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Transfer and Extension of Forest Landscape Ecology: A Matter of Models and Scale

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2.1. INTRODUCTION

Forest landscape ecology involves examining relationships in spatial geometry among forest elements at broad spatial and temporal scales and higher levels of ecological organization—whether the focus is on physical processes such as hydrology, biological functions such as primary productivity, biophysical processes such as forest fire, or human activities such as forest harvest. In short, forest landscape ecology is a subset of the more general field of landscape ecology, which seeks to understand how spatial patterns and relationships influence forest process. Although, in principle, an understanding of how spatial relationships among individual trees in a stand influence stand growth and productivity could qualify as forest landscape ecology, in practice, the spatial extents of forest landscape ecology are much larger than forest stands; they involve large watersheds and geographical regions. Hence, forest landscape ecology, as used here, should be understood as the study of how spatial patterns and interactions influence the processes and dynamics of heterogeneous forested areas much larger than homogeneous stands of even-aged trees. The science of landscape ecology is defined primarily by its focus on how spatial patterns and interactions influence ecological process, not solely by spatial extents that are large from a human perspective. (At least, that is how it *should be* defined; the point is debated within the community of landscape ecologists.) Nevertheless, when applied to forests, forest landscape ecology deals almost exclusively with large spatial extents.

These large spatial scales are also generally associated with longer time scales, and the temporal domain of forest landscape ecology is much longer than the lifespan of individual trees or even individual stands; it extends toward the time scale of changes in the biogeographical distribution of forests. Moreover, the spatial and temporal resolutions are much coarser than those typically considered in traditional forest ecology. Consequently, the knowledge and information developed in forest landscape ecology addresses broader and coarser spatial and temporal scales than are familiar to the policymakers, planners, and practitioners involved in forest management at national, regional, or local levels. Ironically, it can be argued that the questions and information needs of these "end users" require a consideration of these larger scales, but in our experience, end users of forest landscape ecological knowledge are more accustomed to the smaller scales of traditional forest ecology. This results in a mismatch between the scales of the problems, the scales addressed by the science, and the scales understood by the users. It is not surprising that transfer of knowledge generated by the science of landscape ecology into forestry applications is at best uneven.

Another consequence of the breadth of the spatial and temporal scales in forest landscape ecology is the impracticality of developing scientific knowledge by traditional experimentation. For example, even forested watersheds, which are large relative to the size of most field experiments, may be small relative to the scales of forest landscape ecology. For this reason, simulation models have become an essential research tool for forest landscape ecologists. Such models are evident in all aspects of forest landscape ecological research: studies of forest landscape composition, structure, dynamics, and function, as well as their management. Invariably, these models are also the primary means by which landscape ecological knowledge is conveyed for applications in forest management. This is different from the mostly empirical ecological knowledge traditionally available to forest resource managers.

Given this background, our goals in this chapter are to examine and illustrate the generic barriers to popular use of forest landscape ecological models and to offer potential solutions. We will focus less on what is wrong with landscape ecological models (an advice typically offered to advance modeling concepts), and more on how researchers can make models more attractive to forest resource managers by understanding the user's perspective. Consideration and understanding of the scale of forest landscape ecology are important for both the modelers and the managers. Misunderstanding or miscommunication of the principles of scale could hinder the transfer of knowledge (e.g., models) generated by forest landscape ecology to users. Accordingly, we consider some of the common barriers to understanding the scale of forest landscape ecology that could impede the widespread use of models. Our comments are primarily focused on the communication of scale by researchers and its understanding by managers, but we also identify problems of scale in ecological models and explain the implications of scale, when necessary, to clarify the potential for miscommunication or misunderstanding.

Our presentation is not a comprehensive review of literature—the body of literature on models and scale from the perspective of applied landscape ecology is limited—rather, it is a synthesis of our experiences and insight gleaned from a combined several decades of research in scale, landscape ecology, and forest modeling and our interactions with potential users of landscape ecology in forest management and other applications.

2.2. WHAT ARE FOREST LANDSCAPE ECOLOGICAL MODELS?

Before we discuss the transfer of forest landscape ecological models and their applications to users, let us examine what a *model* means in this context. It is used in landscape ecological parlance with a variety of mathematical, statistical, biological, and social connotations, and the literature is replete with model definitions and descriptions. For example, in a recent discussion of ecological models for resource management, Dale (2003a) offered three broad groupings of landscape ecological models: heuristic (conceptual abstractions showing interrelationships among variables), physical (scaled-down expressions of the real world in two or more dimensions), and mathematical (descriptions of numerical interrelationships among variables). In the context of this chapter, we limit our discussion to simulation models, which are a subset of Dale's mathematical models in which modelers use numerical and computational methods to describe and investigate the behavior of the system being modeled. Simulation models in forest landscape ecology may be developed for various reasons, ranging from exploring (e.g., examining what-if scenarios, in which the known variables or their values and functions can be changed), to predicting (e.g., projecting specific outcomes based on a specific set of known variables and functions). Regardless of these variations, a simulation model, in essence, is a logical and an explicit articulation of an abstracted relationship between known ecological variables and unknown ecological variables. This articulation is quantitative; unknowns are expressed or simulated as a function of known variables and valid only under a given set of circumstances (i.e., the model assumptions). Figure 2.1 describes, in abstract, the essential anatomy of a simulation model in forest landscape ecology.

In principle, a forest landscape ecological model could be any model of the forested landscape at large spatial and temporal extents (as defined above). In

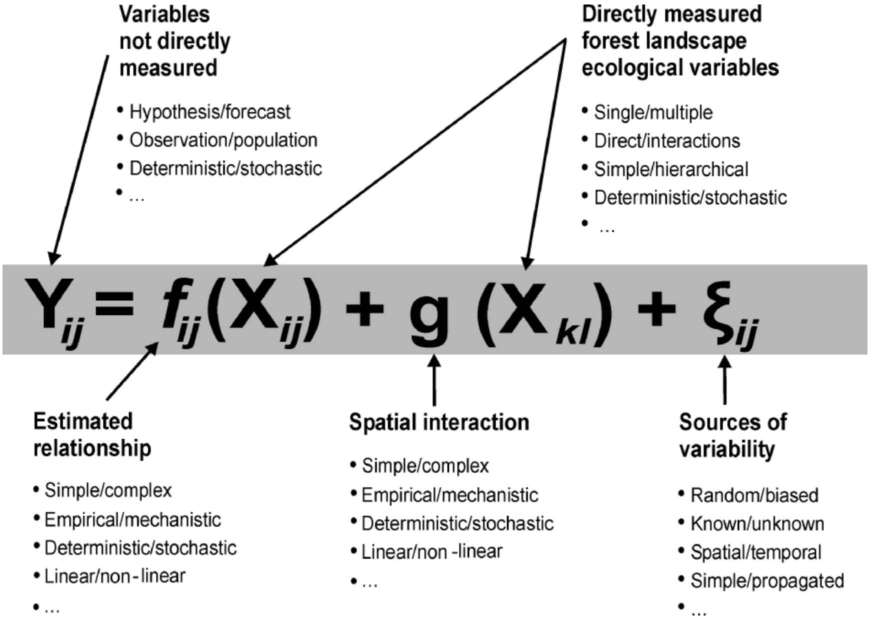

Figure 2.1. Anatomy of the basic components of a forest landscape ecological simulation model. *i,j* represents a two-dimensional index of spatial variability in model components, and *kl* represents the influence of spatial location on *ij*.

practice, forest landscape simulation models tend to focus on variation within those extents and generally disaggregate the landscape into patches, a mosaic of polygons, or a regular geometrical grid of squares, triangles, or hexagons. Thus, most of the considerations that must be addressed in traditional nonspatial or aspatial forest simulation models are compounded by considerations of how measured variables, relationships between known (measured) and unknown (modeled), and sources of variability vary in space, or in the models from cell to cell in the grid or mosaic (Figure 2.1). In addition, forest landscape ecological models must, or should, consider interactions between variables at one location and those at others. Forest landscape models sometimes ignore these interactions, or at least presume they are inconsequential. However, a forest landscape ecological model should at least make this latter assumption explicit if it is to be true to its heritage as a model informed by the science of landscape ecology.

Simulation models differ widely in their variables, assumptions, and functions and these differences may be evident in specific features of model components. Directly measured variables may be single or multiple, deterministic or stochastic, and simple or hierarchical. When applied to a landscape, the spatial variation or the aggregation of spatial variability in these observed variables differs among models. The estimated relationships may be simple or complex, empirically derived or mechanistically constructed, deterministic or stochastic, and linear or nonlinear. The parameters describing the relationships may vary spatially, and each function may change from one location to the next. Sources of variability or "error" in a model can be random or biased, known or unknown, and simple or propagated, and the variability may or may not change through time. When applied to a landscape, spatial variation of these sources may or may not be explicitly considered in the model. More generally, forest landscape ecological models differ considerably in how spatial variation in observed variables, relationships, modeled variables, and sources of error are explicitly represented or spatially aggregated. Forest ecological models can differ greatly; forest *landscape* ecological models differ even more. Regardless of these differences, all forest landscape ecological models can be expressed using the abstraction in Figure 2.1.

Forest landscape ecology offers many different research topics in which model development is common. These range from physical and biological processes to anthropogenic processes, and include models that focus on, for example, hydrology, climate change, forest fires, carbon sequestration, metapopulations, forest succession, harvesting, and urbanization. These different focus areas often lead to variation in how the elements in Figure 2.1 are represented in the models.

2.3. WHO USES FOREST LANDSCAPE ECOLOGICAL MODELS?

Forest landscape ecological models are diverse with respect to their variables and mathematical formulations (Figure 2.1), as well as their use. In addition to their many different scientific uses (e.g., as a heuristic, as a framework for synthesis and integration, to calculate quantities, as spatially explicit hypothesis generators, or to test hypotheses), researchers in forest landscape ecology also use simulation models to integrate and extend ecological information for applied use in forest landscape management (e.g., Buongiorno and Gilless 2003; Jansen et al. 2002; Mladenoff and Baker 1999; Perera et al. 2004). They are intended for use in design, planning, and managing forest landscapes either by generating broad contextual information or by providing answers to what-if questions raised under specific management scenarios. Table 2.1 lists an example set of uses of forest landscape simulation models in management, ranging from legislation to harvest planning.

Simulation models that focus on topics such as climate change, carbon sequestration, metapopulation dynamics, forest fire regimes, urbanization, and pest epidemics provide contextual information to aid in the development of strategic policies and plans for forest management. Primary users of such models are at the higher end of the decisionmaker hierarchy, and range from legislators and policymakers to land-use planners who focus on larger spatial extents and longer time horizons. Simulation models that focus on topics such as forest succession, habitat supply, and harvesting may provide answers to questions raised during forest management planning and decisionmaking at a tactical level. Primary users of such models are forest resource managers who focus on (relatively) smaller spatial extents and shorter time horizons (Table 2.1).

Although these groupings overlap, recognition of the end uses of the model is an *a priori* need for successful model development and transfer of the model to its users. For example, the “push” transfer approach (see Perera et al. 2006) is more effective with legislators and policymakers, because researchers generate scientific knowledge to provide contextual awareness and baseline information in response to forest landscape ecological issues. Some examples of push-based knowledge transfer include the results of metapopulation models, global and regional climate change models, and models of invasive species. On the other hand, the “pull” transfer approach (see Perera et al. 2006 for details) appears to be more common with forest resource managers; in this approach, researchers develop simulation models based on user demand for tools, including decision-support systems. Some examples of pull-based knowledge transfer include harvest simulation models, fire-spread models, and forest succession models. We do not imply that this dichotomy is appropriate in all situations: in most cases a combination of the two transfer approaches may be appropriate. And the push approach, if effective, will often lead to a pull. When push switches to pull, the modeling requirements are likely to change because the models are developed to meet different needs.

2.4. WHAT MAKES FOREST LANDSCAPE ECOLOGICAL SIMULATION MODELS LESS APPEALING TO USERS?

In this section, we examine common barriers to the application of simulation models. Our discussion is embodied in the statement that “we cannot expect people to apply ideas that they do not understand or support” (Gutzwiller 2002a). We found

Table 2.1. Examples of uses of forest landscape ecological simulation models for decisionmaking by a range of users from legislators to forest managers

Decisionmaking hierarchy in forest landscape management	Products of decisions	Spatial extent of influence	Temporal window of decisions	Examples of areas of application	Examples of forest landscape ecological simulation models
Legislators	Legislation	Global, national, and regional	Many decades	Endangered species acts, climate change	Metapopulation models Global and regional circulation models
Policy developers	Policies and guidelines	National and regional	Several decades	Old-growth conservation, emulating disturbance, invasive species	Forest fire regime models Species migration and diffusion models
Forest land-use planners	Forest land-use strategic plans	Regional and subregional	A single decade or subdecades	Design of parks and protected areas, wildlife corridors and habitat supply, watershed management	Watershed models Habitat supply and population models Forest fragmentation and urbanization models
Forest resource managers	Harvest and regeneration tactical plans	Forest management units	A few years	Timber supply, forest fire management, forest pest management	Harvest planning models Fire-spread models Pest epidemic models

that the literature on simulation models and model development does not commonly address this topic: few authors address problems that users face in applying landscape ecological models (e.g., Dale 2003a,b; Gutzwiller 2002b; Perera and Euler 2000; Turner et al. 2002). Their views are summarized in the ensuing discussion, augmented by a synthesis of our own insight gained during decades of experience in model development and transfer to forest resource managers and policymakers.

2.4.1. Unfamiliarity with Topic

The broad spatial and temporal scales of the concepts addressed in forest landscape ecological simulation models are new and exotic to most potential users of these models because these topics were not part of their training. Though this obstacle is temporary, and will gradually disappear with the turnover among forestry professionals, it has been a significant impediment to ready transfer of modeling knowledge to forest resource managers and policymakers and will continue to be for some time. As such, much of the early effort in transferring models involves increasing user familiarity with scale and spatial concepts. These issues are discussed in more detail in Section 2.5.

2.4.2. Uncertainty about the Purpose of Simulation Models

Users, especially those with tactical end-use goals, may expect simulation models to generate information that they can use directly in decisionmaking. Though this is a reasonable expectation, not all simulation models are intended to be decision-support systems. If they are not designed to assist or support specific decisionmaking under predetermined circumstances, attempts to use simulation models to support management decisions can be futile or even counterproductive. Similarly, exploratory models that attempt to reveal emergent properties and provide contextual information must not be used to predict or forecast scenarios for decisionmaking. Such occurrences, not uncommon in our experience, are mostly a result of ambiguity in the model developer's elucidation of the model's purpose.

It is not surprising that users misunderstand the purpose of a simulation model or of modeling in general. Modelers themselves often misunderstand or remain unaware of the diverse purposes behind model development and use and the implications of this diversity. In that context, communication of purpose can obviously be difficult and limited. Modelers have their own biases that blind them to the differences in model specifications required by differences in the model's purpose. Uncertainty and differences of opinion among researchers about the definition of decision-support systems, about how models can support decisions, and about who will use the models to make decisions, contribute to the general confusion about the purpose of simulation models.

2.4.3. Unclear Assumptions and Application Limitations

Even if the model purpose is made clear to users, the specific assumptions, scales, and other premises of simulation models may remain unclear. This occurs frequently when model developers fail to unambiguously explain the model's assumptions and limitations to its users. Developers generally understand the assumptions and limitations of their models, but often fail to make those assumptions and limitations explicit. It is worth noting that researchers who use models developed by others and who may then promote the use of those models through transfer to an application (e.g., management) often do not understand all the assumptions and limitations of the model themselves. The chain of communication between model developers, scientific users of the model, and managers or decisionmakers who apply those merits careful attention.

Though there is no assurance that clear communication of assumptions and limitations will lead to correct use of models, or that correct use will lead to correct policies and management decisions, unclear communication can easily lead to misuse of models. This, in turn, will certainly lead to incorrect or inappropriate—or at least ill-informed—policies and management decisions. As a result, users will lose confidence in simulation models, and this lack of confidence will become a serious long-term impediment to the application of these and other models in forest management.

2.4.4. Dissatisfaction with Abstractions and Assumptions

Often, users of models are uncomfortable defining forest landscape ecological systems based on explicit assumptions, which they believe artificially reduce real-world complexity. In fact, many model developers are also uncomfortable with simplified models. But simulation models are designed to be abstracted representations of ecological systems, with the abstraction governed by strict assumptions, and do not, should not, and cannot address all details of the systems they model. Attempts by some model developers to produce parsimonious models, which emphasize an economy of explanation in conformity with Occam's razor, pose a problem for users who expect models to address all possible details of forest landscape structure and function. At the policy design level, attempting to address social, biological, and economic aspects through modeling is a daunting task for modelers, and for users, even when modelers succeed in developing such complex models. But even an agreement that a model should be parsimonious while still meeting the stated objectives does not guarantee that dissatisfaction with the model's abstractions and assumptions will be avoided. Different understandings of and biases about what is important, what is essential, and what is "just" detail arise from different scientific and management perspectives and can lead to different abstractions, albeit parsimonious, which may not be readily acceptable.

2.4.5. Discomfort with Modeling at Large Scales

Forest landscape simulation models address concepts, use data, and produce simulated scenarios at scales that lie beyond the typical scale of human perception, and this makes understanding of the models difficult. The use of maps and remote sensing helps, but simulation models of large-scale patterns (e.g., species extinction) that use "coarse" data such as satellite imagery or simulation models of low-probability events of occurrence such as infrequent incidence in time (e.g., flooding) or rarity in space (e.g., forest fires), force users to address unfamiliar spatial and temporal extents and intervals and equally unfamiliar resolutions. Similarly, models of large-scale spatial processes that play out only over a long time scale (e.g., climate change and biogeographical redistribution of species) force users to deal with unfamiliar time periods that may well exceed the accustomed scales of forest management. Although we have found that users can implicitly use and synthesize broad-scale information, doing so explicitly and quantitatively through simulation models appears more complicated. This is somewhat ironic for those who work with forests, since managers understand that trees often live relatively long, and the forests they occupy can persist relatively unchanged for multiple human lifetimes. Forest ecologists and managers are accustomed to "standing among the trees to see the forest," but the different scales and perspectives of landscape ecology and forest management make the larger scales and perspectives unfamiliar to individuals with more traditional experience and training. This lack of familiarity generates a significant degree of discomfort with the scales of forest landscape models.

2.4.6. Discomfort with Stochasticity and Variability in Simulated Processes

An important element in landscape ecological modeling is the stochasticity (whether random or biased), as well as spatial and temporal variability. We have found that users accustomed to deterministic knowledge may have difficulty dealing with probability and variability in simulated information. In our experience, users prefer the output of deterministic models, whether those outputs are a single numerical value or a map, and have difficulty with stochastic outputs such as probabilities and variances, whether depicted numerically or as choropleth maps. This is especially true when probabilities and variability are emergent properties of a simulation model and are not necessarily evident to the model's users in the input variables, model parameters, or model assumptions. At times, this discomfort appears peculiar or ironic to model developers because forest management professionals are well aware of the multiple and complex probabilities associated with ecological, economic, and social processes.

On the other hand, the discomfort of some users with stochasticity should not be surprising because it is not limited to users. Modelers also appear to prefer deterministic outputs. The number of deterministic simulation models far exceeds that of stochastic models. As well, model results are presented far more frequently as single deterministic values than as distributions of values, or as an expected value with surrounding probabilistic error. The general bias toward deterministic models is even more pronounced when considering landscape models and maps of model results. If users prefer deterministic model output, it is arguably because the modeling community has led them to expect it and be much less comfortable with probabilistic results.

2.4.7. Distrust of "Black Box" Models

Model users are occasionally uncomfortable using simulation models whose underlying mechanisms are not apparent. Usually, simulation models are designed to conceal complexities in structure and mechanisms, especially when they are designed for applied use. This may present a "black-boxed" appearance to users, who will not be confident in using a tool that they do not understand. Obscuring the model's logic can create significant barriers to use of the model, particularly when the policy or management context for use of the simulation model is contentious.

This distrust may also arise from failure to understand the model's assumptions. When these assumptions are obvious, users may be more tolerant and less distrustful of models that hide their mechanisms. We can be reasonably confident that few users want to see the numerical algorithms used to solve a model's differential equations or care whether the dynamics of a process are modeled using finite differences versus differential equations or ordinary versus partial differential equations or uniform square lattices versus vector-based mosaics of irregular polygons. But other assumptions are likely to be important. Which mechanisms should be made explicit and which should be hidden? Answering this question, and even distinguishing between a "mechanism" and an "assumption" (models do, after all, assume certain mechanisms) is more art than science, and there is no universal solution. Nevertheless, the necessity of hiding certain aspects of the model to enable its use by practitioners, and decisions about what to hide, will continue to be a barrier for certain users and uses.

At the same time, some users are too comfortable using black-box models or treat and use all models as if they were black boxes. As noted above, both scientists and practitioners often use models developed by others without careful consideration of the assumptions, methods, and implementation of the model, and how these factors might influence the results and their interpretation. The degree to which users expect, desire, and trust black-box models, and how this encourages or discourages their use of the models, varies widely.

2.4.8. Distrust of Methods of Model Validation

Forest management professionals are accustomed to forest ecological models for which empirical data can be readily obtained through observation or experimentation and used to validate the simulation results. Simulation models in landscape ecology, on the other hand, produce output that cannot be readily validated based on the user's experience or on available empirical data because of the breadth in scale, complexity, and stochasticity of the ecological processes being modeled. As a result, potential users may distrust these simulation models even when they reflect the best science available. This is especially evident with simulation models of long-term processes such as climate change, species migrations, and disturbance regimes. This is a valid criticism and a predictable impediment to the use of forest landscape ecological models. Especially when they are used to estimate or forecast quantities, and decisions are made to expend resources or enact legislation based on those results, users have difficulty knowing how much trust or confidence they can place in the results.

2.4.9. Unavailability of Computing Technology and Spatial Data

Almost all landscape ecological simulation models are spatially explicit, and require both large quantities of spatial data and significant computing capacity. The exceptional growth of desktop computing over the past 20 years, coincident with the growth of landscape ecology and having contributed significantly to growth of the discipline, has greatly reduced the technological barriers, but some users still may lack access to sufficient data or sufficient computing power to process the data. As well, modelers are always pushing the technological envelope and exploiting the latest computational capacity (e.g., high-performance parallel computing), and a gap will always exist between the needs of state-of-the-art models and the technology and data available to potential users of the models. If not managed properly, this gap can hinder widespread use of more advanced models.

2.4.10. Necessity for Third Party Involvement

The use of forest landscape ecological simulation models usually requires knowledge of geographical information systems, programming, spatial statistics, or all three disciplines. Since most users, whether policymakers or forest resource managers, have not learned this suite of skills during their formal training, they must often rely on experts who can use the models on their behalf, and these experts serve as translators of the messages being communicated by the model's developers. Since these technological experts may not necessarily have a landscape ecological, forest management, or policy development background, knowledge transfer becomes a three-way dialogue rather than a simple dialogue between developer and user. Although this dialogue has improved the application of models in some cases, we have also seen instances where the requirement for a third party acts as a barrier to acceptance of simulation models. We discussed this previously in our example of how scientists using models developed by other researchers and who attempt to transfer the models to decisionmakers or managers may themselves be unfamiliar with the model's assumptions and less sensitive to the model's limitations than those who developed the model. Thus, forest scientists themselves may be third parties and translators who become a barrier to appropriate use of a model.

2.5. IS MISUNDERSTANDING OF SCALE A SERIOUS IMPEDIMENT TO USERS OF LANDSCAPE ECOLOGY?

As noted in the introduction to this chapter, forest landscape ecology deals with large spatial extents with a spatial resolution that is generally much coarser than the individual trees or stands that are more familiar to practitioners. Changes in the forest landscape over these large spatial scales often take place only over long periods of time, and these slow dynamics can only be observed through sampling at relatively infrequent intervals. At the same time, our observational perspective is comparatively fine-grained. We observe daily, seasonal, and interannual changes in trees and stands that might be significant with respect to larger-scale changes, or might only be high-frequency "noise" (i.e., insignificant variation).

With scale so central to forest landscape ecology, misunderstanding of the importance of scale or a failure to incorporate principles of scale in modeling of forest landscapes is likely to create barriers to widespread use of forest landscape ecological models. Conversely, understanding of the importance of scale and disciplined treatment of scale could both provide potential solutions.

By and large, principles of scale are *not* having a positive impact on the application of landscape ecology to forest management. This assessment is based on our combined experience with principles of scale in ecological, landscape, and forest landscape modeling, and observations of their use in forest management. Others also have discussed how understanding the concepts of scale is important to forest landscape ecology and other applications of landscape ecology (e.g., Allen et al. 1984; Bissonette 1997). Forest resource managers are increasingly aware of the importance of scale as modern forest management is moving toward forest landscape management. Forest landscape models that are sensitive to issues of scale, and particularly to large and multiple scales, have been and are being developed with application in forest management as a primary goal. However, we believe that the full richness of the literature on the importance of scale in ecology has not been exploited in the development of models, and that an understanding of ecological scale is not informing the practice of forest landscape management.

This occurs for a variety of reasons. First and foremost, many practitioners simply do not see the relevance of concepts of scale beyond the idea that forested landscapes involve a large spatial extent. If their understanding of landscape ecology is limited to the notion that landscape ecology is simply the ecology of large areas or that landscapes are nothing more than large areas, they may feel they know all that they need to know about scale. Thus, the failure of landscape ecologists to emphasize aspects other than large spatial extents and to counter that bias may have created a barrier to practitioners pursuing a deeper understanding of scale.

Even practitioners and landscape scientists who have moved beyond that barrier may encounter additional barriers to understanding and incorporating the concepts of scale into modeling and practice. These include the possibilities that:

- There has been too little discussion of scale in ecology.
- The discussions of scale that have taken place may not have been sufficiently clear.
- The existing theory and principles of ecological scale may be too esoteric.
- Too much attention may have been placed on multiple scales rather than on the appropriate scale.
- Too little attention has been devoted to the defining principles of landscape ecology.
- There has been too little synthesis of our understanding of ecological scale.
- It is simply too soon for the science of ecological scales to significantly affect landscape management.

In the remainder of this section, we briefly address each of these issues.

2.5.1. Have We Discussed Enough about Scale?

Yes and no. Yes, because there has been much discussion of ecological scale in journal articles and books going back at least 20 years (e.g., O'Neill and King 1998). No, because the more important question is whether all that talk has been clear and effective in communicating the importance of scale to decisionmakers, managers, and other practitioners.

2.5.2. Has the Discussion of Scale Been Clear?

No, as a whole it has not been. There have been good discussions and explanations of the importance of scale in ecology (e.g., Turner et al. 1989), and individual presentations to potential users of this knowledge may have clearly and logically presented definitions of the concepts. However, the body of literature on scale often appears contradictory because different authors have investigated different problems, scales, or contexts without making these differences clear. This situation can generate confusion for individuals who are investigating how scale might influence an application. Perhaps more importantly, different individuals may develop different understandings of scale depending on which portion of the literature they sampled. Differences in understanding can lead to misunderstandings and confusion. The imprecise and inconsistent use of "scale" and "level" (as in the phrase "level of organization") is an example of one cause of confusion (Allen 1998; Allen and Hoekstra 1990; King 1997, 2005).

2.5.3. Has the Theory of Scale in Ecology Been too Esoteric?

Yes, at least in part. There are certainly commonsense aspects of scale that have influenced or are influencing forest modeling and management. One example is that large-scale systems such as forested landscapes require observations over large spatial extents and long time periods, and the scales of observation and management are increasingly being matched to the scale of the system. Similarly, there is an increasing recognition that the forest systems being managed encompass multiple scales, and new management approaches are addressing those different scales. There have also been largely theoretical discussions of scale explicitly targeted at an audience capable of applying this knowledge (e.g., Allen et al. 1984; King 1997). However, other aspects of the theory, including elements with rich potential insights on how to understand and manage large, multiscale systems, have tended to be couched in terms of unfamiliar abstractions and theoretical or mathematical terminology (O'Neill et al. 1989; Rosen 1989). The target audience for these presentations has been other scale researchers, which is fine so far as it goes, but the esoteric nature of these presentations, which comprise a sizable portion of the literature on scale in ecology, makes them unsuitable for practitioners. The differences in the language and style of presentation between researcher and practitioner audiences have been, in part, responsible for the limited influence of the discussion of scale in applied forest management. Some parts of the message are getting through; others are not.

2.5.4. Has There Been too Much Focus on Multiple Scales?

Yes. One of the recommendations to come from the consideration of scale in ecology has been a call for observations and studies at multiple scales. This is scientifically appropriate, but incomplete. It is certainly true that forested landscapes span a wide range of observational scales and involve processes operating at many different scales. It is also true that observations and studies at multiple scales will help determine how different processes operating at different scales are ultimately expressed at the scale of the forested landscape. But lost in this focus on multiple scales has been the equally fundamental message that there may be a single scale of observation, or a small set of scales, that is most appropriate to the specific management problem faced by a practitioner. If one has the objective of management of a forest at a given spatial extent for a given period of time, the theory of scale in ecology argues for finding *the* scale of observation most appropriate to that objective. It does not argue for, in fact argues *against*, looking at all scales encompassed by the scale of the management objective.

The principle of the appropriate scale for observing and understanding ecological systems draws heavily on hierarchy theory (Allen et al. 1984; King 1997, O'Neill 1989; Urban et al. 1987) and argues in favor of a three-scale approach. Hierarchy theory asserts that the focal level L of a system is the level of observable dynamics chosen by the investigator, and in the context of this chapter, is determined by the management objective. A mechanistic explanation of the dynamics at this level is found at the next lower level of organization L-1. However, level L occurs within the context of the next higher level L+1. This higher-level organization simultaneously bounds and is a consequence of focal level L, and both the constraints on the dynamics of that focal level and the significance or results of those dynamics can be found by examining the next higher level L+1. Allen et al. (1984) and King

(1997) and the references cited therein provide further details. Briefly, a three-level approach to nested, hierarchically organized ecological systems implies a corresponding three-scale approach to observing and understanding these ecological systems. The power of this approach lies in its emphasis on identifying the correct focal scale for a given management objective and the scales above and below that scale to discern the context and mechanisms (respectively) that govern that scale. It is this emphasis that has been lost in or obscured by the broader message that multiple scales are at work in any landscape.

A combination of hierarchy theory with the theory of scale can provide guidance on how to find the appropriate scales for a stated objective or application. This example illustrates how a richer understanding of scale can benefit applied forest landscape ecology. The consideration of scale in landscape ecology should be more nuanced than a simplistic recommendation to address only large scales or multiple scales. Such a message can be misinterpreted as a call for the study of multiple, arbitrarily selected scales even if those scales range from small to large. The arbitrary interpretation of multiple scales multiplies the problems for decisionmakers and managers, who are being asked to obtain scientifically sound observations and understanding at many different scales rather than at the most appropriate scale for their problem. The limited resources available to most practitioners would be better applied to identifying, observing, and understanding the most appropriate scale or limited number of scales for their management objectives.

Of course studies at multiple scales are needed to provide guidance for identifying the appropriate scales. Such studies might be required in circumstances in which theory provides uncertain or ambiguous guidance. Studies at multiple scales are also required in the determination of scaling rules or functions (King 1991; Milne 1997; Schneider 1994) that are used to translate information and observations across scales—for example, from the scales empirically accessible by field studies to larger scales of management objectives. In each case, there are uses for a fuller consideration of the importance of scale in landscape ecology.

2.5.5. Has There Been too Little Attention to the Defining Principles of Landscape Ecology?

Yes. Although this is not strictly an issue of scale, it is related to scale. Landscape ecology is a subdiscipline of ecology that focuses on understanding how spatial patterns and structures influence ecological processes (Turner 1989). It is true that most landscape ecology deals with spatial extents measured in thousands of hectares, but that tendency is historical and secondary, not a defining characteristic. The focus on how considerations of scale might help address a large spatial *extent* that encompasses processes at many different temporal and spatial scales has diverted attention from a consideration of how issues of scale might affect our understanding of spatial *patterns* and their influence on processes. Accordingly, the attention to scale, in the narrow sense of "large spatial scale," has detracted from the application of landscape ecology to forest management.

2.5.6. Has There Been Sufficient Synthesis?

No. The large and diverse literature on scale in ecology has not been sufficiently reviewed and synthesized from a scientific perspective. There has been even less effort devoted to synthesizing this knowledge from the perspective of potential application and to addressing problems using the language and examples familiar to the potential users of the knowledge. This lack of a useful and familiar synthesis has undoubtedly contributed to the limited application of considerations of scale and forest landscape ecology to forest management.

2.5.7. Perhaps It’s too Early?

Perhaps. Intensive investigations of scale in ecology and the inevitable debates that have ensued go back more than 20 years. After that much time, one might hope for a more obvious influence of applications of scale in forest management and elsewhere than is currently apparent. The heightened awareness and understanding of issues of ecological scale in the scientific community has in fact influenced forest management to some degree; that is, the scientific deliberations on the challenges of large-scale ecological applications that influenced the growth of landscape ecology are gradually being transferred into applications. Today’s discussions of forest management and ecological applications are different from those that occurred prior to the growth of landscape ecology and its considerations of scale. We suspect that the consideration of larger scales in modern forest management was driven primarily by the advent of satellite-based remote sensing and the accompanying changes in visual perspective, and that the emergence of landscape ecology was simultaneously influenced by these technological changes. But larger-scale applications and landscape ecology have grown together, have had positive influences on one another, and will likely continue to do so. Researchers and practitioners increasingly share their language, concepts, and understanding. The influence of science on practice undoubtedly requires more time to be fully realized. We may simply be anxious to see more impact and influence than the natural time scales of the feedback process permit. Nevertheless, the apparent influence has been patchy. Greater attention to the process of knowledge transfer to promote appropriate use of an understanding of scale in landscape modeling and forest management is called for.

2.6. HOW CAN RESEARCHERS MAKE SIMULATION MODELS MORE APPEALING TO USERS?

In this section, we offer some suggestions on how researchers who develop simulation models can more effectively transfer their scientific knowledge to users capable of applying that knowledge. Our intent is not to popularize simulation models, but rather to promote their judicious and appropriate use so that the gap between knowledge of forest landscape ecology and its application can be bridged in the long term. The points we address below are applicable whether the intended user of the knowledge is a forest resource manager who will use simulation models to support the development of tactical plans or a policymaker who will use simulation models for the development of strategic policy. Our discussion combines the views of several authors (e.g., Dale 2003a,b; Gutzwiller 2002b; Perera and Euler 2000; Turner et al. 2002) with the lessons learned from our own failures as developers of applied models.

2.6.1. Understand the User, Not Only the Use of the Models

When the goal of developers of landscape ecological models is the applied use of their models to solve problems, it is essential that they understand not just the intended use of the model but also the users and how this audience will use it. For example, the research community considers a model elegant if it embodies advanced scientific methods, logic, and computational techniques; in contrast, practitioners consider a model elegant if it is easy to use, appears simple and trustworthy, and produces useful and realistic results that support their efforts to solve problems. The elegant research model can be adapted so that it can be used to solve particular problems if it simulates the appropriate variables, at the appropriate temporal and spatial scales, in response to the appropriate drivers. However, that applicability alone may not be sufficient, and may even become counterproductive.

When a model requires too much data, is too computationally demanding, or involves state-of-the-art concepts and logic that are unfamiliar to the user (e.g., “fuzzy logic”), it may be applicable but it will not be applied. Knowing who the end users are—their educational background, geography, institutional and professional cultures, the resources they have available to implement models, and the practical difficulties they face—will help modelers to understand the users’ perspective and develop models the users are likely to embrace. Accommodating user expectations by understanding who end users are and their specific needs does not diminish and compromise the scientific rigor of a simulation model; rather, it enhances its appeal to the users.

2.6.2. Develop Simple Models

Simplicity in model development is a desirable quality that will increase user acceptance as well as the model’s ease of use. To many model developers, simplifying models means little more than adding a graphical user interface (GUI) between the model and the user. GUIs are useful for concealing intricacies that are not necessary for use of the model, and thereby increase the perceived user-friendliness and convenience of the model. However, models can be made even easier to use and more attractive to the user by designing them based on the principle of parsimony. Potential users of a model may demand more details than are necessary, and in this case, the developer may need to emphasize simplicity over the complexity that would result from addressing all their demands. By parsimony, we mean that the goal is to reduce the complexity of the model’s mechanics by judicious choice of the model's scale, functions, parameters, input data, and outputs. What we suggest goes beyond the typical sensitivity analyses carried out during model construction, in which the model outputs provide the sole guidance. We urge modelers to define the most parsimonious model possible given the user's requirements. Developers should mine the literature on scale in ecological systems for insight into how mechanisms and their functional representation vary with scale in scale-dependent levels of organization. Understanding how the scale of observation (the observer's perspective) influences how the system looks to the observer provides insight into how to adapt the appearance of the model to the user. Another suggestion is to consider developing multilayered models, which contain a hierarchy of submodels that can be coupled or decoupled to attain levels of complexity that can be tailored to the needs of each user. The points at which coupling and decoupling can occur might coincide with scale-dependent levels of organization in a hierarchically organized system, or might reflect how users analyze and interact with the components of the problem.

Designing for simplicity based on considerations of scale and the user's perspective will also help designers to determine which mechanisms should be placed in black boxes (i.e., made invisible to the user of the model). For example, fine-scale mechanisms that are far removed from the larger scale of observation can be concealed so that only aspects (e.g., aggregate properties) that are translated across intervening scales will be presented to the user. These are the kinds of design decisions that are intuitively made while designing for parsimony and simplicity. For example, a deeper understanding of scale in ecological systems could be used to develop simpler models that are parsimonious with respect to scale. The three-level models suggested by the hierarchy theory discussed in Section 5.4 provide one example of this approach. King (1997) discusses application of this approach to an age-structured population model.

2.6.3. Clarify the Limitations of the Model to Its Users

Simulation models are applicable under very specific conditions and assumptions, and are only suitable for specific uses. Model developers cannot assume that these limitations, assumptions, and objectives are clear to the model's users. As we mentioned earlier, ambiguity in explaining a model's limitations leads to misuse in the short term and mistrust in landscape ecological applications in the long term. Researchers must thus make a concerted effort to clearly articulate the intended use (e.g., exploratory versus forecasting) of their models. For example, simulation models developed for discovery and exploration are useful tools to provide contextual information such as the consequences of climate change. However, such models must not be used to forecast specific scenarios, however convincing they may be, or to help managers make tactical management decisions as though they were decision-support systems. Another example relates to simulation models of historical landscapes. Although some of these models provide insights into how present landscapes may have evolved, and into landscape patterns and processes in a different temporal context, direct use of such models to generate blueprints of future landscapes is questionable.

Strict assumptions are fundamental to developing good models, but violating these assumptions (e.g., changing scales, intervals, extents, and periods of application or modifying state variables) can generate false outputs and incorrect inferences. For example, a probabilistic simulation model of the incidence of insect epidemics developed for the current climate and forest composition must not be advocated for long-term use because climate and forest composition may not be static over longer periods. Neither is that model suitable for deterministic spatiotemporal forecasts of the incidence of epidemics. Model developers must ensure that the assumptions and limitations in terms of scale, resolution, ranges of the state variables, and model functions are clear to users, and that users understand the consequences of violating those conditions.

Designing and developing models with simplicity as an objective facilitates the communication of assumptions, limitations, and consequences of violating these premises to the user. It is difficult to understand and communicate all of the assumptions—or even the most critical assumptions—in a complicated forest landscape simulation model. A more parsimonious model is easier for both the developer and the user to understand, and it is easier to explicitly communicate the assumptions and limits of simpler models.

In general, users require more explicit communication of the purpose of a model and the degree of confidence they should place in its outputs, and model results should be presented as probabilities with associated confidence intervals. However, the modeling community should also invest more effort in establishing methods and protocols for determining and communicating how much confidence should be placed in the outputs of their models. As noted above, traditional validation of models against observations is frequently impossible because of the scales involved. Accordingly, alternative approaches for evaluating model performance must be established and communicated to users. Because this is an important consideration that we cannot fully address here, we refer readers to discussions of nontraditional methods for testing model predictions (e.g., Gardner and Urban 2003; Kleindorfer et al. 1998; Oreskes 1998, 2004; Oreskes et al. 1994; Sargent 2004).

2.6.4. Transfer Knowledge to Users Interactively, before, during, and after Model Development

Knowledge transfer related to forest landscape ecological simulation models must extend beyond passive means such as publications, posters, and oral presentations, especially when there is a clear group of users for a model. Whenever possible, researchers must actively initiate and engage in knowledge transfer to users of the model and, rather than waiting to begin knowledge transfer until after the models have been developed, should strive to initiate a dialogue between developers and users at the design stage and continue this dialogue through development and testing of the model. The most effective and appropriately used models will be those that are designed and modified to meet specific user needs, following explicit definition of specifications by the users and iterative improvement based on feedback from the users.

Model developers can engage end users in many ways. Here, we suggest only a few possible avenues. At the outset of the design stage, researchers should engage in a dialogue with the intended users of their model to understand their specific needs and the context in which those needs will be met, and to convey the concepts underlying the model. This exchange is vital because understanding of these concepts is essential to prevent users from subsequently using the model in an inappropriate context. At this stage, users and model developers can also establish a shared vocabulary to prevent miscommunication later in the process. Adopting and adapting the use of formal model specifications would prove useful.

As model design progresses, developers can inform users of the logic and principles behind the model to ensure that they understand and accept the modeling methods. An early understanding and acceptance of model logic and methods by users is preferable to basing eventual acceptance solely on validating the model results using empirical data—something that may not even be possible for some types of model. Many modeling approaches can yield similar matches with observations, but different users will prefer or require different approaches for different uses. Based on this continuing dialogue, model developers will increasingly understand design calibrations that are necessary for the model to meet the needs of its users, and users will increasingly understand the limitations and assumptions that govern use of the model.

Postdevelopment model testing and sensitivity analyses should be conducted using user-provided data, creating another opportunity for users to understand the model and provide feedback to developers. Every interaction between developers and users of the model can be a mutually productive knowledge transfer opportunity and learning experience.

2.6.5. Synthesize an Understanding of Scale from the Perspective of Model Application

Our recommendations for making simulation models more appealing to their users should be complemented by a comprehensive review and synthesis of the current understanding of scale in ecology, and in landscape ecology in particular. The specific aim of this synthesis should be to make what is currently known about scale in ecology more useful in the realm of application. The synthesis should use language and examples familiar to practitioners and other users of the model, and be designed to be used during the process of developing and deploying the model.

2.7. MUTUAL BENEFITS

In this chapter, we have focused on challenges to the transfer and extension of forest landscape modeling knowledge into forest management, and on possible solutions. Our premise has been that forest management will benefit from appropriate use of forest landscape models, and that this use will benefit from explicit consideration of the users and their needs during design and deployment of the models. However, the benefits are mutual. Obviously, model developers who intend for their model to be used in practical applications will benefit when the model is actually used and is used appropriately. But, their discriminate use will also benefit when forest landscape models are designed with these considerations in mind.

It can be argued that one of the guiding principles of Western scientific endeavor is the desire to explain a complex natural world using a finite and relatively small set of simple relationships or laws. Science seeks explanations through simplification and parsimony, and the principle of parsimonious model design that we have proposed in this chapter is in keeping with that goal. We propose that a more explicit and formal consideration of the principles of ecological scale will help move the design of forest landscape ecological models from art to science. Forest management will benefit from better-designed forest landscape models, as will the science of forest landscape ecology.

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