3 A Conceptual Framework for Adaptive Forest Management under Climate Change

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CONTENTS

The consensus among most scientists is that the global climate is changing in response to a rapid increase in greenhouse gas emissions over the past 150 years. This perspective has prompted research on potential changes in future forest conditions so that management interventions might be developed to protect desired ecosystem services. Some of the most significant forest trends expected in response to climate change are: a shift in tree habitats and ranges perhaps in surprising directions (Iverson et al. 2008, 2011; Zhu et al. 2011); an increase in the rate and severity of disturbances such as pest outbreaks, wildfires, acidic deposition, drought, and storms (Allen et al. 2010; Ayres and Lombadero 2000; Breshears et al. 2005; Emanuel et al. 2008; Klos et al. 2009; McNulty and Boggs 2010; Raffa et al. 2008; Soja et al. 2007; Vose et al. 2012; Westerling et al. 2006, 2011); and a reduced ability of some forests to recover from forest disturbances (Thompson et al. 2009). Although these trends are projected to materialize over the next several decades, the precise timing, location, and intensity of changing climatic effects on forests are uncertain.

Because forests are long-lived, current management decisions carry a legacy that will affect their responses to climatic and biotic conditions far into the future. Understandably, many forest managers are reluctant to change their practices in the near term without persuasive evidence that consequential changes in forest health or productivity are underway. For example, research has shown that decision makers, in many different contexts, tend to favor the status quo (do nothing different) over other alternatives (Samuelson and Zeckhauser 1988), especially in situations where payoffs are uncertain (Kahneman and Tversky 1979). Consequently, forest management that seeks to maintain current forest conditions may dominate decision making, resulting in forests that are poorly adapted to future climate. Although sustainable forest management in the twenty-first century will require a willingness to experiment, learn, and adapt management strategies to changing conditions (Blate et al. 2009; Millar et al. 2007; Seastadt et al. 2008), the inducements needed to alter management regimes are poorly understood. Managers may be more inclined to implement "no regrets" strategies whereby benefits accrue with or without changes in climate (such as fuel load reduction); however, these strategies may be too conservative to increase adaptive capacity over large spatial scales.

The premise of this chapter is that better information leads to better decision making. Our goal, therefore, was to describe a general conceptual framework for an iterative decision-making process based on experimentation and scientific learning (adaptive forest management) that can help practitioners identify their best options when faced with uncertainty about future climate changes and their impacts on forest ecosystems. In addition, this conceptual framework and associated terminology served as guidance to ensure consistency in approach for the subsequent chapters in this book.

SUSTAINING ECOSYSTEM SERVICES

Natural systems are increasingly viewed as critical capital assets that provide a broad suite of ecosystem services valued by people (Daily et al. 2009; Mäler et al. 2008). The Millennium Ecosystem Assessment (2003) listed four categories of ecosystem services: provisioning (such as food, water, and timber), regulating (such as flood control), cultural (such as recreation), and supporting (such as nutrient cycling). Ecosystem services are valued by people because they help to sustain and protect human life as well as improve the quality of life. They derive from ecosystem processes that transform structural and functional ecosystem inputs (such as tree abundance and rates of evapotranspiration) into the outputs that people desire (such as clean water). When the values of ecosystem services are not considered by decision makers, they will be provided at suboptimal levels or not at all.

Climate change is anticipated to alter the amounts and kinds of ecosystem services forests provide (Figure 3.1) through mechanisms we describe in the following as slow or fast ecosystem disturbance processes.

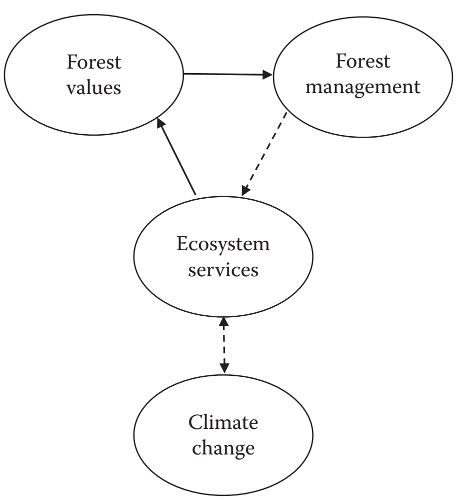

FIGURE 3.1 Diagram showing the linkages among forest values, forest management, ecosystem services, and climate change, with solid arrows indicating the direction of causality and broken arrows indicating biophysical production functions. Note that the downward pointing arrow linking ecosystem services to climate change represents mitigation through carbon sequestration.

Forest management can be used to modify the delivery of ecosystem services by adding or subtracting biophysical inputs. If the provision of ecosystem services is not consistent with the goals and desires of landowners or other stakeholders, the level of management inputs can be changed. The relatively long time lag between the implementation of forest management and the period during which desired ecosystem services are provided greatly complicates forest management decision making.

Adaptation and mitigation are two types of forest management strategies that can reduce the anticipated impacts of climate change. Adaptation—which is the focus of this chapter—refers to actions taken with the goal of decreasing the perceived negative impacts of climate change or increasing the perceived positive impacts (Millar et al. 2007). Investments in adaptation alter the ecosystem production function (the arrow linking forest management and ecosystem services in Figure 3.1) but do not directly influence the rate or magnitude of climate change. In contrast, investments in mitigation have a goal of reducing the anticipated severity of climate change. Within the forestry context, mitigation principally includes forest management activities that sequester carbon (Liao et al. 2010; Pan et al. 2011; Stoy et al. 2008) (the downward arrow linking ecosystem services (carbon sequestration) and climate change in Figure 3.1). To be effective, investments in mitigation and adaptation activities must recognize both the potential trade-offs and the complementarities between these activities (Callaway 2004).

Sustainable forest management means different things to different people. In this chapter, we define sustainable management as any management regime that maintains the productive capacity of forests so that the level of well-being available for future generations does not decline (see the Glossary at the end of the chapter). Mäler et al. (2008) proposed measures of societal well-being based on economic indicators that account for the value of ecosystem services provided by natural systems. Within the forestry context, Adamowicz (2003) recommended that levels of societal well-being provided by forest ecosystem services be assessed by a system that accounts for the value—expressed in units of currency—of forest ecosystem services that enter markets (such as timber) as well as the services that are not marketed (such as subsistence harvesting of mushrooms or aesthetic views). Market and nonmarket economic indicators, measures of market and nonmarket service values, offer a means of comparing the costs and benefits of changes in ecological production functions, thereby providing a basis for managerial decision making.

FOREST DISTURBANCES AND CLIMATE CHANGE

Although forests are owned and managed for a variety of goals and objectives, owners and managers generally seek to create, sustain, and enhance desirable conditions (or states) and avoid undesirable ones. These pursuits reflect the view that: (1) alternative biotic and abiotic conditions can produce alternative forest states, and (2) not all forest states are equally desired. For example, a plantation manager may hold a very different view of the desirability of wildfire than a manager who seeks to maintain and restore natural processes.

In this section, we provide an overview of two classes of disturbances that can alter the structure and function of forest ecosystems. We also review basic concepts describing the ability of ecological and economic systems to persist in the face of disturbances.

Pulse and Press Disturbances

Forest disturbances, by definition, are forces that alter the preexisting state of a forest ecosystem. Within the ecological literature, they have been classified as either press or pulse disturbances, depending on the ecosystem and the response variable of interest (Bender et al. 1984; Glasby and Underwood 1996). A press disturbance (also known as a stress) is a continuing disturbance, such as a gradual warming or gradual changes in other climate variables, that slowly alters the state of an ecosystem. A pulse disturbance (also known as a perturbation) is a short-term, high-intensity disturbance that causes sudden change and rapidly alters the state of an ecosystem. The ecological literature has additionally recognized that slowly changing, underlying control variables can act as triggers for rapid changes when controls exceed critical thresholds (Carpenter and Turner 2001; McNulty and Boggs 2010; Rinaldi and Scheffer 2000).

Increases in temperature and changes in patterns of precipitation can have direct impacts on the delivery of forest ecosystem services. For example, ecosystems (and species) at their range limits, such as native brook trout (*Salvelinus fontinalis*) and spruce–fir (*Picea rubens–Abies fraseri*) species in the Southern Appalachian Mountains, may be highly sensitive to short-term temperature extremes (pulse disturbances), especially when combined with other stressors (McNulty and Boggs 2010). Responses to longer-term climate change (press disturbances), such as rising mean annual temperatures, may take longer to manifest and yet may still produce long-term shifts in plant and insect phenology and other changes in ecological production functions.

Changes in temperature and precipitation from historical averages can also induce indirect (or secondary) impacts on ecological production functions. Perhaps the most dramatic indirect impacts of climate change on forests result from an increase in the frequency and intensity of pulse disturbances, such as wildfires and insect and disease outbreaks (Dale et al. 2001).

Managing Forests Using Resistance and Resilience Options

Organisms and ecosystems must develop physical or biological defenses to protect themselves against disturbances. Scientists have articulated several interrelated concepts that characterize the ability of an organism or ecosystem to survive, return to or maintain the same state when subjected to press or pulse disturbances. Two broad categories of persistence mechanisms have been defined. The first is often referred to as "engineering resilience" (Pimm 1984), or simply "resilience" in this chapter, and describes the length of time required for a disturbed system to return to some initial functional state. The second, "ecological resilience" (Holling 1973), or simply "resistance" in this chapter, is the magnitude of disturbance that can be absorbed before an ecosystem is significantly altered.

Resilience and resistance have been intuitively described using the example of a ball in a landscape of hills and valleys, with valleys of different sizes and shapes representing different "attractors" (organizing forces) into which an ecosystem (the ball) is drawn, and the neighboring hills defining the barriers between attractors (DeAngelis and Waterhouse 1987). Some valleys may be relatively shallow, with low, gradually sloping hills defining their boundaries; when the ball (ecosystem) is displaced from equilibrium by a disturbance, it will return to equilibrium relatively slowly, consistent with low resilience. In contrast, if a valley is relatively narrow and located between hills with steep sides, the ball will return to equilibrium quickly, consistent with high resilience. However, if a disturbance is large enough so that a ball is bumped from a valley over a neighboring hill, the ecosystem will move into a new valley with a different set of organizing forces and attain a new equilibrium (e.g., a shift from forest to shrub-land). The height of a hill describes the degree of ecosystem resistance: a valley located between tall hills provides a lot of resistance to major structural and functional changes resulting from a press or pulse disturbance. In contrast, a valley located between low hills offers little resistance to major changes in ecosystem structure or function that may result from a disturbance.

Within the forestry context, climate change is anticipated to create novel environmental conditions (Seastadt et al. 2008; Thompson et al. 2009) and alter the set of organizing forces affecting forest structure and function. Therefore, management efforts seeking to restore forest conditions to a state that reflects a pre-Columbian climatic regime would be less likely to succeed in providing desired ecosystem services than management based on resistance and resilience concepts. Millar et al. (2007, p. 2145) describe forest resistance management options as actions that "... forestall impacts and protect highly valued resources" particularly at local scales over the near term. Examples of forest resistance management (increasing the height of the neighboring "hills") include creating fuel breaks around high-risk, high-value forests or thinning high-value forests to protect against insect outbreaks. In contrast, forest resilience management options (increasing the steepness of the neighboring "hills") are those that "... improve the capacity of ecosystems to return to desired conditions after disturbance" (Millar et al. 2007, p. 2145). Examples of forest resilience management include activities that ensure adequate regeneration of desired species after a disturbance, for example, surplus seed-banking and focused revegetation (Spittlehouse and Stewart 2003). Finally, Millar et al. (2007, p. 2145) argue for response options that "... facilitate transition of ecosystems from current to new conditions." Intuitively, response options facilitate the movement of a ball across the stability landscape to a new (and desirable) valley. Examples include planting alternate genotypes or new species and aiding species range shifts through assisted species migration or maintenance of continuous transition pathways.

Economic–Ecologic Stability

Although stability concepts such as resistance and resilience initially were applied to natural systems, they have also been adopted by economists studying the impacts of ecological shocks on the stability of economic systems. Economic modeling has begun to recognize the interdependence of economic and ecological systems and has focused attention on the economic consequences of crossing critical thresholds in natural systems. Emerging from these models is a recommendation to use risk management approaches to reduce the probability of natural and economic systems shifting from desirable to undesirable states. For example, Perrings (1998) proposed that economic–ecologic systems be modeled as Markov processes, meaning that the resistance of systems in desirable states be measured by the probability that they will shift to undesirable states. Further, he considered transition probabilities to be functions of policies and management strategies designed to sustain desirable states and avoid undesirable states.

The second approach to risk management that specifically addresses climate thresholds is hedging. With hedging strategies, investments are made in the near term to protect against uncertain but intolerable impacts that may occur if a climate threshold is crossed (Keller et al. 2008; Yohe 1996; Yohe et al. 2004). The concept of a climate threshold (or tipping point) refers to "... a threshold above which damages caused by gradual climate change would climb dramatically" (Yohe et al. 2004, p. 416). Examples include the dieback of the Amazon rainforest (Kriegler et al. 2009), a rapid shortening of wildfire return intervals in the Greater Yellowstone ecosystem (Westerling et al. 2011), and a large-scale change from tundra to boreal forest in Alaska (Chapin and Starfield 1997), thereby changing albedo.

The third approach to risk management in economic–ecologic systems is based on understanding the likelihood of a "fat tail" in the extreme range of economic damage functions. Fat-tailed distributions of future economic losses that could result from climate extremes have much higher than historical probabilities of catastrophic economic damages as critical ecosystem processes are disrupted (Weitzman 2009, 2011). This line of thinking argues that more effort should be directed at understanding the extreme tails of climate-related probability functions rather than focusing on what is thought to be most likely.

The fourth risk management approach to sustaining economic–ecologic systems is based on the view that social well-being ultimately derives from the stock of manufactured capital (such as energy and transportation infrastructure, factories, and offices), natural capital (such as forests, clean air and water, living organisms, and the ozone layer), and human capital (such as health, knowledge, and skills). These three capital stocks constitute the wealth of a society (Arrow et al. 2003; Dasgupta 2008). Recognizing that some ecosystems can shift from a desired state to an undesired state when their resistance is exceeded, Mäler (2008) proposed that resistance ("ecological resilience" in his terminology) of natural capital to sudden, disruptive change should be considered a productive asset. Resistance provides insurance against undesired degradation and loss of natural capital, and the value of ecosystem resistance can be measured by the probability that a system will suddenly shift to an alternative state, multiplied by the difference in the value of ecosystem services provided by the states before and after the shift.

APPROACHING FORESTRY USING RISK MANAGEMENT TOOLS

Available Decision-Making Tools

Within the decision sciences, several approaches have been developed that provide guidance to decision makers faced with uncertainty about the future. These approaches can guide decision making within the context of climate change (Polasky et al. 2011). Each approach provides an opportunity to evaluate future consequences of current decisions and to learn from past decisions.

A standard approach to decision making under uncertainty, largely developed within the economics literature, is the expected utility model. This model uses information on probabilities of different futures, in combination with a set of possible management actions, to identify actions that maximize expected benefits (Shoemaker 1982). A second model to aid decision making under uncertainty is the maxi–min model (von Neumann and Morganstern 1947), which was developed to help identify the management action that produces the "least bad" outcome. A third approach is Bayesian updating, which combines a prior probability distribution of future conditions with newly collected data to estimate an updated probability distribution. This approach may be particularly useful for adaptive management under climate change (Prato 2005). A fourth approach, based on the concept of "safety first" (Roy 1952), is to make decisions that minimize the probability of losses exceeding some given critical threshold.

Finally, scenario planning is an approach to decision making that helps characterize hard-to-quantify uncertainties through construction of scenarios about how the future may unfold (Polasky et al. 2011). Scenario planning can be accomplished without assigning probabilities to future forest conditions that may result from a changing climate. The key to scenario planning is to define future threats and then identify management activities that would mitigate the impacts of those threats.

Implementing a Conceptual Framework for Adaptive Forest Management

This section proposes a risk management framework for forestry that integrates the concepts of ecosystem resilience and resistance with an economic perspective of social well-being. For purposes of this chapter, we defined risk as the functional relationship between a set of ecological or economic outcomes and the probability that each will occur. Uncertainty is the lack of knowledge about the parameters of probability distributions. Our framework reorients the problem of selecting preferred management strategies into a search for management options that shift anticipated distributions of future forest conditions (the structure and function of the assemblage of dominant plant species found at a given location) toward desirable outcomes using resilience, resistance, and response options. We illustrate our framework with a graphical depiction and explain how the framework could be implemented using several steps. Throughout our description of the framework, we explain the concepts using an example drawn from the Southern Appalachian Mountains, the high-elevation spruce–fir ecosystem that is found on ridges and mountaintops in North Carolina, Virginia, and Tennessee. The future of this ecosystem is threatened by a warmer climate (including hot spells), drought, and more severe storms (North Carolina Department of Environment and Natural Resources 2010). In addition to these direct climatic threats, acid deposition and insect outbreaks also pose threats to this ecosystem (Boggs et al. 2005; McNulty and Boggs 2010).

Step 1: Identify indicators of forest conditions—The first step in the development of a conceptual framework for forest management under climate change is to identify one or more indicators of forest condition that are thought to be critical to the provision of desired ecosystem services and are sensitive to a changing climate. Although we use a two-dimensional figure to illustrate a probability function associated with a single measure of forest condition, a three-dimensional figure could be used for two measures of forest condition, and so forth. More climate change variables may increase the complexity but not the basic form of the interactions (Tian et al. 2012).

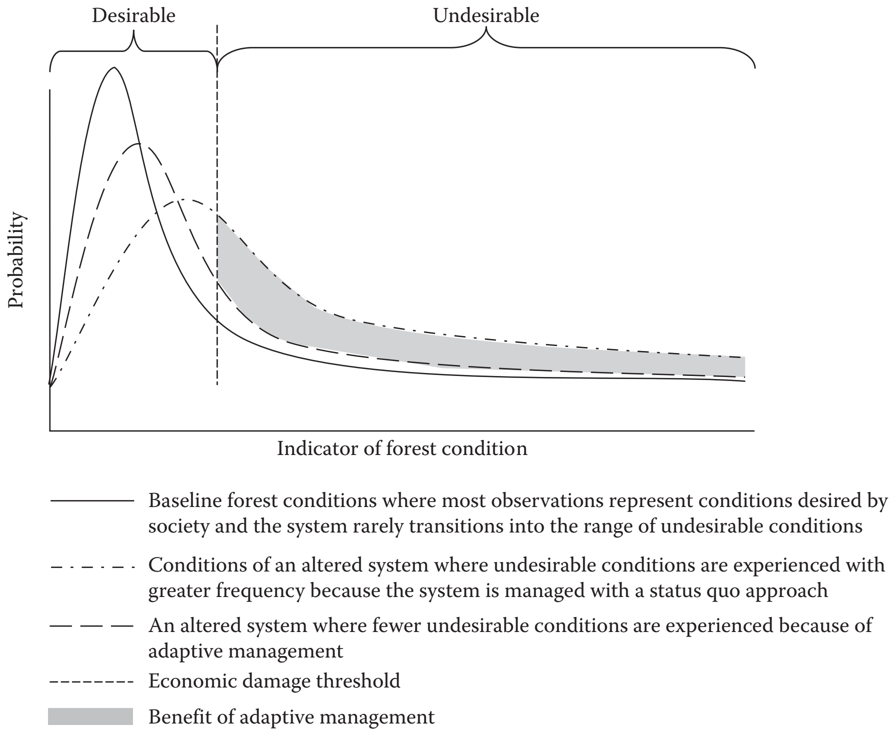

FIGURE 3.2 Schematic showing how future climate may change the probability density function of forest conditions in a given location.

Although undesirable forest conditions are always possible (Figure 3.2), forest ecosystems generally persist in the range of forest conditions desired by forest managers under current (baseline) climatic conditions and management regimes. This is because current forest management strategies have developed under a range of observed climatic conditions and disturbance regimes, and are implemented to prevent or minimize impacts or to facilitate postdisturbance recovery. The range of forest conditions depicted in Figure 3.2 represents factors such as forest structure and function and rates of carbon sequestration/net primary production (Kurz et al. 2008; Running 2008) that are sensitive to climate variables. For an example of an indicator of forest condition, we suggest the (live) basal area of red spruce and Fraser fir in the Southern Appalachian Mountains. This indicator is sensitive to both direct (e.g., drought) and indirect (e.g., insect outbreaks) impacts of climate change.

Step 2: Develop a baseline—After selecting one or more indicators of forest condition, the next step is to estimate the relative frequency (relative amount of time) associated with each level of the indicator under baseline conditions. This could be accomplished using historical data, preferably spanning many years (or decades) to provide a reasonable depiction of the proportion of years the indicator was observed in alternative conditions. Although we illustrate relative frequency (probability) concepts using smooth functions, the indicators of forest conditions could be represented by other, less smooth types of functions such as a triangular distribution that only requires estimates of the minimum, maximum, and most common values (Prato 2008).

Under baseline climate and management (Figure 3.2), most of the area under the relative frequency function is located within the desirable range of conditions, wherein valued ecosystem services and consumption goods are being produced. Equilibrium is found in the neighborhood of conditions where the relative frequency function is the greatest (because that is the most frequent level for the indicator). Even under baseline climate and management, an indicator of forest condition can shift from a desirable equilibrium into the undesirable range due to a pulse disturbance (such as a wildfire, insect outbreak, or storm). The transition from desirable to undesirable occurs when valued ecosystem services are either degraded or no longer being produced, resulting in economic losses (discussed further in the following). If an indicator of forest condition has low (high) resilience to a disturbance, the frequency distribution in the undesirable range will have a relatively fat (thin) tail because it takes a long (short) time to recover to equilibrium conditions.

Continuing with the spruce–fir ecosystem example, socially undesirable forest conditions could be depicted by the advanced mortality and loss of Fraser fir basal area after the ecosystem was invaded by the nonnative insect, balsam woolly adelgid (*Adelges tsugae*). Owing to the continued persistence of the adelgid, the system has been unable to fully recover and return to the pre-adelgid equilibrium. Consequently, the structure of the ecosystem has fundamentally changed and the entire relative frequency function has shifted toward the range of undesirable forest conditions (lower live basal area). This shift has increased the relative frequency of the system in the undesirable range and has made the ecosystem less resistant to other disturbances that could continue to fundamentally alter the system, including climate change.

Step 3: Identify consequences of no action—The third step in the development of our framework is to forecast a probability distribution for the chosen indicator(s) of future forest conditions. This step could be accomplished using ecosystem simulation models or expert opinion (Prato 2008). As already described, climate change is anticipated to increase both pulse and press disturbances in forests. These impacts can be illustrated by shifting average or typical future forest conditions toward the range of undesirable conditions, as well as by increasing the relative frequency of undesirable forest conditions. If forest managers decide to maintain the status quo and continue using historical management, not anticipating the change in the distribution of future forest conditions, they run the risk of misallocating management inputs. Misallocation of inputs would occur when managers believe that the probability distribution of forest conditions will not change in the future and they are, therefore, managing with the wrong probability function in mind. The ultimate outcome of misallocation could be a large increase in the area of the right-hand side tail of the probability function. Consequently, expected future economic damages would increase.

Step 4: Design actions (with consequences)—The fourth step in the development of our framework is to identify resilience, resistance, and response options that could shift the probability distribution of anticipated future forest conditions under status quo management back toward the desirable range of conditions (Figure 3.2). Reducing the probability of experiencing undesirable future forest conditions represents the benefit (reduction in future economic damages) of forward-looking adaptive management. The reduction in the probability of experiencing undesirable future forest conditions by shifting from status quo to adaptive management strategies is represented by the shaded area in Figure 3.2.

In our example of the Southern Appalachian spruce–fir ecosystem, adaptive management options could include restoring spruce and fir canopy, increasing connectivity between existing spruce–fir stands, reintroduction of rare species endemic to these forests, and wildfire exclusion (North Carolina Department of Environment and Natural Resources 2010). These activities can increase both the resilience and resistance of this ecosystem to pulse and press disturbances caused by climate change.

Step 5: Identify indicators of economic loss—In the preceding discussion, we have referred to economic damages as indicators of change in social well-being, and now we include them explicitly in our framework. The fifth step is to identify one or more indicators of economic damage that are directly related to the chosen indicator(s) of forest conditions. Economic damage is often measured by the sum of economic costs and losses—with costs incurred to prevent economic loss or to restore systems after a pulse or press disturbance, and losses incurred by the degradation or destruction of a valued ecosystem service. While the measurement of economic costs is relatively straightforward, the measurement of economic damages relies on the implementation of "welfare" economic methods that estimate the loss in market and nonmarket values to a broad spectrum of producers and consumers.

Continuing with our spruce–fir ecosystem example, cultural ecosystem services provided by this high-elevation ecosystem include the provision of recreational opportunities that may be diminished by advanced mortality and decline of these tree species. An economic indicator of the value of this ecosystem service can be measured using nonmarket valuation methods, as has been previously demonstrated (Haefele et al. 1991; Holmes and Kramer 1996; Kramer et al. 2003). As these authors note, in addition to the loss in recreational value incurred by the degradation of this ecosystem by the balsam woolly adelgid, substantial economic losses were incurred by people who do not intend to use the ecosystem, but simply value knowing that a healthy high-elevation ecosystem exists in the Southern Appalachian Mountains.

Step 6: Link economic impacts to forest conditions—After an indicator of economic damages has been selected, the next step in the development of our framework is to quantify how the economic indicator responds to changes in the chosen indicator of forest condition; for example, an increase in economic damages resulting from changes in the area of a spruce–fir ecosystem that had been subjected to insect-induced mortality (Holmes and Kramer 1996). The relationship between the indicator of forest condition and the indicator of economic damage for the forest ecosystem is then plotted (Figure 3.3):

- Quadrant I depicts the probability (relative frequency) function of a forest condition indictor with more frequent undesirable conditions resulting from status quo management under a changing climate (derived from Figure 3.2).
- Quadrant II traces the relationship between the forest conditions and economic damages. It shows that economic damage does not occur until the threshold of economic damage separating the desirable and undesirable forest conditions is crossed. Alterations in forest condition up to that threshold are too small to cause measurable economic damage. However, once that threshold is crossed, economic damages may rise at an increasing rate (faster than the rate that the indictor of forest condition moves into the range of undesirable conditions) as forest conditions are degraded.
- Quadrant III simply translates economic damages on the vertical axis to the horizontal axis, done to enable the plotting in the next quadrant.
- Quadrant IV shows the level of economic damage associated with the probability of each forest condition (the probabilistic damage function) given status quo management.

Two points are worth noting. First, mathematical integration of the area beneath the probabilistic damage function in quadrant IV will provide the expected value of economic damages given the distribution of forest conditions shown in quadrant I. Second, the shape of the probability function of economic damages shown in quadrant IV is determined both by the shape of the distribution of forest conditions shown in quadrant I and the shape of the economic damage function shown in quadrant II. Therefore, the expected value of economic damages, as an indicator of social well-being, is affected both by the distribution of anticipated future forest conditions and the related economic values.

Step 7: Describe probable outcomes of actions—The final step in developing the framework is to replace the probability function of future forest conditions under status quo management with alternative probability functions of forest conditions anticipated using different resilience, resistance, and response options. This step allows a manager to compare the expected economic losses under various management alternatives. Different management options will incur different management costs. Therefore, a forest manager can evaluate alternative strategies by adding the costs and expected economic losses associated with each management option. One criterion for selecting a preferred strategy is to choose the option that minimizes

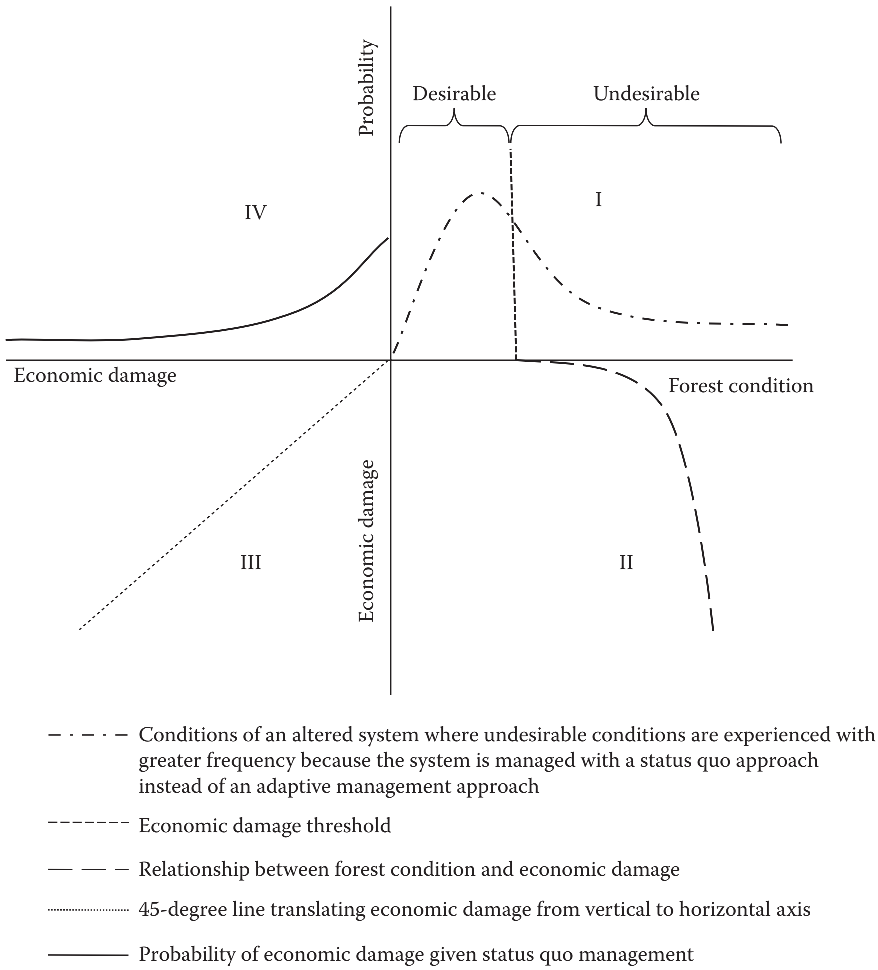

FIGURE 3.3 Four-quadrant diagram showing a conceptual model of the relationship between an identified indicator of forest condition and an identified indicator of economic damage for a forest ecosystem facing climate change. Note that the line in quadrant III merely represents a translation of economic damages from a vertical (quadrant II) to a horizontal plane.

the sum of costs plus expected losses. A second criterion is to choose the option that minimizes the probability of costs plus expected losses exceeding an intolerable level.

Over time, as new information about forest conditions and economic values becomes available, forest managers can update their assessments of how well resilience, resistance, and response options are providing sought-after ecosystem services. New information provides the basis for adaptive management, and by adapting to changing conditions (represented by updated probability and economic damage functions), managers can increase the probability of maintaining and enhancing desirable forest conditions.

FURTHER CONSIDERATIONS

Identifying Ecological and Economic Vulnerabilities

Vulnerability can be defined as the sensitivity of a system, subsystem, or system component to damage or harm resulting from exposure to a disturbance (Turner et al. 2003). It is, generally speaking, the inverse of resilience and resistance. That is, the most vulnerable systems (both ecologically and economically) have low resistance and low resilience. They are sensitive to even minor press or pulse disturbances, the magnitude of the impacts are large, and the duration of recovery is long.

For this chapter we defined three categories of vulnerabilities: vulnerability under current climate (VCC), vulnerability under future climate (VFC), and vulnerability under future climate with adaptive management (VFCAM). Combining the first two vulnerabilities with predicted climate change and the risk of incurring economic losses provides a template for identifying locations or ecosystems with the highest priority for management action; for example, where climate is likely to change the most, where low resistance and resilience causes a high probability of ecological or economic damage (VFC-VCC), and where the effects of management to reduce vulnerability (VFCAM-VCC < VFC-VCC) are large.

Partnerships Are Crucial

Adaptive management requires institutions that are flexible, willing to experiment with new (and perhaps unconventional) approaches, and able to incorporate learning from experience (Holling 2001; Seastadt et al. 2008). Within the United States, the national forests and experimental forests of the U.S. Forest Service are ideally poised for development into widely distributed working laboratories (both geographically and ecologically) to test hypotheses about adaptive management under climate change. Using these forests as laboratories would require close collaboration between the agency's management and research staffs. Such collaboration could lead to the identification of potential resilience, resistance, and response management strategies and to the creation of needed monitoring systems. The researchers could also provide the analytical resources needed to evaluate the alternative management strategies.

To further broaden the usefulness of this climate change-focused forest science, collaborative experiments could also be established across a spectrum of forest ownerships—from universities, to states, to forest industry and nonindustrial private owners. Such broadening would enable the testing of management strategies that recognize a wide range of potential ownership objectives and the diversity of ecosystem services that forests provide.

CONCLUSIONS

In this chapter, we have presented a conceptual framework for managing forests to adapt to climate change within the context of maintaining or enhancing the values that forests produce. Climate-induced changes in forest structure, composition, and function are likely to lead to overall negative economic impacts (costs plus losses). Although climate change could increase the benefits for some forest owners—perhaps by enhancing timber growth rates and timber growing opportunities—it is also likely to result in species range shifts and altered rates of press and pulse disturbances. Such changes would have negative impacts on both the commodity and the noncommodity values derived from public and private forests. Forest management, however, can alter ecological production functions in ways that reduce the overall negative impacts of climate change on ecosystems and the services these forests provide.

Forest management strategies designed to adapt to climate change by maintaining and enhancing desirable forest conditions will be made under conditions of risk and uncertainty. If probability functions can be estimated for indicators of forest conditions and for the parameters of economic damage functions, preferred actions could be selected based on criteria such as minimizing expected cost-plus-loss or minimizing the probability of economic damages exceeding an intolerable level. In situations where information is insufficient to estimate probability functions, other decision tools, such as scenario analysis, would be useful.

Whether conducting a risk analysis as described in our conceptual model is possible or not, forest managers can still consider what resilience, resistance, and response options may be available for managing their forests. The choice of preferred options will likely be very different across the suite of forest ownerships and types, because of varying ownership objectives and the diversity of ecosystem services each forest can provide. Perhaps the greatest challenges to maintaining desired forest conditions under future climates are faced by the owners of nonindustrial private forests. Because much of their forest acreage is passively managed, these owners may be reluctant to invest in enhancing resistance and resilience against future, uncertain levels of disturbances and species alteration. The result would be a large portion of the southern forested landscape that is highly vulnerable to climate change.

Scientific assessments can play a crucial role in designing adaptive forest management strategies. Research conducted across the entire spectrum of state, national, university, industrial, and private nonindustrial forests can be designed to test new strategies for adapting to climate change. An essential ingredient in sustainable forest management will be for all forest stakeholders to engage in maintaining the productivity of forest ecosystems and to develop a shared understanding of the social and economic values derived from productive forests.

GLOSSARY

Adaptation: Actions taken to decrease undesirable impacts of climate change, or that increase positive impacts.

Adaptive management: Iterative decision making based upon experimentation and scientific learning.

Ecosystem production functions: Processes that transform structural and functional ecosystem inputs into the services desired by people.

Ecosystem services: Outputs produced by ecosystems that are valued by people and contribute to their well-being.

Forest condition/state: The structure and function of the assemblage of dominant plant species found at a given location.

Mitigation: Actions taken to reduce the severity of potential climate change, such as sequestering carbon.

Press disturbance: A continuing disturbance, or stress, that slowly alters the state of an ecosystem.

Pulse disturbance: A short-term, high-intensity disturbance, or perturbation that rapidly alters the state of a system.

Resilience: The length of time required for a disturbed system to return to some initial functional state.

Resistance: The magnitude of disturbance that can be absorbed before an ecosystem state is significantly altered.

Risk: The functional relationship between a range of undesired ecological or economic conditions and their probability.

Sustainable management: Management that maintains the productive capacity of forests so that nondeclining levels of well-being are available for future generations.

Uncertainty: A lack of knowledge about the parameters of probability distributions.

Vulnerability: The sensitivity of a system, subsystem, or system component to damage or harm resulting from exposure to a disturbance.

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