Chapter 11
Simulation Modeling of Forest Landscape Disturbances: Where Do We Go from Here?

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Contents

It was nearly a quarter-century ago when Turner and Gardner (1991) drew attention to methods of quantifying landscape patterns and processes, including simulation modeling. The many authors who contributed to that seminal text collectively signaled the emergence of a new field—spatially explicit simulation modeling of broad-scale ecosystem dynamics. Of particular note are the

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works of Turner and Dale (1991), who produced a first comprehensive overview of the prospect of modeling landscape disturbances, and of Sklar and Costanza (1991), who summarized the limited state of landscape modeling across various systems ranging from natural to anthropogenic and from terrestrial to aquatic, all in a single chapter. Concurrent with the growth in landscape ecology, the field of modeling at broader scales has expanded and diversified quite rapidly since these early summaries. This growth is evident in that less than a decade later, Mladenoff and Baker (1999) were able to assemble an entire text on landscape modeling with a focus on the dynamics of forest landscape disturbances. The subsequent proliferation of landscape disturbance simulation modeling has been captured in several reviews (e.g., Keane et al. 2004; Scheller and Mladenoff 2007; He 2008) and compilations (Sturtevant et al. 2004). For brevity, we refer to these models as *forest landscape disturbance models* (FLDMs), an inclusive term that embraces not just forest landscape disturbance and succession models, but also models of risk and hazard assessment, decision-support tools, land-use and cover change models, and models of individual-based processes. This term and its abbreviated form (i.e., FLDMs) were created for convenience only: our intent is not to add to the plethora of terms and acronyms in landscape modeling parlance.

The evolution of FLDMs has been marked by many changes, but we emphasize three aspects in particular. First, there has been an increase in the number of disturbance types and agents being simulated, and a change in how they are perceived by modelers. Early efforts focused on wildfire and some insect pests, but now the suite of disturbances included in FLDMs, at least in North America, is numerous and continues to expand. During the early stages, disturbance processes were generally simulated as individual external disturbance agents that periodically influenced forest landscapes, independent of vegetation dynamics. Now, there is an explicit recognition of the synergistic effects of interactions among individual disturbances and the dependence of those dynamics on changes in the forest landscape's composition and spatial patterns.

The second aspect relates to a gradual shift in modeling approaches. Early on, there was a heavy emphasis on empirical approaches that primarily relied on observations of past disturbance events based on the assumptions that the patterns exhibited by disturbance agents were stationary and that the responses of the forest landscape were static. Now, modelers are beginning to dispel the belief that knowledge of past disturbances is sufficient to understand what could happen in the future; instead, they are promoting an understanding of the mechanisms that drive disturbances as well as the dynamics of landscape composition. The nonstationary characteristic of forest landscape disturbances, driven by changes in contextual factors such as climate and anthropogenic influences, is an often-discussed topic among FLDM developers.

The third aspect relates to the advances in computing technology and data capture. The early limitations of computing capacity—hardware, programming languages, networking, and affordability—and the limited availability of high-resolution data are far less relevant now than they were even a decade ago.

Technological advances in computation have surpassed the underlying science that supports the processes being simulated by FLDMs, except perhaps in few extreme circumstances. Progress in technology has enabled modelers to develop common (shared) modeling platforms, adopt modular designs that foster interactions among modelers, and remotely exchange vast amounts of information. An unfortunate consequence of advanced computing and data technology is the misplaced goal of pursuing technologically advanced models, which may occur at the expense of models that are imbued with rich and relevant science.

Our goal in this chapter is twofold. First, we present a synopsis of the contents of this book. Beyond being a summary of the salient points that were made in various chapters, we hope that the emergent messages described here will present an adequate view of the current state of our topic—simulation modeling of forest landscape disturbances. Thus, despite the small sample size of only 10 chapters, we hope to capture what is "here and now" based on the examples provided by the contributions of other chapter authors. Second, we present thoughts on future directions or "where do we go from here?" addressed to the community of forest landscape disturbance modelers. Rather than specific prescriptions and remedies, these are general considerations about modeling (not disturbance ecology) that modelers should ponder as their modeling efforts grow, advance, and diversify.

11.1 Where Are We Now?

As mentioned above, we have assumed that the types of disturbances addressed in the preceding chapters, and the modeling approaches and methods described therein, provide a reasonable overview of the present state of FLDMs. This includes many facets of quantifying and simulating forest landscape disturbances: the behavior of disturbance agents, including their interactions with forest landscapes and the effects of contextual factors (i.e., broader-scale and external drivers such as climate and socioeconomic factors); the response of forest landscapes to disturbance agents; the recovery of forest landscapes; and assessment of the risk of disturbances. Even though this book includes only 11 chapters, its 28 authors represent a variety of topics, geographies, perspectives, and views that collectively embody more than 250 years of experience in FLDM development and application. Admittedly, a more complete and global picture of the present state of FLDMs could be constructed through a thorough and exhaustive literature review and synthesis, but that's a task we leave to colleagues who will be motivated by the discourse presented in this chapter.

In the following sections, we summarize the main points made by authors in each chapter, guided by Table 11.1, which provides an overview of their respective focus and key messages. We have grouped the chapters using the broad categories of abiotic, biotic, and integrated disturbances, followed by landscape recovery based on Fig. 1.1 in Chap. 1.

Table 11.1 Summary of the present state of modeling, major knowledge gaps, and future needs for each disturbance type presented in the individual chapters in this book

Chapter number/ authors	Chapter type	Modeling focus *Disturbance type*	Chapter focus	Main messages	
				Present state	Major knowledge gaps and future needs
2. Mitchell and Ruel	Review	Windthrow *Pulse*	A review of empirical and hybrid empirical–mechanistic modeling approaches to simulate windthrow susceptibility, with scaling from tree to stand and landscape scales	• There are many empirical models based on tree- and stand-scale outcomes • Many hybrid mechanistic models link tree vulnerability to environmental and management factors	• Representation of airflow through complex stands and partial harvests • Understanding of tree collisions and damage propagation within stands • Model validation across a broader range of forest conditions
3. Gustafson and Shinneman	Case study and review	Drought *Press*	An illustration of empirical approaches and a review of the potential for mechanistic approaches to simulating effects of drought-induced mortality on stand composition	• The primary focus is empirical, but mechanistic models in development are also discussed	• Understanding of the mechanisms of tree mortality related to moisture stress • Empirical studies to link tree mortality to multiple stressors • Approaches to scale from trees and sites to broader scales (e.g., landscapes)
4. McKenzie and Perera	Synthesis	Wildfire regimes *Pulse*	An exploration of the modeling approaches used in wildfire-regime simulation models, based on the orthogonal concepts of abstraction and complexity.	• Approaches range from empirical to hybrid and mechanistic • This is a relatively mature field of simulation modeling.	• Understanding of nonstationarity and dynamical properties of fire regimes • Modeling of interactions with other disturbances • Approaches that minimize `cumulative error and increase the transparency of outcomes

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Table 11.1 (continued)

Chapter number/ authors	Chapter type	Modeling focus *Disturbance type*	Chapter focus	Main messages	
				Present state	Major knowledge gaps and future needs
5. Sturtevant et al.	Review and synthesis	Spruce budworm (SBW) *Pulse*	A synthetic review of the evolution of modeling approaches to describe SBW dynamics	• Modeling approaches are well developed, but poorly integrated with other ecological processes and with ecosystem recovery.	• Ability to simulate outbreak severity and duration • Appropriate scaling techniques (time and space) • Improved integration of insect population dynamics with host tree effects • Integration of elements from different scientific paradigms that are consistent with current science
6. Regnière et al.	Case study	Mountain pine beetle (MPB) *Pulse*	An illustration of the individual-based model (IBM) approach to evaluate the response of MPB to climate change	• IBMs represent a new and expanding topic • The MPB IBM is limited to nonspatial processes	• Knowledge of insect biology; effects of tree distribution on host finding by the MPB and its attack ability; indirect effects of climate on host trees • For spatial modeling, how to accurately simulate MPB dispersal • For scaling up, how to manage a large number of objects (here, individuals)
7. Birt and Coulson	Review	Southern pine beetle (SPB) *Pulse*	A synthetic exploration of modeling SPB dynamics while considering the disturbance agent as an endogenous property of the forest landscape system	• SPB models exist, but are not well integrated into a holistic and integrated modeling approach	• Knowledge of the processes underlying the transition from endemic to an outbreak state • Scaling techniques (time and space) • Integrated modeling as a coupled human–forest–insect system • Need to move from predictive modeling to exploratory modeling using mechanistic approaches

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Table 11.1 (continued)

Chapter number/ authors	Chapter type	Modeling focus *Disturbance type*	Chapter focus	Main messages	
				Present state	Major knowledge gaps and future needs
8. Keane et al.	Case study	Disturbance interactions *Pulse and press*	A demonstration of highly integrated mechanistic modeling of abiotic and biotic disturbances to examine their emergent interactions	• Integrated mechanistic modeling is in the early stages of development • Most ecological responses to disturbances will result from complex interactions • Computing technology enables the development of integrated and complex disturbance simulation models	• Understanding of the relationships among disturbances and their effects • Inclusion of additional abiotic and biotic disturbance mechanisms • Mechanistic response functions for ecological processes
9. Wimberly et al.	Review	Coupled human–natural systems *Press*	A review of modeling approaches to simulate the reciprocal effects of anthropogenic and natural disturbances by coupling forest landscape models (FLMs) with land change models (LCMs)	• FLMs and LCMs are fairly well developed, but independently of each other • Integration is possible with existing models, but is still at its very early stages	• Data to initiate and parameterize more complex integrated models • Understanding of processes to connect disturbance effects with land-use change • Common inputs, algorithms, and model structures • New conceptual framework that captures feedbacks and reciprocal influences

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Table 11.1 (continued)

Chapter number/ authors	Chapter type	Modeling focus *Disturbance type*	Chapter focus	Main messages	
				Present state	Major knowledge gaps and future needs
10. Scheller and Swanson	Case study and review	Forest recovery	An examination of the modeling of key ecological processes involved in the recovery of forest landscapes from disturbances	• The post-disturbance recovery stage is often overlooked or oversimplified in models • Models are moving from empirical toward mechanistic approaches	• Understanding of the drivers and processes to clarify which must be included in models • Scale-appropriate data to populate more detailed models • Approaches to model mixed severity and simultaneous overlapping disturbances • Integration of the forest recovery stage in other models

11.1.1 Abiotic Disturbances

As Mitchell and Ruel (Chap. 2) explain, empirical windthrow models can represent site and management conditions at the tree and stand-scale and provide insights into landscape-scale patterns of wind disturbance. However, empirical models offer limited insights into the underlying mechanisms and are of limited use in as-yet unobserved situations. Hybrid–mechanistic modeling approaches are used to predict the behavior of individual trees under wind loads—individual trees fail if the critical wind load exceeds the stem strength or anchorage strength—and can be aggregated to simulate stand- and landscape-scale outcomes. Some spatial effects, such as sheltering by upwind trees, are accounted for, while others, such as tree-to-tree collisions, are not. By including regional wind patterns and incorporating the models into decision-support systems, climate change scenarios can be explored. Many knowledge gaps remain, some of which can be addressed through expert knowledge. Predictive models can be improved via interdisciplinary collaboration.

Using case studies, Gustafson and Shinneman (Chap. 3) present two stages of modeling in the relatively new field of simulating the effects of drought on forest landscapes: empirical correlations between stress and species responses and mechanistic simulations of the mortality induced by moisture stress. Although moisture stress has been modeled for decades, modeling drought as a disturbance (i.e., as episodes of drought-caused tree mortality) is recent and is still in the early stages of development. Deterministic approaches, although common and simple, have many disadvantages: they are not realistic, they simulate uniformity and homogeneity in disturbance patterns, and they do not account for changes in the climatic context. Furthermore, drought-based tree mortality is a confounded outcome: cumulative stress resulting from drought can predispose trees to biotic disturbance agents, such as insects and diseases, whose prevalence may be independently affected by climatic change. Additional drivers such as changes in atmospheric chemistry can likewise affect plant water use and moisture stress. Mechanistic modeling approaches based on tree physiology are poised to better address the cumulative effects of stress agents, and their effects on forest mortality.

In their synthesis, McKenzie and Perera (Chap. 4) observe that modeling of wildfire regimes is a relatively mature field of study, so that current paradigms in this field can inform simulations of other forest landscape disturbances. For example, it is clear that the stochasticity of wildfire events and the effects of a changing climate are not replicated in observations of the past. Therefore, predefining properties of individual disturbances or fire regimes in general will fail to capture the dynamism, emergence, and stochasticity that characterize forest landscapes and will not be robust to changes in disturbance regime characteristics. Mechanistic modeling has advantages in this regard, but it is also possible to “over-model” by including extraneous mechanisms, which can produce false precision at fine scales, and to misrepresent wildfire disturbance at broad scales. The degree of abstraction and complexity embedded in simulation models must be question- and situation-specific, and most importantly, must be scale-specific.

11.1.2 Biotic Disturbances

In reviewing the evolution of spruce budworm (*Choristoneura fumiferana*) modeling over a period of five decades, Sturtevant et al. (Chap. 5) illustrate the long-term process of model building to inform our understanding of complex disturbance dynamics. Advances in spruce budworm modeling have been neither linear nor continuous, but rather they have emerged from competing and often incomplete paradigms that explain limited observations collected at inherently restricted spatial and temporal scales. Insect disturbance modeling is often complicated by nonlinear and cross-scale interactions among components that operate at various scales. Despite extensive investments in research, comprehensive modeling approaches have not readily emerged because of the inherent unpredictability and specificity of these ecological systems, as is the case for biotic disturbances in general. Sturtevant et al. present a vision of a hybrid approach that blends scientific paradigms, modeling approaches, and empirical and mechanistic relationships, using the framework of landscape disturbance and succession models.

In describing an individual-based model (IBM) that simulates mountain pine beetle (*Dendroctonus ponderosae*) responses to temperature changes, Regnière et al. (Chap. 6) present an excellent example of a highly mechanistic simulation model of the behavior of a disturbance agent. Their chapter is unique in that it focuses on a single model, and their in-depth case study illustrates a specific modeling paradigm (i.e., IBM). The IBM approach can help to identify knowledge and data gaps and can be used to simulate low-probability events. In this approach, the built-in responsiveness to changes in the climate context is governed by relatively simple rules that affect individual responses to the environment. IBM is a generalizable strategy that is particularly well-suited to insect disturbance, since outbreaks are emergent properties that result from the summation of individual responses. However, there are difficulties involved in up-scaling coupled disturbance mechanisms from tree (individual) to landscape scales and in applying the IBM approach to simulate outbreak behavior in time and space, which may be beyond the current computing capacity.

Birt and Coulson (Chap. 7) discuss many considerations for advancing models of the forest disturbance caused by the southern pine beetle (*Dendroctonus frontalis*). The vision of potential positive effects of disturbances is often overlooked because of the common socioeconomic perspective that disturbances are destructive. However, if considered as an integral part of a broader ecological system, beyond the scale of the "destroyed" forest stand, disturbances can be perceived as agents of ecosystem renewal. This point, which the authors present for southern pine beetle, is applicable to other disturbances. For some disturbances, adopting a holistic outlook that includes socioeconomic processes will help modelers to better quantify the disturbance regimes and their consequences, and will also help them to communicate about disturbances and educate forest managers. Birt and Coulson argue in favor of simulation models based on mechanisms, although a variety of complementary modeling approaches will ultimately yield the most insight for complex systems. As well, they reiterate the view that past disturbances may not inform the future because of the dynamic nature of forest landscape drivers and the patterns they produce.

11.1.3 Integrated Disturbances

Using a case study of simulating the interactions among three disturbance types (i.e., fire, insects, and disease), Keane et al. (Chap. 8) demonstrate that the indirect effects of climate change on disturbance regimes and their interactions can have far greater influence on ecosystem dynamics than the direct effects. Since these disturbances can act synergistically, their combined effects can be elucidated only with mechanistic models that include the underlying drivers, and cannot be discerned based solely on past observations. Recent advances in landscape models are enabling investigations of such interactions among disturbances; however, empirical knowledge of the underlying drivers that affect disturbance interactions remains a limiting factor. Emergent properties of integrated disturbances, through their reciprocal interactions, can be counterintuitive. Although the specifics of such interactions may be unique to each study area and set of circumstances, the approaches to understanding such interactions are transferable to other landscapes and situations.

Wimberly et al. (Chap. 9) review the coupling between natural and anthropogenic disturbances and the potential for combining land change models (LCMs), which address socioeconomic phenomena, with forest landscape models (FLMs), which focus on ecological phenomena. Although the spatial scales and approaches may differ between LCMs and FLMs, the common conceptual design in both approaches makes their integration possible. Real and complex interactions are inherent in these coupled systems, indicating that the effects can be direct and immediate (as is the case with forest harvesting) or they can be indirect or delayed (as is the case with road networks). Recent efforts in the landscape-scale modeling of coupled human–natural systems have relied primarily on loose coupling of FLMs and LCMs, in which the input from one model is used to drive the other model. Given the reciprocal nature of human and ecological processes, further progress will require interdisciplinary efforts to more tightly couple these modeling approaches.

11.1.4 Recovery

Scheller and Swanson (Chap. 10) focus on modeling a system's recovery after a disturbance. Reciprocal feedbacks between the disturbance and both vegetation and biogeochemical processes are integral to understanding the effects of disturbance on forest landscapes. The complexity and short time horizon of the recovery processes, as well as the many interacting factors and influences complicate modeling efforts of short-term forest landscape recovery, and lead to uncertainty in the outcomes. Four major drivers influence recovery dynamics: biological legacies, nutrient and water fluxes, regeneration mechanisms, and management activities. The two contrasting case studies presented in this chapter demonstrate both the importance of modeling the recovery stage of forest dynamics and the challenges associated with this modeling. Mechanistic approaches are essential to reflect the complexity of the processes involved in forest recovery. Critical requirements to support these approaches are data to parameterize such models, the reconstruction of disturbance effects at regional scales, remote sensing of post-disturbance recovery, and the enlistment of "citizen scientists" to fill data gaps.

11.1.5 Emergent Messages

The chapters in this volume not only spanned a broad range of disturbance types, they also present disturbance modeling from different perspectives. For example, three sequential steps relevant to modeling forest landscape disturbances are addressed in the chapters at different levels of focus and detail (Fig. 11.1). Chapters 5 and 7 focused on methods of simulating the disturbance agent's behavior and the response of the forest landscape separately, whereas other chapters (3, 4, 8 and 9)

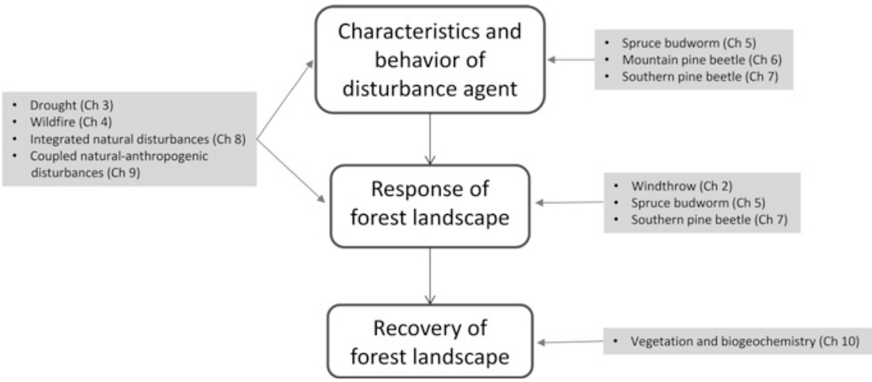

Fig. 11.1 The three major steps involved in simulating forest landscape disturbances, and the modeling domains addressed in the chapters of this book

addressed these steps together. Chapter 6 detailed only the first step, and Chap. 2 focused on the second. Chapter 6 described simulation of the behavior of a disturbance agent (mountain pine beetle), given certain forest characteristics and climate drivers, whereas Chap. 2 addressed the response of a forest's structure to a physical disturbance agent (windthrow, given the presence of wind storms). Even though most chapters alluded to post-disturbance vegetation changes, only Chap. 10 focused explicitly on the recovery of forest landscapes after disturbances.

To illustrate the emergent messages that result from synthesis of the discussion in the preceding 10 chapters, we created a word cloud based on the relative frequency of occurrence of the key terms (Fig. 11.2). This shows that concepts such as interactions, complexity, mechanistic modeling, abstraction, and anthropogenic effects were more commonly addressed by chapter authors than stochasticity, validation, hypotheses, communication, and model parsimony. It appears that these "common" terms in the word cloud are interrelated. Below, we examine the concepts associated with these terms first and address the "less common" terms later in the text.

Spatially explicit interactions are inherent in forest landscape disturbances: a common theme in this book is the relative strength of the reciprocal interactions between vegetation and the various disturbance agents in time and space. Abiotic disturbance agents—particularly those that are most directly linked to weather and climate patterns (i.e., in this book, wind, drought)—have comparatively limited feedback with vegetation in terms of modifying disturbance regimes. Although vegetation does have a localized influence on disturbance effects, for example via size- or species-specific susceptibility to the disturbance (e.g., the likelihood of being blown over, as in Chap. 2; the relative tolerance of drought, as in Chap. 3), its relative influence on the behavior of disturbance agents is limited compared with larger-scale factors, such as hurricane frequency and regional drought episodes. In contrast, biotic disturbance agents have comparatively strong reciprocal feedbacks with vegetation dynamics (e.g., Chaps. 5–7). Furthermore, the absence of a host species can make its associated biotic disturbance agent become irrelevant. Wildfire disturbance lies between these two extremes because it is an abiotic disturbance that is strongly influenced by both weather and climate and by the specific fuels

Fig. 11.2 The relative importance (frequency of mention) of 10 key terms in the independent contributions in this volume (Chaps. 1–10). The font size is proportional to the frequency of occurrence of the words in the text; however, the terms are randomly positioned within the figure

produced by the vegetation (Chaps. 4 and 8). Thus, it is more general than most insect pests (fire occurs in most of the world's forest ecosystems), but less general than wind (all trees become susceptible to windthrow at extreme wind speeds).

Moreover, interactions among disturbances are complex, a fact that all chapter authors point out. Press disturbances influence pulse disturbances. (See Chap. 1 and Table 1.1 for their definitions.) For example, drought stress may change the characteristics of the forest landscape, and this, in turn, will influence the behavior of wildfire. As well, some pulse disturbances influence other pulse disturbances. For example, a windthrow event may modify forest fuel availability, thereby altering the behavior of wildfire. Anthropogenic disturbances may alter natural disturbances both directly and indirectly; for example, indirect press disturbances such as road networks can change water tables (thus, can affect wildfire spread) and direct pulse disturbances such as harvesting can change stand properties (thus, can affect windthrow), thereby affecting subsequent disturbance dynamics. The relative strength of reciprocal interactions between disturbance agents and vegetation dynamics has important consequences for overall system complexity. Changes in contextual factors such as climate may be subtle until thresholds are reached, after which the response can be pronounced; examples include changes in temperatures and precipitation (drought) and in lightning patterns (wildfires).

As our knowledge of individual disturbance domains matures, there is a concurrent move by modelers of all disturbances toward mechanistic modeling. All authors in this book argued in favor of such a move, and noted that the limitations of simple empirical models and extrapolations appear to be increasingly recognized by researchers. The once-popular and primary method of understanding forest landscape disturbance regimes solely based on past occurrences is either being replaced or complemented by scenario-based simulations that depend on an understanding and quantification of the underlying ecological processes. This is evident in simulations of the susceptibility to a disturbance and the vulnerability if one occurs (Chap. 8). This area of research stems from a long tradition in risk and hazard analysis, but has become quite sophisticated in terms of the science underlying the description of risk factors and their interactions with disturbance processes in time and space (e.g., Chaps. 2 and 5). It is also evident in approaches for addressing the concept of emergent disturbance regimes, where disturbance events initiate, spread, and terminate based on first principles of biology, physics, and chemistry to generate dynamic disturbance regimes that are influenced by both external drivers (e.g., climate variables) and internal properties (i.e., reciprocal interactions among vegetation composition, arrangement, and structure). It is possible to model disturbance behavior that emerges from an even lower level of organization, such as the cumulative behavior of individual disturbance agents rather than disturbance events. This method is suitable for simulating biotic disturbances such as insects or human disturbances, as affected by the behavior of individuals (e.g., Chaps. 6 and 9). Simulating disturbances as emergent system properties sets the stage for investigations of the interactions among disturbances—the consequences of which are often greater than the sum of their parts (Chap. 8).

All authors in this book recognize the complexities that are involved in mechanistic modeling, and the difficulties in scaling and selecting the ecological processes that need to be modeled. Limitations emphasized by several authors include those related to data, and specifically the quality, resolution, and extent of the data resources needed to parameterize, initialize, or validate models. More importantly, significant scientific limitations remain as a result of incomplete understanding and knowledge of various processes; for example, we do not fully understand the drivers underlying the "death spiral" associated with tree stress (Chap. 3), cross-scale interactions (Chaps. 5 and 7), and thresholds that influence many disturbance types, including insect outbreaks, diseases, and wildfire (Chap. 8), nor the key drivers and processes crucial for forest recovery (Chap. 10). Nonetheless, landscape disturbance modeling, like virtually all other disciplines in ecological modeling, will always be subject to the middle-number paradox in ecosystems (sensu Allen and Hoekstra 1992), and expectations must be tempered accordingly (Chap. 4).

The shift toward mechanistic modeling is also perhaps motivated by the recognition of the nonstationarity of contextual factors. This includes a wide acceptance of the prospect of changing climatic conditions as well as inclusion of anthropogenic influences on a forest landscape's structure and function. The latter are perhaps more complex and unpredictable because many social, political, and economic factors influence the behavior of human populations. Still, many have argued that simulating forest landscape disturbances in isolation from anthropogenic effects is only an academic exercise, because "real-world systems" include human effects through modification of landscape patterns (e.g., by forest harvesting, road construction, and the control of disturbance agents that considerably modify the behavior of landscape-scale disturbances). Therefore, the integration of socioeconomic phenomena as constraining and controlling factors may be essential.

Some common knowledge gaps also emerged from the individual discourses by chapter authors. Foremost was the uncertainty involved with understanding which ecological processes are crucial for inclusion in mechanistic FLDMs, and extending those key fine-scale mechanisms to broader scales; this was echoed by all chapter authors. Paucity in knowledge is also evident in relation to factoring in anthropogenic influences, as emphasized by Chaps. 7 and 9. As the processes are scaled from fine to broad, and multiple mechanisms are added, the relative lack of knowledge on error propagation (Chap. 4) and validation (Chap. 2) also could become an impediment to developing mechanistic FLDMs. Some of these difficulties can be, at least in the short term, alleviated by resorting to expert knowledge (Chap. 10).

In summary, the following messages resonate throughout the chapters in this book:

- *Disturbance regimes are complex*, but they nonetheless need to be examined and understood in a way that accounts for as much of the complexity as possible. Abstraction of the ecological system and of the disturbance and recovery processes can be simple or complex, depending on the question and the modeling goal.

- *Disturbances in forest landscapes are dynamic and therefore nonstationary*. They are dynamic because there are many interactions and feedback mechanisms with other ecological processes. They are nonstationary because the forest landscape patterns (and processes) change over time, and the contextual factors (that are beyond the scale of the disturbance mechanisms) can change outcomes.
- *Past disturbance processes are informative, but they may not indicate what is possible or probable in the future*. Simple extrapolation of past information into the future, however convincing and accurate, may be inappropriate in dynamic systems that are moving into novel conditions.
- *Understanding the mechanisms that govern the behavior of disturbance agents, the responses of the forest landscape, and its recovery processes is very important* and, however daunting, will be the solution to exploring disturbances under possible future scenarios, as well as testing models as hypotheses to advance science. This is true notwithstanding the need to be parsimonious with the mechanisms that are quantified and modeled.
- *Excluding anthropogenic influences, focusing on one disturbance at a time, and ignoring forest landscape recovery mechanisms are no longer the most effective strategies*. Simulating scenarios with long time trajectories may not be valid unless the human effects, climate change, and interactions with other disturbances, as well as how forests landscapes evolve, are considered and included in modeling efforts.
- *Computing and data-gathering techniques may have advanced well beyond our capacity, as ecologists, to conceive and quantify ecosystem processes*. These former bottlenecks are rarely an impediment to developing sophisticated FLDMs, with few exceptions such as extending IBMs to large forest landscapes. At the same time, FLDMs must not be guided and motivated by technological advancements. What is needed is not a consideration of what is technologically *feasible*, but rather what is ecologically *sensible*.

11.2 Where Do We Go from Here?

With increasing and broadening awareness of ecological disturbances and their consequences in forest landscapes, we expect the role of FLDMs to continue to expand. They have been and will continue to be fundamental tools to inform research on disturbance ecology through the iterative process of model development, confrontation of models with data, and refinement or development of new models to incorporate the resulting insights. The scientific role of model development has a special meaning in the field of forest landscape ecology, since landscape-scale experimental manipulation is complicated, if not impossible. Consequently, scientific advances in FLDM development will likely be supported by the growing demand for modeling tools by forest landscape managers,

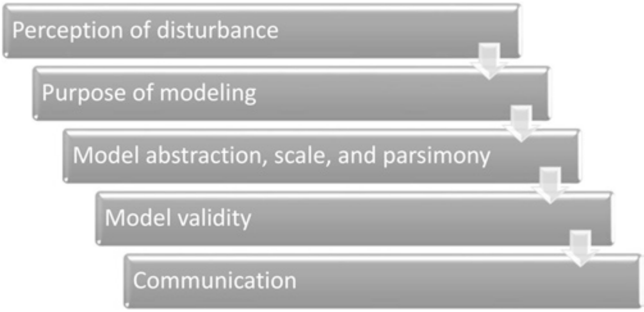

Fig. 11.3 Considerations for developers of forest landscape disturbance models. The directionality implied by the arrows is not necessarily linear; there are many feedback loops involved in successful model development based on continuous learning and adaptation

who increasingly view FLDMs as an integral part of their strategic and tactical decision-making. Also, FLDM developers will have access to rapidly advancing scientific knowledge, improved empirical data on forest landscape patterns and processes, as well as superior computing technology and programming languages.

In the rest of this chapter, we present a collection of considerations for those who develop FLDMs with the goals of advancing science and applied decision-support (Fig. 11.3). We address these considerations from five perspectives: the perception of disturbances; the purposes of modeling; abstraction, scaling, and parsimony of models; model validation; and communication.

1. **Perception of forest landscape disturbances**

Disturbances can be perceived as continua in multiple dimensions (Fig. 11.4). For example, they can be considered simultaneously based on:

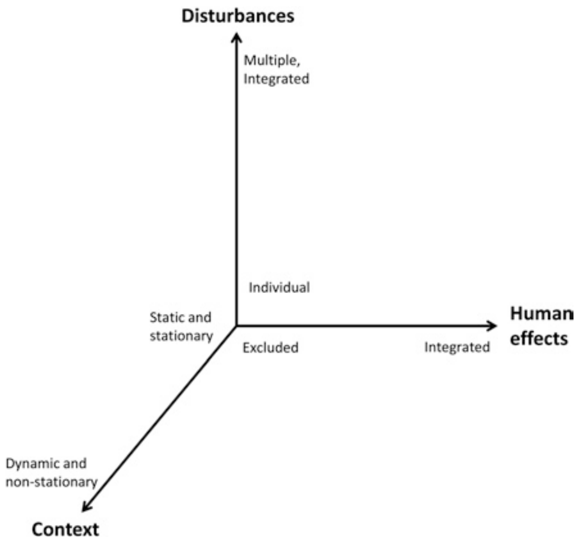

Fig. 11.4 The characteristics of the forest landscape disturbances that are included in a simulation model can be perceived along many dimensions. This illustration shows only three such axes, and does not necessarily suggest orthogonality among the dimensions, nor linearity in scale

(a) The number of disturbances considered, starting with a simplified scenario of a single “type” of disturbance (i.e., a single causal factor), and progressing toward a complex suite of many interacting (integrated) disturbances
(b) The influence of human activities, ranging from no anthropogenic influence to indirect influences on disturbances through anthropogenically altered landscape patterns and direct influences by controlling the disturbance agents. For example, socioeconomic factors such as vagaries in the markets for forest products, shifts in cultural perceptions, demographic changes, and changes in human settlements can all influence forest landscape disturbances.
(c) Ecological context changes, starting with the assumption of stationary contexts and extending to dynamic (nonstationary) contexts that dynamically influence disturbance processes. Evolution of novel ecosystems as a consequence of changes in context, such as climate change, atmospheric pollution, and species invasions, is a distinct probability.

“Real world” applications demand a high degree of complexity from FLDMs, and a more inclusive view of disturbances by model developers. Although model developers may envision and pursue an idealistic and complex FLDM that would capture all disturbances, including all human activities, under a range of scenarios related to context changes, in reality the success of such a pursuit will not initially be high. Such a pursuit may go beyond current theoretical knowledge, technological and information capacity, and even computing capabilities. We therefore caution modelers that FLDM development should move in the direction of developing comprehensive models only with due rigor, as knowledge and capacity make this expansion both rational and feasible. In the meantime, they should eschew models that try to address as many issues as possible and that therefore address none well, since such models may be less useful than simpler models that address a few select disturbances well. During this process of advancement, while FLDMs continue to evolve and become more complex, an explicit articulation of the domain in which we perceive a disturbance to occur (which we consider essential state assumptions for modeling) will help define the FLDM’s scope for its developers, and will clarify its intent and utility to those who apply the FLDM.

2. **Purposes of modeling**

As we pointed out in Chap. 1, the differences among the purposes of FLDMs (i.e., prediction, forecasting, projection, and scenario exploration) are not mere academic distinctions; they matter greatly because they affect how models are developed, perceived, and applied by users. Nearly 40 years ago, Overton (1977) noted that the modeling literature did not contain clear statements of models’ goals and objectives. This is still true, as Evans et al. (2013a) echo in their meta-review of ecological model typologies that range from tactical uses to strategic purposes. Here, we reiterate that for successful development and use of FLDMs, both the model developers and the users must clearly understand the purpose of the model. This is especially the case for constraining how the FLDM output must be viewed (Fig. 11.5).

Fig. 11.5 The range of purposes and expected outcomes of forest landscape disturbance models. Adapted from Hall and Day (1977) and Bugmann (2003)

It is common for practical users of FLDMs, such as forest managers, to demand precise and deterministic predictions of where and how forest landscape disturbances will occur. Though other fields of ecology may argue for predictive models (e.g., Evans et al. 2013b), we contend that the degree of certainty required to make such predictive and forecasting applications suitable for tactical purposes is an impossible expectation with current FLDMs. The most appealing and robust use of some FLDMs is to support long-term explorations of how forest landscapes are disturbed, and how they recover. For example, all chapter authors in this book note the need for discovery, and we emphasize that a robust understanding of the emergent properties of forest landscapes must be the goal of FLDMs. These would include the properties that are evident when individual-based disturbance events are scaled up to populations, which will elucidate the synoptic characteristics of the disturbance. Such discoveries could be made either by mechanistic modeling or by sophisticated statistical modeling of past disturbance events, provided that the latter cover a large enough sample space to capture the spatial, temporal, and stochastic variability of the system that is being simulated. Another possible discovery is a depiction of the properties that may emerge from interactions among disturbance agents, which is only feasible with mechanistic modeling efforts. Such explorations of synoptic properties of forest landscape disturbances and scenario-based simulations of future possibilities of ecosystem patterns and processes must be the primary goal of FLDMs. In this context, it is the responsibility of the model's developers to clearly articulate the purpose of their model (including its limitations) to those who will want to apply the model.

3. **Abstraction, Scaling, and Parsimony of Models**

Numerous interrelated ecological factors—structures and functions—are linked to a given landscape disturbance process. Scoping the domain of the modeled processes, identifying which processes are relevant, and selecting only the most significant ones can be a difficult task. However, as philosophers have reiterated, it is abstraction that leads to universality, parsimony, and rigor, as well as to clarity in science. Therefore, abstracting the essence of complex and interrelated ecological phenomena in forest landscape disturbances is not just desirable, but is an essential task in developing FLDMs.

Strong arguments have been made for increased complexity in ecological models (e.g., Evans et al. 2013a), but this does not mean that the inclusion of more mechanisms will necessarily make models better or that these more complex models will advance the science more effectively. In fact, Duarte et al. (2003) note the pseudo-complexity of ecological models and the tendency for "mechanism creep" (i.e., the incorporation of insufficiently well understood or of low-importance mechanisms) during model development. We think that the temptation to over-model a system can be prevented by carefully considering the scale-relevancy of ecological processes. Even though advances in computing and data-acquisition technologies have immensely helped forest landscape modelers, this progress could become an impediment to making FLDMs appropriately parsimonious. That is, models should only include mechanisms that we understand sufficiently well to be confident the model will produce more realistic results, and must exclude mechanisms that do not have important effects on the model's outcomes. With increased computing capacity and efficiency in programming languages, and the ready availability of high-resolution data, modelers may feel compelled to develop more complex models, just because they can. Although it may appear ridiculous to suggest this, it is not inconceivable to expect FLDMs to include molecular-level processes! But even if such complex models are elegantly built, they would have very high uncertainties and an increased risk of error propagation.

Appropriate scaling of ecological processes is a crucial step in model conception. Since most ecological processes are scale-specific, adoption of an appropriate scale is the key to correctly representing a forest landscape system and its processes, as well as to the discovery of emergent properties. Because ecologists are typically burdened by the intuitive familiarity of the phenomena they study and by their anthropocentric views, objectively choosing the correct scale can be difficult (Wiens 1989; Allen and Hoekstra 1992). Fortunately, many excellent explanations of ecological scale exist to assist FLDM developers (e.g., Wiens 1989; King 1991; Levin 1992; and many chapters in Peterson and Parker 1998). Also of value for forest landscape disturbance modelers is hierarchy theory (sensu Allen and Starr 1982; O'Neill et al. 1986), which helps to further unravel issues of scale and abstract ecological processes. Understanding the hierarchy of ecological process relationships will help simplify the view of complex interrelationships that might otherwise appear relevant and important (Fig. 11.6). As a starting point, we argue that FLDM developers should aim for no more than three hierarchical levels of

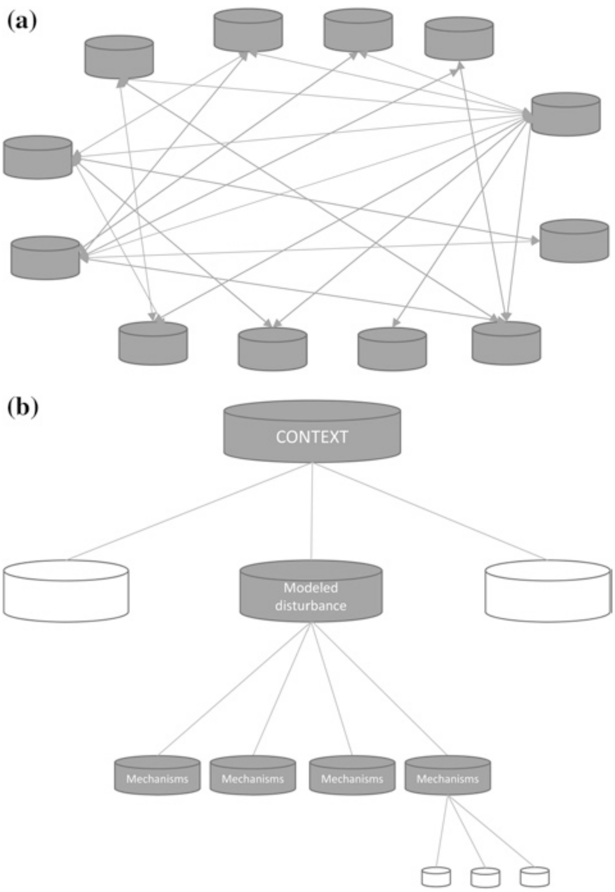

Fig. 11.6 An abstract depiction of how scaling can help simplify model conception. **a** Many interrelated ecological processes related to disturbance processes appear essential, complex, and detailed if they are not scaled hierarchically. **b** After scaling as a nested hierarchy, three levels emerge: the context, the focal disturbance process, and the key mechanisms that drive the disturbance process. This helps modelers to comprehend and address only the essential processes (*gray*), and ignore superfluous processes (*white*)

ecological processes: the context, the focal disturbance process, and the key mechanisms that drive the disturbance process.

4. **Model validation**

It is clear that for ecological models to be credible, they must be considered *valid*. However, it is not necessarily clear what "validity" means. Borrowing from the allometric and other statistical models used in ecology, many modelers consider model validation to be the simple act of comparing model outputs to empirical observations. The ecological modeling literature is replete with such examples. However, this ignores the possibility that an incorrect model can still produce results that match observed data, and the possibility that a correct model can produce results that do not match the observed data. This is especially true for FLDMs, which aspire to simulate ecological patterns and processes at scales that exceed our capacity to observe, and that produce probabilistic scenarios. Simple confrontation of past observations (single data points) with a set of simulated patterns (a probability distribution), even if statistically viable, may not prove that FLDMs are valid and credible. Many, in particular Oreskes and her colleagues (e.g., Oreskes et al. 1994; Oreskes 1998, 2003; Oreskes and Blitz 2001), have stressed that establishing model credibility involves verification, evaluation, and assessment of the *whole* modeling procedure (Fig. 11.7). This includes "validation" of the assumptions, input data, and model logic (conception, scale, and sub-processes), and finally, and only then, assessment of the output. Accordingly, the major focus and the responsibility of model developers should be on establishing the credibility of the model's structure: its logic, components, and assumptions.

5. **Communication**

There are two important facets to communicating in the context of FLDMs, especially with the user community. First, model developers must articulate about their FLDMs. This aspect of knowledge transfer—the necessity to unambiguously and explicitly communicate the premise, value, and limitations of a model to a user community—was raised by landscape ecology modelers nearly a decade ago (King and Perera 2006), but this topic has still not gained sufficient recognition. Modelers must not assume that users are aware and informed of the purpose,

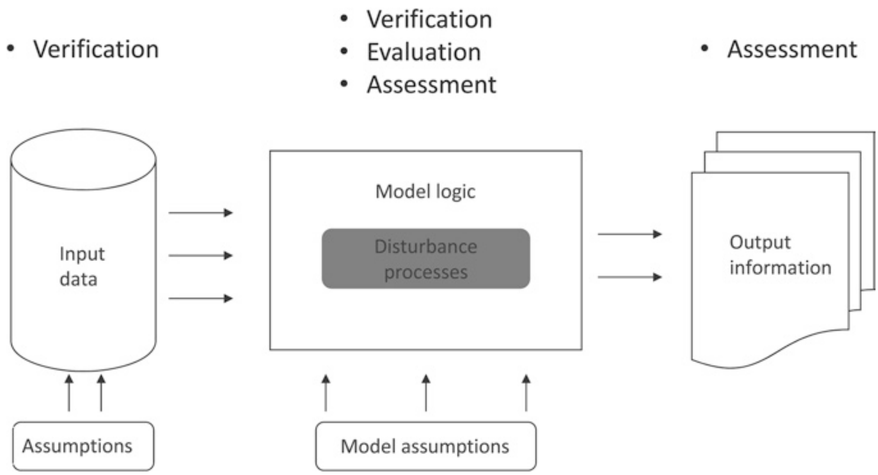

Fig. 11.7 Validation of an FLDM involves critical examination, evaluation, and verification of all steps in the simulation of a disturbance process, not just comparing the model outcome to observed data

assumptions, structure, limitations, and results of a FLDM. This is a risky assumption, since miscomprehension by users will lead to misuse and abuse of models, and that may lower the credibility of both models and modelers, perhaps even more so than poorly constructed models. Although enthusiastic efforts to clarify the value of FLDMs are admirable, model developers must be careful not to engage in aggressive marketing and promotion of their products, as this leads to poor communication and possibly unmet expectations. Also, ambiguity in expressions, including the use of incorrect terminology, can lead to incorrect use and expectations of FLDMs. An example is the frequently incorrect use of the phrase "prediction" in modeling parlance that leads to applications of models for inappropriate purposes, and misinterpretations of model outcomes.

Second, model developers can use models to communicate about forest landscape disturbances. Simulating scenarios as what-if explorations provides powerful tools to gain insights about forest landscape disturbances that are otherwise beyond the bounds of empirical observations. For example, the spatial and temporal probabilities and heterogeneity of disturbances are hard to comprehend based on few historical observations. As well, the notion that history will repeat, and therefore that past disturbances are predictive of future disturbances, can be challenged using FLDMs. This is especially true for disturbance regimes that are nonstationary in response to changing contexts. Another aspect worth communicating is that, from an ecological perspective, not all disturbances are destructive. When some disturbance agents are viewed at a broader scale, above the scale of the forest communities that have been disturbed, the agents may appear as endogenous and the disruptions they create as integral to the broader ecological system.

11.3 Conclusions

During the two decades since their naissance in North America, simulation models have become a mainstay in landscape ecology research. They are also vitally important tools that aid policy development, strategic plans, and decision-making in land management. This trend is nowhere more evident than in modeling broad-scale disturbances in forest landscapes. Aided by advances in technology—more powerful computing and better data acquisition—the field of forest landscape disturbance modeling has flourished. The many and different discourses in this volume provide evidence for that growth, including the variety of disturbance types that are modeled and how they are modeled. The relative degree of maturity in modeling and understanding of disturbance agents is a continuum, ranging from wildfire and insect pests, which have been studied and modeled at broad scales for decades, to phenomena such as drought and disease modeling, which are relatively new topics.

Nonetheless, several common messages have emerged:

- a shift toward mechanistic models that are based on understanding and quantifying ecological processes,
- integration of nonstationarity in disturbance behavior due to feedback from many stochastic dynamics in forest landscapes and changes in climatic and other contextual factors,
- including interactions with many other simultaneous disturbance processes, and
- integrating anthropogenic influences in simulations of forest landscape patterns and processes.

Such advances in process-based modeling, including the integration of multi-scale feedbacks among processes and the interactions among multiple disturbance types, were not available even a decade ago. In addition, modeling of the recovery of forest landscapes has also begun to mature. The responses that are being studied and tracked now include biochemical and geochemical processes and biomass, which are important complements to projections of a forest's species composition.

We believe the future of FLDMs to be promising. The topic of forest landscape disturbances is drawing increased attention from scientists and forest managers alike. The variety of disturbances being modeled, the rigor of the modeling procedures, and the number of FLDMs are all increasing. However, despite the progress that has been made in this field, potential traps exist. One is the pursuit of increased complexity. The detailed inclusion of all possible ecological processes is not synonymous with enhanced rigor; on the contrary, it may be the opposite. In many cases, more parsimonious models are more appropriate. Another trap is viewing amplified computing power as a goal rather than as a tool for achieving a goal. Although technology is a great aid to modelers, it is not, by itself, a reason for developing simulation models.

Modelers can maintain their momentum and avoid such pitfalls by adhering to a suite of best practices. Specifically, modelers should:

(a) pursue, whenever possible, parsimonious rather than complicated models;
(b) conceive and scale the modeled processes based on ecological concepts rather than based on the available computing technology and data;
(c) develop models collaboratively to facilitate ensemble modeling and cross-comparisons;
(d) evaluate a model's structure, logic, and assumptions rather than validating models based solely on the match between their outcome and observed data;
(e) treat models as hypotheses, and vigorously strive to test those hypotheses, and continuously improve the model's logic; and
(f) communicate about models to users continuously and actively rather than passively.

With this, we echo many other colleagues who have voiced the same sentiment: imbue simulation models with rich science, consider the models as hypotheses, and strive to simplify models to focus on the fundamental drivers over extraneous detail.

Finally, FLDMs are a powerful and indispensable tool for policy developers and managers of forest landscapes. They can be applied to help propose strategic objectives, examine plausible scenarios, and evaluate alternative management goals—all without having to rely exclusively on past experiences and evidence. When broad-scale experimentation is impossible, and when state assumptions based on a description of the past will not remain valid under a changing context (e.g., climate change, anthropogenic change), only the virtual explorations facilitated by FLDMs can inform us of potential emergent ecological patterns and processes in forest landscapes.

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