



Future Invasive Species Research Challenges and Opportunities

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16.1 Introduction

Introductions of new invasive species continue with ever-expanding global trade, and the increase in invasive species does not show any sign of saturation for most taxonomic groups. However, some non-native species may arrive in an area and fail to become established or have no measurable impact. Thus, the protection of valued ecosystems depends on reliable knowledge about the species that are or might be invading, the ecosystems that are being invaded, the potential magnitude of different types of harm, the availability and effectiveness of management responses, and the desired state of ecosystems under protection. Primary research is a vital means of gathering that knowledge.

There has been considerable progress in research that focuses on understanding the broad range of impacts invasive species have in their introduced environments. This includes their interactions with ecosystem processes, climate change and disturbance, social and cultural dynamics, and economics. There have also been advancements in management tools and techniques for predicting and preventing their establishment, detecting and managing established populations, and restoring impacted ecosystems. The previous chapters provide an assessment of our cur-

rent state of knowledge about invasive species, their effects on ecosystem processes, and their management with a particular emphasis on lessons learned that apply to multiple species. Each chapter identifies critical knowledge gaps and areas for future research that are specific to a particular topic area. The intent of this chapter is to highlight common and significant research challenges and opportunities. Our goal is not an exhaustive review of the material of each chapter, but to highlight four broad research challenges that, if tackled, could make far-reaching contributions to our understanding of, and response to, biological invasions.

16.2 Improve Our Understanding and Quantification of the Ecological Impacts of Invasive Species and the Mechanisms of Invasion

Invasive species impact terrestrial and aquatic ecosystems, both directly and indirectly, by numerous means such as killing resident species, lowering the abundance of resident species, reducing biotic diversity, or altering nutrient cycles. As noted in Chaps. 2 and 3, most of the research quantifying the

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impacts of invasive species has been species-specific, short-term, qualitative, locally scaled, and focused on ecological and biological systems. Quantitative impact assessments, long-term impact studies, and models that characterize impacts are needed across larger, regional scales, with an increased focus on multiple species and a much wider range of taxa at the population and community levels. Quantifying impacts is essential to justify the need to be proactive in addressing invasive species issues, to quantify costs, and to promote collaborative agencywide efforts, and is critical to help decision makers weigh options so cost-efficient and effective programs can be developed, particularly under highly constrained budgetary environments. Understanding complex interactions, ecosystem processes, and impacts that cascade across trophic levels is a major research challenge. For example, invasive species may directly or indirectly affect other trophic levels in food webs, and subsequently alter carbon and nutrient cycling, but how this happens is not well known. Examining impacts to other disturbances, such as the alteration of fire regimes from invasive grasses, allows more comprehensive quantification of the extensive deleterious impacts that invasive species can have across the landscape. In addition, more research is needed to assess the regional impacts of invasive species on important ecosystem services, such as providing ample clean air and water.

The ability to estimate the potential impacts of invasion would be facilitated by a better understanding of the mechanisms of invasion, as well as ecosystem invasibility and resilience. Many studies have examined what makes an ecosystem prone to invasion, including which species are likely to be invasive, and the role of propagule pressure. There is still no clear paradigm, however, that can explain the invasion process (Chap. 5). For example, how much is the impact of invasion dependent on the abundance or density of an invading species? It is extremely challenging to design research to develop a deeper understanding of the interactions among propagule pressure, functional traits of invasive species, abiotic and biotic resistance, and the role of disturbance. New knowledge is needed on the ecological differences between invasive species and non-native species that do not become invasive, including the development of models to predict the likelihood of invasion into specific ecosystems, based on species functional traits and interactions with the resident ecosystem.

Finally, inventory and monitoring programs and high-quality distribution data are necessary for managing invasive species and for developing quantitative ecological, economic, and social impact assessments (Chap. 9). A wide variety of programs track invasive species at multiple scales. Nevertheless, there are still gaps in our knowledge. For instance, the USDA Forest Service Forest Health Protection program monitors forest conditions, and there are insect and disease risk maps for forested landscapes. Yet there is a great need for improved modeling, data collection, and mapping

of non-forested systems, aquatic habitats, and invasive plants. The most consistently identified gap across numerous disciplines is the relative paucity of spatially referenced data describing the extent and magnitude of invasive species. The use of citizen science or crowd source data can help address this issue, but data quality must be improved to broaden its applicability as a tool. There is also a great deal of work that needs to be done to standardize inventory, survey, and monitoring protocols among agencies and partners.

16.3 Develop Better Knowledge and Models of How Climatic Variability and Change May Impact Invasive Species

Environmental changes, and changes in precipitation and temperature, will alter all aspects of invasion, from introduction pathways to species establishment, spread, and impacts across multiple sectors (Chap. 4). Understanding how invasive species may respond to disturbances will allow the development of impact assessments, as well as prevention, management, and restoration tactics that consider the future. Responses and approaches may change across time and space as environmental conditions change. To begin to understand the effects of environmental changes and invasive species impacts in the future, it will be necessary to identify multiple interacting climatic and other drivers of invasive species establishment and spread. Most studies have examined the impacts of climatic variability and change on individual invasive species in simplified systems based on one physical component of climate change (e.g., temperature, soil moisture, elevated carbon dioxide (CO₂)); these components are rarely studied in conjunction with biological interactions (e.g., competition) and other stressors and disturbances. For example, increased CO₂ may increase plant biomass or productivity, but how competition may factor into this isn't well known. Realistic studies in natural settings over larger landscapes and across multiple environmental gradients could provide insights into the potential future of how invasive species distribution or function may change.

The potential rate at which species may adapt to future climate conditions through evolutionary processes should be considered (Chap. 4). For example, knowing the genetic structure of invading populations is most likely necessary to identify how climate change can drive or inhibit their spread. Genomic studies of relatedness and genetic variations among invading populations are needed for developing robust models of spread in a changing climate. Research is also needed to determine how and to what extent climate change acts as a selection process on invasive species. New knowledge on the interactions between climate change and genetic processes,

such as hybridization and polyploidization, will be critical for explaining how invasive species adapt to climate change.

While predictive modeling frameworks that incorporate climatic change are highly useful, they may require the development and application of spatially explicit models of invasive species distribution and spread at relevant spatial scales. This endeavor involves constructing species-specific models capable of projecting potential future spread under a range of climate scenarios. Many current species distribution models can predict areas of potential introduction (climate matching or suitability) and potential changes in future climatic habitats, but they rely on past conditions which often makes them less successful in predicting what might happen in the future, especially as conditions become more novel. The ability to project future invasive species distributions in response to climate change can be enhanced when multiple models using different approaches (e.g., empirically based or process based) are used in conjunction with multiple climate change scenarios. As with other aspects of invasive species research, high-quality baseline species distribution data on invasive species are needed for developing quantitative predictive models.

There is also evidence that climate change may alter the efficacy of management tactics for control and restoration of invaded ecosystems, including the use of herbicides or mechanical methods to manage invasive plants. This will require a better understanding of how climate change will impact the interactions between invasive organisms and their chemical and biocontrol agents, as well as the effectiveness and resilience to agents. Research is also needed for improving other management and restoration strategies under varying climates following invasions.

16.4 Develop Additional Cost-Effective Tools, Techniques, and Approaches for Invasive Species Detection, Prevention, and Control As Well As Approaches for Restoration of Invaded Ecosystems

Four broad strategies are used to protect natural and other resources from invasive species: prediction and prevention, early detection and rapid response, management and mitigation, and rehabilitation and restoration (Chaps. 6, 7 and 8). In general, preventative measures that are targeted at the highest risk species (i.e., those species that are most likely to invade and cause severe harm) are considered the most cost-effective. Rapid responses (i.e., eradication or containment) to newly invading populations are considered the next best alternative to exclude potentially damaging invasive species from occupying their full potential range. Reactive efforts to manage and mitigate invasive species and their impacts can be costly, and “success” can be a matter of perspective.

However, the public may not be aware of the benefits of prevention and, understandably, may be focused on those species that are well established and causing harm. For those pernicious species, the goal is not necessarily to eliminate all individuals but to reduce their densities to manageable levels.

Research to distinguish non-native species that might cause harm from those that are likely to be benign and to identify pathways by which harmful species might be introduced would help to predict and prevent high-risk species from invading. For potentially harmful species, regulators and resource managers need to know where these species are likely to occur and cause harm over time; this information is integrated in spatially explicit invasive species risk assessments. As noted above, incorporating the effects of future climate and human behaviors into the assessments could provide valuable new insights. New approaches are needed to reduce and reflect uncertainties in those assessments in ways that support decision making. Extensive empirical observations of invasive species in both their native and non-native ranges would be extremely useful to rigorously test new theories and models and identify opportunities for substantive improvements in prevention.

Preventative efforts are seldom perfect, making rapid response strategies necessary to protect natural resources from new invading species. These strategies would benefit from an improved understanding of the dynamics of low-density populations, along with new techniques and technologies to detect and eliminate invading species, and bioeconomic analyses to determine when such efforts might be cost-effective. Researchers should evaluate the role citizen scientists might play in national surveillance systems for the early detection of invasive species. When a target is found, managers need eradication or containment options that are specific to the target and leave resident species unaffected. Managers would benefit from new frameworks to incorporate social issues related to eradication into their decision-making processes.

For well-established invasive species, natural resource managers need tools for analyzing risk and uncertainty in order to prioritize when, where, and how intensively management efforts should occur. Unfortunately, many public and private land managers often operate in “triage mode” when it comes to managing invasive species. They will require new, effective tools and approaches; these management alternatives may stem from advances in genetic technologies, remote sensing, chemical ecology, biological control, or other fields. Their decisions should account for ecosystem uniqueness, potential invader impacts, management goals, available tools, and chances of success. The idiosyncratic nature of each decision requires information from ongoing lines of research and will inspire new avenues of research. Some questions may be very specific, relating to the etiology and epidemiology of an emerging disease or the

impact of microbial communities on allelopathic compounds from invasive plants, for example. Others are seemingly more general, such as how the severity of impact changes as the abundance of an invading species declines.

Regardless of the target restoration state (historic or other defined future condition), research suggests that restoration will be more successful if ecosystem function, resilience, and resistance to future invasions are emphasized and monitored to ensure long-term success. However, a well-developed knowledge base and infrastructure to accomplish this goal for all invasive species do not exist. For example, a greater understanding of the resilience and resistance of different ecosystems is needed, as are improvements in plant seeding technology, native plant seed availability, and other revegetation approaches to advance system recovery following degradation or invasive plant control. Guidance and protocols need to be developed that include taking predicted environmental changes into consideration while keeping costs down. Breeding programs are needed to develop resistant hosts that can provide actual solutions to invasive insects and diseases within reasonable time periods, but there is currently a lack of infrastructure and expertise necessary to support such programs. For aquatic invasive species, with their ecological idiosyncrasies and potential for rapid adaptation to new environments, the need for new tactics, strategies, and understanding at a broad scope is likely.

Even when existing science is available for guidance on restoration and rehabilitation, costs to implement many approaches can be operationally prohibitive, especially if landscape-level restoration is needed. Economic models (discussed below) can help to determine the costs and benefits of implementing restoration activities versus accepting the degraded site as a novel community and utilizing any ecosystem services it may provide. However, there is a dearth of landscape-scale operational, economic, and feasible restoration approaches for many invasive species.

16.5 Broaden the Understanding of the Cultural, Social, and Economic Impacts of Invasive Species Presently and Over Time

Invasive species can create important economic and social impacts across many diverse segments and sectors of society. Indeed, understanding economic and social impacts is critical for raising awareness among decision makers and the public of how invasive species may detrimentally impact multiple sectors of society, and why actions to treat invasive species may be proposed. The lack of comprehensive investigations into impacts from invasive species, including the full value of ecosystem services lost, can be a barrier to policymakers and others in forming meaningful lists of priori-

ties and realistic management strategies. Across most aquatic and terrestrial invasive species taxa, decision makers lack quantified economic impacts (both direct and indirect) of invasive species at the local, regional, national, and international levels. As noted in Chap. 9, there is increased recognition of impacts to other resources and systems, such as animal and human health, urban ecosystems, public safety, infrastructure and transportation, and indigenous peoples. Most damage estimates from invasive species at the national (or even global) scale merely add up values from several studies or generalize across diverse landscapes, invasive species, and impact methods. Such studies estimate very high impact values but may violate some of the most basic rules of economic analysis and can do more harm than good (Chap. 14).

In many respects, the challenges from, and responses to, invasive species are social constructs. “Harm” from invasive species reflects a reduction in social, cultural, and economic value that people ascribe to resident individuals, populations, or ecosystems. Similarly, responses to invasive species reflect the degree of willingness to protect or restore threatened entities and to preserve their associated current or future value. Of course, those values must be balanced against other social values such as freedom of movement or economic development. There has been little social science research conducted in the United States on general awareness, attitudes, and behaviors toward invasive species or the entities they threaten. More information is needed about how and why public and private land managers perceive invasive species as problems, and what types of information, assistance, and resources would be most helpful in managing current invasions and the risk of future invasions.

Economics provides a formal framework for exploring tradeoffs among different management alternatives for invasive species. Those tradeoffs are not inherently fiscal, but currency is a useful metric to measure many but not all values. Increasingly, managers and policymakers are considering the efforts to control invasive species as an investment. Research to determine how to measure and forecast future returns on such investments, perhaps as a basis for prioritizing management activities, is needed. Of course, progress in this area will depend on more general advancements in the non-market valuation of ecosystem services. In addition, economics may provide useful approaches for incorporating ecological and management uncertainties into decision-support tools.

Socioeconomic research also provides a lens into human behavior and, in this case, may provide insights about drivers at local, regional, or international scales that can influence the distribution, abundance, and diversity of invasive plants, pathogens, and animals. This may require new methods to incorporate socioeconomic conditions and human dimen-

sions data into pest risk models and to characterize how future human behaviors and related patterns might change pest risks. In particular, more research is needed on the effectiveness of actions specifically intended to change behaviors (e.g., laws and regulations) to lower the spread of invasive species.

Socioeconomics plays a critical role in the success of invasive species management. For example, cooperation across landowners is essential for successful areawide management of invasive species. A greater understanding of factors that determine the likelihood and effectiveness of landowner cooperation, and whether there are tradeoffs between likelihood and effectiveness of landowner cooperation, is needed. Information is also needed about the scale at which landowners should cooperate with one another to be able to affect invasive species management at a landscape scale. Landscape-scale management can engender conflict, particularly among stakeholder groups with different perceptions of the values at risk from an invasive species. Greater interdisciplinary research between biological and social scientists could unveil new approaches for addressing the complexities and uncertainties in invasive species management and reduce the potential for associated social conflicts among stakeholders.

Invasive species can have unique cultural impacts for Native people (Chap. 12). Tribes throughout the country are actively working on invasive species management, often in partnership with other agencies, to protect biocultural diversity. A number of successful collaborations exist between Native tribes and biological scientists to address invasive species, particularly tree pests and diseases, yet more research is needed by or with tribes to understand how cultural values, traditional knowledge, political sovereignty, and other policy issues affect invasive species management.

16.6 Conclusion

The assessment consolidates the state of science for invasive species from a comprehensive array of topics pertinent to invasive species. The information from this assessment is targeted to be useful for multiple stakeholders and decision-

and policymakers to more effectively manage invasive species. While considerable progress has been made in understanding multiple aspects of invasions, we highlight four broad research challenges and gaps: (1) improved understanding and quantification of the ecological, economic, and social impacts of invasive species and the mechanisms of invasion; (2) development of better knowledge and models of how climate change may impact invasive species; (3) more cost-effective early intervention, eradication, and control methods and approaches for managing existing invasive species populations; and (4) a better understanding of the economic, social, and cultural dynamics of invasive species. High-quality standardized spatial data for invasive species distribution and abundance across the landscape, change detection (monitoring, longitudinal data sets), cutting-edge tools and technologies, and international cooperation will be needed to support progress for all of the challenges (Chaps. 10, 11 and 13).

The challenges identified here subsume numerous other questions that are described in the preceding chapters. The lists of research needs should not belie the significant advancements that are being made in invasive species research which are also captured in the preceding chapters. The knowledge gained has unquestionably improved our ability to protect lands and waters from the harmful effects of invasive species, yet so much more needs to be done.

Progress to meet these challenges will require close collaboration among professional and citizen scientists, land managers, decision makers, the international community, and other stakeholders. There is an overarching need to develop meaningful measures of progress toward achieving these outcomes. Progress cannot be measured merely by the number of research products (professional presentations, peer-reviewed publications, patents, etc.) produced, but ultimately by the degree to which people, cultures, and natural resources are protected from the harmful effects of invasive species.

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