6 Early Intervention Strategies for Invasive Species Management: Connections Between Risk Assessment, Prevention Efforts, Eradication, and Other Rapid Responses

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6.1 Introduction

Managing invasive species becomes increasingly difficult and expensive as populations of new pathogens, plants, insects, and other animals (i.e., pests) spread and reach high densities. Research over the past decade confirms the value of early intervention strategies intended to (1) prevent invasive species from arriving within an endangered area or (2) detect and respond quickly to new species incursions (Baker et al. 2009; Ewel et al. 1999; Holden et al. 2016; Leung et al. 2014). The goal of such biosecurity approaches is to keep or return the density of invasive species to zero so that damages from those pests might be prevented or to confine populations to localized areas so that damage from those species might be limited (Magarey et al. 2009). Prediction, prevention, early detection, eradication, and other rapid responses, all components of proactive management, are less costly and more effective than reactive tactics (Epanchin-Niell and Liebhold 2015; Leung et al. 2002; Lodge et al. 2006; Rout et al. 2014) (Fig. 6.1). Prediction is achieved through *risk assessment* (a process to forecast the likelihood and consequence of an invasion) and *pathway analysis* (a process to evaluate the means by which invasive species might be brought into an area of concern). Prevention is achieved through a variety of measures including regulations and quarantine treatments. Indeed, pathway analyses and subsequent regulation of those pathways are considered "the frontline in the prevention of biological invasions" (Hulme 2009) and cost-effective approaches (Essl et al. 2015; Keller et al. 2007; Leung et al. 2002; Tidbury et al. 2016). Surveillance is fundamental to early detection, and if a target species is detected, the primary rapid responses are eradication, containment, or suppression (reviewed in Beric and MacIsaac 2015). Early intervention strategies often operate at spatial scales that are much greater than the scale at which most land managers operate. Success thus requires effective coordination among researchers, regulators, and managers at international, national, sub-national, and local levels.

Early intervention strategies for invasive species share many elements with integrated pest management (IPM) approaches that are used against well-established pests (Venette and Koch 2009). In broad terms, IPM requires (1) clear articulation of a goal for the system; (2) background

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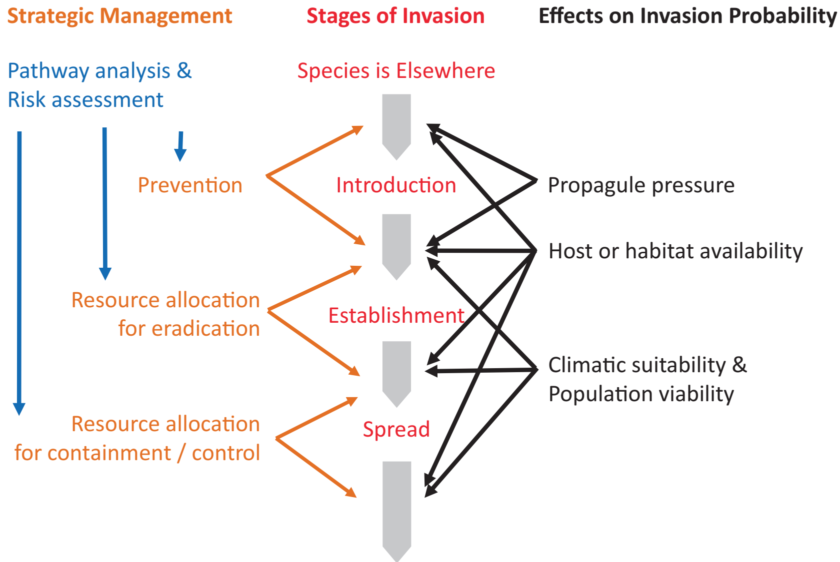

Fig. 6.1 Relationship between the stages of pest invasion, opportunities for strategic management, and factors that affect invasion probability (*red* depicts stages of invasion; *black* depicts factors influencing invasion probability; *blue* depicts analyses that facilitate when and where management should be targeted; *orange* depicts management options)

knowledge of the complex of pestiferous species (species with ability to cause harm) that might affect a system (i.e., prior experience); (3) systems to monitor for the presence and abundance of those species (i.e., sampling tools and plans); (4) guidance on when management is worthwhile (e.g., economic thresholds); (5) a suite of complementary tools and tactics to affect the abundance or impact of unwanted species (e.g., resistant plants, pesticides, and biological control agents); and (6) follow-up methods to ensure that interventions are successful. Current IPM programs have evolved through years of intensive research on the biology and management of single species in a range of systems and environments.

Early intervention strategies for invasive species expand on principles derived from IPM. For example, prior experience is supplemented with information about the suite of pestiferous species that affect similar ecosystems globally. Pest risk assessments attempt to help distinguish those non-native species with a high probability of causing harm from those that might not be harmful. Likewise, both general and specific tools and techniques are needed to find newly invading species and quickly and accurately identify them. Many responses to invasive species are similar to those for well-established pests, but early intervention strategies for invasive species may also involve quarantines, regulations, or more intensive approaches to ensure pest elimination or containment. These measures may be imposed and paid for by governments and immediately affect producers and other stakeholders. Because early intervention efforts have the potential to conflict with other social values (e.g., limits to freedom of personal movement or trade), a reliable, scientifically credible assessment of the likelihood that an alien species will cause harm is needed to determine whether the benefits of a preventative measure outweigh its costs. The design and implementation of early intervention strategies often do not have the benefit of years of research and must contend with significant uncertainties about the biology of threatening alien species, how those species might affect different ecosystems, and the effectiveness of management responses, especially under budget constraints. Research is underway to more accurately measure these uncertainties, reduce them, and provide tools to address uncertainty in decision-making (e.g., Koch et al. 2009; Yemshanov et al. 2015).

This chapter summarizes major research accomplishments on early intervention strategies, with a special emphasis on risk assessment, for invasive species. We emphasize results that apply to multiple alien taxa. References to particular invasive pathogens, plants, or other pests are provided to illustrate general concepts. The unique interplay between science and regulation needed to devise early intervention strategies may be unfamiliar to some researchers, so we provide overviews of regulatory procedures to illustrate how research results may inform regulatory decisions. Space constraints prevent us from addressing the diverse research projects that provide a basic understanding of the biology of threatening invasive species, even though such knowledge is imperative for conducting rigorous pest risk assessments and effective early intervention strategies.

6.2 Risk Assessment

6.2.1 Definitions of Risk

The word "risk" has many definitions across disciplines. "Risk" is used colloquially to describe an undesired consequence of an event (e.g., cancer as a consequence of smoking), but is technically defined as the product of the probability that an undesired event will occur, sometimes described as 'exposure,' and the consequences of the event, sometimes described as 'effect' (Kaplan and Garrick 1981). This definition underpins the definition of pest risk assessment for invasive species (IPPC 2016b). The unwanted event is typically the entry (i.e., introduction or arrival), establishment, and spread of a particular alien species into an uninvaded area (all related to 'exposure' in broader risk assessment parlance), and the consequences are the economic, ecological, or social impacts of invasion (all related to 'effect').

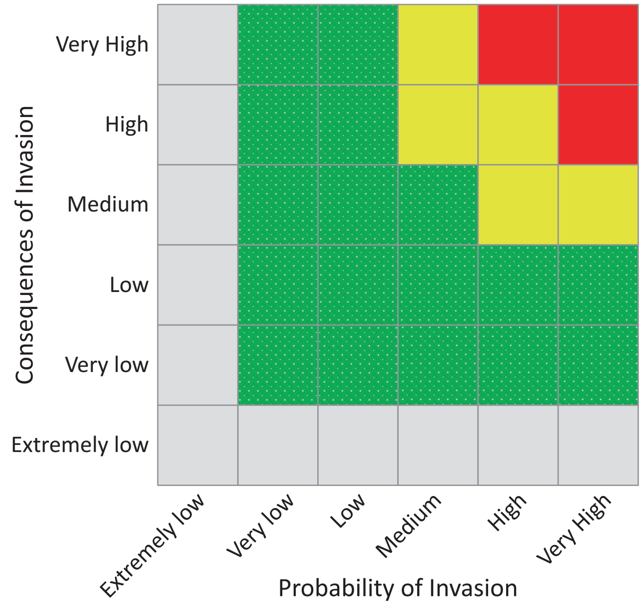

Fig. 6.2 Pest risk matrix depicting how the likelihood and consequences of invasion affect overall risk (*red* = high risk; *yellow* = moderate risk; *green* = low risk; *grey* = effectively no risk)

6.2.2 Introduction to Risk Assessment

Risk assessment is broadly defined as a process to determine the probability that a specified negative event will occur and the magnitude of its effect. While the process sounds simple and general guidance is available (e.g., Baker et al. 2009; Venette 2015), no requisite standards or techniques exist to quantify risks for invasive species (Hulme 2003). Typical approaches for assessing risks associated with invasive species often focus on identifying pathways and processes of introduction and movement, characterizing susceptible hosts and suitable environments, and evaluating the potential consequences of spread and establishment in previously uninvaded areas (Andersen et al. 2004; Pheloung et al. 1999; Venette 2015). However, data on the behavior of alien species and their biology in novel landscapes are often scarce or nonexistent, which leads to coarse representations of risk that are based extensively on expert judgment or simple analytical approaches (Andersen et al. 2004; Gray et al. 1998; Landis 2003; Landis and Wiegers 1997; Rafoss 2003). The results of such analyses are largely qualitative and usually are assigned an ordinal risk rating (e.g., high, moderate, or low risk). Qualitative assessments (Fig. 6.2) may be adequate to assist managers or policymakers in making decisions, such as whether to allow importation of certain commodities or to prioritize particular pests for survey. Baker et al. (2015) provide a decision-support system to determine when qualitative or quantitative analyses may be needed for decision-making.

Quantitative estimates of risk may help to focus discussions on complex policy issues (Gray et al. 1998). Such advanced models require numerical models capable of representing invasion processes in realistic environments and processing large geographical data sets (Yemshanov et al. 2009b). In fact, Andersen et al. (2004) identified multiscale decision-support systems as one of the urgent research needs for better risk assessments of invasive species.

Ideally, risk assessment is conducted within a preventative approach to screen species before the species arrives in a new country or region (i.e., "pre-border"). Because a history of harmful invasion elsewhere is a consistently accurate predictor of invasion in a new region (e.g., Gordon et al. 2008), cost-effective risk management could start with this single question (as implemented for the USDA Animal and Plant Health Inspection Service Plant Protection and Quarantine (APHIS PPQ) Not Authorized Pending Pest Risk Analysis list; USDA 2015). However, as more species are moved with global trade (Bain et al. 2010; Kaluza et al. 2010; Yemshanov et al. 2012), a history of previous invasion may be unavailable to use as a guide. Therefore, risk assessment is also conducted "post-border" after a damaging alien species has been detected within a country to prioritize management efforts. Frequently, assessments must be performed rapidly, incorporating any available information, especially in response to new pest incursions.

Methods for risk assessment depend on both the mode(s) of potential entry into the region of interest and the type of species involved. Unintentional introductions are most common among those species that are inadvertently moved with the transport of people, goods, or commodities (e.g., marine organisms in ballast water, forest insects in solid wood packing, or crop pests on imported plants) and often involve alien species that have caused harm elsewhere (i.e., proven to be invasive outside the area of concern). Conversely, plants, pets, livestock, and biological control agents are often deliberately introduced. These alien species may or may not have a history of causing harm and will generally have perceived benefits, for which they are being imported. While pre-border pathway analysis is required to assess the probability that a species will unintentionally arrive, that probability can be assumed to be 1.0 for deliberate introductions. Though environmental variables (climate, substrate, etc.) may limit the potential for establishment and spread of many introduced species (e.g., Kearney and Porter 2009), deliberate care, especially of intentionally introduced plants, may overcome initial environmental constraints to establishment (Mack et al. 2000). Assessments of entry, establishment, spread, and impact are required to support biosecurity decisions for intentional and unintentional introductions.

Pest Risk Assessment and Commerce Entry potential is dynamic through time, so decision-makers need guidance from risk analysts and other researchers on the potential of an alien species of concern to invade locations of interest (Lodge et al. 2006; Muirhead et al. 2008). Recent research has demonstrated that the entry (and often the subsequent spread) of invasive organisms has been facilitated by humans and their various economic activities (Hulme 2009; Hulme et al. 2008; Kaluza et al. 2010; Lounibos 2002; Westphal et al. 2008). The long-distance spread of alien species has been linked to patterns of historical settlement (Brawley et al. 2009), marine and terrestrial trade and transportation (Bain et al. 2010; Blakeslee et al. 2010; Kaluza et al. 2010; Yemshanov et al. 2013), and human population density, and national wealth benchmarks (Pyšek et al. 2010). Most markedly, increases in the number of new invasive species that have invaded the United States have corresponded with the expansion of international trade, which now regularly features long-distance, rapid transport of raw commodities and finished goods (Bain et al. 2010; Bradley et al. 2012; Pyšek et al. 2010).

In North America and elsewhere, the rate of growth of trade volumes is expected to exceed the rate of economic growth (UNCTAD 2007; WTO 2008). The transportation corridors that facilitate this trade also have become critical avenues for introducing alien species (Tatem et al. 2006). The complexity of modern transportation networks and the range of socioeconomic factors that influence trade flows (and the potential spread of alien species) are also projected to increase (Pyšek et al. 2010). Under these circumstances, rapid assessments of the potential origins of new (or anticipated) species introductions are a critical starting point in identifying possible pest outbreaks and strategizing measures for immediate response and screening. General biosecurity concerns are not grounds to impede trade, so the challenge becomes to identify specific threats and take appropriate actions to mitigate those threats based on the best available science following International Plant Protection Convention (IPPC) standards (Devorshak 2012). Research in this area has benefitted significantly from international cooperation (Chap. 13).

Assessments of the Potential Entry of Alien Species Assessments of entry potential can be undertaken with modeling tools that trace the movement pathways of an alien organism from its suspected region(s) of origin to locations of interest (e.g., Carey 1996; Muirhead et al. 2006; Pitt et al. 2009; Wang and Wang 2006; Yemshanov et al. 2013). In general, data on the gross trade volume may serve as a crude proxy to estimate the anticipated number of new pest incursions in a region of interest. Several studies have modeled the entry potential of pests as a function of changing climate (e.g., Magarey et al. 2007), socio-political and economic events (such as the recent global financial crisis; e.g., Koch et al. 2011), or the impact of new trade rules (e.g., Costello et al. 2007). A dynamic representation of the pest entry process also provides a more reliable depiction of multiple reintroductions over time (Koch et al. 2009; Rafoss 2003; Yemshanov et al. 2009a). However, determining the finer scale geographic distribution of these new incursions usually requires a more detailed analysis of the movement of specific commodities and cargoes that may have a high probability to carry invasive species through a region's network of trade routes and transportation corridors (Hulme 2009; Hulme et al. 2008; Kenis et al. 2009). Where comprehensive data on commodity movement and species incursions are available, data-driven models of invasion risks can be produced. For example, Koch et al. (2011) outlined procedures to combine broad- and fine-scale data on trade and commodity movement with historical pest records to estimate establishment rates for alien forest insect species in urban areas across the United States. Increasingly, direct-to-consumer import via internet sales overcomes earlier pathway constraints and poses an additional threat for purposeful imports (Humair et al. 2015).

Pathway analyses provide keen insights on propagule pressure, now recognized as a key determinant of invasion success (e.g., Lockwood et al. 2005; Simberloff 2009; Wilson et al. 2009). Propagule pressure describes the composite number of individuals of an alien species that are introduced to an area and is a reflection of the number of introduction events (i.e., propagule number) and the number of individuals introduced per event (i.e., propagule size). As propagule pressure increases, the probability of establishment in otherwise suitable environments is likely to increase, but propagule size and number may affect the nature of this relationship differently (Lockwood et al. 2005). Propagule number can affect the likelihood that a species arrives during climatically suitable periods while propagule size can affect the level of genetic diversity in a given introduction (Novak 2007). Propagule size also affects the ability of the nascent population to overcome random demographic effects, like chance variation in the number of females born to a population, or Allee effects, processes that disproportionately affect small populations and can lead to negative population growth rates, such as the challenge of finding a mate (Drake and Lodge 2006; Leung et al. 2004). Policy analysts have suggested that placing a greater emphasis on devising methods to reduce propagule pressure may provide substantial gains in efforts to prevent future invasions (Hulme et al. 2008; Meyerson and Pyšek 2013; Reaser et al. 2008).

Assessment of Areas Suitable for Establishment of Alien Species Assessments of the potential for establishment typically focus on a single pest and require extensive information about the threatening or invading species and the endangered area. Frequently, analyses begin with listing the environmental factors and resources (e.g., soils or hosts) that might support or limit a pest's distribution. As the development of many pathogens, plants, arthropods, and some vertebrates is dictated by temperature and moisture, an evaluation of climate suitability can be particularly informative. Climate suitability for pest establishment can be assessed by analyzing the climatic conditions of regions where the species is known to exist and using the resulting models (alternatively known as ecological-niche, species-distribution, or climate-envelope models) to forecast the quality of the environment for establishment in endangered areas (e.g., Jarvis and Baker 2001; Peterson et al. 2011a; Venette et al. 2010). Alternatively, data from properly designed experiments to ascertain how population growth or decline is governed by temperature or moisture can be used to develop mechanistic models of the suitability of climates for the persistence of an invading population through time (e.g., Pattison and Mack 2009).

Assessments of Potential Spread by Alien Species The study of the ecology and mathematics of spread by alien species is a long-standing, rich, active area of research (e.g., Phillips 2015; Shigesada and Kawasaki 1997; Skellam 1951). The potential for an invasive species to spread from points of introduction into climatically and ecologically suitable areas largely depends on that species' biological capacities, specifically its population growth rate and dispersal ability, and other means by which the species may be moved. Spread can be facilitated by humans (such as by transportation or movement of goods and commodities), hence the assessment of spread risk often involves characterization of patterns and modes of human movement, but not always in the specific context of trade; for instance, Tatem (2009) investigated the spread of invasive species via airline passenger travel. In any case, when knowledge about the factors that control the behavior and microevolution of a species in a novel environment is lacking, estimates of a species' survival and spread are ambiguous. In this case, comparing historical spread records of the species in similar climatic regions, or in other areas where it is known to exist, can help to estimate an approximate range of spread rates in the area of concern.

Assessments of Potential Impacts from Alien Species Risk assessments also depend on forecasts of the potential extent of ecological (Chaps. 2 and 3), social (Chap. 12), or economic impacts (Chap. 14). Alien organisms can damage economically valuable host resources and negatively affect the state of economically important agricultural systems and native ecosystems (e.g., estuaries). Assessing economic risks implies a valuation of economic consequences and impacts from an introduction and spread of an alien organism. The potential extent of economic damages may justify enacting quarantines or other regulatory actions aimed to eradicate or contain the spreading populations or, if containment is no longer feasible, to slow the rate of its spread (Epanchin-Niell and Wilen 2012).

Pest risk assessments can also focus on indirect economic effects, such as impacts on trade (Arthur 2006; Breukers et al. 2008; Surkov et al. 2009), anticipated changes for exports and access to markets (Cook 2008; Elliston et al. 2005; Juliá et al. 2007), changes to the production costs in domestic markets (Macleod et al. 2003; Soliman et al. 2010), or large-scale impacts at the macroeconomic level (Wittwer et al. 2005). Some other harder-to-assess risks include potential impacts on ecosystem structure or function, social infrastructure, recreational activities (e.g., fishing or use of firewood), and factors associated with human health (e.g., water quality or productivity of important agricultural crops). The estimation of non-market impacts caused by alien invasive species requires application of special techniques, such as hedonic analysis (Holmes et al. 2010), contingent valuation (Mohammed 2014), stated preference (Morse-Jones et al. 2014), and benefit transfer methods (Loomis et al. 2014).

Impacts from invasion have proven difficult to forecast reliably, and methods to more accurately forecast impacts over space and time are an active area of research (Kumschick et al. 2015; Venette et al. 2010). The framework to assess impact as proposed by Parker et al. (1999) and reviewed in Chap. 2 is extremely useful conceptually. The framework asks (1) where an alien species is, now or in the future; (2) how abundant is it or might it be; and (3) what impact it is having or might have on a per capita basis. The ecological impact of each alien species is not expected to be constant in space or time but will depend on the response of interest (e.g., species losses or changed abundance), an outcome of complex interactions between the invading species and biotic and abiotic components of the recipient ecosystem. As a result, some previous efforts to measure impact have met with mixed results. For example, assessments of impacts from wetland invasions by purple loosestrife (*Lythrum salicaria*) have ranged from no clear impact or insufficient evidence (Farnsworth and Ellis 2001; Hager and McCoy 1998; Lavoie 2010) to clear negative effects (Blossey et al. 2001; Schooler et al. 2006).

6.2.3 Assessments for Intentional Introductions

Here, we focus on risk assessments for two types of intentional introductions: alien plants for consumption or planting and classical biological control agents for alien plants or arthropods.

Assessments for the Intentional Introduction of Alien Plants The "Weed Risk Assessment" (WRA) system developed in Australia (Pheloung et al. 1999) is widely used, either in its original form or with slight modifications, to assess intentional introductions of plants. Research has demonstrated that this tool accurately identifies over 90% of harmful plant invaders, misidentifies fewer than 10% of non-invaders as invasive, and requires further evaluation (biased toward non-invaders) for fewer than 15% of species; this accuracy is consistent across temperate, tropical, island, and continental applications (Gordon et al. 2008). This primarily trait-based tool was originally designed for pre-border use. The weed risk assessment system used by the USDA APHIS PPQ Plant Epidemiology and Risk Analysis Laboratory, hereafter referred to as PPQ WRA (Box 6.1), is based on the Australian approach (Koop et al. 2012). The PPQ WRA framework draws from international standards for phytosanitary measures (IPPC 2016a, 2016c).

Assessments for the Intentional Introduction of Classical Biological Control Agents for Invasive Plants or Arthropods The enemy release hypothesis contends that invasive species are problematic because they have escaped the effects of natural enemies (e.g., herbivores, predators, parasitoids, or pathogens) that kept the invader at a low density in its native range (reviewed in Liu and Stiling 2006). So, the premise of classical biological control is that reintroducing those natural enemies to established invading pests should lower the densities of those invading pests, an approach that is more sustainable and less disruptive than many chemical or physical approaches to pest management. For classical biological control agents of plants, the challenge is to ensure that agents, typically pathogens or insect herbivores, only affect the targeted weed, not other valued plants such as crops, ecologically important plants, or federally listed threatened and endangered species (reviewed in Schaffner 2001). These efforts are meant to guard against unintended outcomes. For example, the weevil *Rhinocyllus conicus* was introduced from Europe into North America in 1968 to control invasive thistles (primarily in the genus *Carduus*) but has now been recovered from at least four *Cirsium* spp., including Platte thistle (*C. canescens*), a close relative of the federally listed Pitcher's thistle (*C. pitcheri*) (reviewed in Louda 2000). Similarly, assessments for classi-

Box 6.1: Overview of the Weed Risk Assessment (WRA) Framework Used by the US Department of Agriculture, Animal, and Plant Health Inspection Service, Plant Protection and Quarantine (USDA APHIS PPQ)

The USDA APHIS PPQ uses the WRA when an applicant seeks a permit to import or export a new, as-yet-not-approved alien plant species for planting into the United States. The agency conducts its own analyses with the best scientific information available, some of which may be provided by the applicant, but typically it would not be conducting primary research in support of the application. The assessments are conducted to evaluate the likelihood of a plant taxon becoming weedy or invasive, and to determine where it might become established in the United States. Analyses are based on a logistic regression model that is used to quantify a plant taxon's ability to escape, establish, and spread outside of intentional cultivation, and thereby cause harm to U.S. plant resources (Koop et al. 2012). The PPQ WRA relies on a series of questions to generate risk scores for the plant taxon's entry, establishment, spread, and impact potential. Decision or risk thresholds (1) maximize the model's ability to correctly identify the likelihood that a plant taxon will become a non-, minor, or major invader; (2) minimize predictive errors; and (3) translate risk scores into final risk ratings: low, moderate, or high. Taxa rated as a moderate risk undergo further screening of life history and behavioral traits associated with invasiveness, as expressed throughout the taxon's geographical distribution. The global distribution of a plant taxon is used to infer which plant hardiness zones, Köppen-Geiger climate classes, and mean annual precipitation bands might be needed for establishment and to identify areas in the United States that meet those criteria. Entry potential is assessed only if the taxon is not already present in the United States and is based on the likelihood of intentional or accidental entry. Risk scores are generally higher for taxa valued by society or cultivated outside the United States. Uncertainty in the risk score is assessed by using Monte Carlo simulations to generate 5000 simulated risk scores and analyzing the distribution of outcomes.

cal biological control agents of invasive arthropods are intended to ensure that the proposed agent affects only the targeted species (reviewed in van Lenteren et al. 2006). The released tachinid fly *Compsilura concinnata* in 1906 to control the gypsy moth (*Lymantria dispar*) and browntail moth (*Euproctis chrysorrhoea*) causes significant mortality in the cecropia moth (*Hyalophora cecropia*) (Elkinton and Boettner 2012) and exemplifies the undesired outcome. These examples of unintended consequences of biological control are relatively limited, and modern pre-release screening procedures and safety reviews minimize potential impacts to non-target species (Hajek et al. 2016).

In the United States, screening of alien natural enemies to assess their safety and suitability for environmental release as biological control agents of invasive plants or arthropods does not involve a formal quantitative risk assessment process, and decision-making does not rely exclusively on data acquired, and analyses generated, by the APHIS PPQ. Instead, researchers (also known as 'petitioners') may submit petitions to the APHIS PPQ, ultimately to gain approval to release classical biological control agents into the environment. Petitions summarize taxonomy, geographic distribution, life history, and ecology of the target species and candidate biological control agent(s). Frequently, the petition includes the results of pre-release host range tests to determine the suite of species upon which the agent might feed or infect. Host range testing often follows a centrifugal phylogenetic approach, with extensive testing of the target and closely related taxa and less emphasis on more distantly related taxa (e.g., Evans and Tomley 1994). The petition includes a description of experimental methodology, results, and analyses used to assess host specificity and impact of the candidate agent. Known and potential environmental impacts associated with the target plant and candidate biological control agent(s) are described. A general description of procedures to obtain the approval to release a new biological control agent in the United States is given for invasive plants in Box 6.2 and for arthropods in Box 6.3.

6.2.4 Assessments for Unintentional Introductions of Alien Species

Assessments of unintentional introductions typically focus on alien species that are likely to cause harm, often with an emphasis on a single species or a suite of species associated with an imported good. A complete assessment would evaluate both the likelihood that a species would invade and the consequences of that invasion (Venette et al. 2010). Clear

Box 6.2: Overview of Procedures to Obtain Approval to Release Classical Biological Control Agents for Weeds in the United States

All relevant information that must be included in a petition to release a new, non-native biological control agent of weeds is described in the USDA (2016). This guide is also used by the Technical Advisory Group for Biological Control Agents of Weeds (TAG-BCAW, or TAG) to appropriately review petitions. TAG is a scientifically independent, voluntary committee comprising members appointed by Federal agencies, such as the USDA, U.S. Department of the Interior, Environmental Protection Agency, and U.S. Department of Defense, along with representatives of the National Plant Board, the Weed Science Society of America, and Canadian and Mexican governments. TAG advises petitioners and provides USDA Animal and Plant Health Inspection Service Plant Protection and Quarantine (APHIS PPQ) with recommendations about the safety of releasing candidate agents based on the completeness and robustness of information presented in petition documents. TAG serves in a purely advisory role.

If TAG recommends that the APHIS PPQ approve the release of a specific petitioned agent and APHIS PPQ concurs with that recommendation, then the ensuing issuance of a permit by APHIS for the environmental release of the agent is considered a Federal action, requiring compliance with the Endangered Species Act (ESA) and the National Environmental Policy Act (NEPA). To address NEPA requirements, the APHIS PPQ develops an environmental assessment (EA) providing a concise summary of the material presented in the petition and potential effects on the quality of the human environment that may be associated with the release of the candidate agent, and compares these to potential effects of alternative actions, including a no action option. Evidence and analysis provided by the EA determines if a Finding of No Significant Impact (FONSI) can be reached; if not, then a more detailed environmental impact statement (EIS) must be produced. The EA's 30-day public comment period is publicized in the Federal Register. The EA is one of the relevant reports included in the biological assessment (BA) submitted to the U.S. Fish and Wildlife Service (USFWS) for a so-called Sect. 7 consultation, to satisfy ESA compliance. The EA provides descriptions of the action to be considered (i.e., release of the agent); specific areas that may be affected by that action; listed species (i.e., threatened, endangered, or species of interest), or their critical habitats that may

(continued)

Box 6.2 (continued)

be affected by the action; the manner in which the action may affect listed species or critical habitats, and an analysis of any cumulative effects; relevant reports; and any other relevant information on the action, the affected species, or critical habitat. If the USFWS concurs with "may affect, not likely to adversely affect" determinations regarding listed species and critical habitats included in the BA, they then send the APHIS PPQ a concurrence letter, which completes the ESA consultation; the concurrence from the USFWS is then incorporated into the EA. Although many groups comment on the safety and host specificity of candidate classical biological control agents, none of the stages in the review process leading to the issue of a permit involves a formal quantitative risk assessment.

Box 6.3: Overview of Procedures to Obtain Approval to Release Classical Biological Control Agents for Arthropod Pests in the United States

Petitions must be submitted to the USDA Animal and Plant Health Inspection Service Plant Protection and Quarantine (APHIS PPQ) in a format that follows North American Plant Protection Organization (NAPPO 2015). The APHIS PPQ issues permits required for interstate movement of non-native entomophagous biocontrol organisms for the purpose of environmental release or for research or releases that will occur outside of containment facilities. Regardless of the number of scenarios requiring a permit, issuing a permit triggers the same requirements for the APHIS PPQ's compliance with the National Environmental Policy Act (NEPA) and the Endangered Species Act (ESA) as described in Box 6.2 for phytophagous biocontrol agents. Environmental assessments (EAs) are produced by the APHIS PPQ and then publicized in the Federal Register with notification of a 30-day public comment period; if no additional, credible adverse effects stemming from the release of the agent are identified, then a Finding of No Significant Impact (FONSI) is issued. The EAs for entomophagous biological control agents contain generic statements about the potential impact a candidate agent might have on threatened or endangered species. However, these statements likely have little bearing on the outcome of the actual Sect. 7 consultations with the U.S. Fish and Wildlife Service.

standards govern the conduct of a risk assessment when the assessment will factor into decisions on international trade (IPPC 2016a, 2016c). In the United States, for example, those assessments are typically prepared by the APHIS PPQ when an importer/exporter makes a request to begin shipping a plant or plant product to this country that has not been approved previously. However, other organizations within the United States may conduct their own risk assessments to prioritize their own management activities or support local biosecurity needs. Those assessments would not necessarily follow international standards.

While pest risk assessment strives to assess the joint probability of introduction (or entry), establishment, spread, and impact, typically for an individual species or a suite of related taxa, pathway analysis focuses on introduction events, often for multiple alien species that might be moved into an area of concern on a common conveyance. Pathway analysis can be a component of pest risk assessment (Box 6.4), or it can be conducted on its own, for example, to identify introduction hotspots. Assessing the risk of introduction may require attention to multiple pathways of introduction, including the identification of potential vectors (such as wood packaging materials for wood-boring alien insects; IPPC 2016c) and regions from which the species is most likely to arrive.

Pathway analysis has several interpretations. Perhaps the most common interpretation is that it examines, in a broad sense, the kinds of species, their relative rates of arrival and, in some cases, their most prominent destinations associated with a commodity type or group (e.g., avocados, Hennessey 2004; live plant imports, Liebhold et al. 2012). Alternatively, pathway analyses may target an industry that depends on a particular commodity (e.g., the horticulture industry, which relies on the global trade of live plants and seeds; Reichard and White 2001). This particular interpretation also extends to categories unrelated to trade (e.g., airline passenger baggage; Liebhold et al. 2006). A somewhat different interpretation of "pathway" involves a more geographically explicit perspective, which focuses on the primary routes between origin and destination locations. This latter type of pathway analysis has been applied, for example, to examine the trade and transport of goods that may carry wood-boring insects (Colunga-Garcia et al. 2009; Koch et al. 2011; Yemshanov et al. 2012), and can have a domestic (e.g., recreational travel and firewood movement in the United States; Koch et al. 2012, 2014) or international focus. Such analyses also may include quantitative modeling of the links between origins and destinations using geospatially depicted networks (e.g., Koch et al. 2014; Paini and Yemshanov 2012; Yemshanov et al. 2012, 2013). No matter the interpretation of the pathway analysis concept, a potential outcome of such analyses is an assessment of the likelihood of pest introduction or spread that can feed into more comprehensive pest risk assessment efforts.

Box 6.4: Overview of Procedures for Pest Risk Assessment

General guidance for the preparation of pest risk assessments that may affect international trade is described in the International Standards for Phytosanitary Measures from the International Plant Protection Convention (IPPC). For many alien species, pest risk assessment starts with identifying the potential pest species of concern, the area for which information is needed, possible locations of pest origin, and likely pathways by which the species could enter an uninvaded area (IPPC 2016a). At this stage, qualitative and descriptive information is collected to help understand the species' present distribution and to identify susceptible hosts and possible vectors of spread. Some of this qualitative and quantitative information is intended to provide insight on how the species might enter, spread, and establish viable populations in the uninvaded area.

The next stage of the assessment may include more sophisticated analyses of the likelihoods of the organism's introduction and spread, as well as analyses of potential economic consequences and environmental impacts (IPPC 2016c). Key information collected for these later stages may include details on dispersal mechanisms (e.g., rates and patterns of movement), relative susceptibility of known host species, reconstruction of the history and timing of the invasion, and identification of the critical vectors of entry that must be controlled to prevent new arrivals of the species. Other relevant information that may affect the likelihood of establishment includes an invader's life cycle, survival rates, and natural enemies in the uninvaded area. Such knowledge helps assessors to understand whether the organism under consideration can be expected to establish and cause recurring harm in a newly invaded area or might be present for a short time and have transient effects. Ultimately, the level of complexity that is incorporated into the risk assessment may depend on decision-making goals (e.g., possible imposition of trade restrictions may necessitate a detailed assessment) or the nature of the species of concern (e.g., a well-known species that is expected to be low-impact may only require a basic assessment).

6.2.5 Assessments of Management Tactics

While pest risk assessments focus on biological invasions as the unwanted event, the same general risk assessment framework can be used to prioritize management efforts and estimate the risks posed by strategies and tactics used to manage the invasive species (Sing et al. 2005). The latter approach can help identify whether "the cure is worse than the disease." In this context, the additional unwanted event is harm from efforts to manage invasive species. For example, the unwanted event could involve reduced density of native plants as a consequence of herbicide applications. The risk assessment framework here, termed "comparative risk assessment," provides researchers and policymakers with guidance to estimate and compare risks from the invasive species and its potential management strategies.

The purpose of comparative risk assessment is to qualitatively and quantitatively compare different environmental risks for the purpose of improved decision-making. Despite the need to systematically compare risks to make more effective policy decisions, there are relatively few examples of this activity in the literature (Peterson 2010; Peterson and Shama 2005). In some cases, the necessary risk assessments have been conducted, but the outcomes have not been directly compared (Antwi et al. 2008; Davis et al. 2007; Peterson et al. 2006, 2011b; Schleier et al. 2008). Sing and Peterson (2011) argued that the decision to initiate control programs for invasive pests often occurs without first considering the ecological or economic evidence to support that decision. Frequently, risks from associated management tactics are not formally part of the decision matrix.

The comparative risk assessment approach often is limited by a lack of quantitative effect and exposure data (Drake et al. 2006; Drake and Lodge 2006). In addition, the data that are available may be highly uncertain, especially when the proposed management strategy is biological control (Schleier et al. 2008; Sing et al. 2005). However, effect and exposure data for other management tactics, such as pesticides, may be more certain and readily available. The problem then becomes one of comparing risks among stressors in which the accuracy and uncertainty of individual risk assessments vary appreciably.

When risks are difficult to compare quantitatively because of challenges in identifying common endpoints and the existence of large differences in uncertainties associated with estimating effect and exposure, the use of comparative qualitative or semi-quantitative risk assessments may be a solution. Although quantitative risk assessments are almost always preferred over qualitative risk assessments (Cox et al. 2005; Schleier et al. 2008), employing comparative qualitative assessments has been proposed to unify seemingly disparate assessments and establish a common frame of reference for subsequent decisions (Gentile and Harwell 2001; Landis and Wiegers 1997). For example, Sing et al. (2005) retrospectively evaluated risks associated with insects that feed on invasive toadflax (*Linaria* spp.), and Sing and Peterson (2011) assessed risks for Dalmatian toadflax (*L. dalmatica*) and yellow toadflax (*L. vulgaris*) in North

Fig. 6.3 Dalmatian toadflax (*Linaria dalmatica*) and two biological control agents, *Rhinusa* spp. (*top right*) and *Mecinus janthinus* (*lower right*)

America (Fig. 6.3). A third environmental risk assessment could be conducted on the herbicides used on the two toadflax species. Based on the three risk assessments, a unified comparative risk assessment could be conducted, possibly using simple yet quantitative risk metrics such as risk quotients (Peterson 2006). This type of comprehensive assessment would at least provide a starting point for evaluating multiple risks of the invasive species and the management tactics being proposed.

6.2.6 Key Findings for Risk Assessment

- Early intervention is the most cost-effective approach to manage invasive species. By keeping invasive species out of an area of concern through regulatory or technical approaches, the potential damages from those species are avoided.
- Global trade has provided several pathways for new pest introductions. The number of countries engaged in trade and the diversity and volume of products moved in trade create significant opportunities for the movement of a pest species outside its native range.
- Risk assessment provides a useful framework conceptually and analytically to evaluate the potential for future adverse impacts from unwanted events. The outcome of pest risk assessment typically provides a clear strategic direction for biosecurity decisions and a foundation for tactical actions. Pest risk assessments attempt to forecast the likelihood that individual species will invade and cause economic, ecological, or social harm. Pathway analyses, which may be part of pest risk assessments, attempt to characterize how suites of pests might be moved into areas of concern.
- Effective risk assessment requires close collaboration between scientists (i.e., risk assessors) and decision-makers (i.e., risk managers). The challenge for scientists is to balance rigor and timeliness to obtain an acceptable degree of accuracy in their assessments, while the challenge for risk managers is to clearly articulate information needs to support time-critical decision-making (Venette 2015).

6.3 Prediction and Prevention

Risk assessments provide the backbone of prediction and prevention, often viewed as the first lines of defense in proactive, pre-border, biosecurity strategies (Venette 2015). Prediction is fundamentally the outcome of the pathway analysis or pest risk assessment. Prevention refers to the integrated suite of tools and strategies that are intended to lower risks from those pathways or species to acceptable levels. Quarantine regulations (e.g., prohibiting species or items from entering an area of concern because they may harbor threatening species) are a prominent component of prevention, as are quarantine treatments designed to disinfest pathways of threatening species. Several analyses have indicated that prevention is one of the most efficient strategies for managing invasions; by preventing propagules from arriving, all of the costs associated with impacts and management can be prevented (Leung et al. 2002; Lodge et al. 2006).

6.3.1 Prediction

Researchers have determined that the importance of different introduction pathways varies considerably among invasive species. For example, the dominant pathway responsible for the transport of most invasive plants has been intentional imports for ornamental, agricultural, soil-stabilization, or other uses (Hulme et al. 2008). Several species of plants had been introduced to arboreta or other cultivated settings where they subsequently spread into surrounding regions. Intentional introduction is also considered the most common pathway for invasions by birds, mammals, and fish. Some insect species that were introduced as biological control agents at a time when assessment standards were less rigorous also have spread into unintended environments (e.g., Louda 2000).

In contrast to such intentional introductions for the above groups, most invasive insects and plant pathogens have entered either with plants, wood, or as “hitchhikers” on other material (Kenis et al. 2007; Kiritani and Yamamura 2003). Analysis of pest interception data from the APHIS PPQ revealed that the pathway responsible for the entry of most forest insects and diseases into North America has been importation of plants (Liebhold et al. 2012). Plants are the perfect medium for moving herbivorous pests because they provide food and shelter during transportation. Historically, large numbers of sap-feeding and foliage-feeding insects accidentally entered the United States when unregulated imports of plants allowed infested plants to freely enter the United States in large numbers (Liebhold and Griffin 2016). Enactment of the Plant Quarantine Act of 1912 led to quarantine restrictions on plant imports by the USDA and subsequently decreased the establishment rate of new plant pests.

However, following World War II, the movement toward free trade led to enormous increases in import rates. These trends plus the advent of more efficient trans-oceanic shipping technologies (e.g., containerized cargo) led to massive movement of solid wood packing material (SWPM). Though not fully recognized until the last two decades, SWPM provides a very effective pathway to move pests, particularly bark- and wood-boring insects (Haack 2001, 2006). Examples of pests that have likely entered North America with SWPM include the emerald ash borer (*Agrilus planipennis*), the Asian longhorned beetle (*Anoplophora glabripennis*), and laurel wilt disease (caused by the fungus *Raffaelea lauricola* and vectored by the beetle *Xyleborus glabratus*). Current increases in the online trade of plants (Humair et al. 2015) have created new opportunities to import potentially problematic plants and pests (Keller and Lodge 2007).

6.3.2 Prevention

The search for quarantine treatments for goods and commodities is a broad and active area of research. For example, new solutions are being sought to disinfest ballast water of aquatic alien invasive species (e.g., Tsolaki and Diamadopoulos 2010) or commodities of pests that might affect forests or rangelands (e.g., compression of imported hay to control insects; Yokoyama 2011). Many approaches focus on specific technologies, while systems approaches rely on integrating several techniques to rid a commodity of invasive species when any one technique may be insufficient to achieve a desired biosecurity standard (Follett and Neven 2006). The Forest Service is actively conducting research to identify quarantine treatments capable of eliminating invasive pathogens or insects from wood or wood products.

In 2002, the IPPC, recognizing the potential for damage from invasive pests, adopted a harmonized international standard for phytosanitary measure (ISPM) for treating SWPM (IPPC 2016d). The standard, called ISPM 15, requires the treatment of SWPM with heat or methyl bromide fumigation to eliminate wood- and bark-boring insects (Box 6.5). Specifications for these treatments were developed, in part, from investigations conducted by the Forest Service Research and Development scientists (Haack and Petrice 2009). The addition of a bark standard that requires nearly all bark to be removed from SWPM has contributed to a large reduction in risks (IPPC 2016d). The IPPC requires that exporting countries use a stamp on each piece of SWPM to certify that ISPM 15 treatments were conducted (Fig. 6.4).

A series of studies, organized by the National Center for Ecological Analysis and Synthesis, sought to quantify the potential economic benefit of ISPM 15. Part of this work included quantifying the rate at which wood-boring insects have entered the United States and their economic impacts (Aukema et al. 2010, 2011). Other research quantified the effectiveness of ISPM 15 in reducing woodborer approach rates (Haack et al. 2014) and the costs of ISPM 15 to trade (Strutt et al. 2013). Finally, Leung et al. (2014) used all of this information in a cost/benefit analysis to show that, while ISPM 15 had a negative economic effect in the initial decade

Fig. 6.4 Example of an approved stamp for solid wood packing materials. The stamp, denoting the country of origin, the treatment facility, and the treatment type, signifies that a piece of wood has been treated in compliance with International Standards for Phytosanitary Management (ISPM 15) from the International Plant Protection Convention

Box 6.5: Preventing the Movement of Forest Pests in Wood Packing and Lumber: Research to Demonstrate the Value and Achieve the Goals of International Standards for Phytosanitary Measures No. 15 (ISPM 15)

Investigations into treatments for ISPM 15 have benefitted from, and contributed to, research into developing quarantine treatments for export of lumber or whole logs. The most common treatment mandated for international movement of dried lumber or green lumber is heat applied until the core temperature reaches 56 °C for 30 min, often called the "56/30 standard." The deleterious effects of methyl bromide on the environment and stratosphere have led to global efforts to drastically reduce the production and use of this fumigant. Concomitantly, research on promising alternatives to methyl bromide has been ongoing since the early 1990s. Although log schedules have been devised and set between countries engaged in log trade, no comprehensive, international convention has been established for treatment of whole logs in international trade.

Past testing of heat treatment focused on insect and nematode pests, but this has recently shifted to evaluating the 56/30 standard for its utility to kill fungal pathogens in wood. Heat treatment is not suitable for wood or wood products where quality (e.g., color change or drying effects) is a concern; however, steam treatment was found to be effective in heating large timbers (Simpson 2001). Vacuum plus steam thermal treatment is currently being evaluated as an alternative to heat treatment and fumigation for eliminating invasive insects and tree pathogens in logs. Log degrade was minor, and product (veneer) quality was unaffected in a vacuum steam trial with logs from five hardwood species (Chen et al. 2016). Time to reach 56 °C for 30 min (to core) required 17–29 h of treatment under 200 mm Hg vacuum.

Dielectric heating with microwaves or radio frequencies simultaneously heats throughout the wood profile as compared with kiln and oven treatments that rely on thermal conduction from outer wood to the core. Industrial-sized wood blocks that were subjected to microwave energy to reach 56 °C for 1 min resulted in 100% mortality of high numbers of the pinewood nematode (*Bursaphelenchus xylophilus*) (Hoover et al. 2010). Microwave treatment is more rapid and similar in efficacy to previously tested treatments for this pest. Further investigations are needed to ensure that minimum lethal temperatures for target pests are reached and that the desired internal temperature is reached based on predictions from surface temperatures. Radio frequency heating was found to reach or exceed 56 °C for 1-min hold time in trials with large wood blocks infested with high numbers of pinewood nematodes (Uzunovic et al. 2013). One hundred-percent mortality of the nematodes was achieved. Evaluation of dielectric heating for ability to deliver 56 °C throughout a commercial wood profile in industrial-scale operations is needed.

Whole-log fumigation with methyl bromide for export from the United States is currently one of the largest Quarantine and Pre-Shipment (QPS) use exemptions for that chemical. The best available fumigant alternative options for quarantine-level disinfestation of logs and other wood products are sulfuryl fluoride and phosphine as their use at the commercial scale would require few or no changes to current industry practices and infrastructure. Data on pest eradication efficacy and economic viability have been the focus of recent and ongoing research on these alternatives (e.g., Barak et al. 2006, 2010). Because high doses of methyl bromide over a significant time period are required to kill pinewood nematodes and the oak wilt fungus (*Bretziella fagacearum*), much of the ongoing fumigant research has been focused on these organisms (Schmidt et al. 1997; Tubajika and Barak 2011).

after implementation, it ultimately had a positive net benefit via reduced rates of forest pest establishment.

6.3.3 Key Findings for Prediction and Prevention

- Pest risk assessments and related pathway analyses provide a clear, scientific basis to identify future invasive species (not yet present) that may affect forests, grasslands, wetlands, and water bodies. Those analyses support strategic biosecurity decisions (e.g., uses of quarantine treatments or other regulations) to prevent real threats from arriving into an area of concern.
- The use of risk assessment to support complex decision-making can reduce the likelihood of unintended consequences of intentional introductions, such as with plants for planting or potential biological control agents. The goal is to prevent the introduction of seemingly beneficial species from causing unintended environmental, economic, or social harm.
- A potentially daunting aspect of prediction and prevention is the enormity of the number of species or pathways that could be evaluated. Pest risk assessment is not a pan-

acea and is unlikely to uncover *all* potential threats; however, the approach provides a clear, systematic, rational basis for making strategic decisions in light of the significant number of pest threats that must be addressed.
- Development of phytosanitary measures to preclude the movement of pests in pathways (e.g., fumigation of wood containers and pallets) can cost-effectively reduce the risk of unintentional introductions.

6.4 Early Detection and Rapid Response

Early-detection (i.e., biosecurity surveillance) and rapid-response strategies for invasive species provide a biosecurity safety net should prevention efforts fail. These strategies hinge on effective surveillance of the landscape to locate and recognize new species incursions while those populations are localized (Venette et al. 2010). Often the landscape is enormous relative to the resources that are available to conduct surveys. Research has addressed this problem in three general ways. Firstly, a variety of spatial analyses have been developed to support program planning and implementation. These analyses are useful to stratify the landscape into areas where invasions are more or less likely and determine the appropriate amount and allocation of resources in those areas to achieve programmatic goals (e.g., Koch et al. 2011). Secondly, researchers have made technological advancements to find invasive species, such as with environmental DNA (eDNA) (e.g., Jerde et al. 2011) or remote sensing (e.g., Hestir et al. 2008), and improved our understanding of chemical and behavioral ecology to produce better attractants and traps (e.g., Allison et al. 2004). Thirdly, advancements with computer-aided identification, genomic testing, and other molecular diagnostics support the rapid, reliable confirmation of species' identity (McCartney et al. 2003). Broad lines of research address the appropriate response to incursions. Eradication may be difficult, but achievable, particularly if populations can be driven to densities (i.e., Allee thresholds) that are too low for population growth, so that populations go extinct (Liebhold et al. 2016).

Program managers face a difficult challenge in implementing surveillance and response strategies. Often, the overall budget is fixed, forcing a difficult tradeoff between surveillance and response (Bogich et al. 2008; Cacho et al. 2007; Mehta et al. 2007; Chap. 14). The response cannot occur until the pest is detected. The decision to allocate more funds to response potentially allows large populations to build and extensive damage to accrue before detection occurs. Depending on how budgets are allocated, more funds for surveillance may limit response options once the pest is found. Epanchin-Niell and Hastings (2010) note the complexity of the allocation decision as being dependent on program goals, attributes of the invading species, extent and timing of damages, and the effectiveness of the response. Adjusting surveillance efforts to account for spatial variation in the likelihood of pest establishment can substantially reduce overall management costs (Epanchin-Niell et al. 2012).

6.4.1 Spatial Analysis for Program Planning (aka Pest Risk Maps)

For some alien organisms, the amount of available information enables risks to be assessed with a finer grain, spatially explicit approach (Koch and Smith 2008; Venette et al. 2010; Volin et al. 2004). Pest risk maps can integrate several models (i.e., pathway analyses, species distribution models, spread models, and/or impact models) to describe how the probabilities of invasion by a non-native species, and the magnitude of its impacts, might vary spatially within an area of concern (Venette 2015). Pest risk maps are based upon fundamental ecological concepts that address factors governing species' distribution and abundance. The construction of these maps helps to reveal a species' potential distribution, hotspots of entry and establishment, and those areas that are most vulnerable. Maps provide a powerful means to communicate spatial variation in the risk that species will establish and cause damage, and have therefore become a common decision-support tool for managing invasive species outbreaks (Venette et al. 2010).

For decision-makers, risk maps essentially represent a prioritization surface that guides them in allocating tactics aimed to detect and control the spread of invasive species (e.g., Volin et al. 2004). Risk maps are extremely useful to determine whether quarantine restrictions might be warranted if the alien species is not known to be present in the area of concern, to structure an early detection survey if the species might be present, or to describe the potential extent of impact if the species is not managed effectively. For example, Fig. 6.5 describes the potential spread of the redbay ambrosia beetle (*Xyleborus glabratus*) through areas of the Southeastern United States with its preferred hosts: redbay (*Persea borbonia*) and sassafras (*Sassafras albidium*) (Koch and Smith 2008). The value of an individual risk map for decision-making is subject to the constraints of available knowledge about the biology of the species of interest and conditions within the area of concern, as well as the economic and logistical constraints on map production.

6.4.2 Implementation of Early Detection

The extent of biosecurity surveillance depends on budgets and other technical support. Unfortunately, time, infrastructure, and funding constraints seldom if ever meet the con-

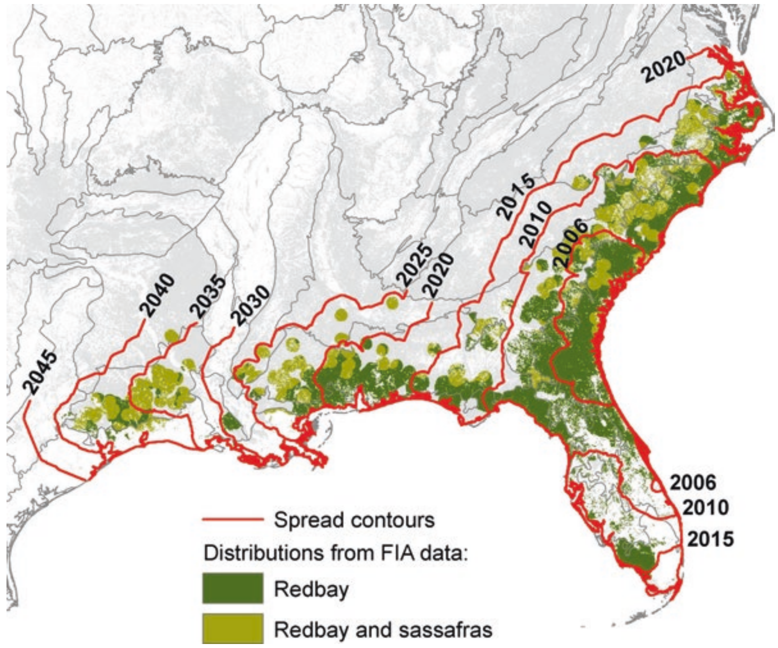

Fig. 6.5 Pest risk map for redbay ambrosia beetle (*Xyleborus glabratus*) spread through the Southeastern United States. (Reproduced from Koch and Smith 2008)

tinuous demand for detection, identification, and response (Saccaggi et al. 2016). Westbrooks (2004) recommends six actions to improve early detections of, and rapid responses to, invasive plants species: (1) public and private partnerships for "early detection and reporting of suspected new plants to appropriate officials; (2) identification and vouchering of submitted specimens by designated botanists; (3) verification of suspected new State, regional, and national plant records; (4) archival of new records in designated regional and plant databases; (5) rapid assessment of confirmed new records; and (6) rapid response to new records that are determined to be invasive." Similar principles were embodied in a national program for early detection and rapid response to invasive bark and ambrosia beetles (Rabaglia et al. 2008); identification of all submitted specimens led to the detection of several invasive species.

APHIS PPQ's Cooperative Agricultural Pest Survey (CAPS) Program funds a network of cooperators to conduct surveys for the early detection of plant pests that are threats to U.S. agriculture or the environment. CAPS targets specific alien invasive pests, diseases, and plants that are not yet established in the conterminous United States. A science-based pest prioritization model is used to determine which pests will be included on annual CAPS Priority Pest lists. Subject matter experts in biology and economics evaluate pest species individually against a weighted set of criteria that address environmental and economic impacts. The Analytic Hierarchy Process (Golden et al. 2012) is used to produce a prioritized pest list.

Detecting invasions of alien species not previously or widely reported in the United States relies on surveillance and reporting by regulatory and research communities, with significant contributions from knowledgeable citizen scientists. Environmental DNA (eDNA)-based detection has improved the accuracy, price, and efficiency for confirming the presence of non-native species, particularly for invasive fish at low population densities within large bodies of water (Handley 2015; Rees et al. 2014). The pivotal challenge for lay contributors to early detection and rapid response is the accurate identification of specimens; this has been somewhat offset by continually improving online identification resources. Currently, documentation of invasive plant and insect identification and distribution can be accessed and records of sightings can be added online through an early detection and distribution mapping system (EDDMapS) website (https://www.eddmaps.org/).

Sentinel sites for invaders can be established outside the known infested area to provide early warning of spread. One example of a collaborative, private–public partnership for early detection is for northward spread of Old World climbing fern (*Lygodium microphyllum*) in central Florida. A similar approach has been used to detect incipient tree pathogens in Europe (Vettraino et al. 2015). Surveillance for alien insects is typically semiochemically based, using strategically arranged traps baited with either pheromones or host attractants (Berec et al. 2015).

Methodologies for the detection of cryptic pathogens in plant tissues and on insect associates have greatly evolved over the past decade (see Chap. 7). Molecular tools are available for screening large numbers of samples collected during detection surveys using high-throughput methods. Detection of multiple invasive pathogens is possible using specific TaqMan® real-time PCR detection assays (Lamarche et al. 2015). The same PCR conditions, utilizing the same thermocycling parameters and chemistry, allowed for high-throughput assay for 10 high-priority and unwanted alien pathogens of trees in Canada (Lamarche et al. 2015).

Other major scientific advances have been made in developing accurate, sensitive, species-specific, rapid, and "suitable for field use" technologies for invasive tree pathogens. For example, such an assay was recently developed for *Phytophthora ramorum* (sudden oak death pathogen) using recombinase polymerase amplification that does not require DNA extraction or extensive training to complete (Miles et al. 2015). Most recently, DNA hybridization assays utilizing specific capture probes and complementary DNA target sequences have been developed with hybridization signaled by fluorescent dyes, chemically induced color changes, radioactivity, or surface-enhanced Raman spectroscopy (SERS) consisting of silver nanoparticles (Yuksel et al. 2015).

6.4.3 Options for Rapid Response

Upon the detection of an incursion by an invasive species, managers generally have four options: (1) eradication, (2) containment, (3) continued monitoring, or (4) do nothing. Options (1) and (2) qualify as rapid responses. Eradication refers to the total elimination (i.e., intentionally driven to extinction) of a species from a specific area. While the concept is not necessarily new, it is only in the last few decades that it has been widely applied to successfully prevent the establishment of invading species, with several hundreds of examples of successful eradication of insects (Liebhold et al. 2016; Mack and Foster 2009; Simberloff 2009; Tobin et al. 2013). Among pathogens, bacteria and viruses are more likely to be eradicated than fungi (Pluess et al. 2012). The most important determinant of a successful eradication is the availability of sensitive tools for detecting the target species, thus allowing for early detection and accurate spatial delimitation. While eradication does not preclude reintroduction, it can reduce the extent of invasion and propagule pressure. Eradications are most successful when infestations are small, for plants, generally <1 ha (Rejmánek and Pitcairn 2002) to ~5000 ha or within 4 years of first detection (Pluess et al. 2012). Simberloff (2009) identified sufficient funding, including for follow-up surveys and treatment, coordination, and enforcement, and an understanding of the biology and ecology of the target organism as components of effective eradication efforts. Additional components for successful eradication include a sustained effort, initial focus on outlying infestations, prohibited reintroduction, and public cooperation (Mack and Foster 2009).

Many types of treatment are used in eradication. For plants, eradication is typically carried out either through physical removal or herbicide treatments. Methods used for eradicating insects include synthetic or microbial pesticides, mating disruption, male annihilation (e.g., trap-out), and the sterile male technique. For vertebrates, newly established, isolated populations may be eradicated with an intensive effort that combines multiple approaches; one example is the eradication of feral swine (*Sus scrofa*) from Santa Cruz Island in California (Parkes et al. 2010). After fencing the island into five zones, pigs were systematically removed from each zone first by trapping, then aerial shooting, followed by ground-based shooting, trailing with dogs, and finally the use of Judas pigs. Over 411 days, 5036 pigs were removed. Genetic engineering technologies are providing new tools such as gene drives, which have been proposed to eradicate alien insects like non-native mosquitoes carrying dengue and Zika virus (NAS 2016).

The effectiveness of an eradication treatment may depend on the extent to which the treatment creates or enhances an existing Allee effect (Liebhold et al. 2016). Because low-density populations, such as those encountered during the early stages of invasion, are prone to extinction as a result of Allee effects, treatments that enhance Allee effects may be particularly efficient (Liebhold and Tobin 2008; Tobin et al. 2011). For example, in sexually reproducing species, mate-location failure may cause a strong Allee effect, resulting in a threshold below which populations decline towards extinction. Tactics such as mating disruption may strengthen such an Allee effect and thus facilitate eradication. Bio-economic models can be used to identify the optimal allocation among multiple treatments, exploiting synergistic influences on Allee effects (Blackwood et al. 2012).

More invading species are likely to arrive in urban/suburban areas (Colunga-Garcia et al. 2010) than in rural areas, suggesting that eradication projects will increasingly occur in residential areas. In these areas, some residents may object to aerial spraying of pesticides or other proposed treatments. This situation presents several challenges: treatment technologies are needed that are widely acceptable to the general public, and new approaches to public outreach and engagement are needed to avoid conflict (Gamble et al. 2010; Liebhold et al. 2016).

Containment is meant to prevent or slow the spread of an invading species and is usually attempted through treatments of delimited populations and imposition of quarantines and other regulations (Pasquali et al. 2015). Many of the same tools for eradication are used for containment, but for containment, the goal is to limit the extent of damages, not eliminate the target pest. Withrow et al. (2015) demonstrated the value of pre-emptive domestic quarantines as a component of rapid response plans, especially if the target species, like the emerald ash borer, is difficult to detect. Technologies for containment are often not specific, which can lead to "scorched-earth" responses (Britton et al. 2011).

6.4.4 Key Findings for Early Detection and Rapid Response

- Risk assessments for unintentionally and deliberately introduced species can be used productively at the landscape scale to distinguish or prioritize species that are already present and require management from those that have naturalized but are unlikely to have significant negative impacts. Where species are already present, information on field invasiveness and impacts should inform those prioritization efforts.
- Management may be warranted for any high-risk species that are: (1) not yet spreading but have been introduced recently; (2) present at low levels but not yet prioritized for management; or (3) not present in the area of interest but where a probable introduction pathway exists. "High-risk" status must be determined at a spatial and temporal scale that matches operational management decision-making. Assessments and risk mapping further can help identify and prioritize species of high invasion risk that should be the focus of early detection/rapid response programs.
- More research is needed to determine an appropriate balance of generalized prevention strategies that exclude many, but perhaps not all, alien species of concern versus specialized prevention strategies that are highly effective at excluding a specific species of concern but may miss an array of other alien pests.

6.5 Information Gaps and Future Directions

Ecological risk assessment emerged as a discipline in the 1970s; however, formal applications of ecological risk assessments to invasive species did not begin until the 1990s and early 2000s (Yoe 2012). In the last two decades, the number of research ideas to improve pest risk assessments has expanded rapidly, especially with respect to species-distribution and spread models (Venette et al. 2010). For example, incorporating effects of climate change (Chap. 4) and human behaviors into the assessments could provide valuable new insights (Venette et al. 2010); few of those ideas to improve pest risk assessment as yet can be considered fully mature.

The greatest barrier to the development of pest risk assessments has been the lack of information about pathways of pest introduction, the distribution and ecology of invading species, the biotic and abiotic conditions within geographic areas of concern, and resultant impacts of invasion. To be useful for many applications to invasive species, spatially explicit data must be collected globally, consistently, and repeatedly, similar to what has been done with the acquisition of meteorological data. Historical presence/absence records for species' distributions are useful, but current information on the phenology and dynamics of a species at several locations may be much more valuable to risk assessment.

This lack of information fundamentally interferes with the development of pest risk assessment as a science. In essence, forecasts from pest risk assessment are hypotheses about the state of future conditions. Those forecasts are grounded in current knowledge but inherently require extrapolations beyond what it is known. How will a species behave if it arrives in an area where it has never occurred? Research, by its nature, cannot prove that a forecast is correct, only that it is wrong. The true test of a pest risk assessment occurs when an alien species begins to invade forecasted areas where it has historically never occurred, an event many organizations and individuals are actively seeking to prevent. Extensive empirical observations are needed of invasive species in their native ranges and in areas where they are invading to rigorously test new theories and models and identify opportunities for substantive improvements.

Some have argued that pest risk assessments have limited value because they are so severely encumbered by associated uncertainties (e.g., Simberloff 2005). Future research is needed to provide ways to meaningfully characterize that uncertainty and formally incorporate it into risk management decisions (Koch et al. 2009; Yemshanov et al. 2013, 2015). This transition may require new thinking about the nature of risk itself.

One important, but sometimes overlooked, aspect of risk is that it can be described in many dimensions. This need should be addressed during future research on pest risk assessment. Although most definitions of risk follow a two-dimensional interpretation (i.e., risk as the product of probability and severity), Yellman (2000) presented a more complex, three-faceted view of risk which includes expected loss, variability of loss values, and uncertainty arising from how risk perception (i.e., the uncertainty of how risk is perceived by decision-makers) is modeled. The best (i.e., the most rigorous) risk assessments extend beyond simple estimates of risk values and attempt to narrow the bounds of uncertainty associated with the phenomenon of interest, so that the decision-making options for responding to risk can be reduced to a manageable size. For industrial applications, the International Organization for Standardization defines risk as an "effect of uncertainty on objectives," where an effect is a positive or negative deviation from what is expected.[1] This definition recognizes that a decision-maker operates in an uncertain environment, so there is always a chance

[1] ISO 31000 is a generic risk management standard that is not specific to any sector or industry and could be applied in a wide range of disciplines.

that the decision-making objectives will not be achieved. Similarly, in engineering disciplines, technical risk denotes the odds that a project will fail to meet the performance criteria (Pennock and Haimes 2002). For project management, risk is often defined as an undesirable situation that has both a likelihood of occurring and a potentially negative consequence for the project (ESA 2000).

The common rationale behind the notion of risk in these diverse contexts is that decisions, and subsequent actions predicated on those decisions, must be undertaken under the assumption that the outcome of those actions is uncertain. Uncertainty is assumed to always be present as a component of risk. This uncertainty can stem from a lack of information about the process of interest or poor understanding of the consequences of decision-making actions based on incomplete information. With respect to invasive species, uncertainty arises when knowledge about the biology, ecology, impact, or management of an alien organism is limited. This uncertainty is exacerbated by the unknown state of future conditions, such as climate, land use, nitrogen deposition, and species composition.

Protection of natural resources from the seeming onslaught of new invading species requires robust management plans that emphasize early intervention strategies. Successful early intervention strategies will require close collaborations between biologists, modelers, resource managers, and policymakers. Researchers will need to work diligently to measure, describe, and reduce sources of uncertainty in their assessments. Policymakers are likely to need more sophisticated tools to understand how scientific uncertainties might affect their decisions. Success in reducing uncertainty will be aided by international collaborations and future interactions with citizen scientists to provide useful real-time information on the extent and impact of invasions as they occur.

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