United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

General Technical
Report
PNW-GTR-523
July 2001

Forest Health Restoration in South-Central Alaska: A Problem Analysis

Darrell W. Ross, Gary E. Daterman, Jerry L. Boughton, and Thomas M. Quigley

Authors

Darrell W. Ross is associate professor, Department of Forest Science, Oregon State University, Corvallis, OR 97331; **Gary E. Daterman** is a research entomologist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, Corvallis, OR 97331; **Jerry L. Boughton** is a silviculturist, U.S. Department of Agriculture, Forest Service, Alaska Region, Anchorage, AK 99503; and **Thomas M. Quigley** is a range scientist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, La Grande, OR 97850.

Abstract

Ross, Darrell W.; Daterman, Gary E.; Boughton, Jerry L.; Quigley, Thomas M. 2001. Forest health restoration in south-central Alaska: a problem analysis. Gen. Tech. Rep. PNW-GTR-523. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 38 p.

A spruce beetle outbreak of unprecedented size and intensity killed most of the spruce trees on millions of acres of forest land in south-central Alaska in the 1990s. The tree mortality is affecting every component of the ecosystem, including the socioeconomic culture dependent on the resources of these vast forests. Based on information obtained through workshops and outreach to resource managers and diverse stakeholders, we have developed priority issues for restoring the land. Wildfire is a major issue, particularly for the wildland-urban interface areas around Anchorage and on the Kenai Peninsula. The tasks of land managers are integrative and multidisciplinary and involve many science-related issues. They primarily revolve around the problem of how to reduce risk of wildfire and ensure reforestation in ways that will accommodate the needs for wildlife habitat, maintain healthy hydrologic conditions, and generally conserve ecological values for the future. The research approach outlines a “what if” scenario of management options based on levels of investment and targets for restoration. Modeling and visualization research would provide previews of future conditions based on levels of investment, selected landscapes, and the desired conditions selected among restoration options.

Keywords: Ecosystem health, forest health, ecosystem restoration, Alaska, south-central Alaska, wildfire, spruce beetle, wildlife habitat, hydrology, urban forestry.

Executive Summary

South-central Alaska has been experiencing a spruce beetle outbreak of unprecedented size and intensity for over 10 years. The beetle-caused tree mortality is affecting every component of the forest ecosystem, including the socioeconomic structure and processes that are interdependent on the biophysical features of these vast forests. Beetle-caused tree mortality has dramatically increased the potential for large, intense wildfires unlike any that have occurred in recorded history. The related changes in forest structure and composition are affecting fish and wildlife populations and their habitats, hydrologic properties, timber values, recreational opportunities, and aesthetic values. In addition, the increasing hazard of wildfire in the urban-forest interface threatens property and human lives. It is important to understand the changes that are occurring in these forest ecosystems to develop plans for restoring healthy productive forests and for preventing similar situations from occurring in the future.

Current conditions in south-central Alaska brought on by the spruce beetle outbreak that warrant accelerated research, development, and applications (RDA) effort related to forest health and productivity are described. Published and unpublished literature related to disturbance in south-central Alaska is reviewed and summarized. In addition, the authors conducted site visits to the affected area and held workshops to query resource managers, specialists, scientists, and other stakeholders with knowledge of south-central Alaska forest ecosystems on their perspectives and concerns about the short- and long-term effects of the beetle outbreak. The proposed RDA framework for this initiative is based on the findings from these reviews, workshops, and site visits.

Research and development emphasis is on three focus areas: (1) understanding the present spruce beetle outbreak, (2) assessing the impacts of the present spruce beetle outbreak on multiple ecosystem values and resources, and (3) evaluating four potential management response scenarios to provide land managers and others with predictions of outcomes associated with each scenario.

Although the massive beetle outbreak of the 1990s has largely subsided, concerns remain about how to prevent the recurrence of another such outbreak. Studies are needed to better understand why the 1990s outbreak developed, and whether management activities might be effective in preventing or mitigating a similar outbreak from occurring in the future. Characteristics of past spruce beetle outbreaks will be compared with the current outbreak to understand why the present outbreak became so widespread and devastating. In these comparisons, we will examine weather patterns and management activities in recent history to help determine if either human activities or external forces were the major cause for the current epidemic and, more important, if clues can be found to help avoid a similar outbreak from occurring in the future.

The second focus area, assessing the impacts of the outbreak, seeks to measure the relative effects of the outbreak on multiple resource values over time and at different spatial scales. We relied heavily on the perspectives of workshop participants in developing this section and developed a list of resource impacts. Surprisingly, concerns about timber harvesting and timber industry were not emphasized as impacts other than indirectly in relation to what future forest development would look like over areas of heavy tree kill. Of greater concern was increasing risks of wildfire, particularly in the wildland-urban interface, and adverse impacts on fish and wildlife habitats.

The third focus area emphasizes how to restore forest health within the vast areas dominated by beetle-killed forest. Various management scenarios are considered. Treatment strategies range from a “no-response” decision to increasing levels of management treatments that react to active treatments for all reasonably accessible areas, and that address multiple resource needs. Through development of models and on-the-ground studies, activities sponsored by this initiative would predict what short- and long-term benefits and other outcomes would result by following the different scenarios.

The success of the proposed RDA effort will depend greatly on the capabilities of participants to integrate their efforts in planning and implementing studies, gathering data, developing models, and synthesizing results. We are proposing the ecosystem management decision-support (EMDS) system as an applications framework for a knowledge-based model to address the broad problem issues of this initiative. This system provides a means to process diverse data about ecosystem features within a single analysis, thereby providing a way to integrate various concerns into that single analysis and account for their interactions. We believe this knowledge-based approach will provide the means to ensure that integration can take place among the diverse issues to be addressed.

The timeframe for this initiative is 5 years, although we realize this is ambitious and optimistic given the magnitude of the management problem and the complex and diverse nature of the research and development needed. Consequently, some of the priority RDA activities may continue beyond the initial 5-year period.

Although this analysis was specifically developed to address forest health problems stemming from the decade-long spruce beetle outbreak in south-central Alaska, we believe its value as a basis for developing a research and development program would apply equally to other ecosystem disturbance and restoration issues. Our approach emphasizes research to assist resource restoration priorities associated with a catastrophic ecosystem disturbance; however, we introduce a framework from which various scenarios relating to ecosystem restoration can be addressed. These scenarios provide flexibility to realistically address the issues in relation to the risks and tradeoffs of proposed management options that vary in their requirements for funds and other resources needed for implementation.

Contents

Introduction

White and Pickett (1985) define disturbance as "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment." All forests are continually influenced by disturbances of many kinds, natural and human-caused, small and large, intense and subtle, frequent and rare. Wildfire or prescribed burning, flooding, drought, windstorms, volcanic eruptions, disease, insect infestations, logging, fertilization, pesticide applications, road building, and urban development are all examples of disturbance. Understanding the ecological and socioeconomic significance of disturbance in its varied forms is crucial to effectively manage forest resources and protect forest health.

The Pacific Northwest (PNW) Research Station and the Alaska Region of the USDA Forest Service are proposing a 5-year research, development, and applications (RDA) program focused on disturbance issues affecting forest health in south-central Alaska forest ecosystems, and particularly on the restoration issues resulting from the vast impacts of the 1990s bark beetle outbreak. The goal of this program is to intensify research efforts in this area to provide new information and tools to assist managers and policymakers in developing and implementing resource management plans. The program will use an integrated approach to analyze the impacts of natural and human-induced disturbances at multiple scales. The purpose of this problem analysis is to provide a framework for planning and implementing the RDA program. The analysis is based on a review of published and unpublished literature and consultations with resource managers, specialists, and researchers with knowledge of south-central Alaska.

Conditions Warranting a Research, Development, and Applications Initiative

Over the past decade, the spruce forests of south-central Alaska have experienced the most extensive and severe mortality in recorded history. This mortality is largely due to infestation by the spruce beetle, *Dendroctonus rufipennis* (Kirby) (fig. 1). From 1920 to 1989, the spruce beetle infested about 2.1 million acres of Alaska forest land (Holsten 1990). In comparison, over the last 10 years, at least 2 million additional acres have been infested.[1] The present outbreak has been most severe on the Kenai Peninsula, in forests to the northwest of Cook Inlet, near Anchorage, Alaska, and in the Copper River drainage southeast of the town of Glenallen, Alaska (fig. 2). Although the outbreak has peaked and is now declining, the level of tree mortality in affected forests is high, often exceeding 90 percent of the overstory. This level of tree mortality is much higher than that which occurred in earlier outbreaks, thus posing immense challenges to natural resource managers as it has the potential of impacting forest health for many decades.

Why the current outbreak is covering larger areas and causing greater tree mortality is uncertain, but there are several hypotheses. South-central Alaska has possibly been experiencing a warming trend in recent years, which could be contributing to the scale and intensity of the beetle activity. Warmer temperatures could potentially increase beetle reproductive success in two ways, by reducing host tree resistance through drought stress and by reducing beetle generation time. Past forest management practices, including fire suppression, also may be responsible, in part, for increasing the susceptibility of forests in this region to beetle infestation. As forests age, trees become larger, and in the absence of disturbances that reduce stand density, their growth rates

[1] Ed Holsten. 1998. Personal communication. Forest entomologist, USDA Forest Service, Forest Health Protection, Alaska Region, 3301 C St., Suite 522, Anchorage, AK 99503.

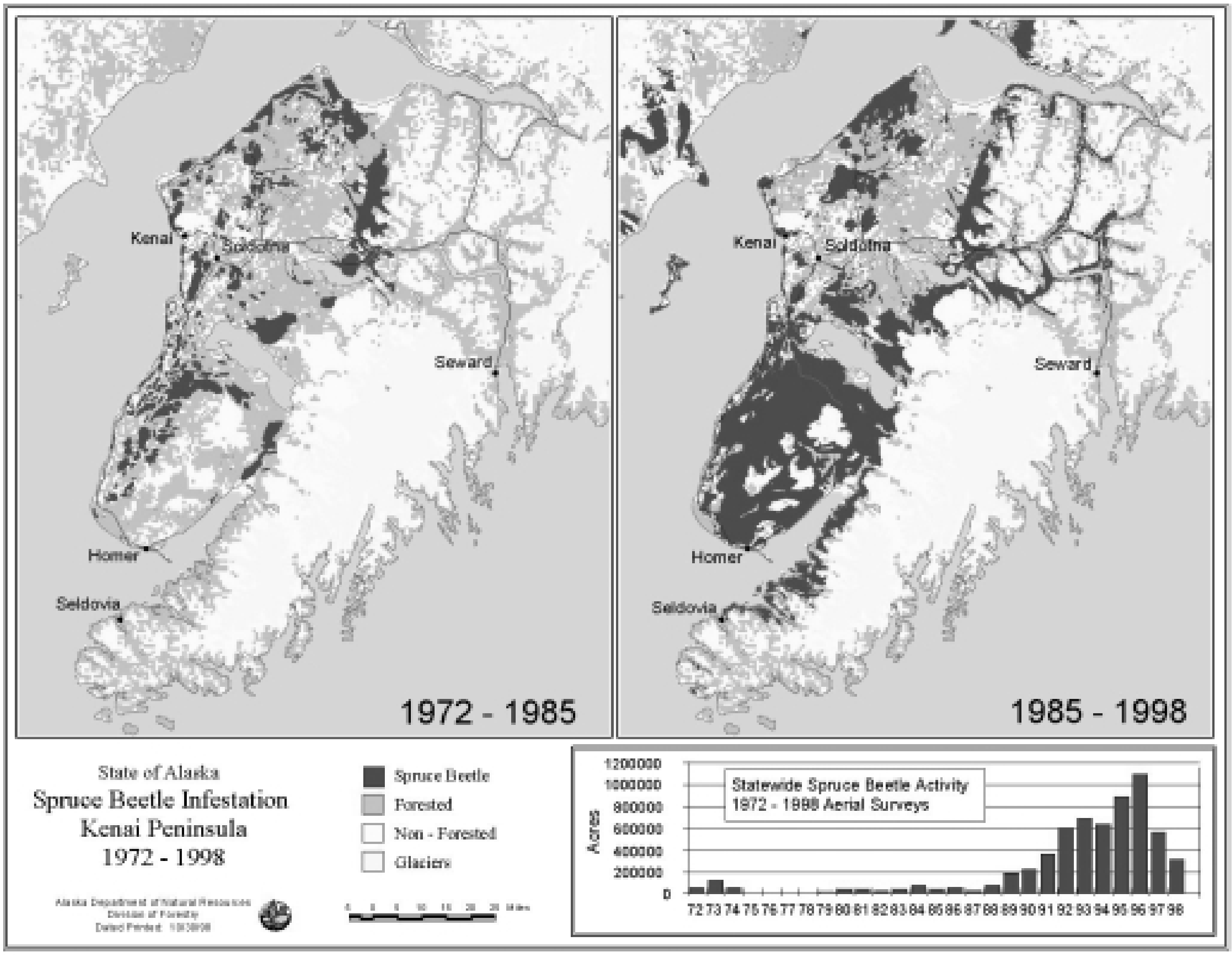

Figure 1—Cumulative spruce beetle infestations on the Kenai Peninsula for the periods 1972-85 and 1985-98. The bar chart indicates annual spruce beetle infestations based on aerial survey data for the years 1972-98.

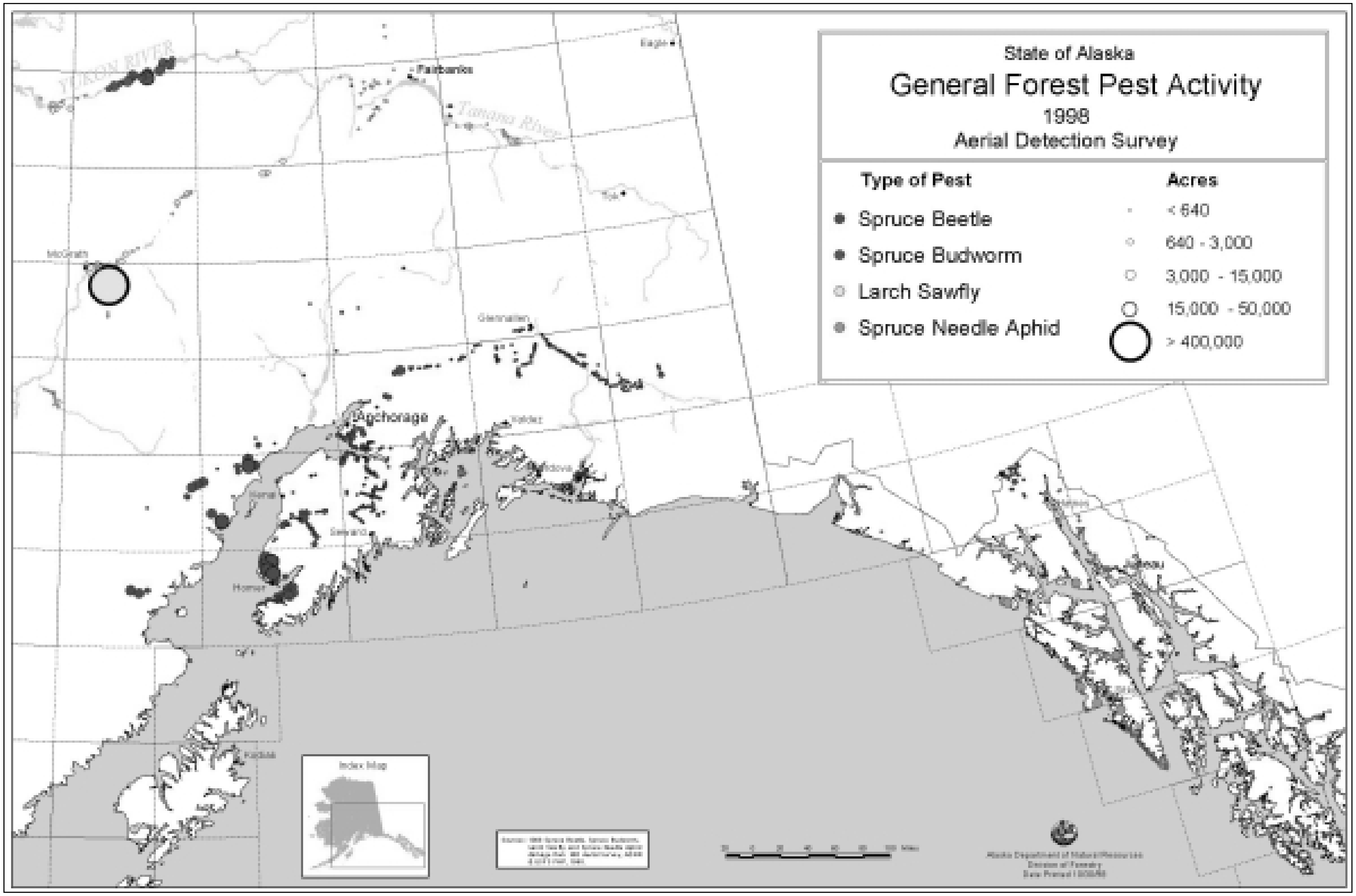

Figure 2—Forest pest activity in south-central and southeast Alaska for 1998 determined from aerial survey data.

decline because of competition with their neighbors. Large, slow-growing trees in dense stands are preferentially attacked by the spruce beetle (Hard and others 1983, Hard 1985, Holsten 1984). Fire suppression and the lack of timber harvesting increased the abundance of highly susceptible spruce forests throughout south-central Alaska.

The spruce beetle is a native insect found throughout the spruce forests of south-central Alaska. It is commonly associated with white, Sitka, and Lutz spruce (*Picea glauca* (Moench) Voss., *P. x sitchensis* (Bong.) Carr., and *P. x lutzii* Little, respectively) but only rarely attacks black spruce (*P. mariana* (Mill.) B.S.P.). Endemic beetle populations persist in scattered individual trees or small groups of trees that are stressed or have recently died (Holsten and others 1991, Safranyik 1988, Schmid and Frye 1977). Windthrown trees are ideal breeding sites because they have little or no defenses against beetle attack (Berryman 1972) and, in locations where snow accumulates, they provide protection from several important natural controls (Schmid 1981). If suitable breeding material becomes abundant, the local beetle population may increase rapidly to densities that are capable of attacking and killing large numbers of healthy trees.

From the mid-1960s to the late 1980s, spruce beetle outbreaks of various sizes developed and subsided throughout south-central Alaska (Holsten 1990). These outbreaks primarily were associated with fires, land clearing, oil and gas exploration, and windstorms that produced large concentrations of suitable breeding material. Since about 1989, spruce beetle populations in south-central Alaska have steadily increased to their current unprecedented levels (Hofacker and others 1993; USDA Forest Service 1996, 1997). During 1995 and 1996, an estimated 57 million spruce trees died owing to spruce beetle infestation throughout Alaska. In 1996 alone, 1.1 million acres of active and newly infested areas were detected, more than any other year since records have been kept (fig. 1). About two-thirds of the infested area is on state and private land, and the remaining one-third is on federal land.

The scale and intensity of the current outbreak are having major biological impacts on the forest ecosystem as well as social and economic impacts on the communities that are dependent on those forests. Fuel levels in the affected forests are extremely high and are continuous over large areas. If wildfires occur in these forests, they will be intense and difficult to control. Although wildfires are normal events that help to sustain these forests, the present combination of fuels, weather, and potential ignition sources never existed in the past and could lead to undesirable conditions in the future. The combined effects of beetle-caused tree mortality and intense wildfire may reduce the spruce seed source to lower levels than has occurred previously, or eliminate it altogether over large areas. Consequently, these areas could be occupied by grass and shrub communities for unusually long periods. Wildfires not only threaten to degrade ecosystem health, but in the forest-urban interface they also are a threat to lives and property. This is a particular concern in the Anchorage area and on the Kenai Peninsula where a large percentage of the Alaska population interfaces with high fuels and fire hazard conditions in areas with limited road access (University of Alaska, Anchorage 1991).

The current levels of tree mortality, with or without wildfire, may significantly reduce the quality of the watersheds on which some of the most productive fisheries in the world depend. The quantity, quality, and timing of water yield from affected watersheds and the input of woody debris to stream channels will be changed for many years to come. These changes likely will affect aquatic communities including the anadromous fish that are a major part of the economy of Alaska. Habitats for many species of birds and mammals are being changed dramatically at the landscape scale. The current and future potential for timber production in infested forests is being significantly reduced. The information that is presently available to natural resource managers and policymakers is inadequate for developing plans to respond to the changing forest conditions resulting from the spruce beetle outbreak and related disturbances that include the continuing potential for intense wildfires. An accelerated RDA program is needed to provide information and tools that managers can use to ensure that forests developing in the aftermath of this outbreak will provide the resources and values that the public will demand from them and, at the same time, be more resilient to disturbances caused by future pests and fire.

Some feel that the present spruce beetle outbreak will have a greater economic and aesthetic impact than the 1964 Good Friday earthquake and the *Exxon Valdez* oil spill combined (Homer News 1998). The scale and severity of the outbreak have caused concern among many public and private interest groups, politicians, the citizens of Alaska, and others who visit the region. In February 1997, the Alaska Society of American Foresters (SAF) released a document entitled “Action Program to Identify and Restore Key Spruce Ecosystems Killed, Infested, or Threatened by Spruce Bark Beetle” in response to a request for information from the state legislature (Alaska Society of American Foresters 1997). The SAF report described the current beetle epidemic as an “environmental emergency,” citing potential negative impacts of beetle-caused tree mortality on fire hazards, forest composition, timber resources, hydrologic resources, recreational opportunities, and fish and wildlife habitats. A task force led by the Kenai Peninsula Borough was formed in January 1998 because of action by the U.S. Senate Appropriations Committee to (1) prepare an action plan to manage the beetle infestations and (2) rehabilitate infested areas (Kenai Peninsula Borough 1998). The task force issued a report in June 1998 entitled “An Action Plan for Rehabilitation in Response to Alaska’s Spruce Bark Beetle Infestation: A Model for Alaska.” The report emphasized reducing fire hazards to ensure public safety, reforestation of affected lands, and public education. The report also recognized the need for further research to provide a firm basis for management decisions. The task force strongly supported the accelerated RDA program on disturbance processes affecting forest health, as proposed by the PNW Research Station and the Alaska Region of the USDA Forest Service.

Despite the concerns about the spruce beetle outbreak, coming to agreement about what actions, if any, are needed to mitigate the impacts of the beetle-caused tree mortality has been difficult (Daniel and others 1991, Sherwonit 1998, University of Alaska, Anchorage 1991). The information that is available from past research on the impacts of spruce beetle outbreaks in south-central Alaska is limited. Debate about the merits of various management activities often is based on opinion and information from areas outside of Alaska such as the Rocky Mountain states. Better information is needed about the multiple-resource impacts of beetle-caused tree mortality in south-central Alaska forest ecosystems, including increased risk for other disturbances such as fire, and the various treatments proposed to minimize negative impacts. The information gained through an RDA effort such as proposed by the PNW Research Station and Alaska Region would provide land managers a more objective basis from which to formulate resource management policy and treatment prescriptions. Although the effects of the current outbreak present challenges for resource managers, they also provide opportunities for research. The study of disturbance ecology often is limited by the lack of information about rare events, for obvious reasons. Research focusing on the effects and outcomes of the current spruce beetle outbreak and related disturbances will not only help policymakers and managers deal with the present situation but also will generate information that may help to prevent or lessen the negative impacts of future disturbances.

The problem analysis will emphasize three focus areas for research and development: (1) develop a better understanding of the dynamics of the present beetle outbreak including interactions with other types of disturbance. This will require retrospective studies to determine the ways, if any, in which the current outbreak differs from those of the past; (2) describe the ecological and socioeconomic effects of the outbreak; and (3) assess the likely outcomes of different management scenarios that could be applied to mitigate effects of the outbreak, and to promote development of more resilient future forests. The management scenarios considered will range from doing nothing to conducting an aggressive fuels-reduction and reforestation program on all reasonably accessible areas.

Objective of the Problem Analysis

The objective of the problem analysis is to identify critical information and technologies needed by resource managers and policymakers to effectively restore forest ecosystem health to areas adversely impacted by natural or human-caused disturbances. In addition, the problem analysis will identify information and technologies needed to manage resources at the landscape scale over long periods with minimal chances of undesirable effects from natural or human-caused disturbances. The knowledge and technology gaps that are identified will be used to define and prioritize research projects to be funded by the south-central Alaska forest health restoration initiative.

Review of Published and Unpublished Literature

Disturbances in forest ecosystems, whether natural or human-caused, may have either adverse or beneficial effects in the broad context of forest health. The basic premise of this initiative and problem analysis is that the key to restoring, protecting, and maintaining forest ecosystem health lies in the capability to effectively manage ecosystem disturbance.

Disturbance Ecology

Forest ecosystems are complex, diverse, and dynamic assemblages of plants, animals, and micro-organisms. The dynamic nature of forests is the result of periodic disturbances and the intervening recovery processes. Disturbance has long been recognized as an important factor influencing the development of forest ecosystems (Spurr and Barnes 1973). The role of disturbance in shaping forest stands and landscapes, however, has received increasing attention from scientists and natural resource managers during the last two decades. Several recent publications provide thorough reviews of disturbance ecology literature (Attiwill 1994, Oliver and Larson 1996, Perry and Amaranthus 1997, Pickett and White 1985a).

White and Pickett (1985) define disturbance as “any relatively discrete event in time that disrupts the ecosystem, community, or population structure, and changes resources, substrate availability, or the physical environment.” Disturbance in forest systems often is equated with changes in the abundance or condition of overstory trees. This is understandable because trees are the dominant organisms that define a forest ecosystem. Many other components of the ecosystem, however, such as predators, mycorrhizae, and understory vegetation, are vulnerable to disturbance as well (Perry and Amaranthus 1997). Disturbances affect all levels of organization from the individual, population, and community, to the ecosystem (Pickett and White 1985b).

Many types of natural and human-caused disturbances occur that affect forests including tornadoes, hurricanes, windstorms, earthquakes, volcanoes, landslides, floods, droughts, fires, ice storms, freezing events, avalanches, insect outbreaks, disease, animal damage, invasion by exotic plants, pollution, climate change, logging, pesticide applications, road building, and other developments (Oliver and Larson 1996, White and Pickett 1985). Disturbances differ in magnitude or intensity, size and shape of area affected, timing, and frequency (Runkle 1985). Consequently, the effects of disturbance on forest composition, structure, and functions can differ from relatively minor to catastrophic. Furthermore, disturbances are usually not uniform. They typically produce varied effects, thereby resulting in a mosaic of patches that may in themselves be internally heterogenous (Pickett and White 1985b).

The generally accepted view of the role of disturbance in ecosystem dynamics has changed dramatically over the last century. In the early 1900s, disturbances were viewed as unusual events that promoted or retarded the predictable development of forests from an early-seral to climax stage (fig. 3). The concept of the climax community dominated terrestrial ecology theory at that time. The climax was viewed as a stable, equilibrium condition that was the endpoint of the inevitable process of succession. The climax community for a given location was presumably determined by the soils, topography, climate, and past evolutionary history of the organisms in the area. In this context, disturbances simply moved the ecosystem forward or backward along a clearly defined successional path. In simple terms, disturbance reset the successional clock (White and Pickett 1985).

There is now a greater appreciation for the dynamic nature of forest ecosystems and the integral role of disturbance in defining system structure, composition, and processes (fig. 4). Disturbances and their effects are highly variable ranging from frequent, small-scale, low-intensity events to rare, large-scale, high-intensity events (Oliver and Larson 1996). Disturbances are not isolated events but are linked to other areas and times through climate, atmospheric processes, and stand history (Perry and Amaranthus 1997). A given disturbance may increase or decrease the probability of subsequent disturbances. For example, bark beetle epidemics that create large volumes of woody debris may increase the likelihood of stand-replacing wildfire (Geiszler and others 1980). Alternatively, a silvicultural thinning may reduce the probability of a bark beetle outbreak by changing the microclimate of the stand (Bartos and Amman 1989, Schmitz and others 1989) and by enhancing the resistance capabilities of the residual trees (Larsson and others 1983, Mitchell and others 1983).

It is now clear that disturbance may not only reset the successional clock but also may change the direction of successional processes leading to communities that would not have existed in the absence of the disturbance. In essence, by using the prior analogy, disturbance may change the face of the clock. For example, frequent low-intensity ground fires maintained open, parklike conditions in presettlement ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests of the inland Pacific Northwest (Mutch and others 1993). The understory vegetation in these forests was a diverse mixture of grasses and forbs. The death of individual trees or small groups of trees provided space for patches of regeneration to become established by seed falling from surrounding mature trees. The resulting patchy, uneven-aged stand structures were dependent on frequent, low-intensity fires. Fire exclusion as a pervasive management policy has allowed shrubs and trees to become more abundant in the understories of these forests. The higher fuel levels and fuel ladders now present make these forests susceptible to intense, stand-replacing fires (Agee 1993). The forests that develop after these stand-replacing fires will be unlike those that were maintained by the frequent, low-intensity fire regime.

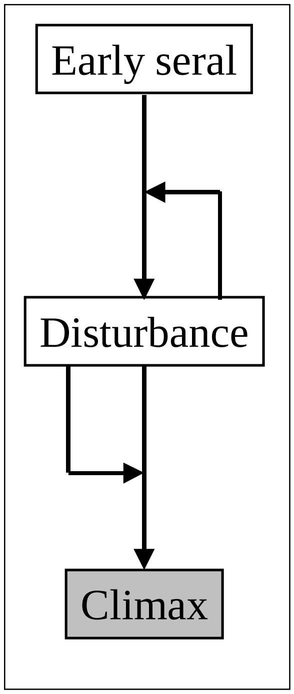

Figure 3—A simple model of forest ecosystem dynamics emphasizing plant succession and the climax plant community that dominated terrestrial ecology theory in the early 1900s. Disturbance has a relatively minor role and does not influence the ultimate endpoint of succession. This model has been discarded in favor of a more complex model illustrated in figure 4.

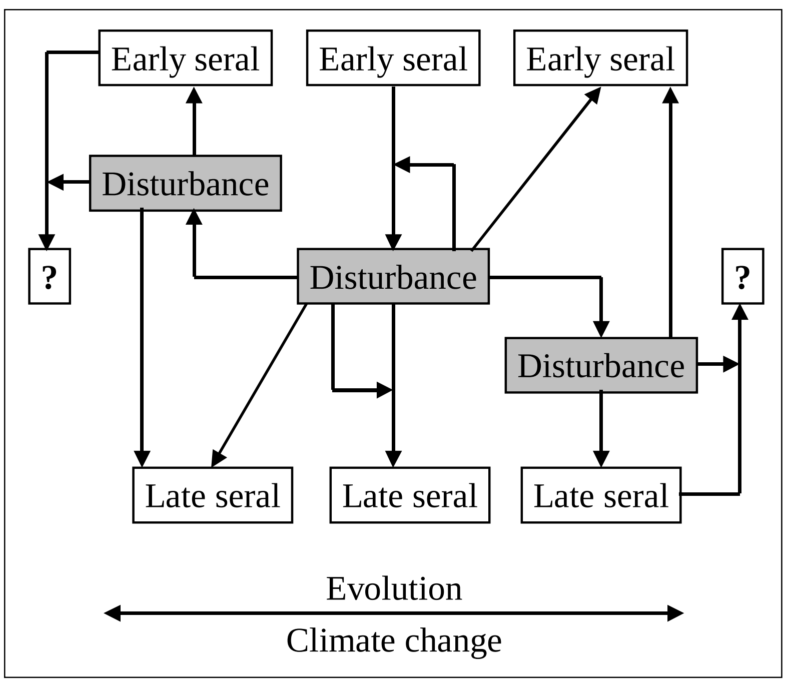

Figure 4—A complex model of forest ecosystem dynamics emphasizing the integral role of disturbance in defining system structure, composition, and processes.

Disturbance regimes are influenced by climate, topography, soils, and vegetation (Perry and Amaranthus 1997). Certain forest stands and landscapes are more susceptible to specific disturbances than to others. Forests susceptible to a particular disturbance will tend to magnify the intensity and spatial extent of the disturbance. In contrast, other forest landscapes may be resistant to the same type of disturbance; that is, they may be able to absorb the disturbance with little effect on forest composition, structure, or functions. Of the factors that influence disturbance regimes and their effects, vegetation is the only one that can be easily manipulated by resource managers, thereby representing the primary mechanism by which managers can mitigate the effects of natural disturbance. By understanding natural disturbances and anticipating where future problems are likely to arise, resource managers can prescribe silvicultural treatments to reduce the likelihood of negative impacts from future disturbances (Oliver and Larson 1996). Risks, however, cannot be eliminated altogether. All management actions have tradeoffs associated with them. The challenge for managers is to apply the best combination of actions to produce resilient, productive, and sustainable ecosystems.

From the perspective of resource managers considering how to respond to disturbance events, two questions assume primary importance. First is the disturbance within the normal range of variation associated with the historical disturbance regime for that system? Or, conversely, is the disturbance actually a perturbation (as defined by White and Pickett [1985]) arising from the influence of humans on the system? In most cases, it is unlikely that we will be able to answer this question with certainty because of the relatively short period for which we have historical records, and our limited ability to reconstruct past conditions and disturbance regimes. Although reconstructive techniques such as fire scar, charcoal, and pollen analysis are available, they are unable to give a complete picture of the spatial extent, intensity, and other attributes of past disturbances. These techniques also cover only a small fraction of the long history of forest development in any area. The lack of a clearly defined reference precludes quantification of this question in many cases (Attiwill 1994). Perhaps the more appropriate question is whether the disturbance threatens the continued existence of ecosystem components, structures, or functions over the long term at the landscape scale. This leads to the second question of concern to resource managers: Even if the disturbance is within the historical range of variability for the system, does it threaten the long-term expectations of society for producing resources and values from the system, i.e., sustainability? For example, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests in the Oregon Coast Range developed after extensive and severe wildfires that burned at infrequent intervals (Agee 1993). Few would argue that we should allow these disturbances to occur now or in the future even though they are in the range of historical variability. The loss of life, property, and resource values resulting from such a disturbance would be socially unacceptable. Although the biological and physical sciences can provide new knowledge and technologies that are essential for restoration of ecosystems, expertise in the social sciences also will be needed to answer questions surrounding issues of social acceptability.

Although as a society we may not wish to allow natural disturbance regimes to function unhindered, that does not mean that we cannot preserve ecosystem components, structures, and functions. With adequate knowledge, we may be able to impose some regulation on these dynamic systems that would allow for their preservation while simultaneously protecting the resources and values that society expects from them (Attiwill 1994, Oliver and Larson 1996).

The recent change in perspective regarding the role of disturbance in ecosystem dynamics has heightened interest among scientists and natural resource managers in studying ecological responses to disturbance. Only through an understanding of natural disturbances and the changes they engender can we develop efficient and sustainable systems for managing natural resources to meet the needs of society.

Disturbance in South-Central Alaska Forests

In general, human influences have been minor in the forests of south-central Alaska compared to other parts of the United States. One exception is the northeastern part of the Kenai Peninsula that has been heavily influenced by humans since the 1880s through mining, railroad construction, timber harvesting, and other activities. Intentional or accidental human-caused fires have affected these forests for a long time (Scott 1980). The incidence of human-caused fires apparently increased after the arrival of white settlers in the early 1900s (Langille 1904, Viereck and others 1986). Since the beginning of active fire suppression in Alaska around 1940, the number of reported fires has increased, but the area burned has decreased (Foote 1983). Until recently, timber harvesting was primarily for local use around cities and other developments and to clear the land for other uses such as farming and rights-of-way. In the past several decades, an increase in timber harvesting with the development of markets for raw wood products has occurred particularly in response to the increasing beetle-caused tree mortality. Still, only a small portion of all forested land has been directly impacted by human activities.

The forests of south-central Alaska are subjected to various natural disturbances including windstorms, fire, insect infestations, disease, avalanches, earthquakes, animal browsing, flooding, landslides, fluctuating water levels, and invasion by weeds. Over the past century, windstorms, fire, and spruce beetle infestations have been the most obvious and well-studied disturbances affecting spruce forests in this region. These disturbances often are linked together through their effects on stand structure and tree physiology. Spruce beetle outbreaks frequently follow windstorms or fires that create a concentrated supply of favorable breeding sites (Holsten 1990, McCullough and others 1998). Blowdown on the Kenai Peninsula is usually a localized event, but subsequent bark beetle-caused tree mortality may affect much larger areas. Trees that are blown over or broken by wind or scorched by fire are ideal breeding sites for beetles as the natural defenses of such trees have been lost or greatly weakened. Once beetle populations reach high densities in the stressed or dead trees, they then have the capability of attacking and killing healthy trees. The beetle populations may remain at high densities for several years, killing large numbers of mature trees before some combination of natural controls brings the population back to endemic levels.

Since 1920, spruce beetle outbreaks in south-central Alaska have ranged in size from 100 acres to the current outbreak of over 2 million acres (Holsten 1990, USDA Forest Service 1997). Dendrochronological data from the Kenai Peninsula has produced evidence of two earlier spruce beetle outbreaks during the 1810s-1820s and the 1870s-1880s[2]. Both these outbreaks affected the central and southern portions of the peninsula, but the later outbreak was more severe than the earlier one. This same study found no evidence of fire after bark beetle outbreaks before the Pothole Lake fire in 1991, and the Crooked Creek and Hidden Creek fires in 1996.

---

[2] Berg, E. 1998. Spruce bark beetle history studies, Kenai Peninsula, interim report 1994-1997. Anchorage, AK: Kenai National Wildlife Refuge. Unpublished report. On file with: U.S. Fish and Wildlife Service, Kenai National Wildlife Refuge, Box 2139, Soldotna, AK 99669.

Another disturbance related to the current spruce beetle epidemic is an outbreak of a secondary bark beetle, *Ips perturbatus* (Eichhoff) (Holsten 1998). Although *I. perturbatus* has caused white spruce mortality in interior Alaska in the past, this is the first time that it has caused noticeable mortality in south-central Alaska. The mortality was originally attributed to *Ips tridens* (Mannerheim) but has subsequently been determined to be caused primarily by *I. perturbatus,* with a small amount attributed to *I. concinnus* (Mannerheim) (Holsten 1996, 1997). All these *Ips* species normally infest only dead or stressed trees including those already infested by the spruce beetle. Consequently, they have not previously been considered important pests (Furniss and Carolin 1977). *Ips perturbatus*, however, was recently found killing live white spruce after thinning and pruning treatments to minimize spruce beetle-caused tree mortality on the Kenai Peninsula (Holsten 1996, 1997, 1998). Apparently, the populations of *I. perturbatus* built up to high levels in trees killed by spruce beetle and were then able to attack and kill live trees nearby.

Fires can occur in south-central Alaska from about April through October, although most occur during May, June, and July (Foote 1983, Langille 1904, Noste 1969). Historically, fires have been less common in coastal than in interior Alaska because of higher amounts of rainfall, lower temperatures, rapid decay of fuels, and a lower incidence of lightning (Gabriel and Tande 1983, Noste 1969). Lightning-caused fires occur less frequently in south-central Alaska than in all other parts of the state except the Arctic region. From 1957 to 1979, 61 lightning-caused fires occurred in south-central Alaska ranging in size from 1 to 5,600 acres (Gabriel and Tande 1983). Before settlement, the fire regime in south-central Alaska was apparently characterized by long return intervals between large and intense wildfires, which resulted, at times in the occurrence of mature forests over large areas[3]). Fire-return intervals in white spruce forests in interior Alaska have been estimated to range from 100 to 200 years (Yarie 1981). Because of less frequent ignitions and less favorable burning conditions, return intervals in white spruce forests of south-central Alaska presumably would be longer. Fire-return intervals for black spruce forests on the Kenai National Wildlife Refuge range from 46 to 62 years (DeVolder and Anderson 1998).

Most fires in south-central Alaska are human-caused and occur around population centers, along transportation routes, and in high-use recreational areas (Gabriel and Tande 1983). Fire frequency increased in the late 1800s and early 1900s with the arrival of miners and the construction of railroads. From 1914 to 1953 on the Kenai Peninsula portion of the Chugach National Forest, an average of 22.5 fires occurred per year, about 73 percent of which were related to the railroad (see footnote 3). Since the 1950s, the major causes of fires in the same area have been campfires and debris burning. Currently, over 99 percent of fires in this area are human-caused. The risk of wildfire has increased significantly in this area over the past decade because of the massive increases in fuels created by the widespread tree-killing caused by the spruce beetle outbreak.

---

[3] Potkin, M. 1997. Fire history disturbance study on the Kenai Peninsula mountainous portion of the Chugach National Forest. Anchorage, AK. USDA Forest Service. Unpublished report. On file with: USDA Forest Service, Chugach National Forest, 3301 C Street, Suite 300, Anchorage, AK 99503-3998.

Several hardwood tree species are present in south-central Alaska in pure stands or in mixtures with conifers. Some of the most common species are paper birch (*Betula papyrifera* Marsh.), quaking aspen (*Populus tremuloides* Michx.), balsam poplar (*P. balsamifera* L.), and black cottonwood (*P. trichocarpa* Torr. & Gray). One of the more important disturbances affecting the establishment and growth of hardwoods is browsing by moose (*Alces alces* L.) (see footnote 2), which may have either adverse or desired impacts depending on management objectives and the moose abundance and behavior.

Other disturbances in south-central Alaska are less obvious, have more localized impacts, or cause more subtle effects. This does not lessen their importance in influencing forest ecosystem dynamics. Many insects and diseases affect tree establishment, growth, and survival (Holsten and others 1980). Avalanches, earthquakes, flooding, and drought may affect stand dynamics and increase susceptibility to other disturbances such as bark beetle outbreaks and fire. These other types of disturbances should be studied and considered in developing resource management plans. In light of the current spruce beetle epidemic, high fuels and fire hazard conditions, and limited resources for research, however, these other disturbances assume secondary importance.

Effects of the Bark Beetle Outbreak on Forest Health

The extensive tree mortality that resulted from the spruce beetle outbreak affects all aspects of the forest ecosystem. Some of the ways in which the outbreak affects particular ecosystem components and processes are described in this section.

Watersheds—Watershed vegetation affects the physical, chemical, and biological properties of forest streams. The characteristics of the vegetation can influence the amount and timing of water yields (Kostadinov and Mitrovic 1994). Alterations in vegetative cover resulting from insect infestations and other disturbances including human activities can be reflected in streamflows. In Colorado, streamflows increased for as much as 25 years after a spruce beetle outbreak, apparently owing to reduced interception and evapotranspiration (Bethlahmy 1975, Love 1955, Mitchell and Love 1973). The dead trees were not salvaged, and regeneration was not abundant on the beetle-impacted watersheds. The effects on water yields might have been less if young trees had become established on the watersheds soon after the beetle infestation (Bethlahmy 1975). In a southwestern Montana watershed where a mountain pine beetle (*Dendroctonus ponderosae* Hopkins) infestation killed 80 percent of the lodgepole pine (*Pinus contorta* Dougl. ex Loud.), a 15-percent increase occurred in annual water yield for 5 years after the infestation (Potts 1984). In the same study, fall and winter low flows were increased 10 percent, and snowmelt runoff was 2 to 3 weeks earlier compared to the preoutbreak conditions. In a British Columbia watershed where mountain pine beetle mortality followed by clearcut logging removed 30 percent of the forest cover, mean annual water yield increased 26 percent for 6 years after logging (Cheng 1989). Peak flows also increased by 21 percent and occurred almost 2 weeks earlier after harvesting.

Riparian vegetation has important effects on physical and biological processes in forest streams (Beschta 1998). Wood and leaf litter are the primary sources of energy in shaded, lower order streams. Litter from various tree species exhibits differential decay rates and is consumed by invertebrates only after it reaches a particular condition. Where more sunlight reaches the stream, such as in higher order streams or when the vegetative canopy is disturbed over lower order streams, primary production contributes more to the energy base. Primary producers not only depend on available nutrients, but also influence stream chemistry. The type and amount of litter that enters a forest stream can have far-reaching effects on nutrient and energy regimes and the resident biological communities (Triska and others 1982). In addition to providing nutrients and substrate for biological activity, large woody debris that falls into streams affects channel patterns, forms pools of various sizes and depths, dissipates energy of flowing water, and traps sediments. The size, amount, and species of large woody debris entering streams can significantly affect the physical and biological characteristics of the stream (Sedell and others 1988). Changes in forest stand composition and structure after a spruce beetle outbreak could significantly alter stream ecosystems for long periods, including their suitability as habitat for anadromous fish. The successional processes that follow a spruce beetle outbreak, whether natural or human altered, will determine the magnitude and duration of any changes in the lotic system.

Wildlife habitats—Spruce beetle-caused changes in stand structure and composition can have positive, negative, or neutral effects on wildlife populations depending on the habitat requirements of each species (Schmid and Frye 1977). Large mammals such as deer (*Odocoileus* spp.*),* elk (*Cervus elaphus* L.), and moose may benefit initially from an increase in forage production in the more open stands. Woodpecker populations may increase during an outbreak in response to the abundant supply of insect prey (Koplin 1969). As insect populations decline, however, food will become limiting and woodpecker populations will decline also, despite the abundance of nest sites. Small mammals that feed on spruce seed may suffer from a decline in available food after beetle outbreaks, whereas other species that feed on grasses and forbs may increase (Schmid and Frye 1977). The extent and duration of effects on wildlife populations will depend on the characteristics of a particular beetle infestation. Outbreaks that produce high levels of tree mortality and cover large areas likely will result in more severe and longer lasting impacts on wildlife habitat than less intense and localized outbreaks. The type of vegetation that becomes established in openings resulting from beetle-caused tree mortality and the successional processes that follow, including subsequent disturbances, will determine the duration of changes in wildlife populations.

Little empirical data exists on the response of wildlife populations to spruce beetle-caused tree mortality in Alaska. Consequently, responses of most species must be inferred from knowledge of their habitat requirements. For example, reproductive success of Townsend’s warblers (*Dendroica townsendi*) in Alaska is greatest when they nest high in large-diameter spruce in stands with low densities of woody shrubs (Matsuoka and others 1997). Because spruce beetles selectively remove the largest diameter spruce from infested stands and create openings for establishment of herbs and shrubs, habitat for the warblers would presumably be less favorable after a spruce beetle outbreak. Nineteen species of land birds have been identified as species of high regional concern in the southern coastal region of Alaska (Handel 1997). Most of these species are likely to be adversely affected by the changes in forest conditions that occur after spruce beetle infestation and timber harvesting. Research is needed to generate definitive conclusions about the effects of spruce beetle infestations and related silvicultural treatments on wildlife populations.

Fuel conditions and fire hazards—Fuel conditions and fire hazards change with time after beetle infestation and tree mortality. Trees killed by the spruce beetle gradually deteriorate and fall to the forest floor. Needles and small branches fall from dead trees within the first several years after beetle attack, thereby increasing surface fuel loads. Larger branches gradually deteriorate and break off the snag over longer periods. Eventually, the bole becomes unstable and the snag falls to the forest floor. The time that a snag remains standing depends on characteristics of the tree, such as wood chemistry, root structure, and cause of death, and climatic variables, such as precipitation, temperature, and wind patterns. In some areas, spruce snags remain standing for relatively long periods. In Colorado, 85 percent of beetle-killed spruce was still standing 25 years after an outbreak (Mielke 1950). In contrast, over a 16-year period in a Lutz spruce forest in Alaska, the spruce beetle killed 352 trees per acre, and about 175 of those had fallen to the ground (Holsten and others 1995). Debris that falls to the forest floor initially increases fire hazards, but the hazard gradually declines as the debris decomposes. In addition to effects on fuels and fire hazards, trees that fall to the ground are important in maintaining site productivity and biodiversity. They influence the physical structure of the forest floor and soil, provide a source of nutrients, increase the water holding and cation exchange capacities of the soil, and provide habitat for microorganisms, plants, and animals (Maser and others 1988).

Fire hazards may increase significantly after insect infestations. In Ontario, Canada, repeated defoliation by the spruce budworm, (*Choristoneura fumiferana* (Clem.)), caused high rates of mortality to balsam fir (*Abies balsamea* (L.) Mill.) (Stocks 1987). Surface fuel loads and fire hazards increased for 5 to 8 years after budworm-caused mortality as the dead trees broke apart and fell to the forest floor. Fire potentials gradually declined after 8 years as the surface fuels decomposed and vegetation became established on the sites. Twenty years after a spruce beetle outbreak on the Kenai Peninsula, there was significantly more sound, dead wood (more than 3 inches in diameter) compared to uninfested areas (Schulz 1995). In addition, there was significantly greater cover of bluejoint grass (*Calamagrostis canadensis* (Michx.) Beauv.), a fine, flashy fuel that facilitates rapid spread of fire. The combination of fine fuels and sound, woody material can potentially produce intense fires. Because they are exposed to the wind and sunlight, standing dead spruce trees dry out quickly after wet periods. These standing dead trees can potentially torch and initiate spot fires even after the needles have been lost. If stands are open enough to allow winds to reach surface fuels, fires may spread more rapidly than in stands of live trees with a closed canopy.[4] The present fuel conditions in spruce beetle-impacted stands of south-central Alaska may lead to severe and unpredictable fire behavior (Alaska Society of American Foresters 1997).

In addition to the heavy fuel loads, several other conditions in south-central Alaska contribute to the higher than normal fire hazard. Temperatures over the last several decades have been warming (see footnote 2), thereby resulting in a longer fire season. Also, the growing population in south-central Alaska is leading to increasing probabilities of human-caused fire ignitions.

The forests of south-central Alaska have evolved in response to periodic fires of natural or human causes. Although uncontrolled fires may be consistent with management objectives in some locations such as parks and wilderness areas, they may be unacceptable where they threaten lives, property, and resources. Prescribed burning and other silvicultural activities can reduce the risk of severe wildfires causing undesirable losses, although potential impacts of these management activities on ecosystem values also must be considered in the prescription and planning processes (Omi and Kalabokidis 1991).

---

[4] Vanderlinden, L. 1991. Fire behavior considerations for Cooper Landing Contingency Plan. Report of the Alaska Interagency Type I Incident Management Team. Unpublished report. On file with: U.S. Fish and Wildlife Service, Division Refuges, 1011 East Tudor Rd. Anchorage, AK 99503

Forest regeneration and successional processes—Spruce beetle outbreaks may significantly modify stand structure, composition, and ecological processes including plant succession. The magnitude of these effects depends on preoutbreak stand conditions and the severity of the beetle outbreak. The most obvious effect of beetle-caused mortality is reduced stand density (Holsten and others 1995). Mortality may range from scattered trees to almost complete removal of the overstory. Because the beetles selectively remove the large, older trees, the average and maximum tree size and age usually are reduced during an outbreak (Schmid and Frye 1977, Schulz 1996, Veblen and others 1991). Spruce beetle-caused mortality is most often followed by a release of codominant or understory trees or associated herbaceous and shrub vegetation rather than establishment of regeneration by spruce seedlings (Holsten and others 1995, Lieffers and others 1993, Miller 1970, Veblen and others 1991). Residual trees may exhibit accelerated growth after a spruce beetle infestation in response to the increase in available site resources (see footnote 3, Nienstaedt and Zasada 1990, Schulz 1996). Salvage logging activities that kill advanced regeneration and cause soil disturbance may result in some spruce seedling establishment (Schmid and Hinds 1974). Logging, however, also may lead to invasion by herbaceous plants and hardwood trees that exclude conifer regeneration in the absence of vegetation management activities (Fox 1980, Lieffers and others 1993, Schulz 1997).

An exposed mineral soil or mixed mineral soil-organic matter seedbed is required for natural regeneration of white spruce after disturbance (Nienstaedt and Zasada 1990, Zasada 1972). Unless spruce beetle mortality is accompanied or followed by another disturbance such as windthrow, fire, or logging, these seedbeds will be rare or nonexistent. Even when appropriate seedbeds are present, natural regeneration may not become established. Little seed is dispersed farther than 400 feet downwind from a seed source (Nienstaedt and Zasada 1990, Youngblood and Max 1992, Zasada 1972). In some cases, the failure of natural regeneration has been attributed to the lack of an adequate seed source near disturbed sites (Timoney and Peterson 1996). Because spruce beetle kills the largest trees in a stand, which are also the primary cone-bearing trees, seed production can decline dramatically after an outbreak. Depending on site quality, good spruce cone crops occur only every 4 to 12 years (Nienstaedt and Zasada 1990). Competing vegetation can prevent seedling establishment and may reduce the survival and growth of established seedlings (Haeussler and others 1990, Krasny and others 1984, Newton and Cole 1996, Rivard and others 1990, Sims and Mueller-Dombois 1968). Because of the combined effects of these factors, much of the space around spruce beetle-killed trees will become occupied by other plant species.

The plant community that will develop on a given site after a spruce beetle infestation depends on several factors including the plants that were present on the site before the infestation, distance to seed sources, seedbed conditions, and weather conditions after the infestation (Zasada and others 1992). In boreal forests, two plant species that are likely to increase in abundance after spruce beetle infestations are bluejoint grass and fireweed (*Epilobium angustifolium* L.) (Holsten and others 1995). Although both of these plants can reduce the establishment, survival, and growth of spruce seedlings, bluejoint grass can interfere with spruce regeneration more than fireweed. Because fireweed has less negative effects on spruce seedlings, it may be beneficial to encourage fireweed to prevent establishment of bluejoint grass (Landhausser and others 1996). Bluejoint grass may compete with tree seedlings for soil moisture and nutrients, lower soil temperatures, prevent spruce seed from reaching the seedbed, shade seedlings, and cause snowpress and smothering (Haeussler and others 1990 Hogg and Lieffers 1991, Lieffers and others 1993, 1990, Rivard and others 1990). Birch and aspen also may be released or become established after beetle-caused spruce mortality, particularly when followed by salvage logging or fire (Schulz 1997). These hardwoods grow more rapidly than spruce and will dominate the site if they achieve a competitive advantage (Zasada and others 1992). Spruce, however, is intermediate in shade tolerance and may survive in a hardwood understory for 50 to 70 years (Nienstaedt and Zasada 1990). Although spruce can survive in the understory, it will grow more slowly than in an open situation (Krasny and others 1984, Lieffers and Stadt 1994, Lieffers and others 1996). Resource managers may need to prescribe silvicultural activities after a beetle infestation to ensure the proper mix of plant species to meet their objectives.

Silviculture—At endemic population densities, the spruce beetle kills, at most, small groups of trees and causes little impact on silvicultural plans. In campgrounds or other high-use sites, it may be necessary to remove beetle-killed trees to reduce the risk of falling trees causing injuries, death, or property damage. Salvaging high-risk trees under these conditions is a relatively small additional cost to forest managers. In contrast, when beetle epidemics result in high levels of tree mortality and cover large areas, the disruption of management plans and associated costs can be substantial. Premature harvesting of stands can result in considerable loss in value. Not only are trees sometimes harvested before their economically optimal rotation age but logs from beetle-killed trees yield less lumber and lower quality products because of various defects and decomposition that increase with time after tree death (Parry and others 1996, Werner and others 1983). Log prices during outbreaks also may be depressed owing to the increased availability relative to demand. These factors combine to produce significant financial losses where forests are managed for timber production.

Salvage logging of spruce beetle-killed trees may reduce the economic impacts of an outbreak where timber management is an objective (Fitzgerald 1954). Logging also may be used to reduce fire hazards and influence the direction of plant succession to meet various management objectives. Harvesting may create seedbeds that facilitate regeneration of birch, aspen, and spruce (Schulz 1997, Zasada and others 1992). Harvesting alone will not ensure reforestation with the desired species mixture (Fox 1980), but if carefully planned and implemented as part of an integrated vegetation management plan, harvesting can help to ensure desired future conditions and resource values (McInnis and Roberts 1995, Packee 1990, Youngblood 1990). Stand-replacement prescribed burning can be used as an alternative to or in addition to harvesting for forest restoration (Vanderlinden 1996). Harvesting or prescribed burning and subsequent activities such as site preparation, planting, and weeding allow resource managers to control the direction of plant succession rather than rely on chance to produce desired conditions (Newton and Cole 1996, Wagner and Zasada 1991, Zasada and others 1992). All these activities, however, represent additional management costs. Whether or not harvesting or prescribed burning and followup treatments are justified depends on resource management objectives.

Social and economic values—The spruce forests of south-central Alaska provide many resource values including recreational opportunities, aesthetic enrichment, wildlife and fish habitats, timber, and watershed protection. Research on the impacts of spruce beetle-caused tree mortality on resource values is limited. The potential economic impact of the spruce beetle on timber values is obvious; however, these impacts are not always simple to calculate because of the many vagaries of supply and demand in worldwide wood product markets. Although beetle-killed spruce may lose their value as saw logs within a few years, in the environment of south-central Alaska, they may remain valuable as a source of pulp for up to 50 years (Scott and others 1996, Werner and others 1983).

Many other resource values are even more difficult to quantify. For example, residents of Homer, Alaska, have expressed feelings of loss related to emotional and spiritual impacts as they describe their reaction to the current spruce beetle epidemic (Homer News 1998). In a survey of south-central Alaska residents, loss of scenic beauty and increased fire danger were identified as the two most important impacts of the spruce beetle outbreak (Daniel and others 1991). In the same study, both resident and visitor perceptions of scenic beauty declined consistently with increasing amounts of beetle-caused tree mortality. Noncommodity value losses associated with spruce beetle-induced changes in forest conditions in south-central Alaska were assessed to be in the millions of dollars for combined impacts on wildlife habitats, water resources, recreation, real estate values, and fire prevention and suppression (Golden 1996).

Spruce Beetle Management Strategies

Although risk of additional tree-killing from the current beetle outbreak has largely subsided, risks from future outbreaks will be a continuing concern for the region. Consequently, management approaches to control bark beetle activity are important to the successful management of future south-central Alaska forests. This consideration is especially important for learning how to shape future forests that are more resilient to beetles and other disturbance agents, and thus prevent future outbreaks of the magnitude of the 1990s epidemic.

Because certain types of trees and forest stands are more susceptible to the spruce beetle than others (Hard and others 1983, Holsten 1984, Holsten and others 1991, Schmid and Frye 1976), silvicultural treatment is considered the first line of defense in rendering a forest stand or landscape more resistant to bark beetle outbreaks. A second or supplemental line of defense against bark beetle damage involves using behavior-modifying chemicals such as pheromones. Produced by the beetles themselves, pheromones are environmentally-safe compounds that can be used to manipulate the behavior of beetle populations in ways that will prevent unacceptable tree-killing.

Knowledge of the tree, stand, and site conditions that are favorable to spruce beetle populations provides the basis for risk and hazard rating systems that predict the probability of an outbreak and the damage that is likely to result from an outbreak (Reynolds and Holsten 1994a, 1994b, 1996). These systems can be used to prioritize stands for silvicultural treatments to reduce hazard and risk. Operational versions of spruce hazard and risk rating models are included in a computerized, knowledge-based decision-support system, SBexpert, along with an online textbook and bibliography (Reynolds and Holsten 1997). Thinning mature spruce stands to a basal area of 60 to 120 square feet per acre, depending on site quality, may reduce stand susceptibility to beetle infestation (Hard and Holsten 1985). Silvicultural treatments are most effective for reducing hazard or risk when applied before or in the early stages of an outbreak. Once a beetle population reaches epidemic proportions, virtually all trees in the forest are susceptible to attack.

The amount and location of host trees or logs suitable for beetle colonization are important determinants of risk of spruce beetle infestation (Reynolds and Holsten 1994b, Schmid 1981). Human-caused disturbances such as right-of-way clearing and logging should be planned to prevent the accumulation of large-diameter spruce slash at the time that beetles are dispersing, unless the material will be removed from the forest before the next beetle flight period. Salvage logging may be required after natural disturbances such as windstorms and fires to prevent the buildup of spruce beetle populations that could attack and kill live trees. If recently killed trees must be left in the forest, some treatments such as limbing can reduce the quality of the material as breeding sites for beetles (Hard and Holsten 1991).

Since the discovery of bark beetle pheromones, efforts have been underway to develop them into management tools to reduce or prevent beetle damage by modifying the behavior of beetle populations (Borden 1989). Most bark beetles produce at least two types of pheromones, aggregation and antiaggregation (Wood 1982). Aggregation pheromones are usually composed of a blend of compounds that are attractive to flying beetles. These chemicals are particularly important for stimulating the mass attack behavior necessary for beetles to overcome the resistance of live trees. Antiaggregation pheromones usually are composed of one compound and regulate density of beetle attack and colonization behavior. The antiaggregation pheromones are important for minimizing intraspecific competition among developing larvae and the related survival success to the next generation of beetles. Both aggregation and antiaggregation pheromones have been identified and reported for the spruce beetle.

Aggregation compounds known to attract spruce beetles when placed on host trees or in artificial traps either alone or in various combinations include frontalin (Dyer 1973), alpha-pinene (Furniss and others 1976, Kline and others 1974), seudenol (Furniss and others 1976) verbenene, and MCOL (methylcyclohexenol) (Werner 1994). In Alaska, the most attractive lure that has been tested is composed of a mixture of frontalin, alpha-pinene, and MCOL (Werner 1994). The most common management application of aggregation pheromones has been to bait trap trees or lethal trap trees (i.e., sprayed with insecticide) (Dyer and others 1975, Gray and others 1990, Holsten and others 1991). Current research is exploring the possibility of using pheromone-baited traps to influence the amount and distribution of beetle-caused tree mortality (Werner 1994, Werner and Holsten 1995).

The antiaggregation pheromone, 3-methycyclohex-2-en-1-one (MCH), has been shown to inhibit the response of spruce beetles to aggregation pheromones and felled host trees (Kline and others 1974, Lindgren and others 1989). The potential management application of the antiaggregant is to distribute the synthesized version over an area to be protected, thereby resulting in a “no vacancy” signal to beetles that would otherwise infest the trees in that location. Results of experiments with MCH, however, have been inconsistent, and no operational treatments using the material have been developed[5] (Werner 1994, Werner and Holsten 1995). If MCH or another antiaggregation compound could be proved effective, it would be possible to use the material to protect high-valued stands in the same way that MCH can protect high-valued Douglas-fir trees threatened by the Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins) (Ross and Daterman 1995).

Conceptual Model of a Research and Development Program

The biophysical components of the forest ecosystem determine the capabilities for resource management, and the socioeconomic components set the expectations (fig. 5). It is through the policy development process that conflicts among the desires of stakeholders and biological potentials are resolved and resource management goals are defined. The responsibility of the resource manager is to implement the resource management goals through the development of a long-term plan and the application of appropriate treatment prescriptions. The ecosystem is not only influenced by human-caused disturbances but also by various natural disturbances. Forests are inherently

[5] Darrell Ross, 1999. Personal communication, associate professor of forest science. Oregon State University, Corvallis, OR 97331.

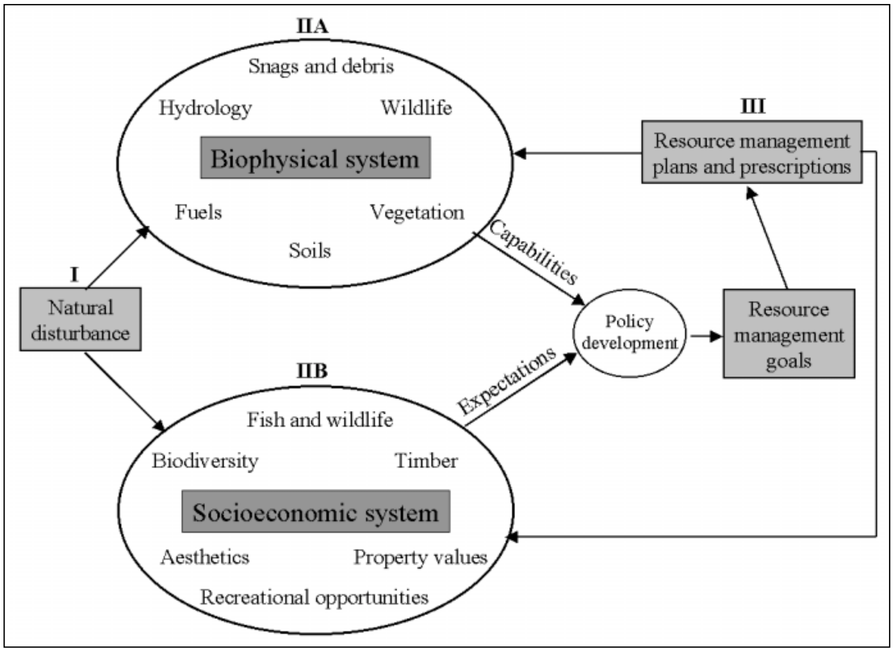

Figure 5—A conceptual model of the forest resource management environment illustrating the interactions among the biophysical and socioeconomic systems and the influences of natural and human-caused disturbances on the system. Roman numerals identify the three general focus areas for research and development.

complex, variable, and dynamic systems. Thus, a single forest stand cannot provide all the resources that an entire forested landscape can provide over long periods. Historically, some areas were good habitat for particular species of plants, animals, and micro-organisms, whereas others were not; yet across the landscape, the habitat requirements of all species were met. The challenge for resource managers is to develop programs for the long-term sustainable production of resource commodities and values at the landscape scale while preserving the integrity of the ecosystem. This section will describe a research approach for helping resource managers meet this challenge in south-central Alaska.

Research programs must generate the kind of information and technologies that will support the efforts of managers to achieve their goals. Managers need basic information on ecological relations and processes at multiple spatial and temporal scales. For example, a manager needs to know how populations of wildlife species respond to specific environmental changes resulting from a natural or human-caused disturbance at the stand level over a period relevant to the generation time of each species. Because some processes such as dispersal and migration might occur at scales that are not relevant at the stand level, managers also need to know how these populations respond to changes at the landscape scale for periods equivalent to multiple generations. In addition to basic ecological information, managers need to know how various ecosystem components will respond to management activities. Again, these studies are needed at variable spatial and temporal scales. Finally, managers need to know how changing forest conditions will affect the socioeconomic system. Some of the information and technologies that managers need can be generated through the synthesis of existing knowledge and the development of models. Other needs, however, can only be met by gathering empirical data from field studies.

The research and development efforts proposed by the south-central Alaska forest health restoration initiative can be divided into three focus areas:

1. Develop a better understanding of the present spruce beetle outbreak. Superficially, the present outbreak appears to be different than any other in recorded history. It is important to document the ways in which this outbreak differs from earlier ones so that similar situations can be avoided in the future or negative impacts associated with them can be minimized. This area of research corresponds to the “natural disturbance” box (I) in figure 5.

2. Assess the biophysical and socioeconomic effects of the present spruce beetle outbreak in the near and long term. The current outbreak is influencing every component of the forest ecosystem at the stand and landscape scales. Hydrologic processes, fuels and fire hazards, fish and wildlife habitats, vegetative structure and composition, and soil properties are all changing because of beetle-caused tree mortality. The magnitude and direction of these changes needs to be documented as a basis for deciding whether or not management actions are needed and, if so, what types of treatments should be used. Also, the outbreak is affecting the socioeconomic system that is dependent on these forests. Recreational opportunities, property values, timber production, biodiversity, fishing and hunting opportunities, and aesthetic appeal are all changing in response to beetle-caused tree mortality. Understanding the socioeconomic effects of the beetle outbreak is as important as understanding the ecological impacts. This area of research corresponds to the “biophysical system” and “socioeconomic system” boxes in figure 5 (IIA and IIB).

3. Develop management options to restore forest health, and predict the outcomes of alternative treatment scenarios at multiple scales. Before implementing management plans and stand-level prescriptions, it is important to have a clear understanding of how the proposed actions will affect the biophysical and socioeconomic systems at multiple scales. Currently, there are needs for both short-term actions to mitigate further negative impacts of the beetle-caused tree mortality and long-term actions to restore the health and sustainability of the ecosystem and make it more resilient to future disturbances. Short-term actions might include fuels-reduction programs to reduce the probability of wildfires causing loss of lives, property, and resource values. Long-term actions might include reforestation efforts to improve fish and wildlife habitats, regulate the quantity and quality of streamflows, provide timber resources, and develop vegetation patterns and forest structures that will be more resilient to beetle outbreaks and wildfires in the future. This category of research will provide the information and technology to support the “resource management plans and prescriptions” box in figure 5 (III).

Focus Areas for Research and Development

In the following sections, three focus areas for accelerated research and development are described: Understand the present bark beetle outbreak, Assess the near- and long-term effects of the bark beetle outbreak, and develop management options to restore forest health.

In each section, examples of specific projects are included. The inclusion of study descriptions in this document does not necessarily mean that those particular studies would be approved for funding, but they are included as examples to facilitate further discussion of research and development priorities. Furthermore, projects that are not included here may be identified and approved for funding at a later date. A steering group composed of representatives of the PNW Research Station and the Alaska Region of the USDA Forest Service will make the final decisions on funding priorities. These decisions will be made in consultation with informal working groups composed of experts in the various subject areas.

Understand the Present Bark Beetle Outbreak

As previously described, the current spruce beetle outbreak differs in many ways from any other spruce beetle outbreak in recorded history. The current outbreak covers a larger area and is causing higher percentages of tree mortality than occurred in earlier outbreaks. In addition, *Ips* species are causing significant tree mortality for the first time in parts of south-central Alaska. It is important that these differences are documented and that the likely reasons for the differences are identified. Projects will be designed to address the following three objectives: provide information to resolve the present debate about the current outbreak, its causes, and its relation to previous outbreaks; determine the extent of the tree mortality being caused by the *Dendroctonus* spruce beetle and the various species of *Ips* bark beetles. Identify the conditions promoting such outbreaks so that efforts can be made to avoid or mitigate similar situations in the future. These objectives can be accomplished by using various retrospective techniques. Examples of potential research projects include the following:

1. Compare the spatial and temporal dynamics of the current and past spruce beetle outbreaks by using existing data sources such as vegetation maps, infestation maps, aerial survey data, pest management reports, anecdotal descriptions, and weather records.

2. Study the relations between temperature and moisture regimes (e.g., drought) of past beetle outbreaks. Use models such as the mapped atmosphere plant soil system (MAPSS) to predict future distribution of vegetation under various climate scenarios and the probability of occurrence for diverse disturbance events.

Assess the Near- and Long-Term Effects of the Bark Beetle Outbreak

Watersheds—No published information seems to be available on the effects of spruce beetle infestations on watersheds in south-central Alaska. Based on research in other areas, beetle-caused tree mortality is expected to increase water yields, change the temporal patterns of water yield, cause a temporary increase in debris inputs, increase primary production in lower order streams, change water chemistry, and alter aquatic plant and animal communities. Some of these changes could last for as long as 25 years. Managers need to know how streams in beetle-infested watersheds will change. Projects will be developed to provide tools for managers to assess the effects of disturbance on watershed conditions and to formulate appropriate management plans and prescriptions to respond to those changing conditions. Examples of potential research projects include the following:

1. Develop or adapt an existing model to predict hydrologic properties of watersheds after spruce beetle outbreaks and other disturbances.

2. Develop a method for characterizing aquatic health and watershed conditions.

Wildlife habitats—Empirical data currently are lacking on the response of various wildlife species to spruce beetle infestations, and related fuels accumulation and fire events, in south-central Alaska. The results of workshops and discussions with individuals representing various land management agencies in south-central Alaska made it evident that several case studies have been established to determine the responses of selected birds and animals to the beetle-induced changes to forest structure and composition. These studies represent a modest and preliminary effort to determine the response of wildlife to the changes in forest conditions brought about by spruce beetle infestations, fire, and silvicultural treatments. More studies like these will be needed to provide the information for formulating effective management plans and prescriptions. Projects will be developed to identify the habitat requirements for species of interest and to evaluate those requirements with respect to landscape structure, disturbance, and recovery processes. Examples of potential research projects include the following:

1. Determine the effects of forest change on moose habitat. Moose populations are indicative of habitat quality for other species that depend on early-successional conditions. Moose populations may respond positively to the shift from mature spruce stands to mixed hardwood-conifer stands caused by spruce beetle effects and fire. Methods for assessing the impacts of spruce beetle-caused tree mortality, fire, and other disturbances on moose habitat include following radio-collared moose, mapping vegetation, assessing browse availability, and measuring reproductive success.

2. Determine the effects of natural and human-caused disturbances on small mammals and birds. These studies would require surveying populations of small mammals and birds in areas with different levels of spruce beetle-caused tree mortality and subsequent disturbances such as fire and harvesting. If sufficient resources were devoted to these studies, reproductive data could be gathered to complement the survey data.

Fuel conditions and fire hazards—Data on present fuel conditions in south-central Alaska are limited. Fuel conditions and wildfire risk will depend on the amount of tree mortality and time since trees died as well as other stand and site variables. Recent wildfire behavior in spruce beetle-infested forests has been intense and unpredictable, thereby illustrating the need for improved fire prediction technologies. Projects will be developed to provide information and tools for managers to use to assess fuel conditions at different times after beetle infestation and other disturbances. An example of potential research includes the following:

1. Develop models to predict fuel conditions in south-central Alaska immediately after spruce beetle-caused tree mortality and after other disturbances, and future fuel conditions at different intervals after the disturbance events.

Forest regeneration and successional processes—Although resource managers generally know how forests in south-central Alaska respond to disturbance, no previous disturbance has been of the scale or intensity of the present spruce beetle outbreak. How the vegetation will respond and the successional pathways that will follow are unknown. In some areas, spruce seed sources are scarce, and the seedbed is unsuitable for spruce regeneration. Artificial regeneration may be needed to ensure spruce regeneration in a reasonable amount of time to meet management objectives. Projects will be developed to provide managers with information and tools to assess the response of vegetation to beetle infestation and other disturbances. An example of a potential research project follows:

1. Determine the changes in plant communities with different amounts of spruce beetle-caused tree mortality in various forest types.

Timber harvest and wood products—The various workshops and assessments of the effects of the spruce beetle outbreak resulted in relatively few concerns about impacts on the timber industry. Concerns about wildfire hazards and impacts on aquatic and wildlife habitats greatly overshadowed issues raised about harvesting timber and the wood products industry. It is likely in the short term that salvage harvesting of dead timber will increase because of obvious causes and related need to reduce fuels. In the long term, the potential options for the timber industry in the outbreak areas will depend on patterns of regeneration of tree species and the socioeconomic incentives and opportunities for commercial activities. One potentially useful study project might be as follows:

1. Predict near- and long-term effects of the beetle epidemic on timber harvesting and development of the wood products industry in south-central Alaska.

Social and economic values—No detailed scientific analyses of the social and economic impacts of spruce beetle infestations in south-central Alaska have been conducted. The changes in vegetation resulting from the outbreak are likely to have many impacts including costs of wildfire suppression; reduced property values; changing real estate insurance premiums; changes in revenues from tourism, hunting, and fishing; and effects on local and regional forest products industries. Various human health and safety issues also are emerging such as injuries to tourists, homeowners, and forest workers from falling trees; increasing risks of moose and vehicle collisions; and health hazards from smoke emissions generated by wildfires or prescribed burns. Projects will be initiated to develop sound methods for assessing these impacts and to apply those methods to assist managers in evaluating alternative resource management plans and prescriptions. The following is one example of a project that is needed:

1. Develop appropriate methods to measure and evaluate the socioeconomic impacts of beetle-caused tree mortality and subsequent disturbances in the forests of south-central Alaska.

Develop Management Options to Restore Forest Health

The current spruce beetle infestation has dramatically changed the forest landscape throughout much of south-central Alaska. Managers not only need information to help them make treatment decisions at the stand level but also to understand the cumulative effects of their actions at the landscape scale. Managers may have several goals such as reducing fire hazards, maintaining quality fish and wildlife habitats, and providing an even flow of timber harvest volumes. They need information and tools to help them plan and schedule management activities at the landscape scale to meet these various objectives.

Evaluating alternative management scenarios—A set of management scenarios can serve as a framework for research that describes future conditions and options. The scenarios will represent a range of alternatives relating to the size and distribution of the areas to receive silvicultural prescriptions and the intensity of treatments applied. A key research task will be to predict, or develop the means to predict, the outcomes and tradeoffs associated with management scenarios that differ by levels of investment in forest health restoration and by degrees of emphasis among diverse resource values. Potential management scenarios to be compared might include the following:

1. Do nothing. Let nature take its course.

2. Hazard reduction. Apply an aggressive fuels-reduction and reforestation program in the urban and forest interface to reduce the potential for loss of lives and property. Conduct normal management elsewhere, with no special mitigation or restoration activities in response to the beetle outbreak.

3. Hazard reduction with limited restoration. This scenario is the same as no. 2, but with additional mitigation and restoration activities on other selected sites. These additional activities might include fuels reduction, reforestation, and habitat restoration on readily accessible areas of special interest such as recreational sites, riparian zones, and viewsheds.

4. Hazard reduction with aggressive restoration. This scenario is the same as no. 3, but with mitigation and restoration activities applied to all reasonably accessible areas.

Modeling and Integration

The three focus areas for research involve complex interdisciplinary studies that could include large-scale field tests. This applies in particular to the third focus area "Develop management options to restore forest health." Testing alternative management scenarios, as proposed for this focus area of research, presents several logistical and financial obstacles. Large-scale field studies are difficult to replicate and require long periods to produce meaningful results. Modeling is a realistic alternative that allows for the comparison of different scenarios involving multiple objectives at a large scale over long periods, but provides results quickly and at minimal cost. Examples of potential modeling projects for evaluating the optional management scenarios include the following:

1. Use modeling techniques to simulate and compare the four management scenarios described previously. For example, a land management activity scheduling model was used in a recent study to evaluate various combinations of treatments to simultaneously improve aquatic habitat and produce wood products over time (Bettinger and others 1998). A similar approach could be used to simultaneously evaluate fire hazard reduction and other forest health restoration objectives that are associated with the respective scenarios described above. Such a model could be used to predict the socioeconomic effects and tradeoffs in different resource values that would be gained or lost with different restoration scenarios. Because the different management scenarios are based on levels of investment and differences in emphasis by management objectives (fire hazard reduction, improved wildlife habitat, enhanced viewsheds, etc.), land managers and stakeholders would have a predetermined indication of what each management scenario would provide in the way of restoring ecosystem health. Because of the multiple resource values and management objectives considered, the design of this model would necessarily be highly integrated. A multidisciplinary research and development effort would provide support for design of the model, with research priorities being guided primarily by the degree of confidence—or lack of confidence—in assigning coefficients for interactions among the variables addressed by the respective scenarios.

2. A second modeling objective would be to design future forest landscapes with the necessary structures, composition, and vegetation patterns for meeting multiple resource needs. These landscapes also would be more resilient to major disturbance episodes and be capable of sustaining healthy ecosystem conditions for the long term. The model, or models, would be flexible, allowing managers with options for planning future landscape scenarios that would be sustainable within the biophysical limits of the area but also provide the mix of resource values viewed as a healthy forest by stakeholders. This would be an integrated effort requiring a multidisciplinary research team with appropriate input from land managers and stakeholders.

3. The concept of integration may be the most significant aspect of this initiative. Indeed, the success of the initiative is dependent on how effectively integration is achieved in planning, in accommodating multiple objectives, in providing for effective interaction across disciplines, and in developing information useful at multiple spatial and temporal scales. Although the term “integration” receives much attention, how it should be implemented is unclear, particularly for restoration of forest health, which involves multiple variables, diverse perspectives, and multiple scales. Our answer is to engage the ecosystem management decision-support (EMDS) system as an application framework for a knowledge-based model for addressing the broad problem issues of this initiative. The EMDS framework integrates geographic information system (GIS) and knowledge base system technologies to provide an analytical tool for environmental assessment (Reynolds and others 1997). This system provides a means for processing diverse attribute data from multiple landscape features within a single analysis, thereby integrating various concerns into a single analysis and accounting for their interactions. The NetWeaver knowledge base engine used in EMDS provides partial evaluations of ecosystem states and processes based on available information and provides useful information about the influence of missing data to improve efficiency of ecosystem assessment. This makes the system ideal for environmental assessments for which there is incomplete information (Reynolds and others 1997). This system may be particularly suitable for initiative efforts because the research framework for the initiative includes major sections on assessment of beetle-caused effects on the ecosystem and “what if” effects of different management scenarios for restoration of the ecosystem and its components. Both of these efforts will address problems at different scales, confront questions where data are incomplete, and involve problems having multiple variables. The EMDS system was designed to accommodate such problems while incorporating information and estimates derived from submodels such as those discussed previously under items 1 and 2 of this section.

For efficient application of the models described above and for implementation of the EMDS system, scientists and managers will need improved monitoring systems that describe and predict key changes on the landscape such as fuel conditions, keystone wildlife populations, habitat quality and location, hydrologic conditions, and pest populations.

Priority Research to Support Evaluation of Management Scenarios

The research needs discussed in this section all were emphasized by managers and other workshop participants on addressing the needs for restoring forest health in the spruce beetle-affected areas of south-central Alaska. These areas of research and development will be considered as priorities for design of the models discussed previously, for incorporation into the EMDS system assessments, and where critical needs exist for new information or technologies to support the evaluation of the different management scenarios. A key area of research emphasis will be to determine their interactions and how they can collectively be addressed to restore forest health at a landscape scale.

Fuel conditions and fire hazards—The high concentration of fuels in spruce beetle-infested forests is creating significant fire hazards throughout much of south-central Alaska, particularly in the urban-forest interface. Study objectives are to document the advantages, disadvantages, and ecological effects of alternative slash disposal and fuel-reduction treatments, and to develop methods to prioritize areas for various fuel-reduction treatments. This information will be useful in evaluating any of the four management scenarios. Examples of potential research projects include the following:

1. Compare the efficacy and tradeoffs associated with alternative fuels-reduction and slash-disposal treatments such as prescribed fire and mechanical removal. Additionally, treatments will be compared for their effects on vegetation and successional processes. This will require field studies to compare alternatives including benefit and cost analyses.

2. Develop models to predict fire effects and behavior in south-central Alaska immediately after spruce beetle infestation and future fire effects and behavior as fuel conditions change with time since beetle infestation. These models should include predictions of smoke production and dispersion. Some field data is currently available but more will be needed to cover all types of stands and fuel conditions. This objective will be met by modifying existing models or by developing new ones. The models will be supported by development of a monitoring system that tracks changes in fuel conditions over time, and links with other key ecosystem changes such as increases in the urban-forest interface situation.

3. Develop a fire risk assessment model for live and beetle-killed forests by using historical temperature data and other appropriate information.

Forest regeneration and successional processes—Spruce beetle-caused tree mortality has reduced forest cover below desirable levels in many infested stands. In the absence of subsequent disturbances such as fire to prepare a seedbed, natural regeneration of spruce or hardwoods will be minimal. In some areas, spruce mortality is so great that seed sources for natural regeneration are inadequate. These studies will be designed to provide information and tools for managers to use to predict the response of vegetation in the absence of treatments and after various fuels-reduction or site-preparation treatments. Examples of potential research projects include the following:

1. Develop technologies to rapidly detect changes in vegetative cover at low cost over large areas. The spruce beetle infestation, fire, climate change, and other natural and human-caused disturbances are rapidly altering the vegetative conditions throughout south-central Alaska. Because of the large land areas and limited resources, current methods for inventorying forest conditions are inadequate. Managers need reliable, cost-effective methods for generating data on current conditions to use in developing management plans and prescriptions.

2. Conduct field studies to compare the survival and growth of various stock types of spruce and hardwood species after different site-preparation treatments under south-central Alaska conditions. Some of these studies have already been established by the PNW Research Station and cooperators.

3. Document response of vegetation to past mechanical and prescribed burning treatments conducted on the Kenai National Wildlife Refuge.

Beetle management strategies—The two most promising approaches for preventing and mitigating adverse effects of spruce beetle outbreaks are silvicultural prescriptions to reduce tree susceptibility to attack and development of pheromones for controlling the behavior of beetle populations. These approaches are considered to help managers know how to shape and manage future forests to ensure greater resilience to disturbance, and not merely for treating the current outbreak.

Considerable research has been conducted on the spruce beetle pheromones and on strategies for using them to minimize the negative effects of beetles on resource management objectives. Pheromones are one of the few options for managing beetle populations and their effects, particularly under the constraints of management scenarios requiring minimal impacts. Pheromones may prove to be particularly useful in preventing the infestation of wind-thrown or otherwise weakened trees, a circumstance that often leads to the buildup of large beetle populations and subsequent infestation of high-value trees.

Silvicultural approaches can render trees, stands, and forest landscapes more resilient to the effects of beetle outbreaks. Species composition, manipulation of age classes of host trees, and vegetation patterns of host and nonhost trees across a landscape can influence the spread and intensity of beetle outbreaks. By integrating this objective with others in alternative management scenarios, land managers can accommodate multiple objectives while designing future forest landscapes that will be more resilient to beetle epidemics. Possible research projects for bark beetle management include the following:

1. Develop a model of a future forest landscape with vegetative attributes that will be resilient to bark beetle epidemics and that will be compatible with other management needs such as providing wildlife habitat, reducing wildfire risks, etc.

2. Develop a monitoring system to detect critical changes in spruce beetle populations that may indicate the onset of outbreak conditions.

3. Conduct field studies to test pheromones in protecting selected, high-value resources from bark beetle outbreaks on broad forest landscapes.

Watershed health strategies—Bark beetle epidemics have profoundly effected the hydrologic characteristics of watersheds, and potentially aquatic organisms including anadromous fish. A key area of research will involve determining interactions and outcomes associated with different management scenarios with varying emphasis on particular management objectives. One example of a research study is as follows:

1. Design a watershed landscape with vegetation patterns, species composition, and other attributes that will be resilient to major disturbances such as the current spruce beetle epidemic or large-scale wildfires, while providing hydrologic needs and supporting multiple resource values for the long term.

Wildlife habitat approaches—The effects of the spruce beetle outbreak have drastically changed habitat quality and quantity for many species, and as successional changes in vegetation occur over time, additional habitat changes will occur. An urgent research need is to develop future a landscapes with vegetative diversity and attributes that will accommodate the desired biota at multiple scales. This desired landscape should be resilient to future beetle outbreaks and wildfires so as to maintain its capacity to support the desired conditions over the long term. The attributes needed to sustain wildlife must be reasonably compatible, at the landscape scale, with management objectives for other desired conditions that define a healthy forest ecosystem for south-central Alaska. Examples of such studies could be as follows:

1. Determine the vegetative patterns and related attributes of a watershed that will support a mix of keystone wildlife species and guilds while providing desired hydrologic resources in south-central Alaska, and that would be sustainable and compatible with other desired conditions for the long-term.

2. Develop a monitoring system that tracks changes in vegetation patterns over time and detects where and when suitable habitat for keystone species is lost or becomes available.

Social and economic values—Alternative scenarios for management response to the effects of the spruce beetle epidemic will necessarily emphasize certain management objectives more than others. This is evident in reviewing the four management scenarios described in a previous section, with one of the less costly scenarios being almost entirely focused on fire hazard reduction and little or no attention given to other resource values such as wildlife habitat conservation or enhancement. More extensive and costly scenarios for management approaches tend to accommodate more variables and desired conditions. Socioeconomic questions arise when decisions are made concerning which objectives will be a priority within given scenarios for a forest landscape. Although nearly all stakeholders agree that fuels and wildfire hazard reduction should be a priority for urban-wildland interface areas, such agreement may not be forthcoming when other resource values such as viewsheds, wildlife habitat, and recreational options are at stake. An example of a research project could be as follows:

1. Develop a process for setting priorities among mixes of management objectives and desired attributes associated with alternative scenarios for forest health restoration in south-central Alaska.

Additional Opportunities for Integration and Cooperative Research

In addition to those previously mentioned, many opportunities exists for cooperation and to build on existing efforts to accomplish integrative projects. For example, the U.S. Geological Survey has an extensive GIS mapping program that would be useful to many of the proposed research projects. They maintain a geospatial data clearinghouse for Alaska on the internet at URL: http://agdc.usgs.gov that includes forest health monitoring data. Another example is the establishment of plots on the Kenai Peninsula in 1987 by the USDA Forest Service, Alaska Region and PNW Research Station to document the effects of spruce beetle infestation on forest structure and composition. Remeasurement of these plots will aid in understanding the changes in south-central Alaska forests resulting from the current spruce beetle infestation. Additionally the interagency group, INFEST, is involved in assessing the impacts of the current outbreak on wildlife habitats. The sharing of resources and data by the various agencies and individuals involved in these and many other projects could be of particular assistance in constructing the integrated predictive models discussed in this paper.

Potential cooperators, in addition to the USDA Forest Service Alaska Region and PNW Research Station currently working on relevant research projects or who might be willing to provide financial or in-kind support of new or expanded research and development efforts include:

- Alaska Department of Natural Resources
- Alaska Department of Fish and Game
- Alaska Fire Service
- Alaska Native Corporations
- Alaska Wildland Fire Coordinating Group
- Canadian Forest Service
- INFEST-agencies concerned with impacts on fish and wildlife
- Kenai Peninsula Borough
- University of Alaska
- USDA Forest Service, Chugach National Forest
- USDA Forest Service, Alaska Region, State and Private Forestry
- USDA Natural Resources Conservation Service
- USDI Bureau of Land Management
- USDI National Park Service
- U.S. Geological Survey

Research and Development Schedule

The forest health restoration initiative for south-central Alaska is intended as a 5-year accelerated research and development effort. Three primary phases are envisioned. Phase one would be an implementation phase during the first year to coordinate collaborators, initiate priority research and development work, and produce a synthesis document and model based on what is currently known about the spruce beetle outbreak and its effects. The primary objective of the synthesis document would be to provide immediate guidance to managers for evaluating treatment alternatives. The second or continuing research and development phase would be conducted over the 5-year life of the initiative and emphasize information gathering, ongoing modeling, and technology development focused on areas of critical needs. Second-phase research and development products would consist of publications, models, and management guidance produced based on results of the ongoing efforts. The final, or completion phase, would take place in year 5 of the initiative with its primary product consisting of a synthesis document summarizing the research and development findings over the life of the project.

Allocation of Research and Development Resources

The disturbance-related research and development needs in south-central Alaska cannot all be addressed with available resources. It will be necessary to prioritize the potential projects and select those likely to provide the greatest return on investment. Criteria for prioritization will be developed through a collaborative process involving a small group of experts with knowledge of the key issues facing resource managers in south-central Alaska. A steering committee composed of representatives from the USDA Forest Service, PNW Research Station and the Alaska Region will make the final decisions on allocation of resources.

Technology Transfer Opportunities

The goal of this research and development initiative is to provide more information and technologies to resource managers to facilitate the long-term, sustainable production of forest commodities and values at the landscape scale. Consequently, technology transfer will be a major consideration in designing, planning, and implementing the program. A regional workshop will be conducted at the beginning of the program to coordinate interested parties in the process and to begin setting priorities for further planning and implementation. The workshop will serve to summarize current knowledge and provide a basis for more detailed development of research plans and priorities. Research managers, research scientists, and various interest groups will be involved in this workshop. Soliciting the input of various interests early in the program will ensure that the results will be useful and widely accepted. Interim products such as publications and computer programs will be disseminated as soon as possible, and many of the above cooperators will share responsibility in carrying out these technology transfer activities. Establishing a website will make information available to a wide audience in a timely manner. As appropriate, additional workshops will be held to feature the timely transfer of new information and technology. This will include a final workshop at the end of the program to summarize the advances made under the initiative, and to help set the stage for developing a final synthesis of information. Workshop proceedings, published in both hardcopy and electronically, will provide information resources for managers. In addition, press releases, newsletters, a website, demonstration sites, and other hands-on approaches also will be used to transfer key information and technologies to managers and stakeholders.

Acknowledgments

Ed Holsten and Beth Schulz, USDA Forest Service, Forest Health Protection, Alaska Region, and Skeeter Werner (retired), USDA Forest Service, PNW Research Station provided relevant literature, unpublished data, and professional insights that were highly useful in preparing this document. Ed Berg, USDI, Kenai National Wildlife Refuge, Susan Howell and Michele Potkin, USDA Forest Service, Chugach National Forest, and Andy Youngblood, USDA Forest Service, Pacific Northwest Research Station, provided unpublished data, progress reports, and draft manuscripts that were valuable in summarizing information on the historical role of disturbance, response of wildlife to spruce beetle infestations, and current reforestation research. Roger Burnside and Jeff Riggs, State of Alaska, Department of Natural Resources, Division of Forestry, provided helpful advice and the mapped insect activity. Jack Walstad, Oregon State University Department of Forest Resources Chair, contributed invaluable advice and insights toward improvement of the document. Roger Ottmar, Susan Willits, Keith Reynolds, Sandy Boyce, and Jane Hayes, USDA Forest Service, PNW Research Station, also contributed detailed and constructive review comments on earlier drafts of this document. Tom Mills and Fred Stormer, USDA Forest Service, Pacific Northwest Research Station, provided strategic direction and helpful guidance at various stages in the development of this document.

Literature Cited

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Washington, DC: Island Press. 493 p.

Society of American Foresters. 1997. Action program to identify and restore key spruce ecosystems killed, infested, or threatened by the spruce bark beetle. Juneau, AK: Society of American Foresters. 11 p.

Attiwill, P.M. 1994. The disturbance of forest ecosystems: the ecological basis for conservative management. Forest Ecology and Management. 63: 247-300.

Bartos, D.L.; Amman, G.D. 1989. Microclimate: an alternative to tree vigor as a basis for mountain pine beetle infestations. INT-400. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 11 p.

Berryman, A.A. 1972. Resistance of conifers to invasion by bark beetle-fungus associations. Bioscience. 22: 598-602.

Beschta, R.L. 1998. Forest hydrology in the Pacific Northwest: additional research needs. Journal of American Water Resources Association. 34: 729-741.

Bethlahmy, N. 1975. A Colorado episode: beetle epidemic, ghost forests, more streamflow. Northwest Science. 49: 95-105.

Bettinger, P.; Johnson, K.N.; Sessions, J. 1998. Improving aquatic habitat conditions over time while producing wood products: an examination of options. Journal American Water Resources Association. 34: 891-907.

Borden, J.H. 1989. Semiochemicals and bark beetle populations: exploitation of natural phenomena by pest management strategists. Holarctic Ecology. 12: 501-510.

Cheng, J.D. 1989. Streamflow changes after clear-cut logging of a pine beetle-infested watershed in southern British Columbia, Canada. Water Resources Research. 25: 449-456.

Daniel, T.C.; Orland, B.; Hetherington, J.; Paschke, J.L. 1991. Public perception and attitudes regarding spruce bark beetle damage to forest resources on the Chugach National Forest, Alaska. Anchorage, AK: [Chugach National Forest]; final report; U.S. Department of Agriculture, Forest Service, Alaska Region. 44 p. Available from: USDA Forest Service, Forest Health Protection, 3301 C Street, Suite 522, Anchorage, AK 99503.

DeVolder, A.D.; Anderson, R.S. 1998. Interim report of the black spruce fire history study, Kenai National Wildlife Refuge, Alaska. Flagstaff, AZ: Laboratory of Paleoecology and Quaternary studies program, Northern Arizona University. 35 p.

Dyer, E.D.A. 1973. Spruce beetle aggregated by the synthetic pheromone frontalin. Canadian Journal of Forest Research. 3: 486-494.

Dyer, E.D.A.; Hall, P.M.; Safranyik, L. 1975. Numbers of *Dendroctonus rufipennis* (Kirby) and *Thanasimus undatulus* Say at pheromone-baited poisoned and unpoisoned trees. Journal of the Entomological Society of British Columbia. 72: 20-22.

Fitzgerald, A.O. 1954. Beetle proofing the big timber country. American Forests. 60: 24-25, 53-56.

Foote, M.J. 1983. Classification, description, and dynamics of plant communities after fire in the taiga of interior Alaska. Res. Pap. PNW-307. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 108 p.

Fox, J. 1980. Forest regeneration of upland areas following logging in interior Alaska. Agroborealis. 2: 31-34.

Furniss, M.M.; Baker, B.H.; Hostetler, B.B. 1976. Aggregation of spruce beetles (Coleoptera) to seudenol and repression of attraction by methylcyclohexenone in Alaska. Canadian Entomologist. 108: 1297-1302.

Furniss, R.L.; Carolin, V.M. 1977. Western forest insects. Misc. Publ. 1339. Washington, DC: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 654 p.

Gabriel, H.W.; Tande, G.F. 1983. A regional approach to fire history in Alaska. BLM–Alaska Tech. Rep. 9. Anchorage, AK: U.S. Department of the Interior, Bureau of Land Management. 32 p.

Geiszler, D.R.; Gara, R.I.; Driver, C.H. [and others]. 1980. Fire, fungi, and beetle influences on a lodgepole pine ecosystem of south-central Oregon. Oecologia. 46: 239-243.

Golden, D.J. 1996. Economic ecosystem indicators in declining forest health. Anchorage, AK: U.S. Department of Agriculture, Forest Service, State and Private Forestry. 39 p.

Gray, D.R.; Holsten, E.H.; Pascuzzo, M. 1990. Effects of semiochemical baiting on the attractiveness of felled and unfilled lethal trap trees for spruce beetle, *Dendroctonus rufipennis* (Kirby) (Coleoptera: Scolytidae), management in areas of high and low beetle populations. Canadian Entomologist. 122: 373-379.

Haeussler, S.D.; Mather, J.; Coates, S.D. 1990. Autecology of common plants in British Columbia: a literature review. FRDA Rep. 158. Victoria, BC: British Columbia Ministry of Forests. 272 p.

Handel, C.M., comp. 1997. South coastal Alaska regional conservation priorities for landbirds. In: Proceedings, south coastal Alaska bioregional working group, boreal partners in flight annual meeting. Anchorage, AK: U.S. Geological Survey, Biological Resources Division, Alaska Science Center: 1-10.

Hard, J.S. 1985. Spruce beetles attack slow growing spruce. Forest Science. 31: 839-850.

Hard, J.S.; Holsten, E.H. 1985. Managing white and Lutz spruce stands in south-central Alaska for increased resistance to spruce beetle. Gen. Tech. Rep. PNW-GTR-188. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 14 p.

Hard, J.S.; Holsten, E.H. 1991. Spruce beetle attacks and surviving beetle brood in limbed and bucked spruce in south-central Alaska. Northwest Science. 65: 205-211.

Hard, J.S.; Werner, R.A.; Holsten, E.H. 1983. Susceptibility of white spruce to attack by spruce beetles during the early years of an outbreak in Alaska. Canadian Journal of Forest Research. 13: 678-684.

Hofacker, T.H.; Fowler, R.F.; Webster, K.; Riffe, M., tech. coords. 1993. Forest insect and disease conditions in the United States 1992. Washington, DC: U.S. Department of Agriculture, Forest Service. 147 p.

Holsten, E.H. 1984. Factors of susceptibility in spruce beetle attack on white spruce in Alaska. Journal of the Entomological Society of British Columbia. 81: 39-45.

Holsten, E.H. 1990. Spruce beetle activity in Alaska: 1920-1989. R10-90-18. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. 27 p.

Holsten, E.H. 1996. *Ips tridens*: A pest of managed stands? R10-TP-64. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. 8 p.

Holsten, E.H. 1997. *Ips tridens:* A pest of managed stands? 1997 update. R10-TP-71. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. 8 p.

Holsten, E.H. 1998. *Ips perturbatus*: A pest of managed stands? 1998 update. R10-TP-77. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. 11 p.

Holsten, E.H.; Thier, R.W.; Schmid, J.M. 1991. The spruce beetle. [Leaflet 127]. Washington, DC: U.S. Department of Agriculture, Forest Service, Alaska Region. 9 p.

Holsten, E.H.; Werner, R.A.; Develice, R.L. 1995. Effects of a spruce beetle (Coleoptera: Scolytidae) outbreak and fire on Lutz spruce in Alaska. Environmental Entomologist. 24: 1539-1547.

Holsten, E.H.; Werner, R.A.; Laurent, T.H. 1980. Insects and diseases of Alaskan forests. Rep. No. 75. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. 217 p.

Homer News. 1998. Our falling forest. Homer, AK. May 21.

Kenai Peninsula Borough. 1998. An action plan for rehabilitation in response to Alaska's spruce bark beetle infestation. Soldotna, AK: Kenai Peninsula Borough. 70 p.

Kline, L.N.; Schmitz, R.F.; Rudinsky, J.A.; Furniss, M.M. 1974. Repression of spruce beetle (Coleoptera) attraction by methylcyclohexenone in Idaho. Canadian Entomologist. 106: 485-491.

Koplin, J.R. 1969. The numerical response of woodpeckers to insect prey in a subalpine forest in Colorado. Condor. 71: 436-438.

Kostadinov, S.C.; Mitrovic, S.S. 1994. Effect of forest cover on the stream flow from small watersheds. Journal of Soil and Water Conservation. 49: 382-386.

Krasny, M.E.; Vogt, K.A.; Zasada, J.C. 1984. Root and shoot biomass and mycorrhizal development of white spruce seedlings naturally regenerating in interior Alaska flood plain communities. Canadian Journal of Forest Research. 14: 554-558.

Landhausser, S.M.; Stadt, K.J.; Lieffers, V.J. 1996. Screening for control of a forest weed: early competition between three replacement species and *Calamagrostis canadensis* or *Picea glauca.* Journal of Applied Ecology. 33: 1517-1526.

Langille, W.A. 1904. The proposed forest reserve on the Kenai Peninsula, Alaska, Oct.-Dec. 1904. Chugach file RG 95. [Place of publication unknown]: National Archives. 45 p.

Larsson, S.; Oren, R.; Waring, R.H.; Barrett, J.W. 1983. Attacks of mountain pine beetle as related to tree vigor of ponderosa pine. Forest Science. 29: 395-402.

Lieffers, V.J.; Macdonald, S.E.; Hogg, E.H. 1993. Ecology of and control strategies for *Calamagrostis canadensis* in boreal forest sites. Canadian Journal of Forest Research. 23: 2070-2077.

Lieffers, V.J.; Stadt, K.J. 1994. Growth of understory *Picea glauca, Calamagrostis canadensis,* and *Epilobium angustifolium* in relation to overstory light transmission. Canadian Journal of Forest Research. 24: 1193-1198.

Lieffers, V.J.; Stadt, K.J.; Navratil, S. 1996. Age structure and growth of understory white spruce under aspen. Canadian Journal of Forest Research. 26: 1002-1007.

Lindgren, B.S.; McGregor, M.D.; Oakes, R.D.; Meyer, H.E. 1989. Suppression of spruce beetle attacks by MCH released from bubble caps. Western Journal of Applied Forestry. 4: 49-52.

Love, L.D. 1955. The effect on stream flow of the killing of spruce and pine by the Engelmann spruce beetle. Transactions of the American Geophysics Union. 36: 113-118.

Maser, C.; Cline, S.P.; Cromack, K., Jr. [and others]. 1988. What we know about large trees that fall to the forest floor. In: Maser, C.; Tarrant, R.F.; Trappe, J.M.; Franklin, J.E.; tech, eds. From the forest to the sea: a story of fallen trees. Gen. Tech. Rep. PNW-GTR-229. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 25-45.

Matsuoka, S.M.; Handel, C.M.; Roby, D.D. 1997. Nesting ecology of Townsend's warblers in relation to habitat characteristics in a mature boreal forest. Condor. 99: 271-281.

McCullough, D.G.; Werner, R.A.; Neumann, D. 1998. Fire and insects in northern and boreal forest ecosystems of North America. Annual Review of Entomology. 43: 107-127.

McInnis, B.G.; Roberts, M.R. 1995. Seedling microenvironment in full-tree and tree-length logging slash. Canadian Journal of Forest Research. 25: 128-136.

Mielke, J.L. 1950. Rate of deterioration of beetle-killed Engelmann spruce. Journal of Forestry. 48: 882-888.

Miller, P.C. 1970. Age distributions of spruce and fir in beetle-killed forests on the White River Plateau Colorado. American Midland Naturalist. 83: 510-515.

Mitchell, M.E.; Love, L.D. 1973. An evaluation of a study on the effects on streamflow of the killing of spruce and pine by the Engelmann spruce beetle. Arizona Forestry Notes No. 9. Flagstaff, AZ: Northern Arizona School of Forestry. 20 p.

Mitchell, R.G.; Waring, R.H.; Pitman, G.B. 1983. Thinning lodgepole pine increases tree vigor and resistance to mountain pine beetle. Forest Science. 29: 204-211.

Mutch, R.W.; Arno, S.F.; Brown, J.K. [and others]. 1993. Forest health in the Blue Mountains: a management strategy for fire-adapted ecosystems. Gen. Tech. Rep. PNW-GTR-310. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 14 p. (Quigley, Thomas M., ed.; Forest health in the Blue Mountains: science perspective).

Newton, M.; Cole, E.C. 1997. Reforestation and vegetation in central Alaska. Spec. Rep. R10-TP-65. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. 80 p.

Nienstaedt, H.; Zasada, J.C. 1990. *Picea glauca* (Moench) Voss, white spruce. In: Burns, R.M.; Honkala, B.H., tech. coords. Silvics of North America, volume 1. Conifers. Agric. Handb. 654. Washington, DC: U.S. Department of Agriculture, Forest Service: 204-226.

Noste, N.V. 1969. Analysis and summary of forest fires in coastal Alaska. Juneau, AK: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Institute of Northern Forestry. 12 p.

Oliver, C.D.; Larson, B.C. 1996. Forest stand dynamics. Update edition. New York: John Wiley and Sons, Inc. 467 p.

Omi, P.N.; Kalabokidis, K.D. 1991. Fire damage on extensively vs. intensively managed forest stands within the North Fork Fire, 1988. Northwest Science. 65: 149-157.

Packee, E.C. 1990. White spruce regeneration on a blade-scarified Alaskan loess soil. Northern Journal of Applied Forestry. 7: 121-123.

Parry, D.L.; Filip, G.M.; Willits, S.A.; Parks, C.G. 1996. Lumber recovery and deterioration of beetle-killed Douglas-fir and grand fir in the Blue Mountains of eastern Oregon. Gen. Tech. Rep. PNW-GTR-376. Portland, OR: U.S. Department of Agriculture, Forest Service. 24 p.

Perry, D.A.; Amaranthus, M.P. 1997. Disturbance, recovery, and stability. In: Kohm, K.A.; Franklin, J.F., eds. Creating a forestry for the 21st century: the science of ecosystem management. Washington, DC: Island Press: 31-56.

Pickett, S.T.A.; White, P.S. 1985a The ecology of natural disturbance and patch dynamics. San Diego, CA: Academic Press, Inc. 472 p.

Pickett, S.T.A.; White, P.S. 1985b. Patch dynamics: a synthesis. In: Pickett, S.T.A.; White, P.S., eds. The ecology of natural disturbance and patch dynamics. San Diego, CA: Academic Press: 371-384.

Potts, D.F. 1984. Hydrologic impacts of a large-scale mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemic. Water Resource Bulletin. 20: 373-377.

Reynolds, K.M.; Holsten, E.H. 1994a. Classification of spruce beetle hazard in Lutz spruce (*Picea Xlutzii*) stands on the Kenai Peninsula, Alaska. Canadian Journal of Forest Research. 24: 1015-1021.

Reynolds, K.M.; Holsten, E.H. 1994b. Relative importance of risk factors for spruce beetle outbreaks. Canadian Journal of Forest Research. 24: 2089-2095.

Reynolds, K.M.; Holsten, E.H. 1996. Classification of spruce beetle hazard in Lutz and Sitka spruce stands on the Kenai Peninsula, Alaska. Forest Ecology and Management. 84: 251-262.

Reynolds, K.M.; Holsten, E.H. 1997. SBexpert users guide (version 2.0): a knowledge-based decision-support system for spruce beetle management. Gen. Tech. Rep. PNW-GTR-401. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 62 p.

Reynolds, K.M.; Saunders, M.; Miller, B. [and others]. 1997. Knowledge-based decision support in environmental assessment. In: Proceedings, ACSM/ASPRS annual convention and exposition. Seattle, WA: American Society for Photogrammetry and Resource Sensing, Resource Technology Institute Tech. Pap. 4: 344-352.

Rivard, P.G.; Woodard, P.M.; Rothwell, R.L. 1990. The effect of water table depth on white spruce (*Picea glauca*) seedling growth in association with the marsh reed grass (*Calamagrostis canadensis*) on wet mineral soil. Canadian Journal of Forest Research. 20: 1553-1558.

Ross., D.W.; Daterman, G.E. 1995. Efficacy of an antiaggregation pheromone for reducing Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins (Coleoptera: Scolytidae), infestation in high risk stands. Canadian Entomologist. 127: 805-811.

Runkle, J.R. 1985. Disturbance regimes in temperate forests. In: Pickett, S.T.A.; White, P.S., eds. The ecology of natural disturbance and patch dynamics. San Diego, CA: Academic Press: 17-33.

Safranyik, L. 1988. The population biology of the spruce beetle in western Canada and implications for management. In: Payne, T.L.; Saarenma, H., eds. Integrated control of scolytid bark beetles: Proceedings, IUFRO working party, integrated control of scolytid bark beetles. Blacksburg, VA: College of Agriculture and Life Sciences, Virginia Polytechnic Institute and State University: 3-23.

Schmid, J.M. 1981. Spruce beetles in blowdown. Res. Note RM-411. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 5 p.

Schmid, J.M.; Frye, R.H. 1977. Spruce beetles in the Rockies. Gen. Tech. Rep. RM-GTR-49. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 38 p.

Schmid, J.M.; Hinds, T.E. 1974. Development of spruce-fir stands following spruce beetle outbreaks. Res. Pap. RM-131. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 16 p.

Schmitz, R.F.; McGregor, M.D.; Amman, G.D.; Oakes, R.D. 1989. Effect of partial cutting treatments of lodgepole pine stands on the abundance and behavior of flying mountain pine beetles. Canadian Journal of Forest Research. 19: 566-574.

Schulz, B. 1995. Changes over time in fuel-loading associated with spruce beetle-impacted stands of the Kenai Peninsula, Alaska. Tech. Rep. R10-TP-53. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. 17 p.

Schulz, B. 1996. Response of residual spruce in beetle-impacted stands in Resurrection Creek drainage, Kenai Peninsula, Alaska. Tech. Rep. R10-TP-62. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. 21 p.

Schulz, B. 1997. Cooper Landing regeneration surveys–preliminary results. Spec. Rep. R10-TP-66. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. 32 p.

Scott, D.R.M. 1980. The Alaska region. In: Barrett, J.W, ed. Regional silviculture of the United States. New York: John Wiley and Sons. 551 p.

Scott, G.M.; Bormett, D.W.; Sutherland, N.R. [and others]. 1996. Pulpability of beetle-killed spruce. Res. Pap. FPL-RP-557. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 8 p.

Sedell, J.R.; Bisson, P.A.; Swanson, F.J.; Gregory, S.V. 1988. What we know about large trees that fall into streams and rivers. In: Maser, C., Tarrant, R.F.; Trappe, J.M.; Franklin, J.E.; tech, eds. From the forest to the sea: a story of fallen trees. Gen. Tech. Rep. PNW-GTR-229. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 47-81.

Sherwonit, W. 1998. Spray or pray? We Alaskans: H4-H10. Anchorage Daily News. July 12.

Sims, H.P.; Mueller-Dombois, D. 1968. Effect of grass competition and depth to water table on height growth of coniferous tree seedlings. Ecology. 49: 601-603.

Society of American Foresters. 1997. Action program to identify and restore key spruce ecosystems killed, infested, or threatened by the spruce bark beetle. Juneau, AK. 11 p.

Spurr, S.H.; Barnes, B.V. 1973. Forest ecology. 2nd ed. New York: John Wiley and Sons, Inc. 571 p.

Stocks, B.J. 1987. Fire potential in the spruce budworm-damaged forests of Ontario. Forest Chronicles. 63: 8-14.

Timoney, K.P.; Peterson, G. 1996. Failure of natural regeneration after clearcut logging in Wood Buffalo National Park, Canada. Forest Ecology and Management. 87: 89-105.

Triska, F.J.; Sedell, J.R.; Gregory, S.V. 1982. Coniferous forest streams. In: Edmonds, R.L., ed. Analysis of coniferous forest ecosystems in the Western United States. US/IPB synthesis series 14. Stroudsburg, PA: Hutchinson Ross Publishing: 292-332.

University of Alaska Anchorage. 1991. Managing beetle-killed spruce on the Kenai Peninsula. Research Summary No. 51. Anchorage, AK: Institute of Social and Economic Research, University of Alaska Anchorage. 2 p.

U.S. Department of Agriculture, Forest Service. 1996. Forest insect and disease conditions in the United States 1995. Washington, DC: U.S. Department of Agriculture, Forest Service. 76 p.

U.S. Department of Agriculture, Forest Service. 1997. Forest insect and disease conditions in the United States 1996. Washington, DC. 81 p.

Vanderlinden, L. 1996. Applying stand replacement prescribed fire in Alaska. In: Hardy, C.C.; Arno, A.F., eds. The use of fire in restoration. Gen. Tech. Rep. INT-GTR-341. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 78-80.

Veblen, T.T.; Hadley, K.S.; Reid, M.S.; Rebertus, A.J. 1991. The response of subalpine forests to spruce beetle outbreak in Colorado. Ecology. 72: 213-231.

Viereck, L.A.; Van Cleve, K.; Dyrness, C.T. 1986. Forest ecosystem distribution in the taiga environment. In: Van Cleve, K. [and others], eds. Forest ecosystems in the Alaskan taiga: a synthesis of structure and function. New York: Springer-Verlag: 22-43.

Wagner, R.G.; Zasada, J.C. 1991. Integrating plant autecology and silvicultural activities to prevent forest vegetation management problems. Forest Chronicles. 67: 506-513.

Werner, R.A. 1994. Research on the use of semiochemicals to manage spruce beetles in Alaska. In: Shea, P.J., tech. coord. Proceedings of the symposium on management of western bark beetles with pheromones: research and development. Gen. Tech. Rep. PSW-GTR-150. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 15-21.

Werner, R.A.; Elert, E.E.; Holsten, E.H. 1983. Evaluation of beetle-killed white spruce for pulp and paper. Canadian Journal of Forest Research. 13: 246-250.

Werner, R.A.; Holsten, E.H. 1995. Current status of research with the spruce beetle, *Dendroctonus ruffipennis.* In: Salom, S.M.; Hobson, K.R., tech. eds. Application of semiochemicals for management of bark beetle infestations: Proceedings of a conference. Gen. Tech. Rep. INT-GTR-318. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 23-29.

White, P.S.; Pickett, S.T.A. 1985. Natural disturbance and patch dynamics: an introduction. In: Pickett, S.T.A.; White, P.S., eds. The ecology of natural disturbance and patch dynamics. San Diego, CA: 3-13.

Wood, D.L. 1982. The role of pheromones, kairomones, and allomones in the host selection and colonization behavior of bark beetles. Annual Review of Entomology. 27: 411-446.

Yarie, J. 1981. Forest fire cycles and life tables–a case study from interior Alaska. Canadian Journal of Forest Research. 11: 554-562.

Youngblood, A.P. 1990. Effect of shelterwood removal methods on established regeneration in an Alaskan white spruce stand. Canadian Journal of Forest Research. 20: 1378-1381.

Youngblood, A.P.; Max, T.A. 1992. Dispersal of white spruce seed on Willow Island in interior Alaska. Res. Pap. PNW-RP-443. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 17 p.

Zasada, J.C. 1972. Guidelines for obtaining natural regeneration of white spruce in Alaska. [series and number]. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 16 p.

Zasada, J.C.; Sharik, T.L.; Nygren, M. 1992. The reproductive process in boreal forest trees. In: Shugart, H.H.; Leemans, R.; Bonan, G.B., eds. A systems analysis of the global boreal forest. Cambridge, MA: Cambridge University Press: 85-125.

This page has been left blank intentionally.
Document continues on next page.

This page has been left blank intentionally.
Document continues on next page.

Pacific Northwest Research Station

Web site	http://www.fs.fed.us/pnw
Telephone	(503) 808-2592
Publication requests	(503) 808-2138
FAX	(503) 808-2130
E-mail	desmith@fs.fed.us
Mailing address	Publications Distribution Pacific Northwest Research Station P.O. Box 3890 Portland, OR 97208-3890

U.S. Department of Agriculture
Pacific Northwest Research Station
333 S.W. First Avenue
P.O. Box 3890
Portland, OR 97208-3890