Invasive Forest Pathogens: Summary of Issues, Critical Needs, and Future Goals for Forest Service Research and Development

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Abstract

Invasive pathogens have caused immeasurable ecological and economic damage to forest ecosystems. Damage will undoubtedly increase over time due to increased introductions and evolution of invasive pathogens in concert with complex environmental disturbances, such as climate change. Forest Service Research and Development must fulfill critical roles and responsibilities to address issues related to invasive forest pathogens. This paper identifies critical, long-term research needs in four key areas: (1) prediction and prevention, (2) early detection and rapid response, (3) management and mitigation, and (4) restoration and rehabilitation. The paper also addresses issues related to national and international collaboration, scientific applications, and communication.

General Overview

In early 2007, diverse forestry professionals from the Forest Service and other institutions were surveyed to help determine the critical issues, needs, and top priorities of invasive pathogen research for Forest Service Research and Development (R&D). The consensus of the feedback received is reported in this section. Synthesized information is reported in more detail in the paper's subsequent sections.

The Issues

Ecosystem damage caused by invasive forest pathogens is often severe, long term, widespread, and difficult to mitigate. These pathogens affect ecosystems across forest landscapes and ownerships by reducing the viability of plant and animal species, decreasing forest productivity, and impairing carbon capture. Global climate change and increasing global trade and travel further escalate the threats from invasive forest pathogens. Continuing commitment and cooperation are critical to develop effective approaches for mitigating ecological, economic, and sociological effects and for managing healthy ecosystems that support human needs. Research to develop these approaches requires the integration of plant pathology with other multidisciplinary expertise, and frequently relies on long-term and/or multiscale studies. Success depends on maintaining and building public support and collaboration among State, Federal, and international forest health specialists and natural resource

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managers. The role of plant pathology research is to acquire new knowledge and to develop and test techniques useful to public agencies, especially the U.S. Department of Agriculture (USDA) Forest Service Forest Health Protection (FHP) program and Forest Service National Forest System (NFS); USDA Animal and Plant Health Inspection Service (APHIS); and other State, national, and international management or advocacy groups. In response to the threats from invasive forest pathogens, a number of critical research needs are identified and several priorities are selected that describe gaps in information, analysis, synthesis, research scope, collaboration, and capacity.

Critical Needs

- The capacity to recognize and identify species and variants of current and future invasive pathogens, hosts, microorganisms, and vectors through the use of classical and molecular taxonomy, fungal and plant systematics, and molecular diagnostic tools.
- Multidisciplinary studies that address and provide attainable solutions to complex forest health issues (e.g., interactions between climate change, atmospheric chemistry, forest fragmentation, land-use change, silviculture, and wildfire and/or insect disturbance on invasive pathogen behavior in the Nation's rural and urban forests).
- Knowledge of ecological and genetic responses to determine the following:
  - Biophysical factors involved in pathogen spread, potential transport pathways, and changes after establishment.
  - Mechanisms of defensive host response to pathogen challenge that are heritable, preformed, or environmentally inducible.
  - Host populations that respond similarly or are ecologically valuable for genetic conservation efforts.
  - Relationships and coevolution among organisms in their historical and geographical context using genomic and phenomic approaches.
  - Potential development of novel species, hybrids, and subspecies with new ecological behavior.
- New tools and methods to predict, detect, and monitor potentially invasive forest pathogens, either prior to introduction or soon after establishment, through integrated collaboration with Forest Service FHP, Forest Service NFS, USDA APHIS, and national and international collaborators.
- Understanding the interactions of current or altered biotic and abiotic factors on the establishment, spread, and effects of invasive pathogens over time and space.
- Assessment and actionable knowledge of invasive pathogen costs to society through integrated economic and social science research with universities and other partners; such information is necessary to prioritize intervention responses (threat analysis and mitigation).
- Biological control and alternative-management techniques.
- Techniques to manage and rehabilitate forest ecosystems affected by pathogen invasions, and management practices that foster resilience in forest ecosystems before they are affected by invasive pathogens.
- Precise baseline information on worldwide distributions of forest pathogens (using molecular diagnostics), distribution of host populations, climate and niche data, and other environmental data through integrated collaboration with the Forest Service Forest Inventory and Analysis (FIA) program, Forest Health Monitoring (FHM) program, FHP, and international collaborators.
- Databases, Web sites, and better coordinated information sharing among forest health professionals as well as effective information exchange and educational outreach to other stakeholders.

Top Five Priorities

1. **Obtain baseline information on worldwide geographic distributions and environmental responses of forest pathogens, strains, hosts, vectors, and associated microbes.** This baseline information is critical to all invasive species program areas worldwide. Systematics expertise, supporting biological collections, and diagnostic tools developed by Forest Service R&D and university partners should be maintained and increased to support survey work (e.g., by FHM, USDA APHIS, and international collaborators). International collaborations are essential to predict, prevent, and detect invasive species introductions to the United States and other countries worldwide. Integrating Geographic Information System-based ground surveys, spatial modeling, and remote sensing can assess and predict organism distribution and environmental influences. Databases of collected information and technologies must be widely accessible for multiple purposes.

2. **Conduct climate modeling, risk assessments, and pathway analyses for priority hosts and pathogens.** Spatial biophysical data must be integrated at the appropriate scales for risk assessment of potential pathogen invasions or evolution of novel invasive pathogens. When combined with evaluations of host susceptibility to invasive pathogens, these assessments are fundamental for predicting and preventing future invasive pathogens, prioritizing the management of established invasive forest pathogens, rehabilitating affected ecosystems, and enhancing ecological resilience.
3. **Determine interactions of invasive pathogens with other disturbances.** Climate change, altered fire regimes, increases in insect damage, forest fragmentation, urbanization, floods, wind, and other human-natural ecosystem interactions will likely exacerbate effects of forest pathogens. Many forest diseases will become more widespread and damaging in changing environments.
4. **Implement long-term, ecosystem-based research to determine appropriate, adaptive management to restore the function and structure of affected ecosystems, enhance endemic biological control agents, identify genetic-based disease resistance for breeding and regeneration programs, foster natural recovery, and improve the resiliency of ecosystems to unexpected future threats.** Short-term research can provide much-needed progress; however, invasive forest pathogens also present many long-term issues that can only be addressed through long-term research.
5. **Build capacity for plant pathology research and associated collaborative efforts for responding to increasing effects of invasive forest pathogens.** The scope and complexity of the identified priority research present a serious challenge to Forest Service R&D within its present internal capacity and ability to leverage collaboration. Although such research requires collaborative, multidisciplinary effort, plant pathologists provide subject expertise and methods of study that are a core need for investigations of invasive forest pathogens.

Introduction

Invasive fungal pathogens have caused large-scale ecological and economic damage to forests in the United States (Lovett et al. 2006). Damage caused by these pathogens has been more severe, long term, widespread, and difficult to mitigate than that caused by any other biological disturbance agent. In the last century, pathogens introduced into our native forests have threatened the extinction of native tree species and critically degraded many diverse ecosystems across North America. Prominent forest diseases caused by invasive pathogens include chestnut blight (Anagnostakis 1987), Dutch elm disease (Brasier and Buck 2001), white pine blister rust (Geils et al. 2010), butternut canker (Furnier et al. 1999), dogwood anthracnose (Daughtrey et al. 1996), laurel wilt (Fraedrich et al. 2008), sudden oak death (Rizzo et al. 2005), pitch canker (Gordon et al. 2001), and Scleroderris canker (Hamelin et al. 1998). Ecological effects of invasive pathogens extend well beyond the affected trees (e.g., white pines, chestnut, elms, dogwood, butternut, oaks, and pines) to include other ecosystem components, such as dependent forest flora and fauna. Forest trees include keystone species providing food and structure for animal species (e.g., grizzly bears, small mammals, birds, etc.) and other plants. Invasive pathogens have severely diminished the productivity, sustainability, and ecosystem service functions of many forests. Damage from pathogens can also alter forest succession and forest species composition.

Invasive forest pathogens can originate from intercontinental or intracontinental movement, range expansion due to climate change, the creation of novel pathogens via evolution or hybridization, or other means (Palm 2001). The likelihood for invasive pathogen introduction will increase, however, as international trade and travel increase. The potential for invasive pathogen establishment and spread will also increase as newly introduced pathogens interact with changing climate, native insect pests and pathogens, wildfire, forest fragmentation, and other natural or human-induced disturbances. Equally challenging are threats from native invasive pathogens (Otrosina 2005). Changing climate, forest management, disturbance regimes, and increased potential for genetic hybridization among existing (and introduced) pathogen populations can initiate or exacerbate disease problems.

Forest Service Research Roles and Responses to Invasive Forest Pathogens

Throughout its history, the Forest Service has played a prominent role in responding to invasive forest pathogens. The following information briefly reviews the roles and responsibilities of the Forest Service R&D deputy area, as determined by congressional mandate, Executive order, institutional directives, and traditional practices.

Background Information

The R&D deputy area of the Forest Service has been mandated by Congress and by Executive order to conduct and facilitate research on invasive forest pathogens, to translate research results into actionable knowledge, and to communicate research results for application in management. In the United States, the Forest Service has a principal responsibility and capability to develop the necessary knowledge and tools for addressing invasive forest pathogen issues across State and regional boundaries. Furthermore, it builds and facilitates multidisciplinary, collaborative efforts among diverse research institutions and stakeholders to address national and international issues of invasive pathogens. It uses its unique and important leadership role to acquire information for the public interest and coordinate research programs to protect or enhance public and private natural resources in rural and urban settings. Because invasive pathogens invariably represent long-term issues, the Forest Service R&D has maintained primary responsibility of long-term research studies (e.g., permanent plots, experimental forests, biological collections, host genetics materials, and data archives) to address long-term issues associated with invasive pathogens. In addition, Forest Service R&D implements its mandated charter to conduct research and study national and international issues of invasive forest pathogens as they relate to the United States, to provide knowledge needed for protecting forests and other terrestrial ecosystems of the Nation.

Key Research Needs for Addressing Invasive Forest Pathogens

Several research needs must be addressed to maintain and enhance the Forest Service's capacity for effective response to invasive forest pathogens.

A strong systematics capability is essential to identify biotic components of disease caused by invasive pathogens. This capability is essential to obtain baseline data on the distribution of invasive pathogens. Specific examples of the needs for systematics capabilities include the following:

- Classical and molecular taxonomic expertise for the identification of invasive pathogens, hosts, associated microorganisms, and vectors.
- Phylogenetics expertise for elucidating evolutionary relationships within hosts, pathogens, and associated microbes (e.g., potential biocontrol agents).
- Advanced molecular characterization and molecular diagnostic tools for diagnostics and monitoring activities.
- Maintenance and expansion of fundamental systematics resources, such as herbaria, survey and collection records, culture collections, and DNA sequence databases.

Knowledge of ecological behavior and impacts of invasive pathogens worldwide is essential for assessing and predicting pathogen threats for specific regions. This information is needed to develop effective mitigation and rehabilitation programs. Research activities that address this need include the following:

- Integrate biological and ecological information of genetically based species groups at appropriate ecogeographic scales.
- Determine genetic and coevolutionary relationships of host-pathogen population structure and dynamics.
- Apply systematics and molecular diagnostic techniques to ensure accurate pathogen identification for integration with ecological data.
- Elucidate pathogen life cycle (e.g., growth, reproduction, survival, host infection, and spread) and epidemiology.
- Evaluate pathogen response and adaptation to hosts, host resistance factors, and environmental factors (e.g., temperature, moisture, soil properties, etc.).
- Refine remote sensing, validated by "ground truthing," to develop precise models of critical environmental factors at landscape, regional, and global scales.
- Delineate hosts and pathogen populations that behave similarly.
- Determine interrelationships of biological behavior with abiotic and biotic environments.
- Develop methods to prioritize resource allocations for managing specific pathogens.

- Provide scientific input to discussions and decisions concerning treatment measures.
- Provide science information and data for policymakers on quarantine and regulatory issues.

Impact assessment and valuation technologies are crucial for successful prioritization and management of invasive pathogens. Focused research objectives that will improve these technologies include the following:

- Understand the ecological, economic, and societal impacts of invasive pathogens.
- Increase the reliability of spatial models for projecting impacts at landscape, regional, and global scales.
- Refine procedures for cost-benefit analysis for management and remediation efforts.

Various forest disturbances exacerbate or significantly interact with invasive forest pathogens. Knowledge of these interactions is needed to strategically manage invasive pathogens. Research objectives to address this need include the following:

- Understand the influences of changes in climate, vegetation, and disturbance regimes (e.g., fire, insect outbreaks, endemic pathogens, forest fragmentation, urbanization, logging, flooding, wind, etc.) to predict distribution, ecological behavior, and effects of invasive pathogens.
- Integrate climate change models with information on the distributions of hosts and pathogens to assess their potential niches and migrational pathways.
- Understand declines and other complex diseases caused by interactions of multiple disturbances, insects, diseases, stress agents, etc., that will likely increase in changing environments at a landscape level.

Many invasive forest pathogen issues require adaptive approaches for effective management. Research outputs that address this need include the following:

- Methods that monitor and assess ecosystem function in areas affected by invasive pathogens.
- Approaches that foster resilience in forest ecosystems to minimize the impacts of future invasive pathogens.
- Techniques that enhance activities of endemic biological control agents and other natural processes to reduce the effects of invasive pathogens.
- Approaches to foster the adaptive capacity of ecosystems for recovery and renewal.

Knowledge of endemic forest pathogens and their hosts is requisite for sound assessment of threats posed by invasive pathogens. Research activities that address this need include the following:

- Coordinate with cooperators to determine baseline information on the distributions of pathogens and strains, hosts, vectors, and associated microbes, their current environments, and likely responses to changing environments; integrate these findings with FIA, FHM, the National Plant Diagnostic Network, and other continuous monitoring data.
- Develop methods that provide reliable taxonomic identification, such as molecular diagnostic methods, for application in surveys of forest pathogen distributions in the United States and other countries. These methods will allow precise documentation of potentially invasive pathogens (with the cooperation of APHIS, FHM, and international organizations).
- Develop and apply genetic and ecophysiological methods to determine the geographic distributions of host, pathogen, and microbe populations, races, and/or hybrids that display distinct ecological behavior and identify ecologically valuable host populations for conservation.
- Conduct phylogenetic and phylogeographic assessments of evolutionary and genetic relationships among hosts and pathogens worldwide.

Extensive collaborations among Forest Service deputy areas and other Federal, regional, tribal, and State governments are essential for managing invasive pathogens across large landscapes. Research input and collaboration are needed to accomplish the following:

- Implement regulations, monitoring, education, and treatments for invasive pathogens.
- Incorporate DNA-based diagnostics into strategies for the detection and monitoring of forest pathogens at ports of entry, at points of distribution, and across forest landscapes.
- Implement regional invasive species plans and coordinate these activities among agencies (e.g., via the emerging Regional Invasive Species Issue Teams).

- Establish databases and other tools to consolidate distribution data and facilitate information sharing among the natural resources research and management communities.

Available and accessible information and data on invasive pathogens are important in the development and implementation of invasive species management projects or programs. Research activities are needed to accomplish the following:

- Provide current Web sites and synthesis papers that communicate key principles and new findings to stakeholders.
- Integrate local, regional, national, and international databases that characterize forest hosts, pathogens, and associated microbes with ecological information, such as geographic distribution, climate data, digital imaging, etc., for developing predictive models and technology transfer.
- Improve the effectiveness of information delivery to those affected by invasive pathogens and develop processes to integrate communities into monitoring and research processes.
- Integrate plant pathology R&D results into invasive pathogen management activities led by FHP, FHM, NFS, States, and other national and international organizations.

Long-term research must be continued to develop management strategies for established invasive pathogens in long-lived forests, where reproductive maturity and ecological succession occur over long time periods. Research activities and research capacity are needed to accomplish the following:

- Improve the monitoring of long-term remediation effects in forest ecosystems affected by invasive pathogens.
- Apply Forest Service R&D research expertise in plant pathology, genetics, and associated disciplines to address vast expanses of forests within the United States that are not recovering from the effects of invasive plant pathogens.
- Maintain the historical role of Forest Service R&D as the primary entity responsible for conducting long-term research, maintaining data records and biological materials from established permanent field plots and supervising a network of experimental forests in the United States.

The Future of Research on Invasive Forest Pathogens

Threats posed by invasive forest pathogens are predicted to continually increase in the future due to increased human-mediated movement of pathogens and climate change. Forest Service R&D must be well positioned and well prepared to address these increased threats. Successful research programs will likely be multidisciplinary and incorporate new technologies. These programs can be directed toward five focus areas, which are discussed under five subsequent headings; the first four areas are derived from program elements of the national strategy (USDA Forest Service 2004): (1) Prediction and Prevention, (2) Early Detection and Rapid Response, (3) Management and Mitigation, (4) Restoration and Rehabilitation, and (5) Scientific Application and Communication. The following sections provide additional information on the future of research on invasive forest pathogens, based on the five focus areas.

Prediction and Prevention

Prediction and prevention is the most effective and economical strategy for managing invasive forest pathogens (Parker and Gilbert 2004). Furthermore, the value of improved methods for preventing and predicting invasive forest pathogens will increase in the future. Phylogenetic, phylogeographic, and population genetic analyses of forest hosts and pathogens on a global basis provide a novel approach for improving predictions of potentially invasive pathogens (Gilbert and Webb 2007). Such analyses determine genetic relatedness among taxa of hosts and pathogens to predict potential hosts of invasive pathogens and predict potentially invasive pathogens before they are introduced. In addition, the genetic relationships among pathogens can allow predictions of potential risks associated with the introduction of closely related species or hybridization and introgression with related endemic species (Brasier 2001, Garbelotto et al. 2004).

Climate modeling, georeferencing the distribution ranges of species across regions and landscapes, and risk analysis can be combined with genetic analyses to identify areas where invasive species may originate and areas at risk for successful establishment, invasion, and/or hybridization of invasive pathogens (Venette and Cohen 2006). Such integrated analyses can also determine the effects of climate change on the ecological behavior of invasive pathogens, and prioritize target areas for

monitoring, in conjunction with risk analysis of commodity shipments from potential sources of invasive pathogens. A well-established, worldwide database, networking among involved parties (e.g., scientists, forest managers, policymakers, etc.), international collaborative research, and worldwide surveys will provide a critical basis and research infrastructure for predicting potentially invasive forest pathogens for the United States and other countries. Close cooperation with Canada and Mexico would be especially useful. Effective predictions of potentially invasive pathogens are essential to improve the efficiency of early monitoring to detect invasive pathogens for specific regions.

The development of regulations to prevent the entry and establishment of new pathogens is trending away from species-specific analyses and toward pathway approaches (Baker et al. 2005). By international consensus, these approaches still require the identification of known pests that can move in the pathway or commodity and designing mitigations to reduce the risk of specific pathogen introductions. However, broad-specturm mitigation measures will also help prevent unknown pests that could be introduced via the identified pathways. Research is needed to identify potentially invasive pathogens and potential introduction pathways so that effective mitigation measures can be developed before they arrive. These research efforts should be conducted in collaboration with other national (e.g., APHIS, Agricultural Research Service) and international agencies that focus on high-risk, high-volume trade commodities, such as live plants, wood products and novelty items, forest seed, wood chips, and peeler cores (USDA Forest Service 2004).

Early Detection and Rapid Response

Based on past experience, improved monitoring is likely the primary activity for realistic, first detection of cryptic, invasive pathogens (Chornesky et al. 2005). Such pathogens are generally detected only after disease foci are identified in the landscape through regular monitoring efforts. Invasive forest pathogens may be eradicated or contained to a local area if detected and eradicated before widespread dispersal has occurred. For example, efforts to contain *Phytophthora ramorum* appear to have reduced its spread in Curry County, OR; however, it is yet to be determined if these efforts will remain effective over the long term (Frankel 2008). During the 20th century, significant forest pathogens remained unrecognized, misdiagnosed, or cryptic until they caused widespread damage (e.g., oak wilt, sudden oak death, and butternut canker). In addition, invasive pathogens can arise by genetic change, evolution, or hybridization, such as what occurred in Europe with alder decline (Brasier 2001, Brasier et al. 2004).

Improved methods and tools to detect invasive forest pathogens and monitor eradication are growing needs (Chornesky et al. 2005). Emerging technologies will foster the integration of genetic and evolutionary relationships with environmental factors and thereby allow for the advanced assessment of newly discovered species. The integration of remotely sensed data, geographical information systems, soils and landform maps, climate matching software, appropriate statistical sampling models, etc., will better define target areas for detection and monitoring surveys (risk maps, e.g., Frank et al. 2008). Collaboration among detection, monitoring, survey, and inventory efforts in urban and community forests will more readily detect nonnative pathogens that may have been introduced by humans (e.g., via planting of infected nursery stock). In addition, information from controlled laboratory studies can also help confirm the potential for interspecific or intraspecific hybridization of forest pathogens and determine environmental tolerances of invasive pathogens.

DNA-based diagnostics are needed to recognize pathogen species, races, and hybrids (Crous 2005). Races or strains of pathogenic microorganisms are often not distinguishable by classical morphological and biochemical methods. In addition, traditional diagnosis of pathogens requires time-consuming host inoculation trials. Furthermore, exotic and endemic organisms can be morphologically indistinguishable but differ greatly in their ability to cause disease; even within a species, strains can behave very differently. In addition, some recent invasive forest pathogens have been shown to be hybrid species—such as the causal agents of Dutch elm disease (*Ophiostoma novo-ulmi*; Et-Touil et al. 1999), bark disease of alder (*Phytophthora alni*; Brasier et al. 2004), leaf rust of hybrid poplar (*Melampsora ×columbiana*; Newcombe et al. 2000), and a new variant of blister rust (*Cronartium ribicola* × *C. comandrae*; Joly et al. 2006). Representative isolates of pathogens must be archived for future study if future DNA-based technology is to be widely applicable for managing invasive forest pathogens.

Nationwide and worldwide databases are needed to compile information about potential invasions of nonnative forest pathogens (Crous 2005). Compiled and archived data on geographic distributions of existing pathogens, along with accompanying

host and environmental information, are needed. ExFor (http://spfnic.fs.fed.us/exfor/index.cfm) is one example of an existing database that could be expanded to include molecular diagnostics and precise geographic locations of forest pathogens worldwide. Analysis of data from systems tracking the movement of plants (e.g., by nurseries, plant hunters and traders, etc.) will provide greater insight and predictive ability about potential introductions. For example, nursery management records, such as importation of exotic plants, location and proximity of species within nurseries, and nursery cultural practices, would be valuable in predicting potential pathogen introduction and establishment. Forest Service R&D can coordinate with APHIS and FHM to develop molecular diagnostic tools (e.g., real-time polymerase chain reaction, microarrays, etc.) to quickly detect known and potentially invasive forest pathogens in surveys of international plant shipments, ornamental and forest nurseries, and urban and periurban forests (Chornesky et al. 2005). Alternative methods of plant material movement should be developed and/or considered. For example, tissue-culture-derived plantlets and certified seed or other propagules should be developed for plants that pose high risk for moving invasive pathogens.

Management and Mitigation

Despite prediction and prevention efforts, invasive forest pathogens often escape and remain undetected until they are well established and causing noticeable damage. Thus, methods to manage invasive pathogens and mitigate their effects are needed. Ideally, management methods should foster naturalization processes that render pathogens less aggressive, hosts more resistant, and biological control agents more active over time. Other management methods are needed to enhance resiliency in forest ecosystems so that they are less affected by unforeseen threats.

Tools to manage and mitigate diseases caused by invasive pathogens must be based on sound scientific knowledge of two general processes: (1) pathogen biology, dispersal, and conditions for infection and population increase and (2) genetic and evolutionary mechanisms that control pathogenicity and aggressiveness on different hosts and in different environments. Remotely sensed imagery can be incorporated to identify distribution, effects, and spatial dynamics of invasive pathogens.

Interactions among climate, forest species compositions, fire and fuels treatments, coexisting pests, vectors, biological control agents, and other components of a vulnerable ecosystem must be understood to determine potential establishment, reproduction, and spread of invasive pathogens (Baker and Cook 1974, Broadbent and Baker 1974, Weste and Marks 1987). Such knowledge will also aid the development of biological control and other management approaches that foster ecosystem recovery and pathogen naturalization processes.

The incorporation of environmental factors (e.g., temperature, moisture, topography, soil properties, etc.) and genetic and biological information in a spatially relational context represents the most powerful approach to understanding the ecological behavior of invasive pathogens. Integrated, multidisciplinary approaches that foster an understanding of the basic biology of each pathosystem and the interacting influences of environmental factors across spatial scales are requisite to any invasive species program. Such integrated information is used to develop stand, landscape, and regional models to aid management decisions and effectively target management efforts for maximum economic or ecological results (Chornesky et al. 2005). These approaches also will contribute to cost-benefit analyses for control actions and prioritization of areas for disease suppression activities.

Forest Service R&D has primary responsibility for long-term research studies, including maintenance of permanent plots, management of experimental forests, preservation of data archives, and maintenance of biological collections (e.g., fungal cultures, herbarium specimens, seed collections, etc.), which are critical to addressing long-term issues associated with invasive pathogens. R&D involvement in long-term invasive species management programs is needed to select and breed for pathogen-resistant trees; develop biological, chemical, and mechanical treatments to manage disease; determine interactions with fire and other disturbances; and facilitate the regeneration and recovery of ecosystems affected by invasive pathogens. Long-term research is needed to develop effective treatments and strategies in an adaptive management context. Far-sighted and diverse approaches are needed to understand and mitigate effects of invasive pathogens on diverse aspects of forest and rangeland ecosystems. Because of potential large-scale, extreme disturbances, such as drought, insect outbreak, fire, and invasive pathogens, the future regenerated forests may differ from the previous forest and may comprise multiple alternative states. The desired outcome of managing vulnerable

or invaded ecosystems is adaptation or change that tolerates the disturbance but retains essential ecological functions and character. Thus, long-term research is essential to address these long-term issues posed by invasive pathogens.

Restoration and Rehabilitation

Unfortunately, numerous examples have occurred where invasive forest pathogens became established, proliferated, and caused widespread damage to forest ecosystems across regions of the United States and elsewhere. In most of these cases, research efforts were abandoned or severely curtailed before affected ecosystems were on track toward recovery (Tainter 2003). Similar to many medical and environmental issues, many invasive forest pathogens cause long-term damage to forest ecosystems that can only be effectively addressed through long-term restoration efforts supported with research and monitoring. Prioritization is needed to determine which damaged ecosystems justify the expenditure of funds for restoration and rehabilitation.

Because distinct pathogen populations respond differently to environmental influences, it is important to consider host and pathogen population structures when assessing threats posed by invasive pathogens before implementing restoration strategies (Burdon et al. 2006). Basic information needs for mitigating invasive pathogen effects include identification of sources of host resistance (e.g., through screening and selection programs); understanding of resistance mechanisms; increasing host resistance through breeding or regeneration programs; the development of rational deployment strategies for resistant plant materials; and identification of threatened, ecologically valuable host populations for conservation. Landscape-level, ecosystem-based research is also needed to develop techniques for restoring ecosystem function and structure, enhancing natural biological controls, fostering natural recovery and stabilization, and improving the resiliency of ecosystems to unexpected future threats (Drever et al. 2006).

Scientific Application and Communication

The primary clients for new information and tools for managing invasive pathogens include natural resource managers, regulatory officials, policymakers, tribal governments, private industry entities, nongovernmental organizations, research scientists, educators, and the public at large (USDA Forest Service 2007). Thus, current and future issues regarding invasive forest pathogens require effective communication through diverse venues (e.g., Web-based tools, workshops, online training, scientific/technical publications, etc.). It is essential that research is directed toward obtaining actionable knowledge regarding invasive pathogen management, and research scientists should be active participants in the communication processes that make research results available and applicable to the clients. Participation in international working groups, such as the International Union of Forest Research Organizations Working Party 7.03.12 (alien invasive species and international trade), is also essential for building international collaborations and exchanging information about invasive forest pathogens.

Critical information regarding pathogen genetic identification, biology, hosts, geographic and ecological distribution (e.g., climate data, slope, aspect, habitat type, soil properties, and other environmental factors), available research literature, etc., should be readily accessible from online databases. Other Internet technology is needed to address specific invasive pathogen issues and connect professionals with different areas of expertise. To maintain quality, ensure accountability, and promote the appropriate use of information and models, the communication process needs to include standard features of the scientific process, such as replication and review. The hypertext capability of digital media should be used to augment information with metadata on sources and other supplemental or supporting documents. Given that uncertainty and complexity are inherent, it is imperative that research maintains credibility and science is responsibly applied.

Raising public awareness of invasive forest pathogen issues is also critical. Social science research is needed to develop effective methods that encourage the adoption of practices across ownerships. Within landscapes, this research is needed to avoid the spread of invasive pathogens and gain an understanding and acceptance of management practices that may be considered as an interference to the public's daily life. The Forest Service also must strive to develop more diverse program delivery methods (e.g., social networking Web sites, podcasts, streaming video, cell phone-mediated information retrieval, television, radio, magazines, partnering with commercial franchise marketing, multilingual communication, etc.) and other integrated tools developed for diverse audiences.

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