Forest Service R&D—Invasive Insects: Visions for the Future

Kier D. Klepzig[1], Therese M. Poland[2], Nancy E. Gillette[3], Robert A. Haack[2], Melody A. Keena[4], Daniel R. Miller[5], Michael E. Montgomery[4], Steven J. Seybold[6], and Patrick C. Tobin[7]

Abstract

The Forest Service has identified invasive species as one of four significant threats to our Nation's forest and rangeland ecosystems and likened the problem to a "catastrophic wildfire in slow motion." Forest Service Research and Development (R&D) has a crucial role in providing insight and options to protect trees, forests, and ecosystems from the threat of invasive insects. Currently, Forest Service R&D, in close cooperation with Forest Health Protection, provides information crucial to the development of tools for studying, controlling, and mitigating several invasive insects in the United States, such as the Asian longhorned beetle, emerald ash borer, banded elm bark beetle, Mediterranean pine engraver, Sirex woodwasp, and hemlock woolly adelgid. Forest Service R&D also strives for a broad, principle-based framework applicable to current and future invasive insect problems. The historic breadth and depth of R&D charges this branch of the Forest Service with playing a leadership role in providing long-term, comprehensive, cross-cutting solutions. Clients and scientists have worked together to identify short- and long-term needs to enhance existing research. Examples of this vision are provided in this paper.

This visionary white paper outlines several specific needs derived from a review of future needs and the strengths and weaknesses in existing programs. These issues are discussed and prioritized under four headings: (1) Prevention and Prediction, (2) Detection and Eradication, (3) Management and Mitigation, and (4) Restoration and Rehabilitation. A special concern has been raised that the Forest Service is losing its capacity to provide biologically based technologies, such as pheromones, biological controls, microbial pesticides, and other environmentally sound mitigation options, unless existing and anticipated gaps in expertise are filled.

The Role of Forest Service Research and Development

Forest Service Research and Development (R&D) has the strategic capability to conduct research on the biology, ecology, and management of invasive insects on a national scale. The Forest Service National Strategy and Implementation Plan for Invasive Species Management (NSIPISM), developed by a multidisciplinary team of specialists, managers, and scientists, serves as one perspective on customer needs of any Forest Service invasive insects program. Specifically, this document states that "...the Forest Service is well positioned to be a leader nationwide and worldwide in the battle against invasive species. Our challenge is to learn to lead collaboratively."

Specifically, Forest Service R&D has the following capabilities:

- Broad existing authorities and responsibilities assigned by the Chief of the Forest Service.
- Expertise in research on land management, entomology, pathology, ecology, and several other specialties.
- National and international presence.
- Relationships with every State and territorial agency with responsibility for invasive species.

[1] Assistant Director, Forest Service, Southern Research Station, 200 W.T. Weaver Blvd., Asheville, NC 28804.
[2] Research Entomologist, Forest Service, Northern Research Station, Stephen S. Nisbet Bldg., 1407 S. Harrison Rd., Room 220, East Lansing, MI 48823.
[3] Research Entomologist, Forest Service, Pacific Southwest Research Station, 800 Buchanan St., West Annex Bldg., Albany, CA 94710–0011.
[4] Research Entomologist, Forest Service, Northern Research Station, 51 Mill Pond Rd., Hamden, CT 06514.
[5] Research Entomologist, Forest Service, Southern Research Station, 320 Green St., Athens, GA 30602–2044.
[6] Research Entomologist, Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618.
[7] Research Entomologist, Forest Service, Northern Research Station, 180 Canfield St., Morgantown, WV 26505.

Strengths and Weaknesses of Forest Service R&D

Forest Service R&D is positioned to address the challenges posed by invasive species to U.S. forest resources. Applicable overall strengths of Forest Service R&D include the following:

- Breadth of skill sets among scientist ranks.
  - Molecular biology.
  - Chemical ecology.
  - Quantitative ecology.
  - Risk assessment.
  - Development of detection tools.
  - Development of management techniques.
- Access to a network of long-term sites.
- Ability to conduct longer term research.
- National presence and strategic plan.
- Ability of geographically dispersed units to address regional and national problems and coordinate across regions.
- Extensive infrastructure (labs, quarantine facilities, experimental forests).
- Ability to determine consequences and devise mitigation strategies for destructive invasive forest insects in advance of their establishment.
- Ability to discover and rear natural enemies, determine their nontarget effects, release them, get them established, and monitor their effect on the target pest and nontarget species.
- Unique partnerships with the National Forest System (NFS) and State and Private Forestry (S&PF), providing access to sites, technology transfer, and management expertise.
- Focus on forest pests.
- Focus on research rather than regulatory aspects.

To adequately deal with future needs around invasive species research, Forest Service R&D must also attempt to address weaknesses, including the following:

- A need for research-quality taxonomic expertise, including morphology, chemotaxonomy, and molecular taxonomy. The cooperation between Forest Service R&D and the Forest Health Protection (FHP) program in training taxonomists for use in the Early Detection and Rapid Response Program is an example of preliminary efforts to address this need.
- The need to strenghten in-house capabilities in molecular genetics and epigenetics.
- The need to integrate skill sets within Forest Service R&D to better address complex, multidisciplinary problems.

The Identity and Needs of Our Customers

In invasive species research, existing (and potential) customers are diverse, including the USDA Animal and Plant Health Inspection Service (APHIS), NFS, FHP, State agencies, and all entities required to have published sources to support their decisions. For these customers, as well as the academic community, publications in peer-reviewed scientific journals remain the standard products. Peer-reviewed competitive requests for proposals have been successful in drawing these customers together into cooperative research on a targeted topic. Careful consideration (with comprehensive user group input) of critical Forest Service R&D needs, however, is essential to credibility, relevance, and buy-in from users and supporters of such a program.

In addition, Forest Service R&D must respond to the technology transfer needs of forest land owners and managers, urban foresters, arborists, nursery and timber industry representatives, nongovernmental organizations (NGOs), Timberland Investment Management Organizations, and Real Estate Investment Trusts. Traditional products (refereed publications, scientific meetings) may not be sufficient to meet their needs. Partnerships with the FHP program, universities, cooperative extension, and NGOs may be especially valuable in this outreach. Partnerships through Forest Service International Programs, as well as international grants, may be useful in cooperating with international collaborators dealing with similar pests.

The development of true research partnerships (including joint study-plans, personnel sharing, sharing of administrative burdens, joint publication through Forest Service and external outlets, and joint presentations) is essential to success in this arena.

Responding to the Invasive Species Strategic Program Area Peer Review Panel

The recent peer review of the Invasive Species Strategic Program Area (SPA) provides some insight for the future of invasive species research within the Forest Service. The specific suggestions for improvement, development, and growth are listed in the following text.

Enhance External Partnerships

The need to focus more on interdisciplinary, cooperative research was clearly identified, although an overemphasis on outside cooperators could lead to Forest Service R&D becoming a funding organization with no ability to conduct research. Bilateral reciprocity agreements are one possible vehicle for addressing this need. The biggest problem in studying nonindigenous insects is the paucity of populations at the beginning of an invasion. One solution would be for scientists in the United States to work on species that are of concern to other countries while their scientists work on species that are of concern to us. Scientists in each country would have a high likelihood of enhancing our knowledge and developing effective solutions. Restricting the number of participating countries (e.g., China, Korea, Sweden, Canada) would ensure balanced reciprocity. Scientists could then justify their work-in-country under the agreement. We also enjoy and employ a broad array of international contact networks (e.g., Chinese Academies of Science and Forestry, International Union of Forest Research Organizations, members of many international pest quarantine research groups). This network provides resources, contacts, and much-needed background information on new species.

Improve Integration Within Federal Agencies

As a Federal Government agency within USDA Forest Service R&D has close administrative and cultural ties with APHIS, the USDA Agricultural Research Service (ARS), the U.S. Department of Homeland Security (within Customs and Border Protection), and other Government agencies. These ties facilitate the sharing of resources and research sites (e.g., ports of entry). Nevertheless, interagency integration could be improved to include better communication, coordination, and definition of roles. In some cases, APHIS is the lead agency in regulating and managing invasive species, and Forest Service FHP has the lead in others; however, neither is a research organization. Forest Service R&D and ARS are research entities engaged to find scientific solutions to invasive species problems. Clearly defined roles and improved communication can lead to better coordination and less competition among Federal agencies.

Improve Communication of Research Results

Communication of research results could be improved by strengthening internal networks (with FHP, S&PF, and NFS), developing a team of communication experts to identify key users and evaluate the most effective methods to reach them, increasing effective use of university extension services, partnering with end users in Forest Service R&D projects, and increasing participation in technical programs. An especially important step will be to engage end users, as much as possible, in research programs from the start in order to facilitate technology transfer and ensure operational compatibility. This approach could include something as technical as systems engineering or even a formal process such as that used in ARS.

Maintain or Enhance Infrastructure

One strength of Forest Service R&D is our extensive infrastructure that provides the facilities and capability to lead a national invasive species research program. To deliver successful programs, it is imperative that this infrastructure—particularly experimental forests, quarantine and rearing facilities, and collections and databases for long-term studies—be maintained and enhanced. Taxonomic expertise is in short supply in many disciplines; this is especially critical for invasive species research. The need to strengthen the interface between molecular technology and invasive insect science can be enhanced inhouse and through partnerships between Forest Service scientists and molecular biologists at universities. Past successes in documenting the source of invasions and connecting genetics to behavior have arisen from this model (e.g., Asian gypsy moth, hemlock woolly adelgid).

Short- and Long-Term Goals

In addressing the recommendations of the SPA review, it is useful to identify achievable, quantifiable goals. By necessity, some of these goals will be realistically set for the short term. Larger strategic goals will capitalize on the ability of the Forest Service to conduct long-term research.

Prevention and Prediction

Prevention and Prediction—Short Term

This goal ties in with broader priorities (identified in the Invasive Species SPA paper, "Overarching Priorities"): Predicting and Prioritizing, and Managing Invasive Species and Altered Systems. The NSIPISM also identifies the following short-term priority issues within the area of prevention:

- Work with APHIS and other partners to conduct analyses on invasion pathways and species risk assessments so that we can identify priorities and develop regulatory response plans.

- Build awareness of invasive species and their threat at all levels and jurisdictions.
- Complete a national research risk assessment to identify high-priority invasive species and continue working in their countries of origin to develop techniques to deal with these high-priority pests before they are introduced into the United States.

Other priority issues include the following:

- Need for more emphasis on developing background information on potential invasive species (e.g., forest insects of China) in English.
- Improved measures to reduce the risks of arrival through pathways such as solid-wood packing material, nursery stock, and other components of international trade and travel.
- Significant advances in the efficacy of fumigation and heat treatments for control of invasive species in solid-wood packing materials that arrive in the United States by sea and air.
- Development of new treatments in support of implementing higher standards for the bilateral shipment of these materials between North America and trading partners in Eurasia.

We also need to develop database systems (both nationally and internationally) to facilitate the transfer of information for intercepted species and prospective invaders. These systems should provide easy online keys and photos of all the stages. We need clear guidelines on acceptable risks and interception thresholds. We need to gather information on known invasive species affecting forests in other world areas and develop quick and cost-effective tools to identify intercepted species, especially because systematic resources are limited. This approach could minimize costs associated with eradication and management and could mitigate impacts to our Nation's forest and rangeland ecosystems.

To be able to create and manage resilient ecosystems, we must increase our understanding of the invasion potential of non-indigenous insects (i.e., species invasiveness) and the habitat characteristics that increase or decrease the ability for a new invader to establish (i.e., habitat invasibility). Understanding invasiveness is critical for improving our ability to predict the threat of nonindigenous species rather than relying on pest status in their native habitat.

Prevention and Prediction—Long Term

Any attempt to understand longer term scenarios involving prevention (and for that matter all other aspects of long-term invasive species research and development) will require, of necessity, predictive models. Models simulating long-term dynamics of invasive species will likewise need to involve consideration of changing forest ecosystems. Climate change has the potential to exacerbate insect outbreak intensity, increase voltinism, and permit the colonization of new habitats previously not susceptible to invasion. Fragmentation and other anthropogenic forces have the potential to drastically alter the movement of distribution of invasive species. The need for these long-term models will likely highlight the need for basic biological and ecological information that will inform their accuracy and utility.

Detection and Eradication

Detection and Eradication—Short Term

This goal ties in with Overarching Priorities 3 (Identifying and Detecting) and 4 (Managing Invasive Species and Altered Systems). NSIPISM also identifies the following short-term priorities for early detection:

- Establish a Forest Service-wide early detection and rapid response emergency fund. Develop guidelines to ensure that funds are immediately available to respond to newly discovered alien species.
- In partnership with the Forest Health Technology Enterprise Team, develop maps of priority ecosystems and habitats placed at risk from invasive species.
- Working with partners, develop rapid response incident teams that cross jurisdictional lines and respond quickly to newly established populations of invasive species.
- In partnership with the U.S. Departments of Homeland Security, the Interior, and Agriculture; State agencies; and others, develop high-speed, reliable, and robust technologies to detect and respond to introduced invasive species.

Other identified Detection and Eradication needs:

- Cooperative efforts with China and the European Union to develop a series of "sentinel forests" surrounding ports of entry to facilitate early detection.
- Development of improved cost estimates of impacts to inform decisions and regulations about international trade, eradication, and suppression efforts.

- Enlistment of public support from birdwatchers, master gardeners, arborists, tree-care professionals, warehouse workers, and others to look for unusual evidence of insect activity.
- Improved understanding of the relative efficacy of eradication tools for different types of invasive insects (e.g., Bt sprays for Lepidoptera [moths], tree removal for woodborers).
- Decision models to provide guidance in implementing eradication measures.
- Development of survey and trapping programs for broad categories of insects.
- Increased research and development involvement in the urban forests of the country.
- Seeking of opportunities to communicate with arborists, golf course managers, urban parks personnel, and city and county land managers about the invasive species problem.
- Elevation of priority of urban areas for future survey and detection efforts.

Detection and Eradication—Long Term

We need to develop new detection technologies, such as olfactory, acoustic, x-ray, ultrasound, thermal, and infrared. A critical component of detection programs is the development of cost-effective delimitation strategies employing lower cost detection tools that can be deployed at the landscape level. We need to develop new eradication techniques, such as the effective use of pheromones and other semiochemicals, to direct or target our eradication efforts in the future. We need to strengthen our collaborations with State agriculture officers and APHIS to facilitate eradication efforts.

Management and Mitigation

Management and Mitigation—Short Term

This priority ties in with Overarching Priority 4 (Managing Invasive Species and Altered Systems). Short-term needs are also identified in the NSIPISM as "Control and Management":

- Complete the comprehensive (all invasive species) inventory and mapping for all national forest land and water, including neighboring land, where appropriate.
- Conduct a comprehensive (all invasive species) risk assessment based on existing information for the specific purpose of identifying priority species and areas for program focus.
- Through research and other means, develop additional tools, such as biological, cultural, chemical, and physical controls, for priority species. Identify mechanisms involved in the arrival of these priority species and their successful establishment.
- Monitor long-term invasive species population trends and measures of treatment efficacy. Make this information readily available to all stakeholders, public and private.

Conducting research into new methods of controlling the spread of, or even the eradication of, isolated populations could yield significant advances. Economic analyses of impacts may aid in prioritizing investment in invasive species research, development, and application.

We need improved cost estimates on the type and extent of treatments that are needed in eradication and management. Chemical controls are often quick and inexpensive in the short run but may have undesirable and unintended nontarget effects. In the case of biological control agents, we must adequately evaluate their ability to establish and suppress populations of the targeted invasive insect.

Management and Mitigation—Long Term

Expanding classical biological control research would require developing primary quarantine and rearing facilities and delivering necessary resources to the units that maintain them.

Restoration and Rehabilitation

Restoration and Rehabilitation—Short Term

This goal ties in with Overarching Priority 4 (Managing Invasive Species and Altered Systems). NSIPISM also identifies several short-term priorities:

- Prioritize and develop native plant stock that is resistant to invasive insects and pathogens. Although this goal is identified in the NSIPISM as short term, it is normally a long-term effort.
- Work internally and externally to identify budget and capacity for implementing the national strategy.
- Establish multidisciplinary invasive species management teams in each region/station to implement the national strategy and implementation plan.
- Update and enhance the Forest Service's invasive species Web site to serve as a comprehensive communication tool.

- Work with partners to (1) develop a targeted marketing strategy to achieve public awareness of invasive species and an understanding of the role citizens can play; (2) complete the invasive species best management practices video series and handbook; (3) expand quarantine facilities for plant, insect, and pathogen control research; and (4) increase the availability of taxonomists to identify new invasive species.
- Work with other agencies, such as the USDA Economic Research Service, to expand economic impact assessments for priority invasive species.

We need to develop prescriptions for habitats and landscapes (urban and natural) that are resistant or resilient to invasion.

Restoration and Rehabilitation—Long Term

We must develop an understanding of mechanisms of tree resistance to invasive insects that are responsible for huge losses of specific tree species. In general, this research is very long term, requiring collaboration among entomologists, molecular geneticists, and tree physiologists. The development of transgenic trees resistant to invasive insects is also a long-term possibility.

Opportunities and Lessons Learned

Opportunities for Increased Efficiency and Cooperation

Because limited resources currently are invested in the area of invasive species research, very little duplication exists among stations and especially within invasive insect research. Nevertheless, some duplication (with communication to ensure complementary efforts) is desirable as individual labs and scientists working on similar problems often use different techniques and approaches. In addition, because the impacts of many invasive insects are national in scope, the scientists working on them frequently conduct research at a broad geographic level. Connections among scientists working on similar problems already exist, but they could be strengthened.

The core areas to maintain and enhance are basic biology, ecology (i.e., landscape, population, chemical), and biocontrol. We must consider Forest Service R&D's current and projected capacity for work on invasive insects, especially our diminished capacity for taxonomy among the research science programs nationally. It would also be helpful to have a database or library of detection baits for invasive species, particularly bark beetles for which we have some chemical ecology background. It is especially important to increase our taxonomic capacity, which would provide long-term institutional memory and structure for detecting nonindigenous species and for understanding and distinguishing them from native ones.

The need for entomologists trained in developing biologically based technologies for use in control programs is acute. Currently entomologists who have little direct training or are near retirement are conducting most of this work. The expertise concentrated in the Northern and Southern research stations should help leverage dollars and maintain critical mass in this area of inquiry, but it is crucial to develop a more geographically effective distribution of resources to face this issue.

Forest Service R&D must think broadly and be flexible. The appropriate mix of basic and applied research will be especially crucial. Some highly specialized basic research is required to develop critically needed biological and ecological knowledge bases; however, a critical need also exists for research with broad applications and the ability to shift among taxa and ecosystems. In particular, mechanistic-based research may tend to have especially broad implications and applications. In most cases, by the time we detect new invasive species, they are already established. Because many invasive species in the United States are not economically important in their native habitat, very little previous research is available; hence, we often are faced with the need to answer even the most fundamental research questions. To be truly effective, Forest Service R&D must partner with FHP, NFS, USDA APHIS, State agencies, and universities. We also need a certain degree of hyperactivity in outreach, such as pest alerts and forest insect and disease leaflets, university cooperative extension publications, presentations at work conferences, and arborists meetings.

Emerging Opportunities in the Arena of Invasive Insects

Invasion pathways and risk assessments are emerging as crucial fields in the study and management of invasive species. Understanding pathways (wood material, plants for planting, other commodities) is being emphasized as a promising approach in preventing the establishment of new invasive species. For

example, recent studies have highlighted the applicability of gravity models to facilitate our understanding of the human-mediated interactions between ports of egress and ports of entry that are critical in quantitatively assessing invasion pathways. Another emerging and increasingly rigorous field is that of risk assessment, which considers the risk of a specific invasive species, the magnitude of the potential loss from the risk, and the probability that such a risk will occur. Both of these areas are being emphasized in the creation and support of threat assessment centers.

A particularly worrisome—and probably under addressed—emerging problem is that of the acquisition of exotic fungi by native insects and the acquisition of native fungi by exotic insects and of the risks that these new relationships pose to native forests. The consequences are unforeseeable, but beetles are great disseminators of fungi. The need for DNA databases for fungal associates of beetles worldwide is thus paramount and would aid in our understanding of, for example, the impacts of ambrosia beetles and the mortality they may cause. Forest Service R&D should assume a leading role in ongoing international efforts to establish and coordinate global databases of molecular tools for species identification (e.g., Consortium for the Barcode of Life [CBOL] and GenBank®). Forest Service R&D should lead efforts to incorporate fungal associates of beetles and forest pests into the All-Fungi Initiative of CBOL. It is imperative that all new molecular sequences are linked with voucher specimens to ensure validity of the species name associated with the sequence. This effort requires the collaboration of taxonomists and molecular biologists. Forest Service R&D should lead the required phylogenetic work to support molecular databases. It is critical to develop molecular markers for species identification, especially for immature stages of native and commonly intercepted exotics.

A real opportunity exists to research ways to manipulate the Allee effect (wherein, in smaller populations, the reproduction and survival of individuals decrease, with the effect usually disappearing as populations grow larger) to facilitate management. Certain processes may lead to a decline in the population of an invasive species with a decline in its density; for example, the use of tactics designed to disrupt mating (mass trapping, release of sterile insects). Research that focuses on the manipulation of Allee dynamics may be especially useful and needed.

At present, we have numerous species of nonindigenous insects in the United States, and many more likely are not yet known to us. Even for those insects that we have detected, however, we lack an understanding of their potential impacts in our forest ecosystems. We especially need to initiate long-term research projects on the impacts of exotic insects on our native ecosystems. Such work will give us a much better idea of the magnitude of their costs (and maybe benefits), thereby providing a comprehensive base to support future research efforts. Long-term studies that record the presence of invasive species across robust spatial and temporal scales can also facilitate the development of models of spread and of the factors and processes that limit or enhance spread rates. This research would provide insight into climatic or biological factors affecting the spread of invasive species and would provide much needed data for risk analysis and policy decisions. Species-specific models could in turn be used to develop broader paradigms of spread applicable to other systems and invaders.

Other opportunities/visions provided by cooperators and customers include the following:

- Establishing a Forest Service-wide emergency fund and technical advisory teams to provide rapid response to new threats of invasive species.
- Increasing the efficacy of research partnerships and collaboration through more stable funding and through the monitoring and measurement of results.
- Establishing Forest Service-wide service centers funded by and overseen by two or more stations to provide mapping, quarantine facilities, molecular technology, etc.
- Increasing research efforts both internationally and nationally to identify ecosystem processes that provide resiliency to invasive species.
- Developing scientifically sound treatments for solid-wood packing material.
- Increasing our ability to detect and predict ecosystem change by better integration of research plots and information with Forest Inventory and Analysis databases.
- Developing improved estimates of the socioeconomic impacts of invasive insects, incorporating improved estimates of the costs and benefits associated with invasive species prevention and control, and collaborating with other agencies such as the USDA Economic Research Service.

Top Priorities

The direction from the U.S. Government Accountability Office and the Office of Management and Budget is that research has to be accountable and productive. With limited funds and people, the Forest Service R&D should maintain a balanced perspective in research endeavors. The effort should be high in short-term efforts that have a high likelihood of producing results. Therefore, efforts on any study should be based on the likelihood that such work will result in creating the science (adding to our knowledge base and developing new approaches), using the science (developing new/more effective tools), and furthering the science (increasing our understanding of risks and impacts).

One possible approach may be provided by considering the different types of pestiferous invasive insects. In this case, it is hypothesized that the likelihood of research creating, developing, and furthering science varies with insect type and with the different strategies of the invasive species strategic plan (table 1). In detecting new invasive species, fast and reliable detection methods are needed. The sooner a new pest is detected, the sooner an eradication program can be initiated, in general, over a smaller area. The feasibility and costs of eradication are directly related to the degree and extent of establishment. For example, lepidopteran defoliator pheromone lures that are effective even at low population densities have been highly effective in detecting newly established populations of gypsy moth that can be cost-effectively eradicated. When introduced in the past, the Asian gypsy moth has been successfully eradicated through the use of aerial sprays, ground sprays, and egg mass surveys because of our ability to detect low-density populations. Therefore, a high priority should be research aimed at developing extremely sensitive pheromone-baited traps for other invasive species. Forest Service R&D scientists have the expertise to tackle this objective.

In contrast with the understanding of pheromones for moths (*Lepidoptera*) and beetles (*Coleoptera*), pheromones are poorly understood for woodwasps (*Hymenoptera*) and for aphids and scales and their allies (*Hemiptera* and *Homoptera*). An early detection system for these invasive insect groups will likely involve either visual inspections or some new technology yet to be developed as opposed to pheromone-baited traps. It might likely be some time before publishable results would arise from such efforts. Work on detection for aphids and scales should be "low." Maintaining such work at a low level over a long period has a high likelihood of accomplishing some significant, but unpredictable, advances in the 25-to-30-year future, basically a "speculation" component to the investment strategy. At present, the best investments in dealing with introduced exotic aphids and scales are likely mitigation at a "medium" level with introductions of biological controls and restoration at a "high" level with a resistance breeding program. Another important component that is higher with aphids and scales would be prevention. Given the lack of ability to produce effective detection and eradication tools for these pests (in contrast with moth defoliators and bark beetles), it is better to find ways to minimize movement of such organisms from their country of origin. Certification programs at processing areas that ensure "Free of aphid or scale" would reduce the need to even deal with them. Similar approaches may be effective in prioritizing research and development regarding other invasive species.

Summary and Skills Needed

As stated in the Invasive Species SPA paper, "Overarching Priorities," "a holistic national strategy will improve sharing of expertise across research Stations, and encourage actions that prevent regional threats from expanding into national ones." We see the need for skills and skilled personnel to make these

Table 1.—*Research investment matrix: relative profitability of research for different groups of invasive insects and strategic goals.*

Strategic goal	Insect group			
	Defoliators	Bark beetles	Wood borers	Aphids/scales
Prevention	Low	Medium	Medium	High
Prediction	Medium	High	High	Medium
Detection	Very high	High	Medium	Low
Eradication	Very high	High	Medium	Low
Mitigation	Medium	High	High	Medium
Restoration	Low	Medium	Medium	High
Education	Medium	Low	High	High

visions a reality. Among the skill sets identified in the "Overarching Priorities" paper, we see the following skills as being especially valuable in addressing Forest Service R&D needs in the area of invasive insects:

- Taxonomic expertise (especially insects and associated microorganisms).
- Systematics (morphological and molecular, insects and associated microorganisms).
- Genetics (classical, population, and molecular).
- Ecology (chemical, population, invasion/disturbance, and landscape).
- Basic biology (especially insects and associated microorganisms).
- Integrated pest management.
- Monitoring design.
- Toxicology and environmental fate (of pesticides).
- Risk assessment.
- Economics (impacts of outbreaks).
- Technology transfer (pest alerts, monitoring, and quarantines).