturbances. Barely one week after Hurricane Frances drenched the region and, anticipating the potential chaos of downed trees, flooding, power outages, food and water shortages, and closed facilities, a decision was made to evacuate to a more hospitable location. In the end, the city was spared significant damage, and our flight appears to have been more precautionary than essential. Our disrupted meeting, however, provides a cogent example of the challenges faced by managers who must make forest protection decisions before the ultimate state of nature, ranging from brutal to benign, is revealed.

Forest protection efforts attempt to reduce the probability and/ or consequences of forest disturbances. Management interventions are costly, requiring significant financial outlays for activities such as aerial surveys, insect trapping, forest thinning, fuel reduction, fire suppression, insect and disease eradication, biological control, timber salvage, and ecosystem restoration. Decisions regarding when and where to incur these expenses are complicated by the fact that the timing and spatial extent of forest disturbances are highly stochastic and difficult to predict. Although the economic and ecological impacts of forest disturbances can be catastrophic, economically significant disturbance events typically occur with low probabilities in locations that are not well known in advance.

During the past decade, resource economists in government and academic institutions have made significant progress in defining and understanding the economic dimensions of forest disturbance processes, and the *raison d'être* for this book is to synthesize the most recent advances in this emerging field of applied economics. It is our premise that microeconomic theory provides a natural foundation for the integration of disturbance ecology with an array of empirical methods that can be used to illuminate the often subtle linkages between forest protection efforts and social welfare. As evidenced in many chapters of this book, this integration requires forays into econometrics, statistics, operations research, market and non-market valuation, and institutional analysis. The authors of this book have individually published in many of the premier peer reviewed journals in natural resource economics, forestry, and atmospheric science, and their work collectively represents hundreds of years of experience in characterizing and analyzing forest disturbances. The book that we have jointly created will, we hope, stimulate thought and further research.

This book was written so that policy-makers, managers, researchers, and students of natural resource economics could rapidly gain familiarity with this field of study. While some of the chapters are quite technical, and some sections of various chapters demand familiarity with advanced concepts, each chapter contains an introduction and conclusion that we hope are accessible to interested readers, and provide the essential messages.

For researchers interested in natural disturbances, this book provides both conceptual approaches and empirical methods that could be applied and advanced in future work. We strongly encourage contact with chapter authors when questions or new ideas arise, and encourage collaborative efforts in new research projects.

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SECTION I

THE ECONOMICS AND ECOLOGY OF FOREST DISTURBANCES

CHAPTER 1

AN INTRODUCTION TO THE ECONOMICS OF FOREST DISTURBANCE

Thomas P. Holmes, Jeffrey P. Prestemon, Karen L. Abt

1. FOREST DISTURBANCES AND ECONOMIC SYSTEMS

Increasing severity of recent wildfires, storms, pest outbreaks, and biological invasions has intensified concern among governmental agencies, private enterprises, and the general public regarding the future of forest resources. Economic analysis can help decision-makers understand the causes and consequences of forest disturbances, as well as evaluate trade-offs, and set priorities. It is the premise of this book that similarities existing among forest disturbances permit the development of a unified framework for economic analysis. This book sketches out how this framework could be constructed, provides an overview and summary of current research in the economics of forest disturbances, and illustrates how economic theory and empirical methods can be applied to address specific disturbances.

From an economic perspective, a forest disturbance can be defined as an event that interrupts or impedes the flow of goods and services provided by forest ecosystems that are desired by people. This definition parallels the ecological definition of a natural disturbance as "…any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment" (White and Pickett 1985, p. 7). Although timber harvesting and land use change are forest disturbances according to this definition, in this book we address large-scale natural disturbances that can be mediated and modified by human actions. Examples of such large-scale natural forest disturbances occurring during the past century include the chestnut blight which largely eliminated chestnut trees from hardwood forests in the eastern United States, Hurricane Katrina which blew down large swaths of forest in the United States Southeast, and the 1988 fires in Yellowstone National Park and surrounding forest ecosystems that burned more than one-quarter million hectares.

Catastrophic disturbances affect both public and private land, and the management interventions applied to mitigate damages will vary depending on the

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objectives of the land manager. Management interventions are typically made with at least one of two goals in mind: (1) reducing the probability (risk) of an unwanted state of nature, and/or (2) reducing the negative consequences if an unwanted state of nature occurs. Interventions can be made prior to (prevention), during (suppression/eradication), or subsequent to (restoration/recovery) a natural disturbance event. Although interventions can be viewed as an optimal capital management problem from the perspective of a private timber manager (chapter 3), this book focuses attention on the economic analysis of interventions by public land managers and policy makers in forest disturbance processes, keeping in mind that public forest health protection programs are often designed to alter the behavior of private forest owners (chapter 19).

Although the use of economic analysis to inform decisions about the optimal level of public investment in forest protection is not new (chapters 16 and 18), the modern practice of forest disturbance economics continues to pose challenges. First, inference and prediction regarding future forest disturbances are characterized both by high variability (fluctuations not explained by deterministic processes) and uncertainty (limited knowledge of model parameters). Rigorous mathematical, statistical, and econometric models are required to address these special characteristics of forest disturbance production. Second, many of the effects of forest disturbances fall upon non-timber goods and services, such as outdoor recreation or aesthetic views. Because few non-market economic studies of disturbances have been conducted to date, and the current level of understanding of these impacts is limited, existing estimates of economic damages from forest disturbances may be severely biased by the lack of information on non-market impacts. Third, understanding the linkages between the costs of management interventions and changes in the net economic benefits provided by forest ecosystems is challenging because of the time lag between interventions and changes in the provision and value of ecosystem services. Consequently, empirical examination of the effects of protection investments requires long time spans, large data gathering efforts, and careful and innovative scientific enterprise.

To motivate subsequent analysis, the following section presents a broad characterization of various classes of forest disturbances and describes how specific disturbance characteristics constrain the set of management interventions that can be employed to mitigate economic impacts. Section 3 then provides an overview of the major lessons learned and presented throughout the remainder of the book. The chapter concludes in section 4 by offering suggestions for future research.

2. FOREST DISTURBANCE CHARACTERISTICS

Forest disturbances can be classified in three broad categories (table 1.1): abiotic events (storms, landslides, volcanoes, droughts, and floods), biotic events (insects, diseases, and invasive plants), and wildfires (a mix of abiotic and biotic disturbances). We further characterize forest disturbances using four key variables that

Table 1.1. Characteristics of forest disturbances and list of book chapters containing applied economic analysis.

Disturbance Type	Disturbance Sub-Type	Rate of Spread	Maximum Spatial Scale	Endogenous or Exogenous	Forest Management Strategy	Book Chapter
Abiotic						
Storms	Tornado	Hours	Small	Exogenous	None	—
	Hurricane	Hours → days	Very large	Exogenous	Salvage	11
	Straight-line wind	Hours→ days	Large	Exogenous	Salvage	—
	Ice	Hours→ days	Very large	Exogenous	Remove hazard trees	—
Volcanoes	n/a	Hours→ days	Large	Exogenous	Restore	—
Floods	n/a	Hours→ months	Medium	Exogenous	Restore	—
Drought	n/a	Months→ Years	Very large	Exogenous	Restore	—
Biotic						
Invasive plants	n/a	Years→ centuries	Very large	Exogenous	Eradicate	—
Pests	Exotic Insects and Diseases	Years→ centuries	Very large	Exogenous	Eradicate; slow spread; pre-emptive harvest; bio-control; salvage	2, 3, 11, 19
	Native Insects and Diseases	Months→ years	Large	Endogenous	Shorten rotation; genetic selection; chemicals; salvage	2, 3, 19
Mixed						
Wildfire	All Ignition Sources	Hours→ months	Large	Endogenous and exogenous	Suppress; reduce fuels; salvage; restore	2-18

influence economic costs and losses: rate of spread, spatial scale, whether the source of the disturbance is endogenous (inside) or exogenous to (outside) the forest, and forest management strategies employed to mitigate impacts. Forest disturbances are of interest to economists when their frequency and size are consequential enough to induce a management or policy response, and economic analysis of forest disturbance generally seeks to identify the optimal level of intervention in disturbance processes by balancing costs and losses. Our classification scheme recognizes that the scope and type of interventions available are a function of their biotic or abiotic nature, spread rate, and sources.

2.1 Abiotic Disturbances

Abiotic disturbances are characterized as deriving from energy sources originating outside of forests, and include climatic and geologic disturbances. Abiotic disturbances are stochastic and difficult to predict far in advance. Neither the probability of occurrence nor the magnitude of effects on forests can be significantly influenced by forest management. Although manipulation of stocking density or species selection may have some effect on reducing damage from abiotic events (Wilson and Baker 2001), the main forest management strategies are to salvage timber and restore landscapes and ecosystems.

2.1.1 Climatic events

Long-term climate change, acting as a slowly changing parameter that conditions the dynamic behavior of fast moving variables, can affect the entire constellation of forest disturbance processes including fire, drought, introduced species, insect and disease outbreaks, hurricanes, windstorms, ice storms, and landslides (Dale et al. 2001). Recognizing this, here we review the fast climatic events that affect forests—tornadoes, ice storms, hurricanes, droughts, and floods.

Tornadoes may damage tens to hundreds of hectares of forest cover (Glitzenstein and Harcombe 1988, Harcombe 1988, Peterson and Pickett 1995), and therefore may have a substantial impact on individual forest owners. However, they are generally too small and infrequent to have an impact on aggregate economic welfare. In contrast, straight-line winds occasionally have large-scale, catastrophic impacts, such as the July 4, 1999, blowdown that damaged 57,000 hectares of forest in the Boundary Waters Canoe Area in northern Minnesota (Schulte and Mlandenoff 2005). Other recent examples can be found in Europe (Nilsson et al. 2004). Tropical cyclones (typhoons and hurricanes) can also cause catastrophic forest damage, as was the case with Hurricane Hugo, which destroyed 1.8 million hectares of forest in South Carolina (Sheffield and Thompson 1992). Large scale climatic events can have substantial economic impacts on timber markets (chapter 9) and, additionally, can cause non-market economic losses to residential properties, public parks, and rural landscapes.

Large, damaging ice (or glaze) storms are infrequent, although they can occasionally cause tree damage over millions of hectares of urban and rural forests (Smith 2000). Management interventions typically focus on the decision of whether or not to remove damaged trees.

Major, infrequent floods can cause tree mortality if soils are saturated long enough to create anoxic conditions, which cause tree roots to die. This was the case in the Midwest flood of 1993 on the upper Mississippi River, which caused extensive mortality to trees and shrubs in the floodplain (Sparks et al. 1998).

Severe droughts can also induce economic costs and losses on forested properties, and impacts on urban forests and residential properties can be particularly severe. For example, the drought of 1934 killed about 25 percent of the trees and injured another 25 percent of the trees in Manhattan, Kansas (Stiles and Melchers 1935). The loss of aesthetic value, shading, and other non-market benefits of trees due to drought is compounded by the costs of removing and replacing dead and dying trees.

2.1.2 Geological events

Geological events are similar to climatic events, releasing large amounts of energy over a short time period. The two types of geological events that are most consequential to forests are volcanoes and landslides. Landslides occur in forested regions with steep topography and can be triggered by heavy rain or seismic events such as earthquakes or volcanoes. Earthquake caused landslides can be a major disturbance in tropical forests, and landslides ranging from 5,000-10,000 hectares have been observed (Veblen and Ashton 1978). Smaller landslides of less than 1 hectare may be quite common in tropical forests with steep slopes (Guariguata 1990). In the United States, landslides not associated with volcanoes are not known to influence forests to an economically significant extent.

Perhaps the best known volcanic eruption-related forest disturbance in the United States was the eruption of Mount St. Helens in southwest Washington in 1980. This eruption affected an area exceeding 70,000 hectares, including a variety of disturbances due to pyroclastic flow, tree blowdown, scorched trees, mudflows, and debris avalanches (Turner et al. 1997). Such occurrences in the volcanoes around the Pacific Rim are anticipated to occur every 100-1,000 years.

2.2 Biotic Disturbance

Biotic forest disturbances result from the propagation, growth, and spread of biological organisms that depend on forest resources to complete their life cycle. These disturbances include a diverse array of native and exotic insects, diseases, and invasive plants. Biotic disturbances are endogenous, and thus have a different suite of interventions available to affect the probability of occurrence and the extent of damages.

Invasive forest plants compete with native vegetation and can reduce the biological diversity of forest ecosystems. The growth and spread of invasive forest plants is relatively slow and predictable, and the primary control strategy is eradication followed by rehabilitation with fast-growing native plants (Miller 2003). A common invasive forest plant is kudzu (*Pueraria montana*), which is thought to cover 3 million hectares in the eastern United States and is expanding at the rate of 50,000 hectares per year (Forseth and Innis 2004).

Forest insects and diseases attack selected tree species, and pest outbreaks typically do not cause mortality to all trees in an infested area. However, population growth and spread can result in damages to public and private goods and services across broad landscapes. Because native trees have not co-evolved with exotic pests, they are particularly vulnerable to successful attack over the entire range of host species. Population growth of forest insects and diseases may follow non-linear or chaotic dynamics (Turchin 2003) and may be triggered or synchronized by atmospheric processes (Williams and Liebhold 2000, Liebhold et al. 2004). Insect and disease outbreaks may also interact with wildfire, complicating predictions of the timing, location, or intensity of biotic disturbances (Castello et al. 1995, McCullough et al. 1998).

The spatial spread of biotic disturbances occurs on time scales of years to centuries (e.g., gypsy moth), which is slow relative to the rate of spread of abiotic disturbances. This slower time scale, together with their host dependencies, permits a greater number of management strategies to be developed to combat biotic disturbances. Timber management strategies are based on the idea that the amount of timber at risk of damage or loss can be reduced by actions such as shortening timber rotations, pre-emptive harvesting of timber in anticipation of an imminent (actively spreading) insect or disease outbreak, and selection or propagation of trees with natural resistance to the pest (Cubbage et al. 2000). Other strategies can be used to protect the aesthetic and non-market values of trees and forests, such as tree removal, the application of chemicals to eradicate or slow the spread of insects or reduce the rate of disease progress on particular trees, and biological control. In the wake of biotic disturbances, timber salvage and ecosystem restoration strategies can be used to minimize short term economic impacts and restore long term economic values.

2.3 Wildfires

The temporal scale of wildfires is intermediate between biotic and abiotic disturbances—wildfires are briefer in duration than biotic disturbances but can be longer than abiotic disturbances. On a spatial scale, wildfires span more than four orders of magnitude (assuming that the smallest wildfire is in the order of 0.1 ha). Large wildfires can equal or exceed the size of most abiotic forest disturbances (except hurricanes) and yet are smaller in area than the most severe biological invasions.

As with biotic disturbances, wildfires are dependent on the availability of sufficient host material, and their extent and spread are limited by weather and climatic conditions. This dependency on host materials—fuels—provides the rationale for management strategies such as prescribed fire and mechanical fuel reduction which are applied with the goal of reducing wildfire spread and intensity. Because wildfires spread over hours to months, and because they often spread in relatively predictable directions, fire suppression can be used to limit fire sizes. Additionally, because the destructive character of large wildfires is patchy, substantial areas of forest may be killed while other areas remain relatively unharmed. Consequently, timber salvage following fire is often a viable management option. Restoration of areas burned by wildfires is also possible, mitigating negative impacts on watersheds and other future ecosystem values (Kent et al. 2003). Finally, it should be recognized that wildfires can convey benefits to fire dependent ecosystems, and the practice of letting some wildfires burn (referred to as "wildland fire use" in the United States) is becoming a more commonly accepted tool for public forest management (Doane et al. 2006).

3. OVERVIEW OF CHAPTERS

The structure of this book reflects our view that: (1) economic analyses of forest disturbance is enhanced by its congruence with ecological understanding (chapter 2); (2) forest disturbances can be modeled as stochastic economic production processes (section II); (3) consistent accounts of market and non-market economic effects of forest disturbances are pre-requisite to planning and decision-making (section III); and (4) economic models can be used to improve decisions taken to mitigate the negative economic consequences of forest disturbances and to set priorities (section IV). Below, we provide an overview of the contents of individual chapters.

3.1 Forest Disturbance Processes

From an economic perspective, forest disturbances are stochastic events that can be modeled as production processes. Some inputs into disturbance production are free (such as drought, lightning, or wind) and other inputs are purchased (such as capital and labor). The stochastic nature of disturbance processes suggests that disturbance outputs can be measured using probability distributions for metrics such as area burned or the number of large fires (chapters 2-7). By conducting statistical and econometric analyses, the economic consequences of management interventions can be identified as shifts in the stochastic distribution of disturbance events that occur in response to the application of purchased inputs.

Forest disturbances are characterized by high variance in the scale of physical and economic impacts (chapters 2-5) which can be explained by a number of factors. First, favorable site conditions for disturbance establishment and spread vary irregularly over time and space. Second, prior disturbances condition the landscape for subsequent events. Third, stochastic exogenous factors such as weather strongly influence the size of individual forest disturbances (chapters 4-6). Fourth, disturbances may be highly nonlinear in their responses to managerial and free inputs, resulting in discontinuous and catastrophic ecosystem behavior (chapter 2).

The processes that govern forest disturbances also include human caused wildfire via unintentional (e.g., campfires and debris burning escapes) and intentional behavior (arson). Arson wildfires can be understood as a production process involving a combination of weather and climate-dependent fuel conditions, economic variables, penalties, and psycho-social phenomena (chapter 7). Consequently, law enforcement and public education campaigns may be effective at reducing the frequency of arson and accidental fires. Managers may be able to mitigate the impacts of arson and other human caused fires through fuels management and pre-positioning of suppression resources.

3.2 Valuing the Economic Impacts of Forest Disturbances

The perspective presented in this book is that a full accounting of the costs and economic losses due to forest disturbances is prerequisite to effective planning and priority setting. The first step is to establish a consistent accounting and data collection framework (chapter 8). Economic systems are connected over time and space—many goods and services are substitutes and complements in consumption, and many inputs are substitutes and complements in production—and economic assessments are sensitive to spatial scale (geographic area to be assessed), temporal scale (time span used to assess impacts), and sectoral scale (economic sectors to be included). Economic assessments need to be conducted across multiple scales, and decision-makers need to be informed of the sensitivity of economic measures to the scale at which economic models are applied.

Forest disturbances such as insect epidemics, hurricanes, and wildfires can have extreme impacts on markets for goods obtained from forests. In timber markets, timber losses and damages affect economic equilibria, both through the pulse of timber salvaged from an event and through reductions in stocks of standing timber (chapter 9). Economic welfare is redistributed after a catastrophic forest disturbance, with some economic agents gaining (e.g., consumers of wood products in the short-term) while others lose (e.g., producers of damaged timber). Timber salvage policies instituted by governmental agencies should be sensitive to the redistributional impacts of such policies.

Forest disturbances can induce a significant loss of wealth for private property owners in the wildland-urban interface. For example, changes in risk perceptions resulting from nearby catastrophic wildfires can induce private property value losses reaching millions of dollars in a single community (chapter 11). Similarly, tree mortality caused by an exotic forest insect can cause losses in property values exceeding a million dollars in an individual community due to the loss of aesthetic values and the costs associated with tree removal (chapter 11). Because wildfires reduce the value of private residential properties, private homeowners have a substantial willingness to pay for public programs designed to protect residences and communities from wildfires (chapter 12).

Wildfires can destroy recreational infrastructure and can alter the quality of outdoor recreation sites. Although few studies have been conducted to evaluate the impact of wildfires on the demand for outdoor recreation, preliminary evidence suggests that wildfires may increase the number of Wilderness visitors in the short-run, due to an influx of curiosity-seekers (chapter 10). Over the span of several decades, however, the economic value of wilderness areas that have experienced large wildfires may decrease because of visitation reductions brought about by the loss of mature forests and the presence of less desirable forest conditions. More research is needed to understand the impacts of wildfires, storms, and invasive species on all forms of outdoor recreation.

3.3 Decision Making in Response to Forest Disturbances

Forest disturbances typically involve an element of surprise, and forest protection decisions must be made before the ultimate state of nature is revealed. A general approach to forest protection is to reduce the risk (probability) that an unwanted state of nature will occur and to take steps that would reduce negative consequences in the event that an unwanted state does in fact occur (chapter 19). One example of this approach is evidenced by the various state and local governmental agencies that have established programs to reduce wildfire hazards in high risk areas through regulations on land-uses and vegetation management (chapter 14). Another example is provided by fuel management programs implemented by private and public forest landowners, which have been shown to reduce both damages and subsequent suppression costs (chapter 13). Much may be learned by examining the successes and shortcomings of existing programs and policies.

Another approach to managing uncertainty about future conditions is to construct forecast models using the best available data. Econometric forecasts of future wildfire suppression costs provide a rigorous means of establishing budget requests by federal land management agencies (chapter 17). Econometric models can also quantify the degree of uncertainty about parameter values and test hypotheses about proposed driving variables. Loss functions can be used to compare the performance of various models and allow managers to use planning tools in ways that reflect their priorities and risk perceptions.

Economists are cognizant of the role that incentives play in decision-making (chapter 16). Incentives regarding wildfire suppression and overall fire program management influence the costs and benefits of high profile suppression efforts by federal agencies. For example, funding wildfire suppression with emergency funds provides little incentive for cost containment (chapter 16). Further, because wildfires can produce ecological benefits, recognition by incident managers of the fuel treatment or other benefits of fire could facilitate improvement of management approaches and reduce associated costs (chapters 15 and 16).

Programs designed to protect forest ecosystems are complex and include many interacting components. For example, governmental programs for fire management include components for fire prevention, detection, fuels management, suppression, and post-fire site rehabilitation. Because of the linkages and feedbacks between components, economic efficiency is compromised when analysis is conducted component-by-component (chapter 18). The development of integrated forest protection programs will likely be worthwhile but present significant challenges because they require models and tools that accurately describe the trade-offs among alternative program inputs.

Forest health protection from invasive species is a public good, in that the benefits from forest protection are shared by other members of the community. This context provides the justification for government intervention. Further, forest health protection is a weakest-link public good. The weakest-link character of forest health protection relegates the level of forest protection attained by a community to the weakest members of the community. Consequently, effective forest health protection programs require that the weakest links be strengthened by targeting information to those most likely to engage in risky behavior. In particular, information describing the weakest-link nature of forest protection should be targeted at private landowners to enhance the likelihood that they will participate in forest protection programs (chapter 19). Weakest links can be identified using economic surveys of household behavior.

4. RESEARCH NEEDS

Economic models need to account for the complexity of disturbance processes so that the efficiency and efficacy of management interventions can be realistically assessed. Nonlinear dynamics and spatial diffusion are challenging attributes of forest disturbances, and further development of statistical, econometric, mathematical, and simulation models that address management interventions across various temporal and spatial scales are needed. In particular, we suggest that research is needed that would enhance the ability to predict catastrophic changes in ecological and economic variables.

Preliminary evidence suggests that the non-market economic impacts of forest disturbances are substantial, but few studies have been conducted. Further studies of the economic damages caused by forest disturbances to private property values, to ecosystem service values provided by public and private forests, and to human health (e.g., smoke from wildfires, wildland use fires, and prescribed fires; dermatitis from caterpillars) are needed. A more comprehensive understanding of non-market economic impacts would illuminate the severity of these threats and provide a larger knowledge base for improved management decisions.

Fire and forest health protection programs need to be evaluated as integrated systems, rather than being evaluated in isolation. The wildfire program is an example, where analysis has focused on the market effects of timber damages from wildfire and wildfire suppression costs. Yet wildfire programs also encompass the outcomes from fuels management and the potential positive impacts of restoring ecosystem function and reducing future wildfire. More generally, forest disturbances such as wildfire, insect and disease outbreaks, and biological invasions interact across broad spatial and temporal scales. Economic and ecological models for integrating the various components of fire and forest health protection programs are needed and will likely lead to lower program costs and greater benefits to society.

The time lag between the imposition of a management intervention and the occurrence of a catastrophic event creates uncertainty about the efficacy of management actions. Models of decision-making under uncertainty is a key topic for future research, and models that incorporate learning as new information is revealed are needed.

Finally, data required for economic analyses of forest disturbances still need improvement. Although economists have developed specialized econometric methods for analyzing non-experimental data, the data available for analyzing forest disturbances is often inconsistent, fragmentary, or unavailable over the time spans at which disturbance processes operate. Improved coordination between economists and the data collection operations conducted within land management agencies would enhance the ability for economists to evaluate trade-offs and provide meaningful and timely information to policy-makers.

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CHAPTER 2

FOREST ECONOMICS, NATURAL DISTURBANCES AND THE NEW ECOLOGY

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1. INTRODUCTION

The major thesis of this chapter is that the economic analysis of forest disturbances will be enhanced by linking economic and ecologic models. Although we only review a limited number of concepts drawn generally from mathematical and empirical ecology, the overarching theme we present is that ecological models of forest disturbance processes are complex and not particularly well-behaved from an economic perspective. We discover that standard concepts in the economists' tool kit, such as asymptotic equilibrium and convex production, may not adequately represent the dynamic behavior of forest disturbances. Consequently, other tools for economic analysis will be required.

This chapter proceeds by first sketching out the economic problems deriving from the peculiar temporal and spatial dynamics associated with forest disturbances (section 2). Then we provide a brief overview of select topics in ecological literature supporting the view that some important forest disturbances exhibit multiple- or non-equilibrial processes and that, additionally, stochastic factors induce high variation in the spatial pattern of disturbance production (section 3). These themes are illustrated by reviewing two models: (1) the classic spruce budworm model of pest outbreak, demonstrating how the interaction of slow and fast ecosystem variables cause multiple equilibria (section 4), and (2) a cellular automata model of forest fires, which demonstrates how the local interaction of stochastic processes can generate the emergence of unconventional spatial signatures at larger spatial scales (section 5). The chapter ends with a summary of the main points and some suggestions for future research (section 6).

2. ECONOMIC EQUILIBRIUM, NON-CONVEX PRODUCTION, AND SPATIAL SCALE

Since the early decades of the twentieth century, the concepts of equilibrium and comparative static analysis (the qualitative change in equilibrium conditions in

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response to a change in a structural parameter) have been central in the development of neoclassical economic theory. Much credit for this development is due to Samuelson (1947) who emphasized that comparative static analysis needs to correspond with an underlying, asymptotic dynamic model. In the standard market model, for example, excess demand is usually thought to cause an increase in price until equilibrium is restored. This result can be found as the solution to an ordinary differential equation describing price dynamics, for which the root of the characteristic equation for the complementary function is negative (Chiang 1974, p. 472-473).[1] The resulting equilibrium is said to be asymptotically stable (Tu 1994, p. 33).

Of particular relevance to this chapter, Samuelson (1947) further recognized that some economic processes move rapidly relative to other, slow long run processes and that it is often convenient to treat slow processes (such as changes in the stock of capital) as fixed parameters while concentrating on the fast processes of economic interest (such as the level of investment, income, or employment). He goes on to note that due recognition needs to be given to the evolution of the slow variables in order to study the development of the economic system over time.[2]

In this chapter, we propose that some economically important forest disturbance processes, such as pest outbreaks and fires, result from the interaction of variables across fast and slow timescales, and that policy-relevant economic models need to recognize the impacts of long-term ecosystem dynamics on the fast behavior of economic variables. Because movement in a slow ecosystem variable (e.g., forest foliage, fuel accumulation) can induce a sudden, catastrophic eruption in a fast variable (e.g., area infested by pests, area burned) which is linked, in turn, to various economic variables (e.g., pest eradication costs, fire suppression costs, economic damages), simple comparative static analysis may provide uninformative predictions of changes in economic variables. This more complex situation arises when the root(s) of the characteristic equation describing system dynamics are non-negative, and the Implicit Function Theorem breaks down (Tu 1994,

[1] It may be recalled that the general solution to a first-order differential equation is of the form $p(t) = Ae^{rt}$ where p (say, price) is a function of time (t) and r is the root of the characteristic equation of the complementary function describing the deviation of p(t) from asymptotic equilibrium. If $r < 0$, then p(t) will asymptotically converge to the particular integral describing equilibrium as $t \to \infty$.

[2] This decomposition into slow and fast variables was also suggested by Simon and Ando (1961) regarding the aggregation of variables in a dynamic macroeconomic system. They argued that aggregation could be accomplished by classifying the variables of an economic system into a small number of sectors. Because the dynamic interactions within a sector reach equilibrium relatively rapidly, an index representing the equilibrium condition for each sector could be established and then the slower interactions between sectors could be studied.

p. 241). Intuitively, the equilibrium path is not asymptotically stable and may suddenly jump to a different domain.[3]

A recent Symposium held by the Beijer Institute of Ecological Economics in Stockholm focused attention on the implications of discontinuities in ecosystem dynamics for economic analysis, and emphasized the importance of understanding Nature's non-convexities (Dasgupta and Mäler 2004).[4] One of the themes of the Symposium was that bifurcations in equilibrium paths, representing ecological thresholds, manifest across time and therefore require dynamic analysis. Non-convexities in ecosystem production due to discontinuities are consequential for economists because, under these conditions, a decentralized price system cannot reliably guide the economy to an optimal solution and other institutions are required for efficient resource allocation (Dasgupta and Mäler 2003).[5] Fortunately, when the economic planner is confronted with discontinuous ecosystem production, optimal economic programs can be evaluated using optimal control methods (Brock and Starrett 2003, Crépin 2003, Dasgupta and Mäler 2003, Mäler et al. 2003).

Although economists are generally familiar with dynamic processes operating over time, they are less familiar with dynamic processes operating over space. Spatial dynamics have been extensively studied by ecologists who have recognized that characteristic spatial patterns in complex adaptive systems can emerge purely from interactions at the local level (Levin 2002, Chave and Levin 2003, Hastings 2004, Pascual and Guichard 2005), and the use of statistical analysis for detecting complex patterns of spatial dynamics is an emerging discipline in ecology (Gumpertz et al. 2000, Turchin 2003, Liebhold et al. 2004).

Statistical models have been productively employed in the economic analysis of management interventions to control wildfires (Davis 1965, Ward et al. 2001, Prestemon et al. 2002, Bridge et al. 2005) by recognizing that, if wildfire occurrences converge to a statistical distribution, then interventions can be evaluated by identifying corresponding changes in the parameters of the statistical distribution. Some spatial patterns associated with forest disturbances are not well-behaved in

[3] The case of the backward-bending supply curve provides a good example of an unstable equilibrium separating two stable equilibria. Small shifts in demand can cause catastrophic jumps in price and quantity (Clark 1976).

[4] A standard assumption of economic analysis is that production sets are convex, where a set is convex if the line joining any two points of the set is also entirely within the set. Non-convexities in forest production have been studied for the case of multiple local optimal solutions in a continuously differentiable multiple-use benefit maximization problem (Swallow et al. 1990) and for the case of multiple-use forest production with bifurcations occurring in the production possibility set (Crépin 2003).

[5] Standard comparative static analysis of forest protection programs that equate the marginal benefit of a management intervention with the marginal input cost may likewise provide inadequate guidance for optimal economic decisions if forest disturbance production is non-convex.

that they are scale invariant (i.e., they display self similar patterns across scales of measurement) as typified by power law relationships (Malamud et al. 1998, Chave and Levin 2003, Malamud et al. 2005). In such cases, innovative statistical methods are required to conduct economic analysis (chapter 4).

3. DISTURBANCE ECOLOGY AND THE LOSS OF BALANCE

The balance of nature paradigm has a long-standing tradition both in Western culture and in the development of ecological theory (Egerton 1973). A quasi-scientific foundation for the balance of nature perspective is found in the essay "The Oeconomy of Nature" (1749), written by the famous Swedish biologist Carl von Linné. In this article, Linneaus presents a view of nature that is divinely ordered and functions like a well-oiled machine (Worster 1994). This perspective was echoed throughout the 19th century, and can be found in the works of George Perkins Marsh (who authored the widely cited conservation classic *Man and Nature* in 1864) and Charles Darwin, both of whom accepted the view of nature as fundamentally orderly and maintaining a permanent structure (Wu and Loucks 1995).

More modern statements of the balance of nature paradigm are found in mathematical-ecological concepts such as equilibrium, stability, steady-state and homeostasis (De Angelis and Waterhouse 1987). Separation of the mathematically tractable concept(s) of equilibrium from the more vague notions of balance-of-nature has allowed ecologists to test equilibrium theories and models, at least in principle. However, even fundamental mathematical models of population equilibrium, such as density dependent regulation of population size, are often empirically untestable because the scale at which density dependence operates may be much broader than the scale at which observations are typically made (DeAngelis and Waterhouse 1987). Notably, when models of static ecosystem stability have been tested, they often fail (Wu and Loucks 1995).

Much interest in ecology has focused on thresholds and alternate stable states in ecosystems (May 1977). More than three decades ago, a critique of the equilibrium perspective of nature was advanced by Holling (1973) who argued that the classical equilibrium concept cannot account for the transient behavior observed in many ecological systems. As an alternative, he proposed a model based on the idea of resilience, which he defined as a measure of the ability of an ecosystem to absorb disturbance before flipping over to an alternative domain of attraction. In particular, Holling (1973) argued that random disturbances such as wildfires and pest outbreaks can drive ecosystems from one domain of attraction to another and he proposed that research should focus on locating the domain boundaries.

A second approach to thinking about ecosystem stability that does not rely on asymptotic equilibrium was provided by Botkin and Sobel (1975). By examining the fire history of the Boundary Waters Canoe Area (BWCA) in northern Minnesota as described by Heinselman (1973), they concluded that static stability was an inappropriate concept either for the analysis or management of fire-dependent ecosystems. They proposed a definition of stability based on θ-persistence which characterizes the bounds attained by ecosystem states (characteristics of interest such as biomass or population). In their view, the trajectory of an ecosystem is θ-persistent about state x_0 if $|x_0 - x_t| \leq \theta$ for all $t \geq 0$. Here, x_0 does not connote a state of equilibrium, but rather a state within the system. By emphasizing the bounds attained by ecosystem states, this perspective is consistent with natural variability concepts that are currently applied by resource managers to maintain biological diversity and understand human impacts on forests (Landres et al. 1999).

Along the trajectory of an θ-persistent ecosystem, various ecological states can be repeated, and thus represent recurrent states. Botkin and Sobel (1975) argue that management interventions should focus on maximizing the size of the state space that is recurrent and that minimizes the recurrence time of desirable states. They go on to argue that the satisfaction of these two conditions "is equivalent to ensuring the aesthetically desirable wilderness status—an ecosystem having maximal structural (species) diversity" (p. 636). We prefer to view this conjecture as a hypothesis and suggest that forest ecosystems in continual flux offer opportunities for economists to evaluate public preferences for dynamic, time-varying ecosystem characteristics.[6]

The shift away from a focus on asymptotic dynamics in ecology can also be found in Hastings (2004) who proposed that transient ecosystem dynamics may hold the key to long-term ecological understanding, where the term "transient" implies rapid changes in the state variable(s) of interest. An illuminating example of transient dynamics is the study of epidemics by Kermack and McKendrick (1927) who, employing a system of nonlinear differential equations, demonstrated that the outbreak and termination of an epidemic depends upon a particular set of infectivity, recovery, and death rates and a threshold population density.[7] The key to this approach was to focus attention on the time course of an epidemic and not on the asymptotic state (which is, of course, the state where the epidemic dies out and may occur where only a small proportion of the susceptible members of the population have been infected). Further, the timescale of an epidemic in humans is shorter than the average human lifespan, and it is this juxtaposition of timescales that has been identified as the essential element for understanding transient dynamics in ecosystems (Rinaldi and Muratori 1992, Carpenter and Turner 2001, Rinaldi and Scheffer 2001, Hastings 2004).

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[6] See chapter 10 for recent empirical evidence of post-wildfire wilderness demand.

[7] For an application of epidemiological methods to an invasive pathogen of trees, see Swinton and Gilligan (1996).