Science Priorities for Reducing the Threat of Invasive Species to Sustainable Forestry

Authors: CHORNESKY, ELIZABETH A., BARTUSKA, ANN M., APLET, GREGORY H., BRITTON, KERRY O., CUMMINGS-CARLSON, JANE, et al.

Source: BioScience, 55(4) : 335-348

Published By: American Institute of Biological Sciences

URL: https://doi.org/10.1641/0006-3568(2005)055[0335:SPFRTT]2.0.CO;2

Science Priorities for Reducing the Threat of Invasive Species to Sustainable Forestry

ELIZABETH A. CHORNESKY, ANN M. BARTUSKA, GREGORY H. APLET, KERRY O. BRITTON, JANE CUMMINGS-CARLSON, FRANK W. DAVIS, JESSICA ESKOW, DORIA R. GORDON, KURT W. GOTTSCHALK, ROBERT A. HAACK, ANDREW J. HANSEN, RICHARD N. MACK, FRANK J. RAHEL, MARGARET A. SHANNON, LISA A. WAINGER, AND T. BENTLY WIGLEY

Invasive species pose a major, yet poorly addressed, threat to sustainable forestry. Here we set forth an interdisciplinary science strategy of research, development, and applications to reduce this threat. To spur action by public and private entities that too often are slow, reluctant, or unable to act, we recommend (a) better integrating invasive species into sustainable forestry frameworks such as the Montréal Process and forest certification programs; (b) developing improved cost estimates to inform choices about international trade and pest suppression efforts; and (c) building distributed information systems that deliver information on risks, identification, and response strategies. To enhance the success of prevention and management actions, we recommend (a) advancing technologies for molecular identification, expert systems, and remote sensing; (b) evolving approaches for ecosystem and landscape management; and (c) better anticipating interactions between species invasions and other global change processes.

Keywords: invasive, sustainable, forestry, management, global change

Worldwide interest in sustainability—an approach to managing natural resources that meets present human needs while maintaining the earth's capacity to meet the needs of future generations—has burgeoned over the past two decades (NRC 1999). Forest management has been a focal part of this transition, because forests occur on about a third of the earth's land surface, support the lives and livelihoods of hundreds of millions of people, and provide habitat for much of the world's biological diversity (FAO 2001). More than 150 nations, the world's largest forest and paper companies, environmental and conservation organizations, scientists, and other stakeholders are now developing approaches for implementing sustainable forestry. Underlying these efforts is the premise that sustainable forest management must be economically feasible, socially acceptable, and environmentally sustainable.

Escalating rates of biological invasions pose a major, but as yet poorly addressed, threat to sustainable forestry in the United States and worldwide. Here we identify priorities for science and technology that could help reduce this threat. As in recent policy applications, by "invasive species" we mean "a species that is not native to an ecosystem and whose

Elizabeth A. Chornesky (e-mail: echornesky@sbcglobal.net) is a freelance analyst and works with various nonprofit organizations on science and policy issues related to global change, conservation, and sustainability; she can be reached at PO Box 22665, Carmel, CA 93922. Ann M. Bartuska was executive director of the Nature Conservancy's Invasive Species Initiative while this article was being prepared; she is now deputy chief for research and development for the US Department of Agriculture (USDA) Forest Service, Washington, DC 20090. Gregory H. Aplet is a senior forest scientist at the Wilderness Society, Denver, CO 80202. Kerry O. Britton is the national pathologist for forest health protection with the USDA Forest Service, Forest Health Protection, Arlington, VA 22209. Jane Cummings-Carlson is a forest pathologist with the Wisconsin Department of Natural Resources, Fitchburg, WI 53711. Frank W. Davis is a professor at the Donald Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106. Jessica Eskow is manager of environmental strategies at International Paper, Savannah, GA 31402. Doria R. Gordon is a senior ecologist with the Nature Conservancy and a courtesy professor of botany at the University of Florida, Gainesville, FL 32611. Kurt W. Gottschalk is a research forester and project leader for disturbance ecology and management of oak-dominated forests at the USDA Forest Service, Northeastern Research Station, Morgantown, WV 26505. Robert A. Haack is a research entomologist and project leader for biology, ecology, and management of exotic invasive forest insects with the USDA Forest Service, North Central Research Station, East Lansing, MI 48823. Andrew J. Hansen is an associate professor in the Ecology Department of Montana State University, Bozeman, MT 59717. Richard N. Mack is a professor in the School of Biological Sciences at Washington State University, Pullman, WA 99164. Frank J. Rahel is a professor in the Department of Zoology and Physiology at the University of Wyoming, Laramie, WY 82071. Margaret A. Shannon is an associate professor with the University of Buffalo Law School, State University of New York, Buffalo, NY 14260. Lisa A. Wainger is a research scientist at the University of Maryland Center for Environmental Science, Solomons, MD 20688. T. Bently Wigley is the manager of wildlife and watershed programs at the National Council for Air and Stream Improvement, Inc., Clemson, SC 29634.

introduction does or is likely to cause economic or environmental harm or harm to human health" (Exec. Order No. 13112, 64 Fed. Reg. 6183–6186 [1999]). Our focus on US forests and institutions provides a tractable scale for exploring the interplay among the economic, social, and environmental objectives of sustainable forestry. Nevertheless, advances identified here should be applicable to other sustainability contexts and should yield benefits worldwide.

Invasive species impacts on US forests

Over the past century, invasive species in the United States have detrimentally affected all of the attributes of forest ecosystems that sustainable forestry seeks to retain, including biological diversity, forest health and productivity, water and soil quality, contribution to the carbon cycle, and socioeconomic values. By some estimates, the US annual monetary losses of forest products caused by invasive species are more than $2 billion (Pimentel et al. 2000). Further, the effects of forest invaders have proved to be lasting and cumulative, and consequently threaten to undermine the obligation to future generations that forms the foundation of sustainability.

By damaging and killing dominant tree species, invasive pathogens and insects have caused cascading changes in the ecology, function, and value of diverse forest ecosystems (table 1, figure 1). Invasive plants have also significantly modified forest ecosystems by altering fire and hydrological regimes, food webs, and the recruitment of dominant tree species (table 1). New invasions continue with recent invaders, such as the sudden oak death pathogen (*Phytophthora ramorum;* Rizzo and Garbelotto 2003) and the emerald ash borer (*Agrilus planipennis;* 69 Fed. Reg. 55719–55733 [2004]), which could have similarly profound impacts (table 1).

Moreover, US forests have not yet experienced the full number of possible invasions or the full effects of already

*Figure 1. Damage by invasive species to US forests. (a) Extensive summer defoliation due to the European gypsy moth (*Lymantria dispar*), (b) death of oak canopy caused by sudden oak death (*Phytophthora ramorum*), and (c) extensive boring of an ash tree by the emerald ash borer (*Agrilus planipennis*). Photographs reproduced with permission from* www.invasive.org *and taken by (a) Kurt Gottschalk, US Department of Agriculture Forest Service (USDA FS); (b) Joseph O'Brien, USDA FS; (c) David Cappaert, Michigan State University.*

Table 1. A sample of possible future, recent, and past invaders of significance to sustainable forestry in the United States, listed in order of first US detection.

Species	First US detection	Ongoing and possible impacts	References
Nun moth (*Lymantria monacha*)	None	Could cause cumulative 30-year timber losses as high as $2.5 billion if established in three cities. Is the most damaging forest pest in Europe.	USDA APHIS/FS 2000
Sirex woodwasp (*Sirex noctilio*)	None[a]	Could cause cumulative 30-year timber losses as high as $760 million if established in three cities.	USDA APHIS/FS 2000
Asian frost-tolerant bamboos (*Sasa* spp.)	None	Could spread into coniferous forests in the Pacific Northwest that have habitats similar to the bamboos' native forests.	Mack 2003
Emerald ash borer (*Agrilus planipennis*)	2002	Currently in Michigan, Ohio, and Indiana. Could eliminate ash (*Fraxinus* spp.) as a street, shade, and forest tree nationwide. Estimated replacement costs thus far in the six originally infested Michigan counties of $11 billion, with reported annual losses of $2 million in nursery sales.	69 Fed. Reg. 55719–55733 (2004)
Lobate lac scale (*Paratachardina lobata lobata*)	1999	Currently in Florida. Generalist feeder known to affect approximately 150 native shrubs and trees and many native and nonnative species in cultivation.	Pemberton 2003
Sudden oak death (*Phytophthora ramorum*)	1994	Currently in California and Oregon and spreading rapidly. Has been detected in diseased nursery stock shipped from California to 22 states. Could devastate oak (*Quercus* spp.) forests nationwide.	Rizzo and Garbelotto 2003
False-brome (*Brachypodium sylvaticum*)	1939	Currently in Oregon but could spread rapidly. Displaces native understory plants, suppresses forest regeneration, degrades wildlife habitat, and increases fire risk.	False-brome Working Group 2003
Dutch elm disease (*Ophiostoma ulmi* and *Ophiostoma novo-ulmi*)	1927 (1940s for *O. novo-ulmi*)	Occurs in most states. Has killed more than 60% of elms (*Ulmus* spp.) in urban settings where the elm was a valued ornamental and shade tree.	Brasier and Buck 2001
Hemlock woolly adelgid (*Adelges tsugae*)	1924 (West); 1950s (East)	Currently in more than 16 states. Contributing to the decline of eastern and Carolina hemlock (*Tsuga canadensis* and *Tsuga caroliniana*). Alters bird communities and riparian ecosystems where it kills eastern and Carolina hemlock.	Campbell and Schlarbaum 2002, Tingley et al. 2002
Port Orford cedar root rot (*Phytophthora lateralis*)	1923	Throughout much of the range of Port Orford cedar (*Chamaecyparis lawsoniana*) in northern California and Oregon. Infected trees die.	Jules et al. 2002
Balsalm woolly adelgid (*Adelges piceae*)	1908	Attacks most North American true fir species (*Abies* spp.). In Great Smoky Mountains National Park, has caused dramatic declines in Fraser fir (*Abies fraseri*), resulting in changes to understory and wildlife.	Campbell and Schlarbaum 2002
Chestnut blight (*Cryphonectria parasitica*)	1904	Eliminated American chestnut (*Castanea dentata*) from eastern deciduous forests. Estimated value of standing chestnut timber in just three eastern states in 1912 was $82.5 million. Caused declines in wildlife that depended on chestnut.	USDA APHIS/FS 2000
Japanese climbing ferns (*Lygodium microphyllum, Lygodium japonicum*)	1903	Currently in southern states from North Carolina through Florida and west into Texas. Often prevalent in floodplain and upland pine forests. Forms thick mats that smother native ground cover and create links to tree canopies that carry fire and increase wildfire hazard.	Ferriter 2001
White pine blister rust (*Cronartium ribicola*)	Late 1800s to early 1900s	Currently throughout range of eastern white pine (*Pinus strobus*) and in six western states. Diminished economic value of white pine stands. Now killing whitebark and limber pines (*Pinus albicaulis* and *Pinus flexilis*) in western high-elevation ecosystems, thereby eliminating wildlife forage and tree contributions to soil stabilization, snowmelt regulation, and forest succession.	Krakowski et al. 2003
Beech scale insect (*Cryptococcus fagisuga*)	1890 (Nova Scotia)	Currently from Maine to North Carolina and west to Michigan; expected to spread throughout range of American beech (*Fagus grandifolia*). Serves as vector for native and invasive causative agents of beech bark disease (*Nectria coccinea* var. *faginata* and *Nectria galligena*). Disease kills more than 75% of large trees in places, leaving a wake of dense beech sprouts with reduced vigor and economic value.	Houston 1997
Larch casebearer (*Coleophora laricella*)	1886	Currently throughout range of eastern larch (*Larix laricina*). Recently established in the West, where it is now considered the most serious pest of western larch (*Larix occidentalis*).	Campbell and Schlarbaum 2002

(continued)

Table 1. (continued)

Species	First US detection	Ongoing and possible impacts	References
Cheatgrass (*Bromus tectorum*) and Lehman lovegrass (*Eragrostis lehmanniana*)	Late 1800s	Increase fire frequency and intensity when adjacent to forests. Pose a particular hazard to dense western forests that are susceptible to catastrophic wildfires.	Harrod and Reichard 2001
European gypsy moth (*Lymantria dispar*)	1869	Currently in 19 states; spot infestations in 12 more. Defoliates millions of hectares of northeastern and midwestern forests, generating suppression costs of tens of millions of dollars. Record losses in 1981: 5.3 million hectares defoliated; $3.9 billion (1998 dollars) in estimated tree losses.	USDA APHIS/FS 2000
Garlic mustard (*Alliaria pettiolata*)	1868	Currently in more than 25 states. Herbaceous understory invader displaces native plants, impedes tree recruitment, and reduces fitness of native butterflies.	Nuzzo 2000
Giant reed (*Arundo donax*)	1850s	Riparian invader currently in nine states, including national forests in California and Arizona. Thick stands choke waterways and water control structures, generate flammable debris, and displace native vegetation and wildlife (including the federally endangered least Bell's vireo, *Vireo bellii pusillus*).	Herrera and Dudley 2003

Note: Updated distributions of insects and pathogens are based on USDA Animal and Plant Health Inspection Service reports of quarantined pest distributions (3 December 2004; *www.aphis.usda.gov/ppq/*) and USDA Forest Service reports from annual pest surveys (3 December 2004; *www.fs.fed.us/na/morgantown/fhp/*). Distributions of plants from the National Plants Database maintained by the USDA Natural Resources Conservation Service (3 December 2004; *http://plants.usda.gov/*).

a. In Febrary 2005, a single specimen of *Sirex noctilio* was found in a funnel trap sample collected in New York State in late 2004. Establishment of this species in the United States has not yet been confirmed (Hoebeke et al. 2005).

established nonnative species. Despite improvements such as seed purity requirements and impending sanitation regulations for imported wood packing materials (69 Fed. Reg. 55719–55733 [2004]), key pathways for the entry or spread of forest invaders remain open or partially regulated (Campbell 2001). Rates of species movement are on the rise because of increasing international and interstate commerce (Campbell 2001). The pool of potential invading species is expanding as the diversity of woody materials and horticultural products imported to the United States grows and as trade with new partners enables species transfers between previously unlinked regions (USDA APHIS/FS 2000, Campbell 2001, Haack 2001). Continued increases in human access, fragmentation, and disturbance are escalating opportunities for invaders to penetrate and become established in US forests. Climate change will amplify these processes by altering disturbance regimes and the geographic ranges of forest and pest species (Dale et al. 2001, Williams and Liebhold 2002, Logan et al. 2003). As in the past, future invasions are likely to have enormous social, economic, and ecological consequences (table 1).

Prevention and response strategies

Three complementary strategies are essential to counter invasive species in US forests: (1) prevention of harmful new introductions by identifying and impeding pathways for invasive species introduction and spread, (2) detection and eradication of invaders that elude prevention, and (3) long-term management of well-established invasive species (figure 2). The effectiveness of each activity depends on the capacity and will of institutions and people to act and on the availability of and access to adequate knowledge and effective tools. Consequently, here we identify science advances that would better integrate invasive species into decisions affecting sustainable forestry and that would deliver crucial new tools and concepts. This is an outcome-based science plan rather than a conventional research agenda; it focuses on research, development, and applications to enable effective actions. Two themes permeate our analysis. First, reducing the invasive species threat poses problems that are inherently interdisciplinary (Leung et al. 2002), and the priorities presented here incorporate approaches from the social and natural sciences (figure 3). Second, invasion processes occur at geographic scales ranging from site to regional to continental, and can be strategically countered by prevention and management at all of these scales (figure 2). Each science priority we identify is relevant at several scales and would improve the effectiveness of several actions shown in figure 2.

Integrating invasive species into decisions that affect sustainable forestry

Addressing invasive species in sustainable forestry involves many individuals and organizations and, frequently, balancing their varied and sometimes conflicting objectives (table 2). In addition, some level of uncertainty will always characterize species invasions, because predictive systems are imperfect, invasion opportunities and impacts can change, and prevention is unlikely to be 100% effective (NRC 2002). Effective action, under these conditions, requires flexible and adaptive approaches in which forest managers and public agencies share a common understanding of the invasive species threat and have ready access to new information so that they can rapidly respond to change and to the unexpected. Here we discuss how scientific knowledge about invasive

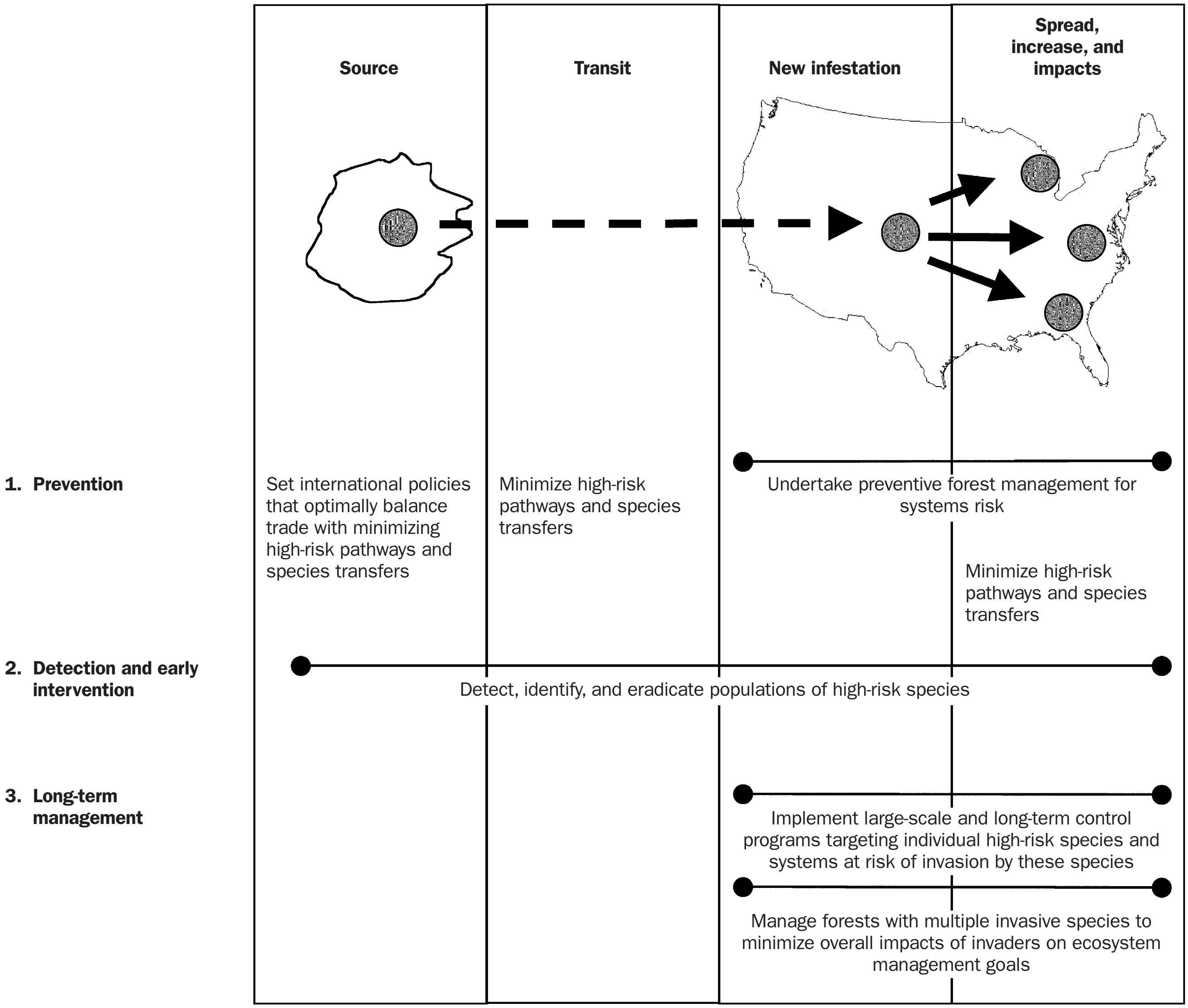


Figure 2. Three complementary strategies for reducing the impacts of invasive species in sustainable forestry. All three strategies are important to minimize not only future invasions but also the impacts and geographic extent of the many well-established invaders that already cause major harm. Countering a single pest can involve all three strategies. Efforts against gypsy moth, for example, involve identifying possible vectors and preventing new introductions of the species' Asian biotype from abroad, eradicating spot outbreaks in new states, impeding enlargement of infested areas, and managing infested areas to minimize damages caused by the moth.

species could be made available, better integrated, and used to improve decisions that affect sustainable forestry.

Build effective metrics into emerging sustainable forestry frameworks. Since 1993, public- and private-sector working groups have been developing several frameworks for sustainable forestry that consist of agreed-upon goals and approaches (SFI 2002, FSC 2004, USDA FS 2004). Participating nations and forest managers agree to report on specific metrics (variously termed "indicators" and "criteria") intended to assess their progress in achieving sustainable forestry. These frameworks hold particular promise for addressing invasive species, because they will encourage collective action across boundaries between nations, states, and land ownerships. Certain metrics and the methods for quantifying them are straightforward; for example, some measures related to forest productive capacity rely on existing forest inventory systems. In contrast, present approaches for quantifying how invasive species affect sustainable forestry's goals are immature and require further development.

One of the most important sustainability frameworks for North American forests is the Montréal Process, a joint initiative of 12 nations, including the United States, that collectively contain 90% of the world's temperate and boreal forests (USDA FS 2004). Participants have identified 67 indicators for measuring performance within seven general

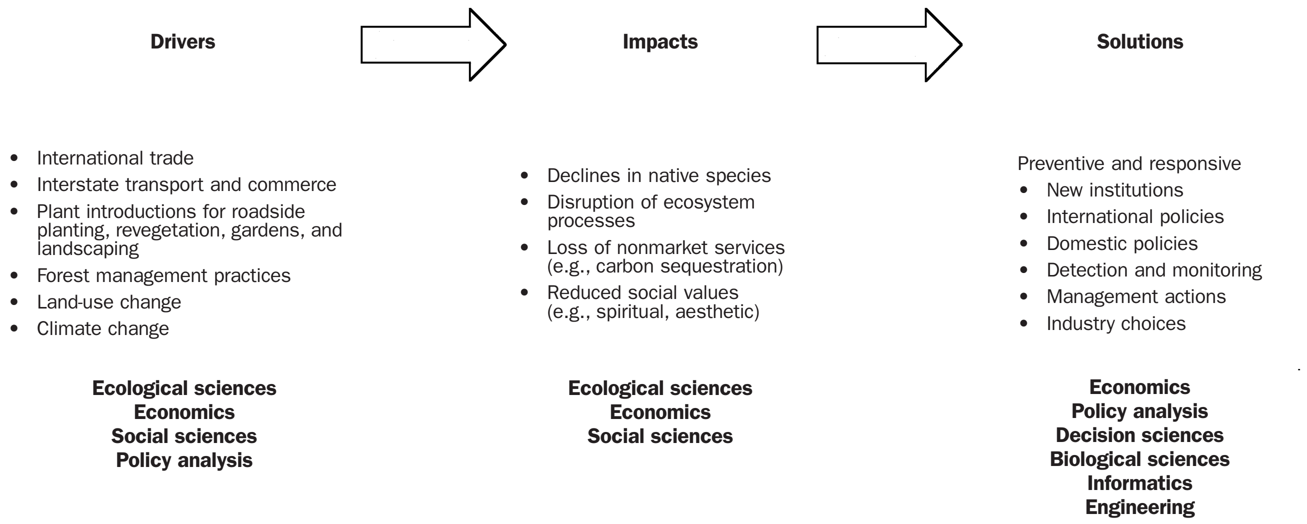


Figure 3. Examples of drivers, impacts, and solutions, demonstrating why an interdisciplinary approach is required to understand, prevent, and reduce the harmful effects of invasive species on US forests.

categories. Of these 67, only 2 refer to exotic species. Indicator 12, developed to help assess forest productive capacity, measures the "area and growing stock of plantations of native and exotic species." Indicator 15, developed to help assess the maintenance of forest health and vitality, measures the "area and percent of forest affected by processes or agents beyond the range of historic variation." However, these two indicators together do not adequately assess the threat posed by invasive species to sustainable forestry. For example, the recent *National Report on Sustainable Forests* (USDA FS 2004), in reporting US implementation of the Montréal Process, does not provide quantitative data on the overall economic and ecological impacts of invasive species on US forests—information that would provide a crucial baseline for weighing invasive species relative to other threats or for evaluating the effectiveness of related US policies and management actions.

Forest certification frameworks are a nongovernmental approach intended to have powerful effects on the policy and management choices of government agencies, timber and paper product companies, and other forest owners and managers. Owners and managers obtain certification that their forests are under sustainable forest management by demonstrating progress in fulfilling specific requirements to third-party auditors. Metrics relevant to invasive species in two of the more widely adopted certifications in the United States, the Forest Stewardship Council and the Sustainable Forestry Initiative, generally assess the extent to which participants minimize risks related to exotic tree plantings and monitor and manage forests to prevent and minimize outbreaks of pests,

Table 2. Social scales of influence and major activities for entities affecting invasive species in US sustainable forestry.

	Major activity				
Entity (organization, law, protocol, etc.)	**International**	**National**	**Regional**	**State**	**Local**
International Plant Protection Convention	T	–	–	–	–
North American Plant Protection Organization	T	–	–	–	–
Montréal Process	S	S	–	–	–
Forest certification programs	S	S	S	S	S
Timber and paper industries	S, M, C	S, M, C	S, M, C	S, M, C	S, M, C
Horticultural industry	C	C	C	C	C
Various industries involved in international trade that use wood packaging materials	C	–	–	–	–
USDA Forest Service	S, M	S, M, P	S, M, P	S, M, P	S, M, P
USDA Animal and Plant Health Inspection Service	T, P	P, Q	P, Q	P, Q	–
State agencies (forestry, natural resources, agriculture)		–	–	M, P, Q	M, P, Q
Nonindustrial private landowners	–	–	–	M	M
Local governments	–	–	–	–	M, P

C, commercial shipments of wood products or packing materials or of plants that might be (or become) contaminated by invasive pests; M, forest management; P, implementation of large-scale pest control programs for invasive species; Q, interstate regulation and quarantines of forest pests; S, development of sustainable forestry principles, criteria, indicators, objectives, and performance measures; T, international trade agreements, protocols, regulations, and quarantines; USDA, US Department of Agriculture.

diseases, and invasive plants and animals (SFI 2002, FSC 2004). While these and other certification systems are creating institutional structures suitable for addressing invasive species, their present metrics do not reflect current scientific understanding of the magnitude of this threat to all of sustainable forestry's goals or of potential solutions.

A need now exists to carefully evaluate whether the Montréal Process and the certification programs identify the correct metrics for fully assessing the invasive species threat and for measuring participants' implementation of appropriate prevention and response strategies. This evaluation should occur through the frameworks' various internal review mechanisms and should integrate external scientists and technical experts. An improved system of invasive-species metrics for sustainable forestry would provide sufficient specificity to track whether participants (a) eliminate pathways of invasive species spread; (b) manage forests in ways that reduce the likelihood of new invasions; (c) monitor with enough sensitivity to detect new invasions early and implement rapid response measures; (d) suppress established invaders, including by participating in area-wide monitoring and management efforts; and (e) consider how eradication strategies will affect other aspects of forest ecosystems and sustainability. At a minimum, reporting on progress toward sustainability should include tracking invasive species' social, economic, and ecological impacts. The review also should recommend the most effective methods for quantifying invasive-species metrics. This will be an important application for many of the advances in database development, spatial technologies, modeling, and other analytical methods identified elsewhere in this article.

Develop improved cost estimates to inform policy and management decisions. Critics charge that government policies and implementing agencies often fail to adequately consider the risks posed by invasive species when making decisions about international trade or evaluating pest control options (Campbell 2001). Yet remarkably little quantitative information exists about the past and projected costs of species invasions for US forests. When available, such information has affected policymaking—for example, in justifying the Animal and Plant Health Inspection Service's impending rules for treatment of solid wood packing materials (69 Fed. Reg. 55719–55733 [2004]).

More and better quantitative estimates of invasive-species costs would substantially strengthen decisionmaking by federal legislators and agencies, making it possible to weigh the outcomes of alternative policy and management actions (e.g., using cost–benefit or cost-effectiveness analyses, as encouraged by the US Office of Management and Budget) in terms that resonate with policymakers and the public. In keeping with sustainable forestry's goals, estimates of past and projected costs and benefits of policies should go beyond conventional economic analyses of market values, such as timber losses and pest suppression expenses. They should also quantify a wide range of nonmarket environmental and social values relevant to sustainability that may be degraded, such as watershed protection, biodiversity, and aesthetic and other amenity values (Naylor 2000, Leung et al. 2002).

Quantifying these nonmarket values will require surmounting certain technical problems. Objective quantifications of invasive species' environmental impacts generally are lacking (NRC 2002), making it difficult to translate these impacts into economic terms. Even with good information on environmental impacts, economic techniques for assigning dollar values to nonmarket goods and services are often costly and controversial. Values can be more easily estimated for well-documented services, such as human health or aesthetic protection, than for complex global services, such as carbon sequestration or climate regulation. Also, standard techniques discount benefits that accrue far into the future—a particular problem for invasive species, since expenditures on prevention or control often precede by decades the benefits derived from avoided harm. Alternative economic approaches should be explored for assessing how invasive species alter the capacity of forest ecosystems to deliver valued services (Daily 1997). Analyses might, for example, compare levels of ecosystem functioning with and without a specific invader present, or evaluate whether removing a species is a cost-effective way to reduce fire frequency or severity (Wainger and King 2001).

International trade decisions will be a key application for improved cost or risk estimates (Leung et al. 2002). Recent trade agreements have left federal agencies struggling to reconcile trade policies that potentially enhance invasion opportunities with their obligations to protect US agriculture and natural resources from invasive pests (Campbell 2001). Further, World Trade Organization (WTO) agreements only allow member nations to impose trade restrictions if they meet high standards of evidence of harm. Balanced economic analyses of imported species and commodities that weigh the full range of risks and benefits and make comparisons to available domestic substitutes could significantly improve the agencies' regulatory decisions, their ability to propose trade restrictions, and the acceptance of agency decisions by affected stakeholders.

Better cost and benefit estimates also could improve pest suppression programs. The speed and sequence of decisions and management actions during the progression of a biological invasion greatly influence effectiveness (Hobbs and Humphries 1995, Naylor 2000); yet invasive species can confound timely decisions (figure 4). Rapid-response decision rules could help resolve this dilemma by providing standard procedures for agencies to follow in times of emergency. At present, agencies develop methods to assess each new situation. Decision rules also would provide a clear rationale for appropriators to fund rapid responses.

Rapid-response decision rules would use objective criteria to assess the risks of a new species invasion, the potential costs and benefits of responding at different points in the invasion process, and the optimal timing for switching from an eradication campaign to suppression. Measuring the benefits of any given response will rest on demonstrating the invasive species' impacts on ecosystem services and other valued qualities. Risk assessments typically integrate situation-specific information, including species' ecological characteristics and their invasiveness and impacts elsewhere; ecosystem qualities that affect invasion vulnerability; and vectors that facilitate invasions. While methods for analyzing and making predictions based on such information continue to improve, risk assessments will always involve some level of uncertainty caused by insufficient information (Anderson et al. 2004). Scenario analysis is one approach that could enable decisionmaking even when uncertainty is great. For example, examining the cost-effectiveness of early eradication under different risk scenarios could help establish the threshold risk level that would justify rapid action.

Build distributed information resources to serve diverse decisionmakers. Diverse people and organizations make decisions every day that determine the impacts of invasive species on US forests (table 2). Unfortunately, the United States lacks the information infrastructure that would enable these decisionmakers to make consistently informed choices (NRC 2002). Despite proliferation of related online databases and information resources, the present US information system on forest invaders is incomplete and fragmented, and access to and analyses of these data are weak, mirroring the global status of invasive-species databases (Ricciardi et al. 2000). Most databases are not yet widely used, especially among the private sector and local governments—entities that own more than half of US forested lands. Detailed information is not readily available on the distribution and impacts of some of the most devastating forest invaders. Notably absent are anticipatory systems for preventive action that would routinely identify emerging pathways, probable new invaders, or ecosystems vulnerable to future invasions. Moreover, standards and protocols for data and information are recent developments, and modern data management practices have not yet been widely adopted by ecologists or forest managers (Green et al. 2005).

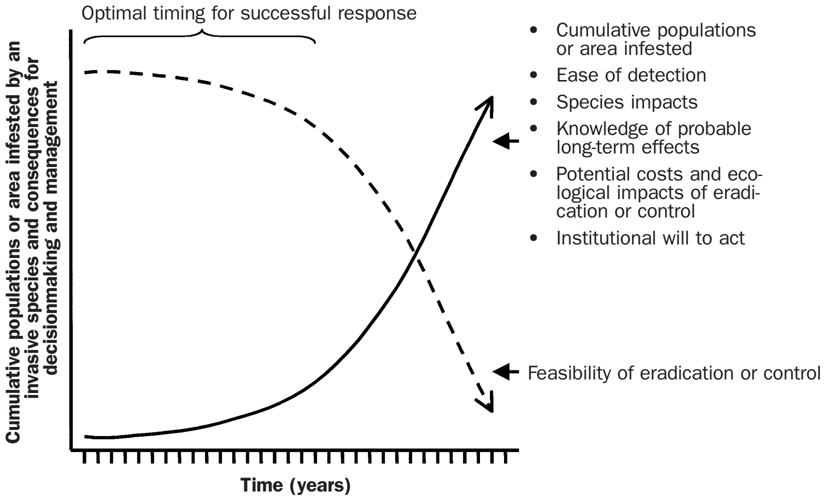


Figure 4. Illustration of how invasion biology confounds timely management decisions. Most species persist at low densities prior to rapid population growth, and during this period often are characterized by small, unstable, and widely dispersed populations that are difficult to detect. Because their full economic and environmental impacts are uncertain, government agencies and forest managers may be unwilling or unable to regulate species movements or to implement eradication programs early in the invasion sequence, although this is precisely when quarantine, eradication, and control are most likely to succeed. Rapid-response decision rules could speed decisionmaking by providing standard practices for evaluating the benefits and costs of early action. (See also Hobbs and Humphries 1995.)

The nation now needs a more comprehensive and dynamic information system on invasive species that presently do or could affect US sustainable forestry (figure 5). Realizing the full power of invasive-species databases will require new tools to mine and link these resources. Internet search engines and algorithms, Web crawlers, and other data-mining and classification techniques could aid in conducting targeted data queries across databases, in linking invasive species information with other data to deliver customized decision support products, and in automating risk alerts (figure 5). Ideally, the system should support distributed decisionmaking and collaborative public processes and deliver database query results in formats easily integrated into forest planning and management. It also should support rapid mobilization by government agencies and forest managers in the face of imminent threats, for example, by providing diagnostic tools and up-to-date biological information and management options. Possible economic or legal impediments to developing spatial data that describe forest conditions or identify the locations of invasive species on private landholdings should be assessed now to help set feasible expectations for the system.

Modification of some key databases would facilitate their use in risk identification (figure 5). The usefulness of the US Department of Agriculture (USDA) Forest Service's national Forest Inventory and Analysis, or FIA, database for identifying areas at risk of invasion would be improved by the inclusion of more data on alternative hosts (e.g., understory plants) and better links to sites with data layers on climate, soils, and high-risk locations (e.g., where host plants are sold in nurseries or bought by sawmills). The USDA's Port Interception Network (PIN) could be used routinely to identify high-risk pathways, if initial occurrences of known forest pests were systematically compared with variables that affect pathways, such as trade volume, commodity type, or shipping technologies and packing material (Haack 2001). The PIN's value for this purpose is currently limited, because it primarily includes pests of "quarantine significance" rather than all intercepted species,

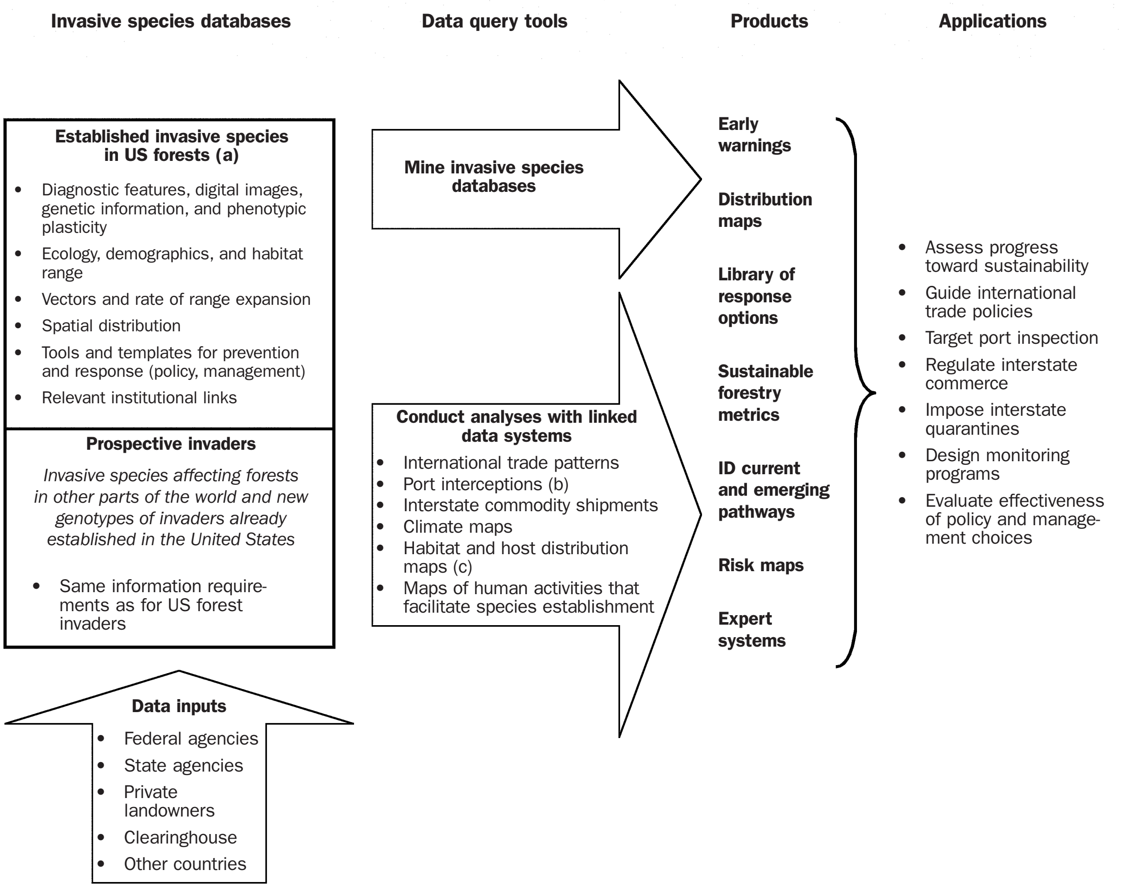


Figure 5. Concept for an informatics system on invasive species in US sustainable forestry. Key current databases on established invasive species (a) are the National Agricultural Pest Information System, or NAPIS, and the Exotic Forest Pest Information System for North America, or EXFOR. Other relevant databases and links to policy and management tools include Web sites maintained by the National Invasive Species Council, the National Biological Information Infrastructure, the Plant Conservation Alliance, the Nature Conservancy, the US Department of Agriculture Natural Resources Conservation Service, the Environmental Law Institute, and the Global Invasive Species Program. Major current information sources on port interceptions (b) and habitat and host distribution (c) are the Port Interception Network, or PIN, and the Forest Inventory and Analysis system, respectively.

and because access is restricted (NRC 2002). Coordinated reporting could significantly speed public and private responses to emerging threats. One possibility is a "national clearinghouse" that allows state agencies, tree-care companies, forest managers, landowners, and others to voluntarily report verified sightings (Kelly and Tuxen 2003).

Developing critical new tools and concepts

Significant needs will always exist for more information about the biology of invasive species and their behaviors in new places. Such information is essential for honing predictions and for designing effective measures to counter individual high-impact invaders. Against that general backdrop, several specific technical and conceptual advances will be essential for addressing invasive species in sustainable forestry.

Advance technologies for detection, identification, and monitoring. Accurate species identification is a key challenge in detection and monitoring. The number of trained taxonomists has dwindled. Physical characters used to identify species can be subtle and difficult to distinguish for nonspecialists, and taxonomic information is incomplete for many groups. Some closely related taxa, particularly different strains or hybrids of pathogens, lack obvious morphological differences. Identification can be further confounded if a pathogen causes various symptoms on multiple hosts, mimics symptoms identical to those caused by other pathogens, or undergoes rapid genetic changes that alter its epidemiology (Brasier 2001). For other taxa, species identifications often must be based on intercepted larvae, seeds, and spores that lack the distinguishing features of later life-history stages (Haack 2001).

Innovations from molecular biology, biotechnology, and digital imaging now hold the promise of providing new and easier approaches for detecting and identifying invasive species. Polymerase chain reaction technologies already are being used to detect plant pathogens in nursery stock (Davidson et al. 2003). As these technologies advance, real-time capabilities using microarray chips could be developed to assay for known pathogens of particular hosts at ports or during preshipment certification. The Central Science Laboratory at Sand Hutton, United Kingdom, is piloting this approach with a microchip that can screen samples for the presence of 250 potato pathogens (Ian Barker, Immunological and Molecular Methods Team, Central Science Laboratory, personal communication, 3 August 2004). DNA microprobes have similar potential for identifying insect larval stages and eggs found within cargo and packing materials (Kethidi et al. 2003). Although developing such identification techniques seems a major undertaking today, this investment will yield significant long-term benefits through improved inspection efficiency and reduced damage. Combining genetic information with improved digital imaging could provide powerful tools for future diagnostic identifications. Supporting the necessary online image and DNA libraries will require comparable advances in data development, archiving, and delivery.

Expert systems that automate risk identification at ports of entry could improve import screening and help fill the pressing need for rapid, flexible, and scientifically valid procedures that meet WTO criteria (Campbell 2001). Development and validation of systems that objectively evaluate intentional introductions might build on current techniques for predicting invasiveness that consider ecological traits, climate similarities between source environments and destinations, or host distributions (Sutherst et al. 1995, Reichard and Hamilton 1997) and that incorporate stochastic aspects of introductions (Mack 2000). Systems integrating data on imports (e.g., product records, receiving ports, containerized freight destinations), US habitat distribution (e.g., climate, soils, forest types), and pest distributions in originating countries could automatically target inspections toward commodities or other vectors known to harbor high-risk species or to come from countries that previously were sources of contaminated cargo. Such expert systems might also inform government inspection goals by providing information on contamination rates and probability of detection, and thereby reveal the extent to which the current inspection rate at US entry ports (2% in 2002) misses contaminants on imported wood products and packaging materials (NRC 2002). Applying expert systems will require setting acceptable levels of risk through transparent processes that consider the full risks of new forest invaders (including risks to biodiversity and ecosystem function) as well as the benefits of commerce (NRC 2002).

Tracking the advance or retreat of invasive species across large areas, often in remote locations, is a particular difficulty for sustainable forestry. Information must be geographically comprehensive, yet sensitive and frequent enough to encounter relatively small populations of invaders when they are easier to eradicate. Additional methods for developing and analyzing remote sensing outputs would help. Researchers have begun to explore applications of remote imagery (e.g., satellite, hyperspectral, multispectral, and aerial photography) for identifying the distribution or impacts of invasive pathogens, insects, and plants and for characterizing their spatial dynamics (Bonneau et al. 1999, Kelly and Meentemeyer 2002, Underwood et al. 2003). Patterns of defoliation, crown dieback, and tree mortality aid in monitoring certain species. Such analyses can pinpoint high-risk locations for more detailed ground surveys. Digital "sketch mapping" is being explored as a means of providing aerial survey results within days of flight. Accelerated research on remote sensing should be coupled with efforts to make the outputs easy to integrate into the activities of forest managers and state forestry organizations.

Evolve ecosystem and landscape management approaches. Despite their capacity to alter ecosystem processes, thus far invasive species have been poorly integrated into the conceptual framework for forest ecosystem management. This shortcoming is unfortunate, because spatial patterns of physical and biological processes across forests can retard or promote species invasions and could be managed to reduce invasion risks (With 2002).

For example, roads, railways, vehicles, and foot traffic provide conduits for various pests to spread, while contiguous populations of host plants and alternative hosts can enhance the spread of invasive pathogens and insects (Parendes and Jones 2000, Trombulak and Frissell 2000, Jules et al. 2002). Adjacent land uses, the size of habitat fragments, and the edge-to-interior ratio of forests all affect invasions (With 2002). Disturbances can open up habitat for invaders or, alternatively, disrupt species' dispersal corridors (With 2002). Fire suppression can intensify pathogen outbreaks by altering stand dynamics, whereas severe wildfires after years of fire suppression can facilitate the spread of invasive plants (Harrod and Reichard 2001, Krakowski et al. 2003). Silvicultural practices affect vulnerability to and recovery from pathogens and insects, as well as the relative abundance of nonnative understory plants (Gottschalk 1993, Houston 1997, Thysell and Carey 2001). Plantation forestry and land-use history may also affect understory communities (Harrington and Ewel 1997), and in some parts of the world plantation trees have become invasive (Richardson 1999). Some invasive species alter fire frequency, hydrology, and other ecosystem processes—changes that may favor further invasions by the same or other species (Vitousek et al. 1996). Interactions among these processes can influence invasive species' spread and success (With 2002).

This empirical and theoretical understanding of how landscape structure and ecosystem condition affect invasions now needs to be synthesized and transformed into management prescriptions that can be tested and improved through adaptive management. These prescriptions should aim to eliminate invasion pathways and opportunities and to minimize impacts where invasive species are established. The synthesis should consider common forest management practices, such as patterns of timber harvest and thinning, fire suppression and burn frequency, revegetation after disturbance, road building, and hunting and recreational uses, as well as natural disturbance regimes. It also should integrate how fragmentation and matrix land uses affect invasion vulnerability. Potential mitigation approaches should be identified, such as whether closing logging roads after harvest reduces invasion risks, or whether interplanting or buffers can slow the spread of host-specific invaders. An important issue will be whether fundamentally different approaches are required for managing forests with few invaders in comparison to those that are highly altered by repeated past invasions; for example, heavily invaded forests might tolerate a greater level of disturbance without experiencing a fundamental shift in species composition.

Spatially explicit models are increasingly important in forest management, conservation, and restoration (Dale 2003). They offer another approach for understanding how landscape structure affects invasions (Hart and Gardner 1997) and for designing effective monitoring and suppression programs against individual high-impact invaders. Models have ranged from static predictive mapping of species based on habitat suitability (Peterson and Vieglais 2001) to various dynamic population- or individual-based models (Sharov et al. 1998, Higgens et al. 2000). Some have projected ecological and resource losses, evaluated the cost-effectiveness of different management strategies, or screened potential invaders on the basis of how interactions with native species might affect their spread. Modeling has proved particularly useful for justifying and targeting resources for large, expensive management efforts (Sharov et al. 1998, NRC 2002). Time-series scenarios of spread under different management strategies now guide multistate gypsy moth (*Lymantria dispar*) suppression (Sharov and Liebhold 1998) and could be applied to other large-scale programs.

Spatial analyses could further explore how suppressing invaders at certain locations can reduce invasions elsewhere by altering source–sink dynamics. Improved understanding of spatial population dynamics might lead to general practices for managing invasive species *for* extinction—that is, encouraging local or regional extinctions by altering habitat fragmentation or connectivity (With 2002), by suppressing populations to maximize extinction probability, or by other means (Anderson et al. 2004). Further integrating economic tools with spatial population models (Sharov and Liebhold 1998, Sharov et al. 1998, Higgens et al. 2000, Leung et al. 2002) could help to optimize control strategies by distributing resources where and when a species' invasiveness and harmfulness are greatest, the treatment costs are lowest, or the chances of success are highest (Wainger and King 2001).

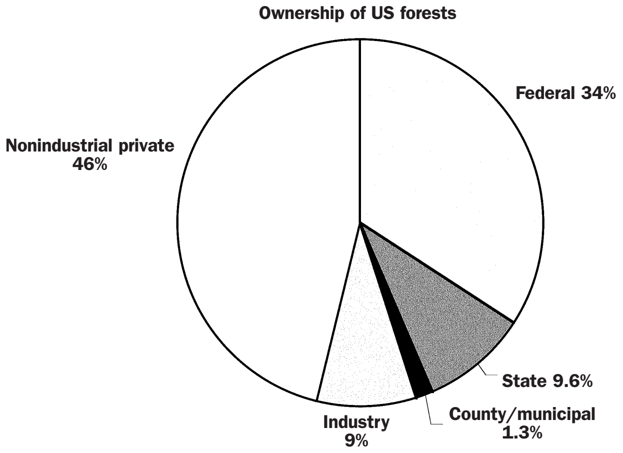
Effective management of invasive species across large forested areas ultimately will require participation by a mosaic of owners and managers having differing goals, cultures, and contexts for their actions (table 2, figure 6). Improved understanding of such variation could aid in developing processes, incentives, or policies that spur multiple landowners and managers to develop shared management objectives; to voluntarily contribute to large-scale prevention, monitoring, or management efforts; or to accept and adopt necessary control technologies.

Better integration of invasive-species issues into tools for forest ecosystem management will be essential. Early forest-planning models optimized harvest schedules for sustainable yield and were not designed to address spatial patterns of ecosystem processes such as wildfire or species invasions. Next-generation forest planning models now being developed incorporate landscape processes (Sessions et al. 1999), offering the potential to better integrate invasive species concerns into routine forest management planning. Meanwhile, even relatively simple approaches, such as GIS-based predictive mapping of site susceptibility to harmful alien species (figure 7), could help raise awareness among forest users and managers about potential risks in currently noninfested areas.

Address interactions with climate and other global change processes. Several global processes, including climate and land-use change, economic globalization, and alteration of nutrient cycles, are contributing to escalating rates of species invasions and impacts (Vitousek et al. 1996, Mooney and Hobbs 2000). Climate and land-use change alter the physical environment and disturbance regimes in ways that can favor nonnative species and alter forest ecosystem vulnerability to invasions (Dale et al. 2001). Economic globalization is not only changing the pathways and rates of species transfers between nations, but also the economic forces affecting local land-use decisions, and thereby indirectly influencing disturbance regimes and invasion opportunities.

The combined influences of global change processes will accelerate over this century, creating major shifts in the distribution of species, ecological communities, and ecosystems. Climate change alone may cause many ecological communities to disassemble, as species ranges shift at different rates in response to a changing climate and interacting variables such as hydrology, fire frequency, atmospheric carbon dioxide, and land use (Mooney and Hobbs 2000, Simberloff 2000, Dale et al. 2001, Hansen et al. 2001). Feedback loops could emerge that amplify these effects, as invasive species that further alter ecosystem functions become widely established (Vitousek et al. 1996). The ranges of many forest pests may shift, insect outbreak behaviors may intensify, and pathogen impacts may increase (Williams and Liebhold 2002, Logan et al. 2003). The social, economic, and ecological value of these systems could change radically and often may be degraded.

Managers, policymakers, and others who implement sustainable forestry need a far better conceptual approach for understanding interacting global change processes and making robust choices in the face of incomplete knowledge. New modeling and scenario-based approaches are needed to examine how interacting global change processes may alter



	Small	Large
Public	State, county, or municipal forests Primary management goals: • recreation • open space	Federal or state forests Primary management goals: • recreation • commercial harvest • biodiversity protection
Private	Nonindustrial forests Primary management goals: • aesthetic value • personal harvest	Industrial or nonindustrial forests Primary management goals: • commercial harvest

Figure 6. Forested lands are owned and managed by a mosaic of public and private owners. Important differences in management goals, access to scientific information and technologies, and the size of holdings potentially affect the ability and willingness of various landowners to prevent and suppress species invasions. More than 30% of privately owned forests are less than 100 acres (40 hectares) each. Pie chart based on data from US Department of Agriculture, Forest Service, Draft RPA 2002 Forest Resource Tables (as of 2 December 2004; http://ncrs2.fs.fed.us/4801/fiadb/rpa_tabler/2002_rpa_draft_tables.htm*).*

forest ecosystem vulnerability and invasion patterns, rates, and impacts (Simberloff 2000). These approaches should identify the ecosystems at greatest risk and help evaluate alternative management and policy options. To aid in building institutional response capabilities, they should describe pending changes over time scales that are relevant to harvest rotation and other business cycles, to the development of government policies, and to public values. Past models emphasized continental-scale shifts in species and ecosystem ranges: now needed are models of population, community, and ecosystem dynamics at scales that match local and regional decision-making.

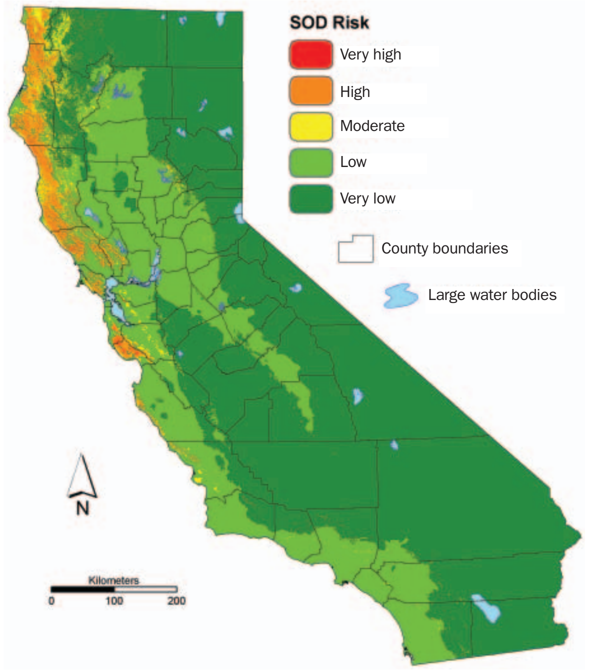


Figure 7. Predicted risk of establishment and spread of sudden oak death (SOD; Phytophthora ramorum*) in California, based on mapped climate variables and the distributions of host plant species (see Meentemeyer et al. 2004). Map is available online (*www.suddenoakdeath.org*) and reproduced with permission of the Sonoma State University Geographic Information Center.*

Important questions will arise about how managers should set appropriate and realistic goals for sustaining the social, economic, and environmental values of changing forest ecosystems—particularly since the feasible baselines for accomplishing these three outcomes could shift substantially. Maintaining present or restoring historical conditions, including species composition, often will not be possible, and sometimes may not even be desirable. One approach would be to specify desired ecosystem services—such as ecological functions, level of biological diversity, and economic outputs—rather than species-specific goals (Daily 1997). The process of specifying these services would need to incorporate the values different stakeholders assign to various services. Sustaining the delivery of desired ecosystem services will require new methods for measuring and monitoring ecosystem state and vulnerability relative to these objectives.

Forests afford a special opportunity for managing ecosystems to prevent, mitigate, or direct adaptation to global change. Many are already manipulated to achieve specific objectives, and methods exist for accomplishing these manipulations at large spatial scales. Forest dynamics are slow, because trees have long generation times, and these systems exhibit significant inertia in changing environments (Iverson et al. 2004). Preempting, minimizing, or reversing the worst impacts of biological invasions exacerbated by global change may often be necessary. Specific invaders or functional groups of invasive species might be targeted on the basis of their probable long-term impacts on ecosystem function and resilience in a future system that has changed and perhaps will change further. Inhibiting, or at least slowing, certain changes in species assemblages sometimes may be desired (e.g., to retain a reservoir of species for restoration or human-assisted range expansions; Hansen et al. 2001). Managers also might direct changes in species composition toward specific ecological outcomes, for example, where rates of species migration are too low to match rates of habitat change or where migratory corridors do not exist. Scientific advances discussed elsewhere in this paper would aid in designing, evaluating, and implementing such management interventions.

Conclusions

We have set forth an interdisciplinary, outcome-based science strategy for reducing the impacts of invasive species on sustainable forestry. This strategy addresses several persistent challenges that have emerged over the past decade as activity related to invasive species has burgeoned. New institutional mechanisms are needed to engage diverse players. Appropriate tools are lacking to tackle invasive species at large spatial scales. Despite explosive growth in online information resources, this information still needs to be translated into actionable knowledge. And invasive species have not yet been well addressed within the context of multiple societal goals or interacting global change processes. Forestry provides a strong platform for addressing these challenges because of its sustainability frameworks, well-developed approaches for ecosystem management, integration of spatial technologies into planning and management, and knowledge base on global change. Consequently, action on the priorities identified here ultimately should benefit not only sustainable forestry but also broader efforts to reduce the harmful impacts of invasive species.

Acknowledgments

This article is the result of a workshop sponsored by the National Commission on Science for Sustainable Forestry (NCSSF) and held at the National Center for Ecological Analysis and Synthesis (NCEAS) in April 2003. We are grateful to NCSSF for funding this project and to NCEAS for providing on-site support. We also appreciate the efforts of three anonymous reviewers whose comments greatly improved the manuscript.

References cited

Anderson MC, Adams A, Hope B, Powell M. 2004. Risk assessment for invasive species. Risk Analysis 24: 787–793.

Bonneau LR, Shields KS, Civco DL. 1999. Using satellite images to classify and analyze the health of hemlock forests infested by the hemlock woolly adelgid. Biological Invasions 1: 255–267.

Brasier CM. 2001. Rapid evolution of introduced plant pathogens via interspecific hybridization. BioScience 51: 123–133.

Brasier CM, Buck KW. 2001. Rapid evolutionary changes in a globally invading fungal pathogen (Dutch elm disease). Biological Invasions 3: 223–233.

Campbell FT. 2001. The science of risk assessment for phytosanitary regulation and the impact of changing trade regulations. BioScience 51: 148–153.

Campbell FT, Schlarbaum SE. 2002. Fading Forests II: Trading Away North America's Natural Heritage. (17 February 2005; *http://fwf.ag.utk.edu/Schlarbaum/FadingForestsII.pdf*)

Daily GD. 1997. Nature's Services: Societal Dependence on Natural Ecosystems. Washington (DC): Island Press.

Dale VH, ed. 2003. Ecological Modeling for Resource Management. New York: Springer-Verlag.

Dale VH, et al. 2001. Climate change and forest disturbances. BioScience 51: 723–734.

Davidson JM, Werres S, Garbelotto M, Hansen EM, Rizzo DM. 2003. Sudden oak death and associated diseases caused by *Phytophthora ramorum.* Plant Health Progress, 7 July 2003. (17 February 2005; *www.plantmanagementnetwork.org/php/2003.asp*)

False-brome Working Group. 2003. Invasive Plant Alert: False-brome (*Brachypodium sylvaticum*). Corvallis (OR): Institute for Applied Ecology. (23 February 2005; *www.appliedeco.org/FBWG.htm*)

[FAO] Food and Agriculture Organization of the United Nations. 2001. State of the World's Forests, 2001. Rome: FAO.

Ferriter A, ed. 2001. *Lygodium* Management Plan for Florida. (17 February 2005; *www.fleppc.org/Manage_Plans/lymo_mgt.pdf*)

[FSC] Forest Stewardship Council. 2004. FSC Principles and Criteria for Forest Stewardship. Bonn (Germany): Forest Stewardship Council.

Gottschalk KW. 1993. Silvicultural Guidelines for Forest Stands Threatened by the Gypsy Moth. Radnor (PA): US Department of Agriculture Forest Service, Northeastern Forest Experiment Station. General Technical Report no. NE-171.

Green JL, et al. 2005. Complexity in ecology and conservation: Mathematical, statistical, and computational challenges. BioScience. Forthcoming.

Haack RA. 2001. Intercepted Scolytidae (Coleoptera) at U.S. ports-of-entry: 1985–2000. Integrated Pest Management Reviews 6: 253–282.

Hansen AJ, Neilson RP, Dale VH, Flather CH, Iverson LR, Currie DJ, Shafer S, Cook R, Bartlein P. 2001. Global change in forests: Responses of species, communities, and biomes. BioScience 51: 765–779.

Harrington RA, Ewel JJ. 1997. Invasibility of tree plantations by native and non-indigenous plant species in Hawaii. Forest Ecology and Management 99: 153–162.

Harrod RJ, Reichard S. 2001. Fire and invasive species within the temperate and boreal coniferous forests of western North America. Pages 95–101 in Galley KEM, Wilson TP, eds. Proceedings of the Invasive Species Workshop: The Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management. Tallahassee (FL): Tall Timbers Research Station. Miscellaneous Publication no. 11.

Hart DR, Gardner RH. 1997. A spatial model for the spread of invading organisms subject to competition. Journal of Mathematical Biology 35: 935–948.

Herrera AM, Dudley TL. 2003. Reduction of riparian arthropod abundance and diversity as a consequence of giant reed (*Arundo donax*) invasion. Biological Invasions 5: 167–177.

Higgens SL, Richardson DM, Cowling RM. 2000. Using a dynamic landscape model for planning the management of alien plant invasions. Ecological Applications 10: 1833–1848.

Hobbs RJ, Humphries SE. 1995. An integrated approach to the ecology and management of plant invasions. Conservation Biology 9: 761–770.

Hoebeke ER, Haugen DA, Haack RA. 2005. *Sirex noctilio:* Discovery of a paleoarctic siricid woodwasp in New York. Newsletter of the Michigan Entomological Society 50: 24–25.

Houston DR. 1997. Beech bark disease. Pages 29–41 in Britton KO, ed. Exotic Pests of Eastern Forests: Conference Proceedings. Nashville (TN): US Department of Agriculture Forest Service and Tennessee Exotic Pest Plant Council.

Iverson LR, Schwartz MW, Prasad AM. 2004. How fast and far might tree species migrate in the eastern United States due to climate change? Global Ecology and Biogeography 13: 209–219.

Jules ES, Kauffman MJ, Ritts WD, Carroll AL. 2002. Spread of an invasive pathogen over a variable landscape: A nonnative root rot on Port Orford cedar. Ecology 83: 3167–3181.

Kelly NM, Meentemeyer RK. 2002. Landscape dynamics of the spread of sudden oak death. Photogrammetic Engineering and Remote Sensing 68: 1001–1009.

Kelly NM, Tuxen K. 2003. WebGIS for monitoring "sudden oak death" in coastal California. Computers, Environment and Urban Systems 27: 527–547.

Kethidi DR, Roden DB, Ladd TR, Krell PJ, Retnakaran A, Feng Q. 2003. Development of SCAR markers for the DNA-based detection of the Asian long-horned beetle, *Anoplophora glabripennis* (Motschulsky). Archives of Insect Biochemistry and Physiology 52: 193–204.

Krakowski J, Aitken SN, El-Kassaby YA. 2003. Inbreeding and conservation genetics in whitebark pine. Conservation Genetics 4: 581–593.

Leung B, Lodge DM, Finoff D, Shogren JF, Lewis MA, Lamgerti G. 2002. An ounce of prevention or a pound of cure: Bioeconomic risk analysis of invasive species. Proceedings: Biological Sciences 269: 2407–2413.

Logan JA, Regniere J, Powell JA. 2003. Assessing the impacts of global warming on forest pest dynamics. Frontiers in Ecology and the Environment 1: 130–137.

Mack RN. 2000. Cultivation fosters plant naturalization by reducing environmental stochasticity. Biological Invasions 2: 111–122.

———. 2003. Phylogenetic constraint, absent life forms and pre-adapted alien plants: A prescription for biological invasions. International Journal of Plant Sciences 164: S185–S196.

Meentemeyer R, Rizzo D, Mark W, Lotz E. 2004. Mapping the risk of establishment and spread of sudden oak death in California. Forest Ecology and Management 200: 195–214.

Mooney HA, Hobbs RJ, eds. 2000. Invasive Species in a Changing World. Washington (DC): Island Press.

Naylor RL. 2000. The economics of alien species invasions. Pages 241–259 in Mooney HA, Hobbs RJ, eds. Invasive Species in a Changing World. Washington (DC): Island Press.

[NRC] National Research Council. 1999. Our Common Journey: A Transition toward Sustainability. Washington (DC): National Academies Press.

———. 2002. Predicting Invasions of Nonindigenous Plants and Plant Pests. Washington (DC): National Academies Press.

Nuzzo V. 2000. Element Stewardship Abstract for *Alliaria petiolata* (*Alliaria officinalis*), Garlic Mustard. Arlington (VA): The Nature Conservancy. (17 February 2005; *http://tncweeds.ucdavis.edu/esadocs.html*)

Parendes LA, Jones JA. 2000. Role of light availability and dispersal in exotic plant invasion along roads and streams in the H.J. Andrews Experimental Forest, Oregon. Conservation Biology 14: 64–75.

Pemberton RW. 2003. Potential for biological control of the lobate lac scale, *Paratachardina lobata lobata* (Hemiptera: Kerriidae). Florida Entomologist 86: 353–360.

Peterson AT, Vieglais DA. 2001. Predicting species invasions using ecological niche modeling: New approaches from bioinformatics attack a pressing problem. BioScience 51: 363–371.

Pimentel D, Lach L, Zuniga R, Morrison D. 2000. Environmental and economic costs associated with non-indigenous species in the United States. BioScience 50: 53–65.

Reichard SH, Hamilton CW. 1997. Predicting invasions of woody plants introduced into North America. Conservation Biology 11: 193–203.

Ricciardi A, Steiner WWM, Mack RN, Simberloff D. 2000. Toward a global information system for invasive species. BioScience 50: 239–244.

Richardson DM. 1999. Commercial forestry and agroforestry as sources of invasive alien trees and shrubs. Pages 237–258 in Sandlund OT, Schei PJ, Viken A, eds. Invasive Species and Biodiversity Management. Boston: Kluwer Academic.

Rizzo DM, Garbelotto M. 2003. Sudden oak death: Endangering California and Oregon forest ecosystems. Frontiers in Ecology and the Environment 1: 197–204.

Sessions JK, Johnson N, Franklin JF, Gabriel JT. 1999. Achieving sustainable forest structures on fire-prone landscapes while pursuing multiple goals. Pages 210–254 in Mladenoff DJ, Baker WI, eds. Spatial Modeling of Forest Landscape Change. New York: Cambridge University Press.

[SFI] Sustainable Forestry Initiative. 2002. 2002–2004 SFI Standard and Verification Procedures. Washington (DC): American Forest and Paper Association.

Sharov AA, Liebhold AM. 1998. Bioeconomics of managing the spread of exotic pest species with barrier zones. Ecological Applications 8: 833–845.

Sharov AA, Liebhold AM, Roberts EA. 1998. Optimizing the use of barrier zones to slow the spread of gypsy moth (Lepidoptera: Lymantriidae) in North America. Journal of Economic Entomology 91: 165–174.

Simberloff D. 2000. Global climate change and introduced species in United States forests. Science of the Total Environment 262: 253–261.

Sutherst RW, Maywald GF, Skarratt DB. 1995. Predicting insect distributions in a changed climate. Pages 60–91 in Harrington R, Stork NE, eds. Insects in a Changing Environment. London: Academic Press.

Thysell DR, Carey AB. 2001. Manipulation of density of *Pseudotsuga mensiesii* canopies: Preliminary effects on understory vegetation. Canadian Journal of Forest Research 31: 1513–1525.

Tingley MW, Orwig DA, Field R, Motzkin G. 2002. Avian response to removal of a forest dominant: Consequences of hemlock woolly adelgid infestations. Journal of Biogeography 29: 1505–1516.

Trombulak SC, Frissell CA. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology 14: 18–30.

Underwood E, Ustin S, DiPietro D. 2003. Mapping nonnative plants using hyperspectral imagery. Remote Sensing of Environment 86: 150–161.

[USDA APHIS/FS] US Department of Agriculture, Animal and Plant Health Inspection Service and Forest Service. 2000. Draft pest risk assessment for importation of solid wood packing materials into the United States. (17 February 2005; *www.aphis.usda.gov/ppq/pra/swpm/*)

[USDA FS] US Department of Agriculture, Forest Service. 2004. National Report on Sustainable Forests—2003. (17 February 2005; *www.fs.fed.us/research/sustain/*)

Vitousek PM, D'Antonio CM, Loope LL, Westbrooks R. 1996. Biological invasions as global environmental change. American Scientist 84: 468–478.

Wainger LA, King DM. 2001. Using economics to prioritize invasive plant threats: Applying site and landscape indicators of risks to ecosystem services and values. Pages 34–51 in Groves RH, Panetta FD, Virtue JG, eds. Weed Risk Assessment. Collingwood (Australia): CSIRO.

Williams DW, Liebhold AM. 2002. Climate change and the outbreak ranges of two North American bark beetles. Agricultural and Forest Entomology 4: 87–99.

With KA. 2002. The landscape ecology of invasive spread. Conservation Biology 16: 1192–1203.


Conservation In Practice
A Publication of the Society for Conservation Biology
Combatting Roadkill
Mapping Urban Sprawl's Collision with Biodiversity
Unintended Consequences of Wetland Restoration
Winter 2004
The Geography of Endangerment • Gary Paul Nabhan
Losing: Gracefully, Creatively, and Humanely • By Jeffrey Lockwood
Win-Win Illusions
Facing the Rift between Poor People and Protected Areas