Invasive Species and Disturbances: Current and Future Roles of Forest Service Research and Development

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Abstract

The success of an invasive species is in large part due to favorable conditions resulting from the complex interactions among natural and anthropogenic factors such as native and nonnative pests, fires, droughts, hurricanes, wind storms, ice storms, climate warming, management practices, human travel, and trade. Reducing the negative effects of invasive species and other disturbances on our natural resources is a major priority. Meeting this goal will require an understanding of the complex interactions among disturbances, development of tools to minimize new invasions, and effective management of systems that have already been changed by invasive species.

In this paper, we suggest desired resource outcomes; we offer considerations for developing management strategies, policies, and practices needed to achieve these outcomes; and we note potential interactions of invasive species with other disturbances. We then identify invasive species-related research and development actions needed to achieve the desired outcomes. Interacting factors that influence desired outcomes include weather conditions, fire, pests, land use decisions, transportation, human health, human travel, and potential deployment of genetically engineered plants and animals. Disturbance and its interactions with invasive species can have ecological, social, and/or economic effects.

Forest Service Research and Development (R&D) priorities should focus on developing strategies, guidelines, and tools for mitigating invasive species and managing affected systems, as follows:

- Modeling the introduction and spread of invasive species to help proactively predict and prevent the introduction and establishment of an invasive species (also see prevention paper).
- Decision support, detection and monitoring tools and strategies for predicting, preventing, detecting, and responding to newly arrived invasive threats (also see prevention paper).
- Risk-cost-benefit analysis methodology to help determine the most effective management options.
- Strategies, systems, and practices for managing changed ecosystems to continue to deliver needed goods, services, and values.
- Tools that enable functional restoration of economically and/or ecologically critical systems.
- Strategies and guidelines to prevent, detect, monitor, and manage invasive species after major disturbances.
- Guidelines for economic, environmental, and social analysis.

Resources needed to accomplish the foregoing outcomes include the following:

1. Modelers skilled in multiobjective stand dynamics and forest management modeling.
2. Integrative specialists whose expertise incorporates ecological, social, and economic effects.

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3. Functional specialists who provide data relating to basic processes and responses for use by integrative specialists and modelers.
4. Communication specialists skilled in print, Web, and novel technology transfer processes to provide support to functional and integrative specialists.

Introduction

The Forest Service and numerous other Federal, State, local, and private organizations recognize invasive species as a significant environmental and economic threat to the Nation's forests and rangelands. Interactions among invasive species and other environmental and anthropogenic disturbance regimes can exacerbate this threat (USDA Forest Service 2003). Actions taken to prevent, manage, and mitigate the adverse effects of invasive species and other threats depend on understanding the synergism among these disturbances and the potential effects of both disturbances and proposed mitigations on resources and on people's lives.

In this paper we suggest desired resource outcomes; considerations in developing management strategies, systems, policies, and practices needed to achieve these outcomes; and potential interactions of invasive species with other disturbances. We then identify invasive species-related research and development actions needed to achieve these outcomes. In the broad sense, our desired resource outcome is that forest and range ecosystems are healthy and productive and provide a sustainable supply of services, products, and experiences that enhance the quality of life for present and future generations.

To meet this goal, we must consider the range and quantity of goods, services, and values that we will require our forests and rangelands to produce in the coming decades. Figures 1 and 2 show estimates of world and U.S. populations from 1950 through 2050. As populations and world economies continue to increase, so will the societal demands on our natural resources. We will rely on these lands to produce water, wood and non-wood products, recreational opportunities, biological diversity, and energy, all while playing a crucial role in climate change mitigation.

Although invasive species can have direct effects on many of these goods and services, it is important to recognize that these effects can also be greatly influenced by interactions with fire, weather and climate patterns, land use changes, and other disturbances. The influence of invasive species on critical natural resources may be increased or decreased in the context of other disturbances.

Future management, policy, and societal needs for research related to managing forests and rangelands under the influence of invasive species can largely be met through quantifying and projecting system behavior and value under different scenarios. At varying time and space scales, these needs include probabilistic projections of the magnitude and direction of change; likely outcomes without intervention; options for management actions, including their costs; and systems and practices for accomplishing these actions. Critical research deliverables include methods and tools for cost-benefit-risk

Figure 1.—*World population and estimates, 1950–2050* (*United Nations 2007*).

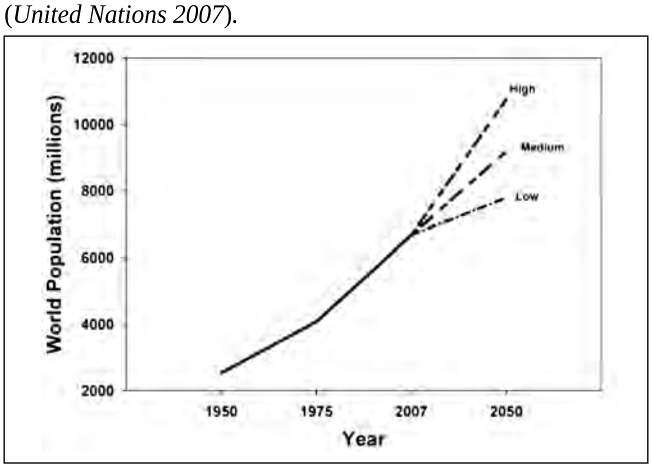
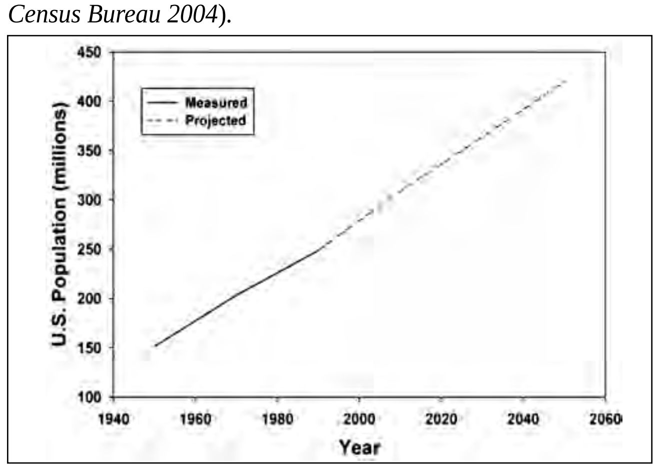


Figure 2.—*U.S. population and estimates, 1950–2050* (*U.S. Census Bureau 2004*).



analysis for invasive species management options; collection of the basic data needed to populate, parameterize, and develop these models; strategies, systems, and practices for managing changed systems to continue to deliver needed goods, services, and values; and the ability to articulate what changed systems can and cannot deliver in probabilistic terms.

Forest and Rangeland Disturbances

A diverse group of natural environmental disturbances has the potential to alter our Nation's forests and rangelands, including native pests, drought, fire, hurricanes, tornadoes, and ice storms. Also a number of anthropogenic disturbances can potentially affect natural resources; these disturbances include nonnative invasive species, international and regional trade, transportation, development, and fragmentation. These disturbances can occur individually but often come in combination, and interactions among these inherent and anthropogenic disturbances are not well understood. Despite our lack of understanding, we know these disturbances (and their interactions) can disrupt ecosystem functions, social benefits, and economies. The resulting effects can be severe and may cause significant lasting ecological and socioeconomic effects. Thus, understanding the effects of individual invasive species and their interactions with multiple factors will enable development of effective approaches for sustaining and enhancing ecosystem functions and resource benefits. Land managers and owners need effective strategies, tools, guidelines, and practices to anticipate disturbances, act to prevent or lessen their effects, and restore the function and productivity of affected ecosystems.

Forest Service R&D has unique opportunities and responsibilities relative to invasive species (USDA Forest Service 2008). The Forest Service is the only Federal agency that maintains a strong research focus on forest pests. Although future trends are not certain, there is consensus that a small fraction of nonnative invasive species will interact with other anthropogenic and natural disturbances to disrupt existing ecosystem functions and adversely affect the goods, services, and values expected from these systems. Also, there is consensus that another small fraction may interact to provide benefits to humankind. Managing these invasive species appropriately will pose an enormous challenge considering our limited understanding of their potential interactions with our wildland ecosystems and with other disturbances. Such understanding is critical to sustainable management of the Nation's natural resources. Our challenge over the next 50 years is to enhance our ability to predict and monitor these phenomena sufficiently to develop effective strategies to productively manage systems increasingly affected by invasive species and to recognize and capitalize on any benefits. The situation is urgent because population increases, human movement, global trade, and climate change will continue to drive changes in the world's biota—increasing the number and complexity of invasive species and disturbance interactions.

Key Disturbances

Our future success in both preventing introduction and establishment and managing spread of invasive species depends on our understanding of the interactions of diverse environments and disturbances as they impact invasive species ecology, and on our ability to manage ecosystems to minimize adverse outcomes. Key disturbances that can impact invasive species success include: severe or changing weather and climate conditions; fire regimes and their management; insect pests and diseases; land use and land cover changes; trade and transportation within and across regions; human health and travel; management practices designed to mitigate disturbance effects; and genetically engineered plants and animals. These types of disturbances are discussed below.

Severe or Changing Weather and Climate Conditions

Climate is clearly changing and, with it, the extremes of weather and climate as reflected in storminess, heat waves, minimum temperatures, droughts, and floods. In addition to chronic warming, multiyear and multidecadal climate cycles are being increasingly documented (Sutton and Hodson 2005). The familiar El Niño-Southern Oscillation (ENSO) brings increased rainfall to the Southwest and South and decreased rainfall in the Pacific Northwest and occurs for a year or 2 every 3 to 7 years. ENSO alternates with neutral conditions or with La Niña, which results in an opposite pattern of NW-SW rainfall (Sutton and Hodson 2005). Cool, wet phases of the Pacific Decadal Oscillation (PDO) increase rainfall in the Pacific Northwest and decrease it in the South and Southwest (especially during La Niña conditions). The PDO shifts from one mode to the other (warm dry phase) at about 20-year intervals. When the warm dry phase of the PDO coincides with an ENSO event, the Pacific Northwest becomes even drier (Mote et al. 1999). Recently, a connection of the Atlantic Multidecadal Oscillation (AMO) with western North American climate at about 60-year intervals has been discovered (see description of precipitation effects, below). The warm phase of the AMO is associated with warmer, drier conditions throughout the Western United States (Kitzberger et al. 2007). Although these climate cycles shift the intensity and frequency of climate variations, they are superimposed on a steady trend of increasing global temperatures. They can temporarily ameliorate or amplify effects of warming by adding still more climate variations, but they do not change the upward direction of the warming trends.

Climate warming is the most important weather variable driving shifts in invasive species distributions (e.g., Logan et al. 2003). With some important exceptions, greenhouse gas-induced warming throughout the next few centuries is expected to be greatest at night, during winter, over land, and toward the poles. Scientists have already observed such patterns in North America, Europe, and Asia (IPCC 2007a). Hence, the most successful invasive species under climate warming are expected to be those that are currently limited by cold winters and cool spring nighttime temperatures. An example of effects of warmer low temperatures is the newfound ability of mountain pine bark beetles to mature twice as fast as they used to, completing two life cycles a year in the Southwestern United States and at least one complete life cycle every year in areas of central British Columbia (Carroll et al. 2004). Warming nighttime temperatures are also responsible for beetle migration to higher elevations in the intermountain West, causing considerable mortality in limber pine populations that previously had not been subject to beetle attacks (Hicke et al. 2006; Logan et al. 2001, 2003).

Precipitation is increasing in some areas, and this trend is expected to continue because climate warming increases the intensity of the hydrological cycle, leading to greater evaporation and evapotranspiration, greater return rainfall, and greater runoff. In higher latitude temperate regions, precipitation increases appear to result from greater frequency of intense storms. Increased hurricane intensity and more hurricane landfalls at more northerly locations are also expected, at least in the Atlantic (Emanuel 2005, Webster et al. 2005). The implications of increased storminess, runoff, and flooding are obvious in enhanced storm damage to trees and increased abundance of damaged trees that can serve as infestation loci for pests such as borers. Meanwhile, the increased areas of soil disturbance from flooding and treefall will subject ecosystems to potential enhanced establishment of invasive plants such as tamarisk in the Southwest. Note that the foregoing illustrates the fact that the effects of climate change are often driven by the increased *climate variability and extremes* that overlie the slow, chronic increase in mean temperatures. This increase in climate variability is predicted to continue with warming and is likely to produce the most obvious effects on ecosystem functioning (Overpeck et al. 1990).

In other areas, greater intensity and frequency of drought conditions are expected, a trend perhaps already being reflected in the presence of chronic drought conditions in the Western United States (Breshears et al. 2005). One recent study concluded that current drought conditions in the West are likely to become the normal situation throughout the 21st century (Seager et al. 2007). Others suggest that current drought conditions in the West may be attributable to 40- to 60-year cycles of warmer and dryer conditions associated with the AMO, as inferred from tree-ring records documenting fire frequency (and therefore climate conditions) over the past several centuries (Kitzberger et al. 2007). Indeed, in lower latitude temperate regions, such as the Southern and Southwestern United States, the subtropical subsidence zone in which most global deserts are located is expected to extend northward during this century. This phenomenon is under way and has already been well documented (IPCC 2007a). One result of the interaction of drought with warmer temperatures is increased stress, which reduces tree and forest resistance to invasive pests and plants. Such a response is clearly evident in the piñon *Ips* beetle-induced dieback of piñon and ponderosa pine on the Colorado Plateau during the 2000–04 drought (Breshears et al. 2005).

Fire Regimes and Their Management

The patterns of wildland fire, both globally and in North America, have changed markedly over the past 20 to 30 years (IPCC 2007b, Westerling et al. 2006). Changes include increased severity of fires in many short-return interval forested systems and increased frequency of fires in many arid and semiarid shrubland systems. The annual average burned area in the United States has increased greatly in recent years (NIFC 2008). Annual burned area on Forest Service lands, for example, has averaged almost one million acres per year over the 20 years from 1987 through 2006. This is nearly four times the average annual burned area for the previous 50 years (1937 through 1986) (USDA Forest Service, 2007). About 1.4 million acres have burned per year on Forest Service lands since 1999 (NICC 2008), and the upward trend is continuing.

Fire interacts with the potential for invasive species in many ways. Removal of native herbaceous vegetation by frequent or high-severity fire, intensive grazing, or canopy closure due to fire exclusion may reduce the seed sources for native herbaceous species and make habitats available for invasive plant species such as introduced annual grasses. Even when fire regimes are restored, lack of native seed sources can make restoration difficult and may even encourage the persistence of invasive species (Brooks et al. 2004). Grazing animals may also provide a vector for disseminating those species on fur or through their droppings. A number of invasive grass species are believed to have been introduced from Spain in the early years of California settlement; many of these species spread rapidly, carried by humans or by being lodged in the fur of sheep and other animals (Bossard et al. 2000).

Fuel breaks and other fire suppression strategies and tactics have been found to promote the invasion of nonnative plant species in the Western United States (Keeley 2006). A specific study of fuel breaks in California found that nonnative plant cover was more than 200 percent higher in fuel breaks than in adjacent forests (Merriam et al. 2006). In addition, cover of nonnative species was greater in areas that had been subject to three or more fires than in those subject to only one fire. Currently no information is available on the role of fuel breaks in the invasion of nonnative species in the Southeast, but the long history of prescribed fire and the high frequency at which it must be applied suggest that nonnative invasive species could already pose extreme threats to forest diversity and management goals. Fuel breaks in the Southeast are roads that follow the perimeter of management compartments and ownership boundaries. Features such as these are ecologically similar to roads that promote invasion of nonnative species by increasing connectivity within the landscape (Foreman and Alexander 1998).

Invasive grass species (e.g., various bromes in the Great Plains; bufflegrass in the desert Southwest, non-native grasses in the East) or shrub and tree species (e.g., tamarisk in the West, honeysuckle and other shrub and vine species in the East) may increase fine fuel loads, fire hazard, and potential fire severity, and may also affect rangeland forage, wildlife habitat and other values. If these invasions lead to more frequent or more intense fires, native species may be further eliminated. Such changes can affect the ecological and resource values of plant communities and the habitat value for associated wildlife species (Brooks et al. 2004; Zouhar et al. 2008).

In other situations, invasive species may alter fuel structure or fuel moisture in ways that lead to decreased fire frequency, such as with the invasion of the succulent iceplant (*Carpbrotia* sp.) into coastal sage ecosystems in southern California (Brooks et al. 2004).

During periods of drought, tree and shrub species can become more susceptible to a number of native and nonnative insect pests and diseases and more susceptible to fire (Logan et al. 2001, 2003). Increases in insects and diseases may further add to the fire hazard in already-stressed stands.

The decrease of vigor and full or partial canopy mortality associated with invasive insect and disease pests may also lead to long-term increases in fuel loadings (e.g., as branches and boles fall to the ground as is occurring in Michigan and Ohio due to emerald ash borer mortality) (Carroll 2003). These high fuel loads have the potential to increase the intensity and severity of future fires, especially on dry sites where rates of decomposition of dead woody material are slow.

Climate models suggest that the trends toward warmer, drier climate and increases in prolonged drought that have occurred over the past 20 to 25 years in much of western North America are highly likely to continue for the foreseeable future. Climate data also indicate that similar trends are beginning to occur in the Northeast. These changes will increase the many stresses on ecosystems that make them susceptible to plant, insect, and disease invasions. We can expect longer fire seasons and increases in the number of large, high-severity fires (IPCC 2007b). We can expect more rapid population growth of insects whose life cycles and distributions are limited by low winter temperatures (e.g., western pine beetle). We can expect increased spread of invasive plant species, such as cheatgrass, that are native to warm, dry summer climates. And we can expect increased difficulty in restoring riparian systems and wetlands that have had their hydrology, vegetation, and fire regimes severely altered by introduced species such as tamarisk and giant reed (*Arundo donax*). Fire regimes may be drastically altered in some areas if invasive (native or introduced) insects or diseases cause permanent alterations in vegetation structure by elimination of key ecosystem dominants (Brooks et al. 2004).

Management can help reduce the effects of these complex interactions in the following ways (see, for example, Brooks et al. 2004; Zouhar et al. 2008):

- Reduction of hazardous fuel loads can reduce fire risk and severity and support the persistence of native species.
- Actively managing forest stands to reduce water and nutrient stress and increase tree vigor can increase resistance to drought-induced fire hazard and to insect and disease attack. Such changes may also affect patterns of snowmelt and seasonal hydrology in cold winter areas.
- Targeted control efforts with manual treatments, herbicides, fire, or biological control may eliminate local populations of invasive species that are causing alterations in fire regimes or other ecosystem properties. Intensive management action (planting, seeding, followup controls) may often be needed to restore desired species and habitats.
- Planting of species (or ecotypes) better adapted to current climatic conditions may decrease the likelihood of further spread of invasive species by increasing the ability of native species to outcompete them.
- Revegetation with species that are not susceptible to (or do, not act as intermediate hosts for) certain insect and disease species can reduce their populations or slow their spread, reducing their impacts on fire susceptible vegetation.
- Active management of fire timing, frequency, extent, and severity (e.g., based on understanding of phenology and fire tolerance/susceptibility of both invasive species and other species) can help limit the spread and reproduction of some invasive species. For example, reintroduction of properly timed frequent surface fire in Eastern U.S. deciduous forests may reduce the vigor and limit the spread of invasive vines such as Japanese honeysuckle (*Lonicera japonica*).

Insect and Disease Pests

Recent regional invasions of nonnative species and outbreaks of native pests threaten the health of our forests, rangelands, and urban forests. Severe outbreaks of Sudden Oak Death disease (*Phytophthora ramorum*), emerald ash borer (*Agrilus planipennis*), hemlock woolly adelgid (*Adelgis tsugae*), gypsy moth (*Lymantria dispar*), white pine blister rust (*Cronartium ribicola*), southern pine beetle (*Dendroctonus frontalis*), western bark beetles (Dendroctonus spp.), and other pests have drastically changed ecosystem function, structure, and composition. These outbreak pests outcompete native species, change the rates of ecosystem processes, alter food webs, and affect native wildlife. For example, by killing hemlock (*Tsuga canadensis*) in the East, hemlock woolly adelgid (*Adelgis tsugae*) also affects trout (Salmoninae) survival in mountain streams by altering stream shade and temperatures (Snyder et al. 2005). Chestnut blight (*Cryphonectria parasitica*) killed American chestnut (*Castanea dentata*) trees, once an abundant, fast-growing, highly valued tree species in Eastern forests that was a preferred food source for wild turkey and a wide variety of other grazers, provided high-quality wood, and was an important sink for carbon sequestration (Jacobs 2005). White pine blister rust (*Cronartium ribicola*) is destroying whitebark pine (*Pinus albicaulis*) in the mountains of the Western United States, an important food source for the endangered Clarke's nutcracker (*Nucifraga columbiana*) (Schoettle 2004). Emerald ash borer threatens ash (*Fraxinus* spp.) species throughout most of the United States. These ash species are widespread in natural forests and are also commonly planted in urban areas (Cappaert et al. 2005). The number and severity of pest outbreaks are increasing. This trend is expected to continue into the future (National Invasive Species Council 2008).

Climate change, increased droughts, more frequent storms, greater human activity, and other changes in disturbance regimes will fuel changes in ecosystem composition that will alter susceptibility to native and invasive pest species. Some pest species may benefit from these changes because of health declines among native organisms stressed by the changes in the conditions under which they evolved. Alien species or species that are not native to the ecosystem may be better adapted to establish and thrive in these changed abiotic and biotic conditions. Often these nonnative species are very adaptable and may work in concert with each other. For example, laurel wilt pathogen (*Raffaelea lauricola*) is carried by an invasive bark beetle (redbay ambrosia beetle (*Xyleborus glabratus*)), invasion by nonnative earthworms (Oligochaeta) may predispose an ecosystem to invasion by alien nonnative plants (or vice versa) (Heneghan et al. 2006), or invasion by one alien plant species may lead to subsequent invasion by a series of other alien plant species (D'Antonio; Meyerson 2002).

Land Use and Land Cover Changes

As world population increases, demand for increased food and fiber production will almost certainly adversely affect the survival of native species and enhance the distribution of invasive species. The number of forest landowners is rising but the average forest tract size is getting smaller, increasing the need for effective communication networks (Sampson and Coster 2000). Conversion of forests and rangelands to agricultural and urbanized lands can accelerate fragmentation of the landscape and inadvertently introduce invasive species. By 2050, approximately 8.1 percent of the coterminous United States is expected to be urban (Nowak and Walton 2005). These urban and urban-interface forest ecosystems will be expected to provide many of the same benefits as extant forest and rangeland ecosystems. Because of their linkages with trade and transportation hubs, however, these urban forests, rangelands and waterways will likely serve as initial invasion sites and as reservoirs of invasive species. Effective monitoring strategies and protocols for potential invasive species activity in these urban systems will play a key role in detection and management efforts.

Trade and Transportation Within and Across Regions

The number of unintentional introductions of invasive species into the United States has increased dramatically since the early 1960s, and it is likely that the rate of introductions will grow over the next several decades. A major factor in this increase has been the advent of the shipping container. These containers have facilitated development of highly automated systems to rapidly load and unload goods from ships and move them from ports to final destinations. The containerization of shipped goods has caused a significant decrease in shipping time and freight costs for many goods. Although enabling an unparalleled increase in global trade, containerization of goods has facilitated a large increase in invasive species introductions (Levinson 2006). These species arrive in dunnage, wood shipping crates and pallets, agricultural commodities, seeds, plant nursery products, pet and aquarium trade goods, ship ballast, etc. The rapid movement of shipping containers on trucks and railroad cars facilitates the movement of invasive species from ports to the rest of the country (Levinson 2006). Inland distribution centers being developed in Kansas City, MO; Columbus, OH; Tennessee, and other inland locations will likely become focal points for invasive species introductions in the future. The number of containers imported into the United States in 2005 was about 25 million (U.S. Department of Transportation 2006a; 2006b). It is estimated that container-shipping capacity will increase by 50 percent over the next 5 years. The accelerating rate of global commerce will result in a continuing increase of invasive species introductions into the United States (Rich 2006).

Human Health and Human Travel

Invasive species can cause disruptions by both directly and indirectly affecting human health. For example, the browntail moth (*Euproctis chrysorrhoea*), a defoliator of a variety of deciduous trees and shrubs, causes dermatitis and respiratory problems when people come in contact with larval hairs. Indirect effects on people are occurring from unforeseen sources. Eleven people were killed in Bandon, OR, in 1936 by a fire propagated by a highly flammable invasive plant, gorse (*Ulex europaeus*), introduced from Europe (Simberloff 1996). Another example is the planting of Australian *Melaleuca*, Asian cogongrass (*Imperata cylindrical*), and Brazilian pepper (*Schinus terebinthifolius*) along roadsides in Florida. These plants have become costly hazards due to increased fires along roadways and are currently being removed at great expense (Simberloff 1996). Invasive species such as birds, rodents, and insects (e.g., mosquitoes, fleas, and lice) can serve as vectors of human disease. The Asian tiger mosquito (*Aedes* (*Stegomyia*) *albopictus*) can serve as an insect vector of disease. This mosquito has a broad host range that includes many mammals, birds, and reptiles and, consequently, can transfer diseases, such as West Nile virus, among many species, including humans (Laqnciotti 1999). In addition, people themselves can serve as vectors for invasive species and foreign disease after traveling outside the United States. The globalization of trade and associated increased business travel, coupled with an increase in leisure travel as a consequence of an increasing U.S. population, will likely continue to generate invasive species health effects on U.S. citizens.

Management Practices Designed To Mitigate Disturbance Effects

Forest Service R&D has a rich history of developing management practices to mitigate individual disturbances in many ecosystems. Often these practices focus on a response to a single disturbance and tend to target a single invasive species or taxon. For example, in the Pacific Northwest native plants are propagated for postfire rehabilitation and to minimize the establishment of invasive plants. Poplars and willows are planted along stream banks to mitigate the effect of floods. Chestnut and American elms are being bred to withstand pathogens. Small-scale field tests have been initiated to evaluate the effects of introduction of hybrid American elm into native ecosystems

(Eshita et al. 2003, Powell et al. 2005). Merkle et al. (2007) review transgenic tree genetics programs and the introduction of resistance into a tree (Merkle et al. 2007). The agency's Sudden Oak Death program represented a rapid, targeted response to an emerging issue (Rizzo et al. 2005). Insecticides and biological controls are used to manage gypsy moth and hemlock woolly adelgid outbreaks (Sharov et al. 2002, Solter et al. 2004, Ward et al. 2004). For the most part, these mitigation practices are not based on environmental, social, and economic cost analyses and are not applied in the context of a management system. Synthesis of this information is needed, and this may be the first step toward the development of risk-cost-benefit analyses.

Future management systems need to provide strategies, decision and implementation tools, and practices that can address multiple disturbances and their interactions over time. Environmental, social, and economic analyses of the benefits and costs will play an essential role in identifying which disturbances to address. These management systems need to be dynamic, be responsive to changing needs, and incorporate the leading edge of knowledge development.

Biological Control

Invasive species can establish and proliferate in their new habitat because they are separated from their coevolved natural enemies. Biological control (biocontrol), a long-term strategic management tool used to suppress target invasive species populations below an economically or ecologically relevant threshold, intentionally unites the target invasive species with their imported or native natural enemies. Biocontrol may be the only viable option for managing infestations occurring at landscape scales or in environmentally sensitive wildlands. Because of our international ties and national partnerships, the Forest Service is well positioned to build teams to conduct cooperative research on invasive species in their native habitats. These relationships provide opportunities for identifying emerging needs, tools for predicting and preventing introductions, and the control of species that have been introduced into the United States. Candidate biological control agents must be carefully studied to ensure that life-cycles and behaviors are matched with the phenological and ecological characteristics of the target invasive species. In addition, because of potential impacts on nontarget species, rigorous prerelease evaluations and long-term postrelease monitoring are needed to provide a scientific assessment of agent safety and efficacy especially under fluctuating environmental conditions, including climate change.

Genetically Engineered Plants and Animals

A significant effort to develop genetically engineered organisms is being made by the corporate sector around the world. Most of this effort focuses on agricultural applications. A developing area is microbes that can enhance ethanol/biofuel production from cellulosic fiber and algae. Within the United States, the use of genetically engineered soybeans, corn, and cotton has become widespread. By 2005, herbicide-tolerant soybeans and cotton accounted for 87 and 60 percent of total soybean and cotton acreage, respectively. Insect-resistant cotton and corn comprised 52 and 35 percent of cotton and corn acreage, respectively, in 2005 (Fernandez-Cornejo et al. 2006). To date, the use of genetically engineered crops in agriculture has failed to generate any disturbances not already inherent in the practice of agriculture (Fernandez-Cornejo et al. 2006).

Several genetically engineered tree species have been developed to date and include hybrid poplar trees containing genes that confer greater tolerance to *Septoria musiva*, a fungal pathogen that limits the use of these trees throughout the Eastern United States (Liang et al. 2001). The only genetically engineered tree that APHIS has approved for commercial distribution is the papaya (*Carica papaya*). This release is limited to Hawaii and was done to prevent the loss of an entire industry from destruction by ringspot virus (*Potyvirus*). The requirement by APHIS for genetically engineered trees to be sterile has prevented the release of all but the papaya. Several approaches are being pursued to generate sterility; most affect some mechanism of flowering. It is possible that releasing tree species, engineered with pest resistance, to breed with the susceptible population of that species could be used to address invasive pathogens and insects. This approach, theoretically, could have addressed chestnut blight and Dutch elm disease and could still mitigate the impact of the emerald ash borer. To date, the use of genetically engineered organisms in the environment has yet to generate novel disturbances. Continued research to address potential unwanted effects coupled with a conservative position on the commercial release of genetically engineered organisms is likely to continue to prevent unwanted effects in the future.

Historically, genetic variation has been managed in various ways, including seed movement guidelines, intensive and specialized breeding programs, and development of unimproved locally adapted, regionally appropriate seed sources. Although genetically appropriate material is called for in our native plant materials policy (FSM-2070) (USDA Forest Service), many species used in our restoration efforts lack suitable seed/propagation sources. In addition to developing locally adapted seed sources, we must also develop strategies, genotypes, and seed sources that will be adapted to both current and future conditions. This effort will involve deploying more genetically diverse populations and breeding for appropriate abiotic and biotic resistances. Successful deployment of the proper planting material requires that the infrastructure be in place to produce sufficient quantities of seed and seedlings.

Research and Development Priorities

Some of the highest priority research and development needs to effectively manage invasive species in the face of multiple interacting disturbances in a rapidly changing environment include:

- **Risk-cost-benefit analysis methodology to help determine the most effective management options.** Development of this methodology is critical to developing options for rational action, including their costs, and includes articulating what changed systems can and cannot deliver in probabilistic terms.
- **Strategies, systems, and practices for managing changed systems to continue to deliver needed goods, services, and values.** The ability to provide effective, responsive management systems rests on quantifying and projecting system behavior and value under different scenarios.
- **Develop tools that enable functional restoration of economically and/or ecologically critical systems.** Tools and guidelines that help identify rational actions based on the risk and cost-benefit analysis of prevention, detection, prediction, and management options are critical to managing disturbed and changing systems.
- **Strategies and guidelines to prevent, detect, predict, monitor, and manage invasive species after major disturbances.** Practitioners and governments have strategies and guidelines based on sound science for preventing, detecting, predicting, monitoring, and managing invasive species in the wake of major disturbances.
- **Guidelines for economic, environmental, and social analysis.** These analysis tools and forecast maps will allow land managers and land owners to make better informed decisions about their prevention, monitoring, management, mitigation, restoration, and rehabilitation activities.

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