REVIEW

Impacts of Nonnative Invasive Species on US Forests and Recommendations for Policy and Management

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ABSTRACT

The introduction of nonnative invasive species (NNIS) into the United States has had tremendous impacts on the nation's commercial and urban forest resources. Of principal concern are the effects of NNIS on forest composition, structure, function, productivity, and patterns of carbon sequestration. In 2006, the Society of American Foresters commissioned an ad hoc team to prepare a white paper on the effect of NNIS on America's forests. The paper was the genesis of this article, which provides an overview of the impacts of NNIS within the United States and includes recommendations for NNIS policy and management.

Keywords: forests, nonnative invasive species, policy

The frequency of introductions of nonnative invasive species (NNIS) into the United States has grown at an alarming rate because of foreign travel, international trade, and human population development patterns (Pimentel et al. 2005, Work et al. 2005). NNIS pose a serious risk to North American forest ecosystems, threatening to change existing ecological trajectories, suppress rare and endangered native species, reduce productivity and biodiversity, and damage wildlife habitat (Chornesky et al. 2005). Effective and feasible management strategies that include monitoring and control of invasive species are needed to maintain sustainable forests.

In 2006, the Society of American Foresters' (SAF) Forest Science and Technology Board (FSTB) commissioned an ad hoc team to prepare a white paper on the effect of NNIS on America's forests. On submitting this paper to SAF's committee on Forest Policy, the chairman of the FSTB asked the group to prepare an article based on the white paper for the *Journal of Forestry*.

Federal environmental agencies have a major role in NNIS management that is mandated by Federal Executive Order 11312 on Invasive Species (Feb. 8, 1999; Executive Order 1999) that calls for federal agencies to minimize the economic, ecolog-

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ical, and human health impacts caused by invasive species. Federal agencies are required to (1) actively prevent the introduction of invasive species, (2) manage and control invasive species, and (3) provide public education to support these efforts. To facilitate this discussion, we need to define several critical concepts. The following definitions are taken directly from the executive order:

Alien Species. With respect to a particular ecosystem, any species, including its seeds, eggs, spores, or other biological material capable of propagating that species, that is not native to that ecosystem (the terms "exotic" and "nonnative" are synonymous throughout this paper).

Control. Eradicating, suppressing, reducing, or managing invasive species populations, preventing spread of invasive species from areas where they are present, and taking steps such as restoration of native species and habitats to reduce the effects of invasive species and to prevent additional invasions.

Introduction. The intentional or unintentional escape, release, dissemination, or placement of a species into an ecosystem as a result of human activity.

Invasive Species. An alien species whose introduction causes or is likely to cause economic or environmental harm or harm to human health.

Native Species. With respect to a particular ecosystem, a species that historically occurred or currently occurs in that ecosystem other than as the result of an introduction.

Examples of Ecological Impacts

This article provides a summary of the major groups of invasive biological organisms and cites specific examples that show the extent and magnitude of the threat of NNIS to our country's forest resources.

Impacts of Tree Diseases Caused by Nonnative Invasive Pathogens

The impacts of North American tree diseases, caused by 20+ nonnative invasive pathogenic microorganisms (Liebhold et al. 1995) on forest ecosystems, deserve serious attention and serve to illustrate the gravity of the issues concerning exotic introductions and invasions. These pathogens affect both forest trees and forest products. Among the most notorious examples are the fungi that cause chestnut blight, white pine blister rust (WPBR), Dutch elm disease (DED), and sudden oak death (SOD).

Chestnut Blight. American chestnut (*Castanea dentata* [Marsh.] Borkh.) was once a major eastern deciduous tree species, comprising 25% of Appalachian forests. Forty years after its introduction at the beginning of the 20th century, the chestnut blight fungus (*Cryphonectria parasitica* [Murrill] Barr = *Endothia parasitica* [Murr.] A.&A.) had spread across the native range of American chestnut (Griffin and Elkins 1986). Ten years later, 80% of American chestnut trees distributed across 8.9 million ac were dead or dying due to pathogenic infections (Anagnostakis 1987). Chestnut blight killed an estimated 3.5 billion trees (Griffin and Elkins 1986). In 1912 alone, losses in North Carolina, West Virginia, and Pennsylvania totaled $82.5 million (Anagnostakis 1987).

White Pine Blister Rust. WPBR (caused by *Cronartium ribicola* [J.C. Fischer ex Rabenh.]), which affects soft pine species, such as *Pinus strobus* and *Pinus monticola*, has damaged thousands of white pine stands across the northern United States. Because the area currently occupied by affected species is substantially less than in pre-European settlement times, continued forest health problems caused by this pathogen threaten to reduce this resource to critical levels (Jain et al. 2004). In the Pacific Northwest, estimated losses from WPBR totaled 5 million ft^3 of timber annually. WPBR is considered the most costly and damaging conifer disease in North America (Maloy 1997, Washington State University 2006).

Dutch Elm Disease. Dutch elm disease (caused by *Ophiostoma ulmi* [Buisman] Nannf. and *O. novo-ulmi* Buisman) is perhaps the most widely recognized epidemic caused by a nonnative pathogen, because of its impacts on urban/shade trees. This disease has devastated valuable shade trees on city streets, municipal parks, college campuses, and other urban landscapes in less than a single human generation. Most of the 185,000 elms (*Ulmus americana* L.) in Buffalo, New York were killed in less than 30 years, and 81% of the 13,000 "parkway" elms in Waukegan, Illinois were killed in just 12 years (Neely 1967). Of 14,000 elms growing in Urbana-Champaign, Illinois in 1944, only 40 remained in 1972 after the introduction of DED and other diseases (Carter and Carter 1974, Sinclair and Campana 1978). During the 1930s, federal and state governments spent more than $11 million over 5 years in an attempt to eradicate DED. Estimated losses from DED total several billion dollars in decreased intrinsic value; diminished real estate value; the cost of tree removal, replacement, and control; and associated research efforts (Sinclair and Campana 1978). Campbell and Schlarbaum (1994) estimated that the cost of removing infested elm trees totaled $100 million/year.

Sudden Oak Death. The SOD pathogen (*Phytophthora ramorum* S. Werres, A.W.A.M. de Cock) probably was introduced from outside the United States (Rizzo et al. 2001). First reported in California in 1995, this exotic fungal-like pathogen has had a devastating effect on tanoak (*Lithocarpus densiflorus* [Hook.&Arn.] Rehder), Coast live oak (*Quercus agrifolia* Née), and California black oak (*Quercus kelloggii* Newberry). Tens of thousands of individual trees have been killed. Many oak species are susceptible to the SOD pathogen, especially northern red oak (*Quercus rubra* L.) and pin oak (*Quercus palustris* Münchh.). *P. ramorum* initially causes cankers on the stem that take several years to spread throughout the tree. Once crown dieback begins, tree death is rapid. The SOD pathogen is particularly difficult to contain geographically because of its capacity to infect *Rhododendron* spp., common commercial horticulture plants (Washington State Department of Agriculture 2008), as well as camellias (*Camellia* spp.), madrone (*Arbutus menziesii* Pursh), bigleaf maple (*Acer macrophyllum* Pursh), and manzanita (*Arctostaphylos* spp.), among other species (O'Brien et al. 2002). Plants from West Coast nurseries carrying *P. ramorum* have been found in eastern states (e.g., Georgia Department of Agriculture 2004, Indiana Department of Natural Resources 2007).

Nonnative Invasive Insects and Their Effects on Forests

Current estimates indicate that more than 360 species of nonnative insects have become established in US forests (Haack and Byler 1993, Pimentel et al. 2005). Approximately 30% of these introduced insects have become major pests. Without natural enemies and specific defenses by native host plants, many introduced insects maintain high population densities and spread quickly (Speight and Wainhouse 1989). As a result, these nonnative insects can cause rapid and considerable damage to forests. Asian longhorned beetle (ALB; *Anoplophora* *glabripennis* Motchulsky), emerald ash borer (EAB; *Agrilus planipennis* Fairmaire), and hemlock wooly adelgid (HWA; *Adelges tsugae* Annand) are examples of introduced insects that are or have the potential to cause significant tree mortality and will have a significant economic impact. In addition, some insects carry pathogens that can kill the tree. Examples include the smaller European elm bark beetle (*Scolytus multistriatus* [Marsham]), a vector of the DED fungus sirex woodwasp (*Sirex noctilio* F), a vector of *Amylostereum areolatum* [Fr.] Boidin, and redbay ambrosia beetle (*Xyleborus glabratus* Eichhoff), a vector of laurel wilt (*Raffaelea lauricola* Harrington & Fraedrich), which is lethal to redbay (*Persea borbonia* [L.] Spreng.).

Asian Longhorned Beetle. ALB was initially detected in the United States in Brooklyn, New York, in August 1996 (USDA Animal and Plant Health Inspection Service [APHIS] 2008). It is thought that this insect entered the country earlier in solid wood packing material from Asia, where it is a pest of hardwood trees, especially sugar maples (*Acer saccharum* L.). Subsequent infestations were reported in Chicago in July 1998, in New Jersey in October 2002, in Toronto, Canada, in September 2003, and in Massachusetts in 2008 (Haack et al. 1997, USDA APHIS 2008). With continued spread of this insect, US urban areas could lose up to 35% of tree cover, or approximately 1.2 billion trees (Nowak et al. 2001). Eradication efforts have been successful in some states. In 2008, ALB was declared eradicated from Illinois and most experts believe that eradication from New Jersey soon will follow. However, eradicating the established infestation in Massachusetts may prove difficult because it is within the northeastern maple forest, home for many susceptible species.

Emerald Ash Borer. Another wood-boring insect from Asia, EAB, is causing even greater concern. First detected near Detroit, Michigan, during the summer of 2002, EAB has been responsible for widespread decline and mortality of ash trees (*Fraxinus* spp.) in the region (Poland and McCullough 2006). Like ALB, EAB became established in a highly urbanized setting with abundant hosts. Although stressed trees initially may be preferred as hosts, even the healthiest ash trees are attacked and killed when beetle populations are high (Haack et al. 2002).

To date, tens of millions of ash trees have been killed by EAB or have been removed in an attempt to reduce the rate of spread. From June 2002 to May 2009, EAB spread from Michigan and Ontario, Canada (2002) to Ohio (2003); Indiana (2004); Illinois (2006); Maryland (2006); Pennsylvania (2007); West Virginia (2007); Virginia (2008); Missouri (2008); Wisconsin (2008); Quebec, Canada (2008); Kentucky (2009); and Minnesota (2009). Human transport of infested ash material, such as firewood, is the primary cause of spread. Unlike ALB, expectations for eradicating EAB are poor because of its wide distribution and the inadvertent transport of this pest (US Government Accountability Office [GAO] 2006).

Hemlock Woolly Adelgid. A genotype of hemlock woolly adelgid (HWA; *A. tsugae* Annand), native to Japan, was introduced to the eastern United States in 1951 and since has had a devastating effect on eastern and Carolina hemlocks (*Tsuga canadensis* [L.] Carrière and *Tsuga caroliniana* Engelm.). [1] Eastern hemlocks usually decline and die within 4–10 years of initial attack.

The adelgid has spread rapidly in recent years, borne by winds or carried by migratory birds, mammals, humans, and infested nursery stock. The infestation now extends from the northeastern tip of Georgia to Maine and covers much of the natural range of eastern hemlock. The potential elimination of eastern hemlock from US forest ecosystems jeopardizes many plant and animal communities. Pest management specialists warn of ecosystem devastation comparable with that caused by chestnut blight (Evans 2004). HWA is related to another destructive invasive pest, the balsam woolly adelgid (*Adelges piceae* Ratzeburg), which has devastated true fir forests (*Abies* spp.) in both the western and the eastern United States for nearly a century (Potter et al. 2005).

Impacts of Nonnative Invasive Plants on Forest Sustainability

Because of human activity, distribution of nonnative invasive plants is expanding across North America and increasing their negative impacts on native biodiversity, wildlife habitat, forest productivity, and fire behavior. Vectors that contribute to the proliferation of nonnative invasive plants, e.g., highways, commonly spread more than one species or life form. As a result, forests in the path of these vectors often are impacted not only by a single species but also by a suite of nonnative species.

Invasive plants come in many different growth forms, including trees (Norway maple [*Acer platanoides* L.], tree-of-heaven [*Ailanthus altissima* {Mill.} Swingle], and tamarisk [*Tamarix* spp.]), shrubs (multiflora rose [*Rosa multiflora* Thunb.], bush honeysuckles [*Lonicera* spp.], Russian/autumn olive [*Elaeagnus angustifolia* L. and *E. umbellata* Thunb.], privet [*Ligustrum* spp.]), vines (kudzu [*Pueraria montana* var. *lobata* {Willd.} Maesen&S. Almeida], Japanese honeysuckle [*Lonicera japonica* Thunb.] and oriental bittersweet [*Celastrus orbiculatus* Thunb.]), and forbs, grasses, and herbs (garlic mustard [*Alliaria petiolata* {M. Bieb.} Cavara&Grande], Japanese and giant knotweed [*Polygonum cuspidatum* Siebold& Zucc. and *Polygonum sachalinense* F. Schmidt ex Maxim.], Japanese stiltgrass [*Microstegium vimineum* {Trin.} A. Camus], gorse [*Ulex europaeus* L.], and leafy spurge [*Euphorbia esula* L.]) (Plant Conservation Alliance 2006).

Tree-of-Heaven. Tree-of-heaven is a prime example of a well-established invasive tree species. Native to East Asia, it was introduced into the United States in the 18th century as an ornamental and later was distributed by nurseries (Plant Conservation Alliance 2006). It also was brought by immigrants to California during the Gold Rush. Currently, tree-of-heaven is found in nearly all of the coterminous states and Hawaii. The species is characterized by rapid spread by windborne seeds and prolific sprouting. It can rapidly establish and dominate sites after introduction and has allelopathic effects on other plants (Gleason and Cronquist 1991).

Common Buckthorn. Both of the major species of buckthorn found in the eastern United States—glossy (*Rhamnus frangula* L.) and common buckthorn (*Rhamnus cathartica* L.)—were introduced from Europe. Now common to the Midwest and New England, the species have been promoted for ornamental uses and wildlife habitat (Webster et al. 2006). Both buckthorns exhibit classic hypercompetitor behavior: they leaf out earlier than their native competitors, resprout vigorously, and produce large amounts of seeds that are spread by birds (Harrington et al. 1989). Buckthorn can suppress tree seedling survival and can stunt height and diameter growth by shading and by belowground competition from their extensive root systems (Fagan and Peart 2004).

Garlic Mustard. Garlic mustard is a herbaceous plant introduced from Europe in the mid-1800s (Meekins and McCarthy 1999) and today is found throughout the eastern United States (Nuzzo 1993). Common in disturbed forests, it also invades mature second-growth forests (McCarthy 1997), a capability considered unusual for an invasive plant species. Garlic mustard's superior competitive ability enables it to reduce biodiversity by suppressing growth of the ground-level flora and tree regeneration. Forest types, including upland oak (*Quercus* spp.) types present on millions of acres of eastern US forests are particularly susceptible to garlic mustard invasion (Meekins and McCarthy 1999).

Kudzu. Originally from Japan, kudzu is a weedy plant that can outcompete and even eliminate native plant species (Mitich 2000). It was introduced into the United States in 1876 as a garden cover and flower. It was being used as a forage crop by the early 1900s and was promoted by the USDA Soil Conservation Service as a treatment for erosion during the 1930s. By 1945, kudzu covered an estimated 500,000 ac in the South (Mitich 2000). The species gradually acquired a reputation as a noxious weed and was officially declared as such by several southern states by 1970 and by the federal government in 1999. Kudzu sends its stems and roots out in all directions from its root crown. Where kudzu is found in American forests, its effects can be devastating, covering regeneration and even mature trees. This invasive plant can create a layer up to 7½ ft thick, blocking light for any plant beneath it (Hipps 1994). Anyone traveling through the Southern Appalachians has seen the devastating effects of kudzu on Appalachian hardwood forests. Treatment with herbicides is the normal method of control for most large-scale infestations. Unfortunately, many of the herbicides that control kudzu also affect the hardwood trees that are present with it. Even where chemical control is feasible, many years of repeated herbicide applications and/or physical removal are required to control this pest.

Nonterrestrial Invasive Organisms and Their Potential Effect on Forest Management

We tend to concentrate on invasive insects, plants, and diseases that directly affect trees and other terrestrial species. But invasive organisms also can alter the ecology of other ecosystems, including forest lakes and streams. It is not uncommon for nonnative, aquatic organisms to make up a large component of the fish and amphibians in forest streams. For example, nearly 50% of the fish species found today in the Muddy Creek Watershed of Oregon have been introduced (US Department of the Interior Bureau of Land Management 1997). In the same watershed, several native fish species are considered sensitive by the state of Oregon or are candidates for federal listing under the Endangered Species Act. Competition between native and introduced species, and even predation by introduced species, can harm native aquatic organisms.

Brook Trout in Western Streams. One example of the impact of nonnative invasive fish on native fish species is the interaction of brook trout (*Salvelinus fontinalis* Mitchill) and bull trout (*Salvelinus confluentus* Suckley) in the western United States. Brook trout was introduced to western streams from the eastern United States and in many cases has displaced or dramatically reduced native bull trout populations. In a stream in Crater Lake National Park, the introduction of brook trout dramatically reduced the stream reaches where bull trout are found. Brook trout has a competitive advantage over bull trout for a wide range of conditions (McMahon et al. 1999). Declines in the bull trout populations also are attributed to the introduction of diseases from brook trout and the development of sterile hybrids between the two species. The decline in bull trout places pressure on forest and land managers to provide favorable habitat and conditions. However, these actions may not be effective in reversing the biological consequences of an invasive species with a competitive advantage.

Nonnative Invasive Mussels. Nonnative mussels combine with other influences to reduce the health and numbers of native freshwater mussels. In the Altamaha River in Georgia, there is concern that human activities, including forest management, have contributed to the decline of freshwater mussels. Endemic mussels, including the Altamaha spinymussel (*Elliptio spinosa* I. Lea) and Altamaha arcmussel (*Alasmidonta arcula* I. Lea), may be declining. The freshwater mussels can be influenced by and be indicators of pollutant loads in streams (Brown et al. 2005), and there is evidence that changes in Native American agriculture may have contributed to its decline (Peacock et al. 2005). The presence of NNIS must be included in the mix of negative influences on native mussel populations. Asian clams (*Corbicula fluminea* Muller) now are in the system and may be in direct competition with endemic mollusks for food (Illinois-Indiana Sea Grant College Program 1999).

The Role of Commerce in Importation and Transportation of NNIS

Healthy forest ecosystems greatly benefit the ecological, economic, and social health of our nation. Facilitating commerce and minimizing barriers to international trade must be balanced with minimizing degradation of our native ecosystems resulting from the introduction of nonnative organisms. Toward this end, the Customs and Border Patrol (CBP) of the US Department of Homeland Security (USDHS) is responsible for inspecting commercial and passenger cargo at key US ports of entry and international mail distribution facilities. These responsibilities formerly were performed by the USDA APHIS (USDHS CBP 2007). Cargo is inspected as part of efforts to prevent or minimize the introduction of invasive diseases, pests, and plants.

In 2004, nearly $1.5 trillion worth of goods were imported into the United States, and almost half arrived by sea (Congressional Budget Office 2006). Sixteen million shipping containers arrive at US ports each year. Container imports, measured in twenty-foot equivalent units (TEUs) [2], increased by 58% between 1999 and 2004. Individual shipments are increasing as the average capacity of container ships grew 39% over the same period (US Maritime Administration 2005). The largest of these ships can carry more than 15,000 containers (Smith 2006, Axsmarine 2008).

Although expanded inspection of incoming shipments should catch more NNIS, there are tradeoffs, including increasing effective shipping times. In studying the mode of transit, transit time, and substitution costs of different types of transportation, Hummels (2001) concluded that each day saved in shipping was worth 0.8% of the value of goods being shipped. A disruption or delay in imports could significantly impact our nation's economy. A study of the closing of West Coast ports in 1992 estimated that the economy suffered a loss of $75 million/day (DRI-WEFA 2002). Disruptions lasting more than a few days could result in even higher daily costs as alternative measures employed by shippers and producers would be less effective as time went by (Congressional Budget Office 2006).

International phytosanitary standards for the proper treatment of wood products have been established that regulate international commerce. Although restricting commerce has costs, preventing introductions is the most effective way to reduce the large costs associated with invasive species. All indications are that the economic impact of NNIS will be massive. Although quantifying the total impact of exotic invasions is challenging, one study provides a glimpse of the potential costs of unmanaged invasions. Based on data derived from surveys of 33% of the communities in Ohio, Sydnor et al. (2007) estimated that total costs to Ohio residents of damage from EAB would range from $1.8 to 7.6 billion or $157 to 665 per resident (man, woman, or child). This total included tree removal costs ($0.7–2.9 billion), tree replacement costs ($0.3–1.3 billion), and losses in landscape value ($0.8–3.4 billion). These costs represent the impact of a single invasive species in one state.

Some transport vectors and source regions carry higher risks than others, suggesting that targeted efforts can reap substantial benefits. For example, because most invasive plants have been introduced for horticultural use and otherwise benign horticultural imports have carried invasive pathogens, education focused on the plant trade and horticultural organizations could be effective in preventing introduction of plants in the future (Reichard and White 2001, Reichard 2007). A global information service that compiles detailed data on species' detections, invasive traits, and habitat preferences would help prevent introductions and facilitate early detection (Ricciardi et al. 2000).

Intranational transport and commerce can spread NNIS that have landed on our shores. Although it is known that transport of firewood (Werres et al. 2001, Michigan Department of Agriculture 2006,), nursery stock (Davidson et al. 2005), and even the movement of family trailers (Sharov et al. 1997) and boats (Johnstone et al. 1985) are responsible for the transport of many species, there is no cohesive strategy similar to the international wood-packaging program for addressing this problem, especially for firewood. However, there are successful examples of programs that are addressing problems related to individual nonnative invasive pests, such as the "Slow the Spread" initiative designed for management of gypsy moth (*Lymantria dispar* L.).

Research and Education Needs

Despite the level of research directed at NNIS, little is known about their potential ecological impact. Our knowledge of the role of humans in transportation and establishment of invasive species and of effective methods of treatment is inadequate, as is our knowledge of methods for predicting and preventing entry of NNIS and for increasing the resistance of forested ecosystems to attack.

Because the invasion process is significantly affected by spatial patterns of physical and biological processes across forest landscapes, ecosystem- and landscape-level approaches must be integrated to effectively manage NNIS (Chornesky et al. 2005). Advanced technologies such as spatial modeling, remote sensing, and geographic information systems are available to address ecosystem and landscape management of current and future invasive species. However, the most powerful approach to predicting and managing invasive species will require the integration of biology, ecology, genetics, and environmental inventory and monitoring. To facilitate ecosystem rehabilitation after an invasion, research is required on several fronts, including invasion ecology, postinvasion management and restoration, public perception, and economic and environmental analysis (Hain 2006).

Extensive collaboration and expanded partnerships among scientists, policymakers, and resource managers are essential to reduce the threat of invasive species and to restore invaded forest and rangeland ecosystems. Ongoing communication among local, regional, national, and international partners is needed to understand the full suite of influences—social, biological, and economic—that affect the establishment and spread of NNIS, and to prioritize research efforts, maximize research outcomes, and communicate these tools and technologies to users.

Recommendations

The following are recommendations, listed in order of importance and achievability.

1. Promote Education and Awareness with Respect to the Issue. Public information and education are an integral part of any awareness program on invasive species. Problems associated with NNIS often begin as "people problems" and evolve into ecological and economic problems. The arrival of NNIS can be accidental, as was the case with many invasive weeds during the 19th century, or it can be deliberate as with tree-of-heaven (Petrides 1998) and gypsy moth. Consequently, public education and involvement should focus on preventing new species from invading, limiting the spread of newly introduced species, and eradication.

Interactive communication among professionals, scientists, managers, and regulators also is needed to prevent a recognized pest from gaining entry or, if the pest is already established, to provide a rapid response that controls its spread or achieves eradication. Public support for drastic prescriptions such as widescale spraying or wholesale tree removal is vital. Without it, control efforts might not go forward.

2. Expand Early Detection and Active Management Efforts and Intensify Enforcement of Quarantines. Given the value and extensive distribution of forests throughout North America, the most cost-effective means to address invasive species is to prevent potentially invasive pests from crossing US borders (Fig. 1; Ciesla 2003, Gray 2006). Early detection methods and prompt eradication efforts are needed once the pest is introduced. Should these programs fail, biological control or silvicultural manipulations to maintain tree species diversity and host vigor offer the best hope for long-term pest management (GAO 2006). Management costs rise significantly once an invasive species becomes established and begins to spread. Thus, more research is needed to develop effective prediction, prevention, and early detection methods. Quantitative risk assessments, identification techniques, pathway analysis, and epidemiology are the keys to this approach. This research will provide the science and knowledge so that the most effective regulations are implemented. Armed with this knowledge, government agencies also must continue, and possibly expand, aggressive enforcement of international and intranational quarantines and apply appropriate civil penalties for bringing these destructive agents into the United States and/or spreading them across our land.

3. Build the Capacity to Increase Understanding of and Treatments for NNIS. NNIS pose significant challenges for decisionmakers attempting to set policy for control and amelioration. Novel methods of control and ecosystem restoration of affected systems are needed because of the

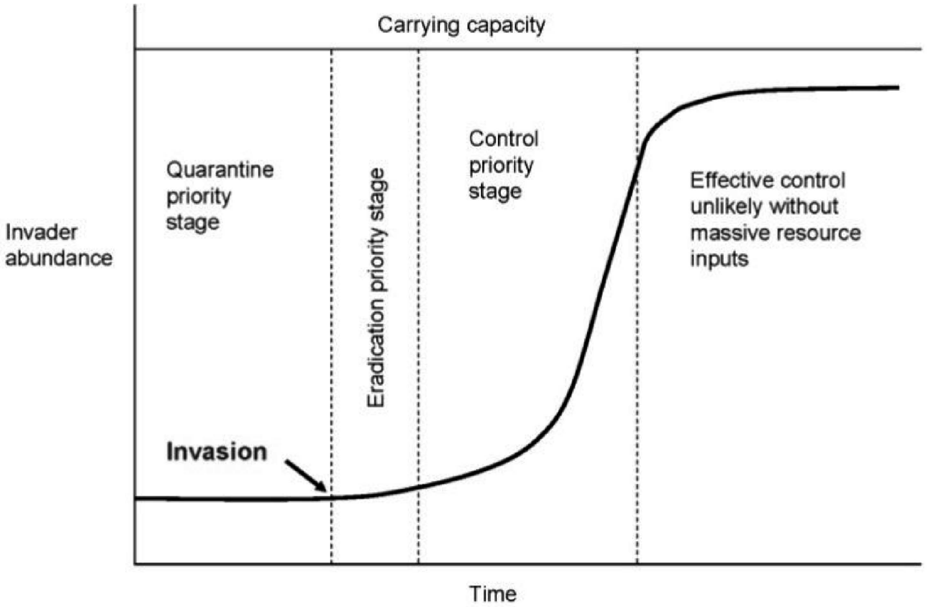

Figure 1. Control costs versus time since exotic invasion. (Redrawn from Hobbs and Humphries 1995.)

dearth of relevant literature. Inventory and monitoring efforts must be improved nationwide. Sparse populations in the establishment phase make it difficult to monitor and plan and subsequent expansion and saturation phases occur rapidly. In some cases, there are no known biological controls for invasive species. More research on the impacts and related science is critically needed.

Identifying research needs to manage current and future threats of invasive species is challenging because of the complexity of interactions among biotic and abiotic factors. Different aspects of the invasion process (e.g., introduction, establishment, and spread) require different research needs, innovative concepts, and new tools. To predict and prevent invasive species introduction, we should collaborate with international partners to create databases that inventory endemic and potentially invasive species. We should develop DNA-based diagnostic tools, which offer great potential for surveying species and determining genetic relationships between species. Basic research is needed in invader biology and the impacts of climatic change on populations to better understand invasion ecology. In addition, research on taxonomy, evolutionary relationships, population genetics, molecular biology, life history requirements, community interactions, and dispersal pathways of the invaders is essential to all aspects of invasive species programs. This basic information is often lacking but can be critical in predicting ecosystem susceptibility and identifying areas where early detection and rapid response programs will be most effective.

To develop this increased knowledge, we must make investments in research capacity in both public and private sectors. Federal, state, and local agencies often lack the ability to focus on invasive species because research positions are unavailable. For example, the five Research Stations of the US Forest Service employ only 13 full-time research plant pathologists who are responsible for addressing the research needs across 745 million ac of forested land in the United States (Tainter 2003, US Forest Service 2008). Likewise, too few research entomologists and invasive-plant biologists are employed by the US Forest Service. The number of research entomologists in the US Forest Service declined from 70 in 1985 to 22 in 2008 (US Forest Service 2008). University systems show similar trends as the number of forest pathologists and entomologists has declined over time. For example, from 1980 to 1990, the American Phytopathological Society identified 74 faculty at US universities whose research and outreach programs focused primarily on forest and shade tree pathology. By 2008, only 34 university faculty were engaged primarily in this field (David Gadoury, pers. comm., American Phytopathological Society, Sept. 23, 2008). The complexity of issues with respect to invasive species demands that we maintain a sufficient number of research scientists from interacting disciplines. Otherwise, management entities, research organizations, and government agencies will be unable to respond to the increasing threat from NNIS.

Policy development is also complicated by conflicting views of what constitutes an invasive species. This is especially true for certain plants. For example, reed canary grass (*Phalaris arundinacea*) is considered an invader from the forest management perspective but an opportunity for fiber development from an agricultural perspective. To be truly effective, policy initiatives will require a coordinated effort among government, academic, and other organizations.

4. Strengthen the Basic Forest Health Curriculum. Courses on forest health are lacking in many forestry schools today. Identification and control of NNIS must take place at the national, regional, and local level. Only by providing sufficient education about invasive species will this multilevel strategy be effective.

5. Encourage Cross-Agency Collaboration and Support Investment in Agency Resources at All Levels. In light of our nation's current economic troubles, a reluctance by politicians to aggressively address NNIS is understandable, but not excusable. The quality of life in the United States is as much a function of the natural resources that contribute—economically, ecologically, and spiritually—to our national sense of well-being as is the size of the paychecks in our pockets. An investment in the resources to detect, monitor, and treat NNIS will pay back many times over in terms of economic health, undiminished recreational opportunities, and ecological stability.

Summary

Invasive forest pests are being introduced into the United States at astonishing rates (Haack 2006). Once established, these pests could have tremendous adverse impacts on our commercial and urban forest resources. The basic tenet of sustainable forest management is "meeting the forest resource needs and values of the present without compromising the similar capability of future generations" (Helms 1998). NNIS threaten not only today's environment, but also the environment of the future.

The challenges facing the United States from the threat of NNIS are neither trivial nor subject to "quick fixes." A concerted, long-term, integrated effort is necessary if we are to sustain environmental quality. A bold vision combined with the political fortitude to maintain appropriate investments in prevention, detection, education, and treatment across political administrations, across government boundaries, and across decades is essential if we are to succeed in managing NNIS.

Endnotes

[1] Havill et al. (2006) suggest a different genotype of the species is native to western North America, which might explain why western hemlock (*Tsuga heterophylla*) trees were not as severely impacted as eastern and Carolina hemlocks.

[2] TEU (twenty-foot equivalent units): the amount of cargo that fits in a 20 × 8 × 8-ft container.

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