Chapter 1
Simulation Modeling of Forest Landscape Disturbances: An Overview

Ajith H. Perera, Brian R. Sturtevant and Lisa J. Buse

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1.1 Background

Quantification of ecological processes and formulation of the mathematical expressions that describe those processes in computer models has been a cornerstone of landscape ecology research and its application. Consequently, the body of publications on simulation models in landscape ecology has grown rapidly in recent decades. This trend is also evident in the subfield of forest landscape ecology, particularly in relation to the topic of disturbance.

A.H. Perera (✉) · L.J. Buse
Ontario Forest Research Institute, Ontario Ministry of Natural Resources and Forestry,
1235 Queen St. E., Sault Ste. Marie, ON P6A 2E5, Canada
e-mail: ajith.perera@ontario.ca

L.J. Buse
e-mail: lisa.buse@ontario.ca

B.R. Sturtevant
Institute for Applied Ecosystem Studies, Northern Research Station, USDA Forest Service,
5985 Hwy K, Rhinelander, WI 54501, USA
e-mail: bsturtevant@fs.fed.us

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Broad-scale disturbances are prevalent in forest landscapes, and sometimes they are inherent to the evolution of those systems: disturbances create patterns and heterogeneity, which in turn influence ecological processes and flows (Turner 2010). The broad spatial and temporal scales of disturbance processes substantially limit our ability to perform the kinds of manipulative experiments necessary to understand the underlying mechanisms of these processes and the spatial patterns they create in forest landscapes. Instead, we can use simulation models as a fundamental vehicle to explore and understand disturbance processes, impacts, and patterns.

As with all ecological models, the simulation models developed for forest landscape disturbances are approximations of nature; that is, they are a simplified portrayal of vastly complex biological, physical, and chemical processes that interact with each other and among scales. Such models are founded on scientific knowledge, logic, and assumptions, and typically require large arrays of spatially explicit input data. The expanding knowledge base and data available to support these models also necessitate their continuous testing, study, and improvement. Simulation modeling of some disturbance types in forest landscapes is relatively mature, whereas for others it remains in the very early stages. Still other disturbances have not yet even begun to be formulated as simulation models.

Simulation modeling of forest landscape disturbances is not only a burgeoning field of research and academic pursuit. This research effort has also led to widespread application of the resulting understanding of forest landscape disturbances in management efforts: It is becoming increasingly common to consider applications of forest landscape disturbance models in exploring and devising land management policies and strategies.

It is in this context that we explore simulation modeling of forest landscape disturbances in this book. Specifically, we examine the present state of knowledge and explore future possibilities for quantifying forest landscape disturbances at broad spatial and temporal scales. This first chapter provides an overview of the topic and a general guide to the scope and contents of the book.

1.2 The Topic

To frame the topic, it is necessary to describe, if not define, what is meant by the three major terms that form the book's title: (a) forest landscapes, (b) disturbances, and (c) simulation modeling. However, we do not intend to embark on an exhaustive review and a critique of the very large body of literature on these topics or to compare and contrast the range of terms and views therein. Such a task is beyond the scope of this chapter. Therefore, while acknowledging that there will be a diversity of views and preferences about these terms, we briefly describe them in the context of the contents of this volume.

1.2.1 Forest Landscapes

By *forest landscapes*, we mean large areas of land dominated by forest cover. From an academic viewpoint, the scale of a "landscape" is best defined from the perspective of the organisms that interact with that landscape (Allen and Hoekstra 1992). More pragmatically, landscape can be defined from the human perspective to provide insights into the processes that affect the system's dynamics at scales relevant to human decision-making. As a working definition, we adopt the description by Perera et al. (2000): a forest landscape is a large geographical unit dominated by a mosaic of forest cover types, sometimes interspersed with non-forest cover types, including those that have been altered by anthropogenic activities. In North America, the source of most of the examples in this book, such milieus include expanses of forest in boreal plains, forests in both western and eastern mountain ranges, and pine-dominated southern forests. In practice, a forest landscape is a unit of land demarcated by a specific research question and method or by a specific management goal—an ecological system that is dominated by spatially interspersed tree communities of different ages and species, and that encompasses other vegetation communities and bodies of water.

1.2.2 Disturbances

By *disturbances*, we propose a description based on those of Rykiel (1985) and Pickett and White (1985): events that cause drastic changes in the state of an ecological system (for our purposes, a forest landscape) in response to a physical or biological cause. Often, the causal agent originates outside the boundaries of the ecological system of interest and results in a *perturbation* of the minimal structure, and therefore the function, of the system (Pickett et al. 1989).

Most such disturbances are considered to be discrete events (Rykiel 1985). Given the short duration of these events, some authors describe them as "pulse" disturbances (Bender et al. 1984). In contrast, continuous and slow disruptive forces can also result in perturbations that create a stress on the system (Rykiel 1985). These have been referred to as "press" disturbances (Bender et al. 1984). Descriptions and definitions of these terms are summarized in Table 1.1. A continuous period of stress can also eventually result in perturbation of the forest landscape's state and of its minimal structure. Perturbations are also scale-related: a disturbance can cause perturbation of an individual system's subcomponents or of the whole system (Pickett et al. 1989). Extreme but rare disturbances represent a distinct category, as they destroy an entire forest landscape system and its structure. These catastrophes are termed "LIDS"—large and infrequent disturbances (Foster et al. 1998).

Regardless of the temporal aspects of a disturbance event, perturbations caused by external disturbance agents markedly exceed the ranges of fluctuations in

Table 1.1 Common terms used to define, describe, and categorize ecological disturbances

Term		Definition and descriptions	Source
Event		Any relatively temporally discrete occurrence that disrupts an ecosystem, community, or population structure and changes the resources, substrate availability, or physical environment	White and Pickett (1985)
		A physical force, agent, or process, either abiotic or biotic, which causes a perturbation (an effect or change in the system's state) of an ecological component or system	Rykiel (1985)
		A change in the minimal structure caused by a factor external to the level of interest	Pickett et al. (1989)
		The cause of a perturbation	Glasby and Underwood (1996)
		An initiating cause (a physical force, process, or event) that produces an effect (a consequence) that is greater than average, normal, or expected	Coulson and Tchakerian (2010)
Type	Abiotic	Events in the physical environment that cause an abrupt change. (White does not use the term "abiotic", but separates physical from biotic effects)	White (1979)
	Biotic	The effects of biological agents such as insect and disease outbreaks	
Origin	Autogenic	The change is driven by biological properties of the system	White and Pickett (1985)
	Allogenic	The change is driven by an external environmental "forcing" function	
Duration	Pulse	A relatively instantaneous alteration of some aspect of the system, such as the number of species (i.e., a sudden and short-term event)	Bender et al. (1984)
		A short-term, high-magnitude change in the ecological environment	Glasby and Underwood (1996)
	Press	A sustained alteration of some aspect of the system, such as species densities (ongoing or long-term)	Bender et al. (1984)
		A long-term, low-magnitude, change in the ecological environment	Glasby and Underwood (1996)

structure and function that are characteristic of the ecological system (Coulson and Tchakerian 2010). Disturbances inherent to ecological systems are termed *autogenic*, whereas those that arise outside the system are referred to as *allogenic*, even though such classifications, as is the case with the terms *endogenous* or *exogenous*, are arbitrary because disturbances are a continuum (Pickett and White 1985) and are highly dependent on the spatial and temporal scales that define the system. Given the ever-increasing extent, intensity, and variety of anthropogenic impacts on forest landscapes, it has become common to separate them from non-anthropogenic disturbances, and refer to the latter category as "natural". Not only is that distinction sometimes arbitrary, the term natural could also mean *typical* (as opposed to *atypical*), *normal* (vs. *abnormal*), and *inherent* (vs. *exogenous*), and may therefore be misleading (Suffling and Perera 2004). Forest landscape systems may be perturbed by a single disturbance agent or by several agents acting independently or interactively. Multiple serial disturbances could result in cumulative effects in forest landscapes, leading to nonlinear or unanticipated responses. Furthermore, with respect to disturbance, the line between "anthropogenic" and "natural" is inherently fuzzy, since humans modify disturbances both directly and indirectly through their actions. However, human actions are also strongly affected by social, political, and economic forces operating at scales much larger than landscapes. Within the context of this book, we acknowledge that these forces shape nearly all forest landscapes, but we do not examine these dimensions in any meaningful way (i.e., from the perspective of disturbance modeling). For this reason, we distinguish between *ecological* disturbances that occur with or without human influence, and *anthropogenic* disturbances that are the direct result of human actions.

All ecological disturbances in forest landscapes can be categorized in the context of the terms described in Table 1.1. Some examples of abiotic and biotic disturbances (White 1979) distinguished by the duration of the disturbance event (Bender et al. 1984) are provided in Table 1.2. Anthropogenic disturbances can be viewed as a third type, with their own duration: pulse (e.g., clearing of land, clear-cut harvesting) or press (e.g., pollution, recreational use).

When aggregated in space and time, various aspects of disturbance events, such as their intensity, extent, and spatial and temporal probability of occurrence, can be characteristic of certain ecological systems. These synoptic properties are termed a *disturbance regime,* which has been variously described and defined (Table 1.3) and which has been assigned a range of attributes (Table 1.4). Some reserve this term for the population characteristics of one disturbance type, whereas others include a suite of different types within a disturbance regime (Suffling and Perera 2004; Coulson and Tchakerian 2010). Individual disturbance

Table 1.2 Examples of forest landscape disturbances based on their type (*sensu* White 1979) and duration (*sensu* Bender et al. 1984)

Forest landscape disturbance trait		Duration	
		Pulse	Press
Type	Abiotic	Earthquake, lava flow, landslide, flood, windstorm, ice storm, wildfire	Drought, water table fluctuation, temperature fluctuation, soil freeze–thaw cycles, soil erosion and deposition
	Biotic	Pest outbreaks, clearing of land, flooding by beavers	Disease, low-intensity harvesting, grazing

Table 1.3 Common terms used to describe and define disturbance regimes

Descriptions and definitions	Source
Disturbance regime depends on the particular disruptive force and responses being studied; descriptors include the spatial extent, magnitude (intensity or severity), frequency, predictability, turnover rate, and rotation period	Sousa (1984)
Disturbance regime is described by distribution, frequency, return interval, rotation period, predictability, magnitude (intensity or severity), and synergistic effects	White and Pickett (1985)
Disturbance regimes are characterized by all natural and human-caused disturbance drivers that are present, their stochastic and regular spatial and temporal distributions, their intensities, and the severities of their effects on the landscape's component ecosystems, including interactions between different disturbance agents	Suffling and Perera (2004)
Disturbance regime represents the ensemble of disturbance types associated with a specific landscape environment	Coulson and Tchakerian (2010)

events that exceed the expected characteristics of a disturbance regime are termed *extreme events* (Alvarado et al. 1998).

Figure 1.1 illustrates the concept of ecological disturbance and the associated terms as they are applied within the context of this book. We identify three major components associated with the entire sequence, which we call the *disturbance process*: the cause(s), effect(s), and result(s) of a disturbance event. These components comprise the intrinsic characteristics of the disturbance agent(s), the interactions among disturbance agents and the forest landscape in time and space, and the resulting altered state of the forest landscape. These are the main domains of study in disturbance ecology, and are the focus of efforts to simulate forest landscape disturbances.

Perturbed forest landscapes recover over time, with changes occurring in landscape composition, patterns, and processes. The landscape will eventually reach a state similar to its pre-disturbance condition or, in some cases, achieve an entirely different state. The nature of the recovery process is the focus of forest succession research, whether the system characteristic being tracked is a process, a pattern, or landscape composition.

1.2.3 Simulation Modeling

By a *simulation model*, we mean (*sensu* Hall and Day 1977; Rosen 1991; Oreskes 2003) a mathematical simplification of an ecological system and its processes (here, a forest landscape and the associated disturbance processes) for the purposes of exploration, scenario-building, projection, prediction, and forecasting. By s*imulation modeling*, we mean the acts of developing or applying a simulation model. Developing a simulation model involves describing the system from a

Table 1.4 Major components of a forest landscape disturbance regime (adapted from Suffling and Perera 2004)

Aspect	Component	Description	Example
How often the disturbance occurs (refers to single disturbance agents)	Frequency	Number of events caused by a given disturbance agent per time period at a given point in a forest landscape	Five blowdown events in 250 years at a given location
The magnitude of the disturbance (refers to single disturbance agents)	Intensity	Amount of energy released by a disturbance event per unit area per unit time	Frontal intensity of a fast-moving boreal wildfire could exceed 50,000 kW m^{-1}
	Severity	Effect of the disturbance on a forest landscape	An average of 55 % of the soil's O horizon burned in one fire versus 5 % in another
	Patch size	Sizes of individual disturbance patches as well as the size distribution of all patches	In a management unit, the average wildfire size is 5000 ha and the modal size is 50 ha
Variability of disturbance (refers to single or multiple agents)	Spatial	How the disturbance varies across the landscape	Some parts of a forest landscape will have a higher incidence of wildfires than others
	Temporal	How the disturbance varies in time	In some years, insect defoliation will be more intense than in others
	Stochastic	Effects of nondeterminism in a disturbance	The characteristics of recurring windstorms will be different, even if they occur at the same place
Diversity of disturbance (refers to multiple agents)	Causal agent	Types of disturbance that occur in a forest landscape	Fires, windstorms, and floods
	Interactions: synergism and antagonism between agents	Influence of disturbance agents on one another	Synergism: a windstorm increases the intensity of a fire Antagonism: a fire decreases the severity of a subsequent insect outbreak

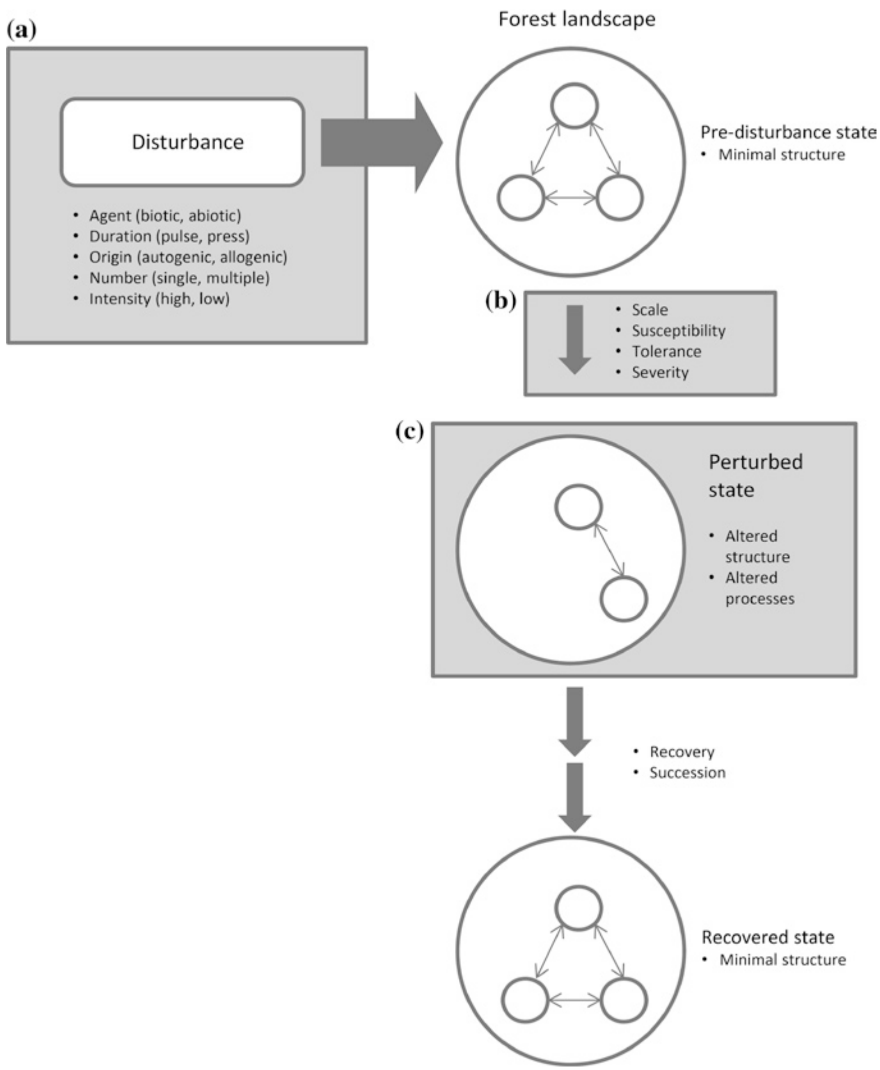

Fig. 1.1 A conceptual illustration of the major components and steps in a forest landscape disturbance process. **a** characteristics of the disturbance agent (the cause), **b** interactions between the forest landscape and the disturbance agent (the effect), and **c** characteristics of the perturbed forest landscape (the result)

reductionist perspective and including only those processes we can readily investigate and quantify. Equations that describe these processes are then encoded in computer algorithms to facilitate efficient computation, graphical visualization, and analyses of the simulated results. The degree of simplification that needs to be attained, and how and what processes are reduced to mathematical expressions, are points that are strongly debated among ecologists: some prefer simple

$$Z = f(XY) + \varepsilon$$

$$Z_{ij} = f(XY_{ij}) + g(XY_{kl}) + \varepsilon_{ij}$$

Fig. 1.2 Basic components of a forest landscape disturbance simulation model: Z = the perturbed forest landscape state, X = pre-disturbance forest landscape state, Y = characteristics of the disturbance, f = interaction between the forest landscape and disturbance, and ε = the sources of variability. A spatially explicit expression includes spatial interactions (g), a two-dimensional index of spatial variability in model components (ij), and the influence of spatial proximity (kl). Modified from King and Perera (2006)

and parsimonious models, whereas others argue for complex and detailed ones (e.g., Logan 1994; Canham et al. 2003; Evans et al. 2013). Landscape simulation models not only address broader-scale phenomena (i.e., at scales above those of individual trees and communities), they are also spatially explicit (i.e., location-specific and account for neighborhood effects). Simulating forest landscape disturbance with a model entails quantifying the characteristics and behavior of the disturbance agents, their interactions with the forest landscape (the perturbation), and the characteristics (perturbed state) of the resulting forest landscape (i.e., a, b, and c in Fig. 1.1).

Such a model expression will include the characteristics of the perturbed forest landscape as variables that are not directly measured (Z), the pre-disturbance state of the forest landscape (X) and the characteristics of the disturbance (Y) that are directly measured, their interaction as an estimated relationship (f), and sources of variability (ε). Because all forest landscape simulation models are expected to be spatially explicit, a spatial interaction term (g) is also included (Fig. 1.2).

There are two major approaches to development of a simulation model, which differ both in concept and in intent and produce models that differ in their applications: the *mechanistic* and *empirical* approaches (Korzukhin et al. 1996; Suffling and Perera 2004; Gustafson 2013). The *mechanistic* approach leads to process-based simulation models, commonly termed mechanistic models, a term we will use in this volume. This approach requires a thorough understanding of the fundamental mechanisms of disturbance and response processes, as suggested by Running and Coughlin (1988), who simulated primary physiological and hydrological processes at a landscape scale more than 25 years ago. In the context of this book, the mechanistic approach describes the physics, chemistry, and biology of disturbance agents, as well as their interactions with the forest landscape (the terms Y and f, respectively, in Fig. 1.2). Therefore, mechanistic models draw heavily on scientific knowledge developed through observations and experiments, and this knowledge forms the foundation for reducing disturbance processes to equations that include spatial interactions and temporal trajectories.

Ideally, all such equations would be based on first principles (Gustafson 2013). In practice, when we lack, or have only partial knowledge, of some aspects of the biological, physical, or chemical properties, various model assumptions are used to replace more definitive descriptions of the interaction term *f* and the sources-of-variability term ε (Fig. 1.2). Even though the individual steps, namely the disturbance (*Y*) and its interactions with the forest landscape (*f*), are known or assumed, the overall outcome of the model (*Z*) cannot be readily known given the numerous factors that influence the interactions (*Y* and *X*) and the myriad interacting steps. Thus, the outcomes of process-based simulation models are an emergent property that cannot be predicted a priori from the individual components of that model (Hall and Day 1977). When such simulations are conducted repeatedly under different conditions, with varying values for the disturbance processes (*Y*) and forest landscape characteristics (*X*), a range of outcome states (*Z*) may emerge. Thus, the modeled characteristics of a perturbed state of a forest landscape will be a probability distribution instead of a single value. This insight into the emergent stochasticity of the disturbance outcome helps modelers to understand the natural heterogeneity associated with disturbance regimes in forest landscapes, and to isolate three key aspects of that variability: its temporal, spatial, and stochastic characteristics (Lertzman et al. 1998).

The other simulation modeling method is the *empirical* approach, which leads to phenomenological models, commonly termed empirical models, a term we will use in this volume. This approach involves generalizing ecological phenomena, as illustrated by Usher's (1992) pioneering demonstration of modeling vegetation succession across a landscape. In the context of this book, empirical modeling involves quantitative descriptions of forest landscape disturbance events and regimes through empirical observations. These models draw heavily on statistical analyses of data from past disturbance events to define their effects on the processes and (mostly) on the outcomes. Here, the interaction between the forest landscape and disturbance (*f*), and the sources of variability (ε), are derived statistically from past empirical observations of *Z*, *Y*, and *X*. Here too, the simulated characteristics of a perturbed state of a forest landscape will be a probability distribution instead of a single value. However, unlike their mechanistic counterparts, empirical models do not have emergent properties with respect to model outcomes or associated heterogeneity.

Despite the conceptual dichotomy between mechanistic and empirical models, almost all mechanistic models of forest landscape disturbances are, in practice, hybrids. They contain many empirical assumptions and modules that fill gaps in the scientific knowledge of ecological processes. Another important point is that all models are provisional in their logic, structure, and components. Over time, models should change to incorporate advances in scientific knowledge. With advances in understanding, model development and applications should evolve toward mechanistic ecological models that are based on first principles of biology, physics, and chemistry (Gustafson 2013). In addition, because models are but hypotheses of numerical implications for ecological systems, continuous testing with data should lead to rejection or modification of some assumptions and model functions, and the development of new ones (Hilborn and Mangel 1997; Evans et al. 2014).

Models also differ in their applications. For example, they differ with respect to why and how they are used for varying purposes such as exploring and understanding ecological systems, developing and testing hypotheses about system behavior, and supporting strategies for ecosystem management and decision-making. During the early stages of the evolution of a subfield in ecology, models are typically developed and used for *descriptive* purposes to increase knowledge of ecological phenomena, to support hypothesis development, and to discover a system's behavior. Later, as the knowledge advances and understanding matures, models become useful for *predictive* purposes (Korzukhin et al. 1996).

Even with advances in knowledge, expecting a high predictive ability from forest landscape disturbance models is perhaps not realistic. To elucidate this point, and following Bugmann (2003), we further divide "predictive" applications of forest landscape disturbance models into four broad categories (Table 1.5). The differences among these categories extend beyond semantics; they are important distinctions that both model developers and model users must understand. The degree of certainty required for the predictive and forecast categories to support tactical applications may not be realistic for models of ecological systems (Bugmann 2003), and may be almost impossible to achieve with forest landscape disturbance models. Conversely, examining synoptic possibilities for future states of forest landscapes under what-if disturbance scenarios to support strategic applications is a more relevant and plausible pursuit (Perera and Cui 2010). Fortunately,

Table 1.5 Possible applications of forest landscape ecological disturbance models, based on the categories and definitions of Bugmann (2003)

Application category	Definition	Goal of application	Example
Prediction	Commonly denotes inference from facts or accepted laws of nature, and implies *certainty*	Tactical: to precisely know the occurrence and characteristics of a disturbance event	Spatially or temporally precise prediction of a wildfire event; that is, of the ignition, extinguishment, extent, duration, intensity, and severity
Forecast	Adds the implication of anticipating eventualities and differs from prediction in being concerned with *probabilities*		Spatially and temporally precise prediction of the likelihood of a wildfire event and of its characteristics
Projection	An estimate of future *possibilities*	Strategic: to discover what is possible and the probabilities of disturbance events and their characteristics	Spatially and temporally explicit portrayal of a single probability distribution for future wildfire events and their characteristics under one set of assumptions
Scenario	An account or synopsis of a *possible* course of action or events		Spatially and temporally explicit scenarios of multiple probability distributions for future wildfire events and their characteristics under varying sets of assumptions

it is this goal of *discovery* (i.e., simulation of scenarios for the possible future states of ecological systems) that appears to be gaining momentum in applications in forest landscape disturbance modeling, with an emphasis on mechanistic models (Gustafson 2013).

1.3 The Contents of the Book

Included in this book are efforts to model an array of forest landscape disturbance types, ranging from physical to biological and from single to multiple. Also included are attempts to model interactions among disturbances by natural agents and anthropogenic effects, and the simulation of forest landscape recovery from disturbance (Table 1.6). The intent of these discourses is to illustrate the diversity of forest disturbance types that occur on landscapes, and approaches to their modeling. As well, these reviews of the various modeling approaches show

Table 1.6 An overview of the chapter contents: intent, disturbance attributes, and the modeling focus and approach

Chapter number and lead author	Intent	Disturbance	Disturbance type	Disturbance duration	Modeling focus	Modeling approach[a]
2. Mitchell	Review	Windthrow	Abiotic	Pulse	Response	Empirical and hybrid-mechanistic
3. Gustafson	Case study and review	Drought		Press	Disturbance and response	Empirical, mechanistic
4. McKenzie	Synthesis	Wildfire regimes		Pulse		Process, empirical, and hybrid
5. Sturtevant	Review and synthesis	Spruce budworm	Biotic			Empirical, mechanistic
6. Regnière	Case study	Mountain pine beetle			Disturbance	Mechanistic individual-based
7. Birt	Review	Southern pine beetle			Disturbance and response	Mechanistic
8. Keane	Case study	Disturbance interactions	Integrated	Pulse/press		
9. Wimberly	Review	Coupled human and natural systems		Press		
10. Scheller	Case study and review	Forest recovery	–	–	Recovery	Moving to mechanistic

[a]Based on the terminology used by the chapter author

the different stages of maturity in model development. Given the authors' backgrounds, the implicit bias is toward North American forest landscapes, although the many case studies capture the geographical diversity within this continent. The chapters written specifically on simulation modeling topics provide a literature review that is not exhaustive, but that is sufficient to summarize the state of knowledge on that topic. They also address topics related to disturbance modeling as syntheses and provide a visionary perspective for conceptual advances. When

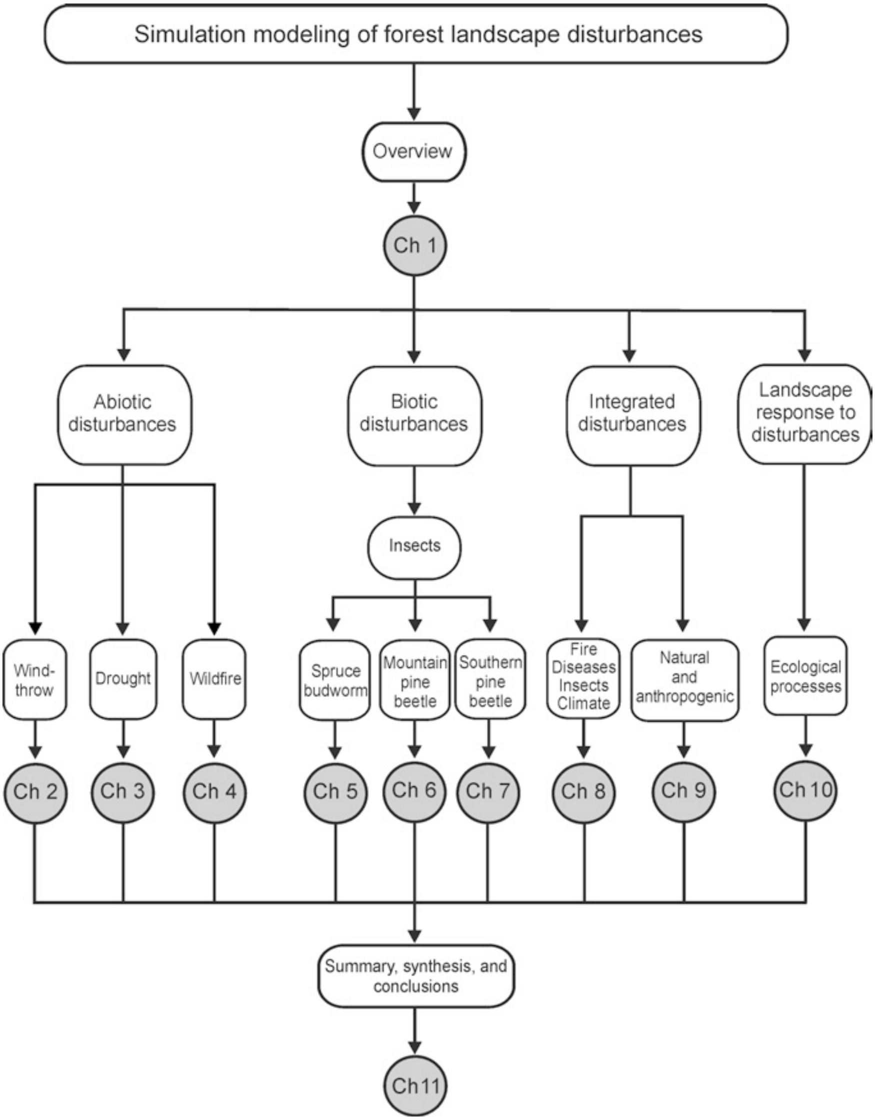

Fig. 1.3 The organizational structure of the chapters

a specific example of model use is described, it is meant only as a case study to illustrate and support a broader argument. Thus, we expect the relevance of the points made in this book to last well beyond the lifespan of typical research papers on model development and applications.

The book begins with the present overview chapter, followed by a series of chapters that focus on modeling of a specific disturbance type. We have organized these into broad groups (abiotic, biotic, and integrated disturbances), with the final chapter addressing the recovery of forest landscapes (Fig. 1.3). The chapters on modeling abiotic disturbance include windthrow in forest landscapes (Chap. 2: Mitchell and Ruel), drought-induced forest mortality (Chap. 3: Gustafson and Shinneman), and wildfire regimes (Chap. 4: McKenzie and Perera). The group of chapters on biotic disturbances addresses forest-dwelling insects that periodically create epidemic-level disturbances: spruce budworm defoliation (Chap. 5: Sturtevant et al.), the response of the mountain pine beetle to climate change (Chap. 6: Regnière et al.), and disturbance by the southern pine beetle (Chap. 7: Birt and Coulson). The two chapters on integrated disturbances focus on interactions between biotic and abiotic disturbance agents under climate change (Chap. 8: Keane et al.) and under coupled natural and anthropogenic disturbance in forest landscapes (Chap. 9: Wimberly et al.). The next chapter, on simulating the recovery of a forest landscape, addresses the dynamics of vegetation and biogeochemistry soon after disturbance (Chap. 10: Scheller and Swanson). We conclude with a summary and a synthesis of the book's contents, as well as insights into future simulation modeling of forest landscape disturbances and their application (Chap. 11: Perera et al.).

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