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Effects of Climate Change on Aquatic Invasive Species and Implications for Management and Research

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ABSTRACT

Global change stressors, including climate change and variability and land use change, are major drivers of ecosystem alterations. Invasive species, which are non-native species that cause environmental or economic damages, also contribute to ecosystem changes. Their interaction, although not well understood, may exacerbate the impacts of climate change on ecosystems, and likewise, climate change may enable further invasions. This report reviews available literature on climate change effects on aquatic invasive species (AIS) and examines state level AIS management activities. Data on management activities came from publicly available information, was analyzed with respect to climate change effects, and included review by managers. This report also analyzes state and regional AIS management plans to determine their capacity to incorporate information on changing conditions generally, and climate change specifically. Although there is no mandate that directs states to consider climate change in AIS management plans, state managers could consider predicted effects of climate change on prevention, control, and eradication in order to effectively manage under changing climatic conditions. Further scientific research and data collection are needed in order to equip managers with the tools and information necessary to conduct effective AIS management in the face of climate change.

CONTENTS

LIST OF TABLES

FOREWORD

(To be included for external peer review)

PREFACE

This report was prepared by the Environmental Law Institute (ELI) and the Global Change Research Program in the National Center for Environmental Assessment (NCEA) of the Office of Research and Development at the U.S. Environmental Protection Agency. It is intended for managers and scientists working with aquatic invasive species (AIS) to provide them with information on the potential effects of climate change on AIS, strategies for adapting their management to accommodate these environmental changes, and highlight further research needs and gaps. As a part of the information gathering for this report, EPA convened two workshops with managers and scientists. The first workshop, held at the ELI offices in Washington, D.C. in June 2006, focused on the current state of scientific understanding of climate change effects on AIS and on identifying research needs and gaps. The conclusions from the first workshop led to two additional activities: (1) a review of state and regional AIS management plans to identify adaptive capacity, and (2) a second workshop to plan a series of review papers that addresses the connections between climate change and invasive species and the resulting complexity. The results from the review of management plans are a significant part of this report and serve as a guide for how states and regional councils may begin to incorporate climate change information into their planned activities for AIS management. The papers developed as a result of the second workshop, also held at ELI in October 2006, will be published as a Special Section in the journal *Conservation Biology*, expected June 2008.

AUTHORS AND REVIEWERS

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EXECUTIVE SUMMARY

Global change, including climate change and variability and land use change are major drivers of changes in ecosystems. Invasive species, or non-native species that cause environmental or economic damages, also cause significant changes in ecosystems and to the services they provide. The effects of climate change on invasive species and their combined effects on ecosystems are not well understood. In some instances climate change may create additional opportunities for invasion or create conditions unsuitable for certain invasive species. Consequently the magnitude of ecological and economic impacts of invasive species may increase, decrease, or remain the same. Although the level of uncertainty about effects is high and developing management responses may seem daunting, because effects will vary regionally with climate and species traits, developing management approaches that incorporate existing climate change information and providing the capacity to add new information are necessary first steps to address climate change effects. This report strives to identify the research and management intersections that can jointly address climate change and aquatic invasive species (AIS) to enable effective prevention, control, and eradication under changing conditions.

The literature review that introduces this report shows that important progress has been made in identifying climate change effects on invasive species, but that our understanding of effects on specific species and interactions of other stressors needs to be improved. Following the literature review is an analysis of existing AIS management plans to assess the capacity of states to modify or adapt their management activities to account for climate change effects. The assessment shows that most states currently do not explicitly consider climate change in their aquatic invasive species management plans, but that many plans can incorporate new information on changing environmental conditions. This finding is not surprising, since states are not currently mandated to incorporate climate change considerations into their management plans. However, the analysis is encouraging, since many of the existing mechanisms may be used to incorporate information on how to adapt AIS management activities to potential climate change effects. If states can adapt their management activities, they will be more likely to maximize the effectiveness and efficiency of their financial resources as environmental conditions change, while still meeting their AIS management goals. In this respect, prevention activities may be the best way to maximize effectiveness and efficiency.

Finally, this report compares information needs of AIS managers with current research to determine where gaps exist. Overall, more information and research are needed on the effects of climate change on:

- Most of the AIS management activities done by states,
- Each step in the invasion pathway (transportation, colonization, establishment, and spread),
- Invasive species impacts (both economic and ecologic),
- Specific invasive species and the ecosystems they invade, and
- Interacting stressors

These topics are extremely broad and illustrate how much more information could be incorporated into decision making. However, there are practical steps that can be taken now to adapt AIS management activities to the altered environmental conditions that are projected to exist due to climate change. Coordination among states, identification of new threats as a result of climate change, identification of ecosystem vulnerabilities, evaluation of control mechanisms, and information management are some of the areas where an understanding of the effects of climate change will be important to our ability to achieve stated management goals in the future.

1. INTRODUCTION

1.1. ORGANIZATION OF REPORT

This report focuses on state research and management needs intended primarily for U.S. states to enable effective prevention, control, and eradication of aquatic invasive species (AIS) in a changing climate. Although numerous federal and international efforts are relevant to—and are affected by—the concepts and recommendations discussed throughout the report, this report focuses on state level programs, plans, and activities because they play a significant role in on-the-ground invasive species prevention and management (ELI, 2002). Furthermore, states are likely to play an important role in driving national policy on both invasive species and climate change issues in the years to come.

The report is divided into four sections and five appendices. As part of the introductory chapter, Section 1 presents the definition of global change and the U.S. Environmental Protection Agency's (U.S. EPA) approach to addressing global change; briefly describes current climate change predictions and the potential effects that future climate will have on ecosystems; describes the impacts that invasive species are having on the environment; and briefly summarizes some of the existing knowledge about how climate change affects invasive species introduction, establishment and spread.

Many state AIS management activities and planned action items, as they are currently structured and outlined in management plans, do not take into account the predicted effects of climate change. The disconnect between invasive species management and potential climate change effects may undermine efforts to achieve stated ecosystem goals under changing conditions. Adapting AIS management plans and practices will not only allow for states to better prevent and control AIS invasions under changing conditions, but will also maximize the effectiveness and efficiency of each state dollar spent on such activities. Section 2 discusses how AIS management may be affected by changes in climate and makes suggestions for modifying leadership and coordination activities, prevention strategies, control efforts, and restoration to incorporate climate change information. Examples are provided of several AIS that are current priorities for many states, the management practices that are used to address these species, and the role that climate change may play in the introduction, establishment and spread of these species. It should be noted that, for the purposes of this report, any modifications to management activities, plans, or programs because of climate change considerations is termed adaptation.

A comparison of available information in the scientific literature with the recommendations of Section 2 reveals that there also is a significant need for scientific, multi-stressor, long-term studies to more fully understand the interaction between climate change and invasive species, as well as a need for species specific information for managers. Section 3 outlines these information needs and research gaps that remain in understanding the interactions between climate change and invasive species. Section 4 concludes with a discussion of management needs for research and information to better manage AIS in the context of a changing climate. The appendices focus on additional information about AIS management and an assessment of climate change implications for AIS management plans.

1.2. GLOBAL CHANGE

Human activities have immense impact on the global environment, which will continue if current trends persist (IPCC, 2007; MEA, 2005; Vitousek et al., 1997a). There are many definitions of global change, depending on the breadth of direct and indirect drivers that may be included. Drivers of change are both human-induced and naturally occurring; however, human-induced changes are the primary drivers of ecosystem change (Vitousek et al., 1997b). Global drivers of ecosystem change can include both direct drivers (e.g., climate change, nutrient pollution, land conversion that changes habitats, overexploitation, and invasive species) and indirect drivers (e.g., demographic, economic, sociopolitical, scientific, technological, cultural, and religious) (Nelson, 2005). Invasive species also can be passengers of direct changes, such as invasive species that exploit recently disturbed habitats (Didham et al., 2005). Of the direct drivers, the terrestrial environment has been most affected by land conversion, often to agricultural use (Nelson, 2005). Overexploitation of fishing resources, pollution, and climate change are examples of major drivers of change in marine ecosystems (Hughes et al., 2002; Nelson, 2005). Primary drivers of change for freshwater ecosystems include modifications and use of watersheds; human contamination of water resources ; altered hydrology; and invasive species (Vitousek, 1994; Nelson, 2005)., Many assessments have recognized climate change as a major driver of change that will play an increasingly important role in the coming decades (IPCC, 2007).

Global change, as defined by the U.S. Global Change Research Act of 1990 (GCRA), "means changes in the global environment (including alterations in climate, land productivity, oceans or other water resources, atmospheric chemistry, and ecological systems) that may alter the capacity of the Earth to sustain life" (Public Law, 101-606 §2(3)). In enacting this law, Congress made the following findings, among others:

- Industrial, agricultural, and other human activities, coupled with an expanding world population, are contributing to processes of global change that may significantly alter the Earth habitat within a few human generations; and

- Such human-induced changes, in conjunction with natural fluctuations, may lead to significant global warming and thus alter world climate patterns and increase global sea levels. Over the next century, these consequences could adversely affect world agricultural and marine production, coastal habitability, biological diversity, human health, and global economic and social well-being (GCRA, §101(a)).

The Environmental Protection Agency (EPA) is one of several U.S. agencies and organizations that are conducting global change research. The EPA's Global Change Research Program (GCRP) in the Office of Research and Development, is assessing the effects of global change on aquatic ecosystems and their services in the context of other stressors and human dimensions in order to improve society's ability to respond and adapt to the future consequences of global change. The GCRP emphasizes the role of climate change, climate variability, and land use change as global change stressors. Increasingly, scientists and policy-makers have recognized invasive species as a global stressor, because of their significant effect on ecosystems (Mooney and Hobbs, 2000; Vitousek et al., 1997a). This report: examines how climate change affects aquatic invasive species, reviews state AIS plans and activities for existing capacity to incorporate climate change considerations into management tasks and strategies; discusses implications for resource management, including informational and data needs, and recommends further research directions based on this discussion.

1.3. INVASIVE SPECIES AND ECOSYSTEM IMPACTS

The introduction of species into new areas is a natural phenomenon that has occurred throughout evolutionary history (Tinner and Lotter, 2001; Graham et al., 1996). In modern times, however, the natural movement of species has been augmented by humans operating in a globalized world. In the Great Lakes, for example, intense vessel traffic from international trade is the major vector for introduction of non-native aquatic species. This region has the highest known introduction rate, with one new non-native species being discovered every 28 weeks (Ricciardi, 2006). The actual number of non-native species introduced into the United States is unknown. Estimates range from 6,600 since European settlement of the U.S. (Cox, 1999) to 50,000 species (Pimentel et al., 2005).

Non-native species (also described as alien, exotic, or non-indigenous species) that are intentionally or unintentionally released into new environments can become invasive species, causing environmental, economic, and/or human health harm. In Executive Order 13112 establishing the National Invasive Species Council, an invasive species is defined as "an alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health." Alien species are also described as non-native species or exotic species (ELI, 2002). It is important to note that not all non-native species are harmful or will become invasive. For example, 8 percent of terrestrial non-indigenous species, 31 percent of non-indigenous insects, and 28 percent of non-indigenous fishes have had beneficial effects (OTA, 1993).   The Asiatic clam (*Corbicula fluminea*) is one such example; it invaded a tidal marsh in the Potomac River in the late 1970's and increased water clarity to a level at which submerged aquatic vegetation reappeared and various aquatic bird populations returned to the area (Phelps, 1994). In fact, only a small percentage of non-native species become invasive and cause ecological and/or economic damage (OTA, 1993). However, for those species that do become invasive, their impacts can be devastating. Available data indicate that invasive species can threaten the very existence of native species in the invaded environments (Sax and Gaines, 2003; Novacek and Cleland, 2001; Mack et al., 2000). Invasive species are a major cause of extinctions worldwide—25 percent of fish extinctions, 42 percent of reptile extinctions, 22 percent of bird extinctions, and 20 percent of mammal extinctions (Cox, 1999). In the U.S. alone, damage and losses from invasive species are estimated at a value of approximately $120 billion annually (Pimentel et al., 2005). Also, despite advances in understanding what makes environments suitable for invasion and determining characteristics of species capable of invasion, it is still difficult to predict which species will become invasive (Richardson and Pysek, 2006; Kolar and Lodge, 2001; Lonsdale 1999; Rejmanek and Richardson, 1996).

This report focuses on aquatic invasive species (AIS), including marine, freshwater, and riparian species, specifically, AIS that are already problematic in one or more states and have the potential to expand into neighboring states as conditions change and become more suitable. However, species also become invasive when introduced into areas with similar climates as their host climate, such as species from the Ponto-Caspian regions to the Great Lakes. Thus, it can be difficult to identify what exactly makes a species invasive. Furthermore, because climate change will have the potential to change ecosystems, the way in which we differentiate and define native, non-native, and invasive species will need to change (Logan, 2006).

AIS can cause a wide range of ecological impacts including loss of native biodiversity, altered habitats, changes in water chemistry, altered biogeochemical processes, hydrological modifications, and altered food webs (Dukes and Mooney, 2004; Ehrenfeld, 2003; Findlay et al., 2003; Simon and Townsend, 2003; Eiswerth et al., 2000; Gordon, 1998). Wetlands, including estuaries, are some of the most invaded habitats in the world (Zedler and Kercher, 2004; Cohen and Carlton, 1998). Some of the most notorious U.S. invaders are aquatic species such as the zebra mussel, purple loosestrife, tamarisk, Asian carp, *Caulerpa* (marine green alga), and the green crab. Section 1.4 below describes the ecological impacts of some of these invaders and the potential impacts of climate change on these species.

1.4. CLIMATE CHANGE AND ECOSYSTEM IMPACTS

The recently released Fourth Assessment Report Summary for Policymakers from the Intergovernmental Panel on Climate Change (IPCC) provides a comprehensive synthesis of the current state of climate change science and a discussion of the projected effects that climate change will have in the coming decades and centuries (IPCC, 2007). Atmospheric carbon has increased from 280 parts per million (ppm) in pre-industrial times to 379 ppm in 2005. Other greenhouse gases such as methane and nitrous oxide are also on the rise. Warming is occurring globally, as evidenced by increases in global mean air temperatures, global mean ocean temperatures, melting of snow and ice in polar regions and high altitudes, and sea level rise (IPCC, 2007). The projected effects of climate change include: warmer and fewer cold days and nights over most land areas, warmer and more frequent hot days and nights over most land areas, increased frequency of warm spells and heat waves over most land areas, increased frequency of heavy precipitation events over most areas, increase in areas affected by drought, increase in intense tropical cyclone activity, and a rise in sea level (IPCC, 2007). Some issues that are less well understood include how precipitation, groundwater recharge, and streamflow will change as a result of climate change (IPCC, 2001).

In addition to the physical changes, climate change is altering ecosystems and species life cycles. Changes include longer growing seasons in mid and high latitudes, shifts in species' ranges towards the poles and higher altitudes, decline of some species, and changes in the reproductive cycles of plants and animals that are cued by climate and seasons (Parmesan, 2006; Root et al., 2003; Walther et al., 2002; IPCC, 2001). In the U.S., species restricted to southern habitats may move north as milder winters allow overwintering. In other cases, less heat tolerant species may decline in their southern ranges, allowing for new species to fill the niches left behind (Aerts et al., 2006). Altered hydrological regimes will also favor some species over others. These changes may be particularly problematic for threatened and endangered species whose habitats are dwindling (McLaughlin et al., 2002) or those with limited dispersal capabilities, if climate change makes their habitats unsuitable. Climate changes leading to increased rainfall or, conversely, drought may also shift invasive species ranges and present new opportunities for invasion. Climate change will also put selective pressure on species, presumably leading to adaptive genetic changes that may influence species success (Barrett, 2000).

Two well known examples of invasive species that alter the invaded ecosystem even without climate change are cheatgrass (*Bromus tectorum*) and salt cedar (*Tamarix ramosissima*). Cheatgrass alters fire frequency and extent, turning shrublands into grasslands, while the drought tolerant and deep-rooted salt cedar dominates riparian forests that were once dominated by cottonwoods and willows (Wilcox and Thurow, 2006; Lite and Stromberg, 2005). Climate change may have positive feedbacks for both of these invasive species, if the southwestern U.S. experiences more frequent droughts, as currently projected (Seager et al. 2007). This interaction between climate change and invasive species may intensify ecosystem effects and possibly increase the spatial extent of these effects.

A dramatic example of a species shifting its range poleward and towards higher altitudes is that of the mountain pine beetle (*Dendroctonus ponderosae*). Historically, the North American native mountain pine beetle has been limited in its range due to climatic conditions—cold temperatures at higher altitudes and latitudes prevented the beetle from completing its life cycle in a single season (Logan and Powell, 2001). With increased warming at higher latitudes and altitudes the beetle is able to complete a life cycle in one season, allowing for range expansion, thus exposing new species of trees to pine beetle infestation, and resulting in epidemic breakouts of the mountain pine beetles in existing and new environments (Carroll et al, 2003; Logan and Powell, 2001). Although this is a terrestrial example, it illustrates two important points: (1) invasive species are already responding to climate change, and (2) some invasive species causing ecological and economic damages due to climate change may be native species. This underscores the importance of considering climate change effects, since species responses may not be limited to the current set of known AIS.

Currently most examples of species range expansions in response to climate change are terrestrial (see Parmesan, 2006; Root et al., 2003; Walther et al., 2002), although aquatic examples are increasing (Parmesan, 2006). One example of a range expansion to higher altitudes is threadleaf water-crowfoot (*Ranunculus trichophyllus*), which has invaded previously non-vegetated lakes in the Himalayas, an invasion attributed to climate change (Lacoul and Freedman, 2006). Another species with a potential to expand its range under climate change and cause great harm to human health is a specific genus of trematodes or blood flukes native to tropical and sub-tropical regions of the world that cause the disease schistosomiasis. These blood flukes could impact human health if the carriers of the blood flukes, tropical aquatic snails, move northward as temperatures warm and conditions become more humid (Tol, 2002). While these aquatic species have not caused the types of damages attributed to mountain pine beetles, the potential exists for other AIS to cause further or unforeseen ecological or economic damages, because changes in temperature and hydrological regime will continue to affect aquatic species.

1.5. CLIMATE CHANGE IMPACTS ON INVASIVE SPECIES

Climate change induced alteration of ecosystem conditions can enable the spread of invasive species through both range expansion and creation of habitats and conditions suitable for newly introduced exotic species. Altered conditions such as increased atmospheric carbon dioxide, modified precipitation regimes, warming ocean and coastal currents, increased temperature, and altered nitrogen distribution can increase invasive species success in some contexts (Ziska et al., 2007; Ziska, 2003a; Ziska, 2003b; McCarty, 2001; Dukes and Mooney, 1999). Because there has been limited research to date on climate change and invasive species, several of the examples discussed below are of terrestrial species; however, we try to make the link to aquatic systems wherever possible.

Several scientific studies have examined whether increased atmospheric carbon dioxide may enable plant invasions. Dukes (2002) examined the growth of yellow starthistle (*Centaurea solstitialis*) in elevated carbon dioxide conditions in monoculture and as a part of a serpentine grassland community and found that the plant increased biomass with increased carbon dioxide in monoculture. In the community setting, yellow starthistle demonstrated nonsignificant increases in establishment, biomass, proportional contribution to the community biomass and reproductive success. Dukes concludes from these experiments that, while carbon dioxide may not dramatically enhance starthistle success in serpentine grassland environments, it may increase its success in non-serpentine grasslands where it has already become established. Other species have demonstrated similar success when grown in monoculture at increased carbon dioxide concentrations, including cheatgrass (*Bromus tectorum*) (Ziska et al., 2005), kudzu (*Pueraria lobata*) (Forseth and Innis, 2004), and Japanese honeysuckle (*Lonicera japonica*) (Sasek and Strain, 1991). Weltzin et al. (2003) examined how elevated carbon dioxide levels might affect plant invasions in various ecosystems and concluded that increasing carbon dioxide levels will cause increases in resources, plant production, soil moisture, and nitrogen uptake, all of which create favorable invasion conditions.

However, because most attempts to predict invasions have been on a small scale and knowledge of invasions is limited, predicting the effects of increased carbon dioxide is uncertain. Additionally, the bulk of the scientific work on this topic has been limited largely to terrestrial environments. The effects of carbon dioxide enrichment in aquatic ecosystems, with the exception of recent research on ocean acidification (Cao et al., 2007; Pelejero et al., 2005), are still much less well understood, especially with respect to aquatic invasive species. Current knowledge indicates that increased carbon dioxide in ocean and freshwater environments may alter macro- and micro- algae and plant dynamics (Feely et al., 2004). However, increased temperatures and altered precipitation regimes are likely to have larger effects than increasing levels of carbon dioxide. One study of emergent macrophytes in lakes showed that increased temperatures led to larger increases in biomass than increased carbon dioxide levels (Ojala et al., 2002). As in terrestrial environments, responses to carbon dioxide may be species specific, but other environmental variables like water temperature and hydrological regimes may be more important drivers in changing the establishment, spread, and impact of aquatic invasive species.

Climate change is predicted to alter precipitation patterns, leading to droughts in some areas and flooding in others due to increased storm intensity. Knowledge of the effects of climate variability, which also causes droughts and floods, can offer some insights into how ecosystems respond to the stress of altered hydrology (Shafroth et al., 2002). There is much evidence in the invasive species literature that ecosystem disturbances encourage pioneer species, and many invasive species are pioneers (Byers, 2002; Lopez-Lopez and Paulo-Maya, 2001; Schnitzler and Muller, 1998). Thus, changes in precipitation due to climate change may affect AIS establishment and dispersal. Increased rainfall may allow for greater dispersal of upstream invasive species to downstream habitats. Zedler and Kercher (2004) hypothesize that wetlands are highly vulnerable to invasions because wetland invasive plant seeds are frequently dispersed by water. Lonsdale (1993) finds that flooding and rainfall are important factors affecting dispersal of the invasive weed *Mimosa pigra* in Australia. The size of the area colonized related to the amount of rainfall in the previous wet season and the data suggest that seed dispersal by flotation is key to rapid wetlands expansion.

Increasing ocean temperatures also may enable new species invasions. Stachowicz et al. (2002) compare recorded sessile invertebrate species recruitment and establishment with temperature data. Their research shows that introduced ascidians (sea squirts) recruit earlier in years with warmer winter water temperatures, while the recruitment of native ascidians did not significantly change with variation in winter water temperature. Because community composition is often determined by which species settles first, introduced ascidians may out-compete native ascidians as ocean temperatures warm. The authors also show that introduced ascidians have higher growth rates than native species at high temperatures. The authors conclude that rising mean winter water temperature is a stressor that may lead to increased invasions by exotic species in New England. In addition, as coastal currents warm, species may shift their ranges northward and become invasive in new areas. Barry et al. (1995) studied intertidal invertebrate assemblages in California over 60 years where near shore water temperatures increased by 0.75°C and summer temperatures increased by 2.2°C. Barry et al. show that southern invertebrate species increased in abundance and expanded their ranges while northern species that were not tolerant of warmer waters declined (1995).

Dukes and Mooney (1999) also discuss increasing temperature in the context of global climate change and find that it enables species invasions under certain circumstances. Mandrak (1989) examined potential invasions in the Great Lakes due to warming, finding that 27 of 58 species examined were potential invaders due to climate warming. McFarland and Barko (1999) examined the effects of increased water temperature on a monoecious hydrilla, finding that the species is better adapted to higher temperatures than previously shown in the scientific literature. Populations of the common reed, *Phragmites australis* also increase with higher-than-average ambient air temperatures (Wilcox et al., 2003). Another effect of warming temperatures may be an increase in the number of sexual versus asexual reproductive periods for plant species. Diaz-Amela et al. (2007) linked the flowering cycles of a Mediterranean seagrass (*Posidonia oceanica*) to warming water temperatures. If these types of changes occur in aquatic invasive species, they may lead to further expansion and impacts.

1.6. INTERACTING GLOBAL CHANGE STRESSORS

Invasive species can be major ecosystem stressors, and their interaction with other global change stressors is not fully understood. Kolar and Lodge (2000) identify global change and other anthropogenic stressors that increase the number or the impact of freshwater invasive species. These stressors are: globalization of commerce (including shipping, bait trade, aquarium and pond trade, and aquaculture); waterway engineering (including canals and dams); land use changes (including siltation, eutrophication, and water withdrawal); climate and atmospheric changes; and intentional stocking. Carlton (2000) identifies a slightly different set of global change and anthropogenic stressors affecting invasions in the oceans, including: overfishing; chemical pollution and eutrophication; habitat destruction and fragmentation; biological invasions (facilitating other invasions); and climate change. In the Great Lakes, human activities linked to aquatic invasions include clear-cutting and farming practices that increase sedimentation and water turbidity, industrial pollution, urbanization, and overfishing (Glassner-Shwayder, 2000). These examples show that there are many stressors interacting to facilitate the establishment and spread of invasive species and to determine the magnitude of their impact. Climate change will interact with existing stressors and may ameliorate or exacerbate their effects; however, little is known about the change in magnitude of effects due to climate change.

Although the above examples illustrate that there are many stressors interacting with invasive species and climate change, land use and land cover changes remain the major global stressors that affect these other stressors (Vitousek, 1994). Land use change and the ecosystem disturbances it causes can also lead to more invasions (Hansen et al., 2005; Mack et al., 2000). Nutrient loading due to increased agriculture, intensification of agriculture, or urban runoff can facilitate invasions of aquatic invasive plants (Lake and Leishman, 2004; Maron and Connors, 1996). Increased development can lead to degradation of habitats, and some studies demonstrate that degraded habitats are more prone to invasion than healthy environments (Mack et al., 2000). Hobbs (2000) discusses the complex nature of land use changes and their effects on invasive species and habitat invasibility. Land use changes include increased urbanization, deforestation, ecosystem fragmentation, and altered agricultural practices (intensification and abandonment).

Two additional major changes in recent history that can alter ecosystem dynamics are: increasing levels of human transformation and domination of ecosystems (Vitousek et al., 1997b) and increasing transport of species leading to a breakdown in biogeographical barriers (Cohen and Carlton, 1998). Hobbs (2000) describes the complex interrelationship between land use disturbances and invasions. For example, land transformation (e.g., increased nutrient or pollution runoff from conversion to agriculture or urban development) can enhance invasion by providing opportunities for establishment. Invasion, in turn, can drive land transformation (e.g., an invasive tree species can convert grassland into forest). These processes may feed back upon each other to facilitate further alteration, possibly causing an "invasional meltdown," which leads to an acceleration in the number of invasive species and impacts (Ricciardi, 2001; Simberloff and Von Holle, 1999).

Climate change will present a major stressor with which managers and decision-makers will need to be concerned, particularly in the context of interacting with other contributors to species invasions. However, scientific understanding of the complexity of invasions resulting from climate change, and making predictions that incorporate these considerations, is not yet well developed. Indeed, one of the major challenges in investigating the interactive nature of global change stressors is the incredible complexity of biological systems. Often, invasive species models consider global change factors in isolation because of the challenges of complexity. For example, the most widely used models to predict invasibility may use temperature as a major component.

2. MANAGEMENT OF AQUATIC INVASIVE SPECIES IN A CHANGING CLIMATE

2.1. STATE MANAGERS' REPORTED CLIMATE CHANGE CONCERNS

Each of the 50 states conducts management actions that address aquatic invasive species problems. Programs and activities vary widely and may include: research to assess current and future invasive threats or identify pathways; detection of newly established species (e.g. monitoring, surveys, inspection); import, introduction, or release requirements for species (e.g., permits and licenses); transport and shipping requirements; quarantine; education and public awareness efforts; control (e.g. biological, chemical, manual); emergency response efforts; and restoration of degraded areas to better prevent against re-infestation.

Many states have formed councils and developed management plans to organize and guide priorities for action and/or have dedicated funding for formal programs to address AIS problems. Other states conduct AIS management on a more ad hoc basis, under the purview of broader agency authorities. For example, a state parks agency might work to eradicate invasive species as part of the maintenance of a state-owned recreational area; a state wildlife agency might seek to protect regulated fish and game species by preventing or controlling invasive threats. In any case, each of the 50 states, albeit to varying degrees, performs some form of AIS management.

In order to determine the information needed to allow state AIS managers to consider and incorporate projected climate change effects into their programs, we inventoried AIS-related management actions in all 50 states (see *Appendix A: Aquatic Invasive Species Programs and Activities*). Research entailed the review of publicly available documents, publications, and online materials. For further clarification when appropriate, we discussed AIS programs, research needs, and management strategies with AIS managers, scientists, and decision-makers. Discussions during two workshops organized as a part of this effort also contributed to the information on climate change concerns.

Results suggest that many managers and decision makers are cognizant of the potential impacts of climate change on invasive species and the effect this driver may have on the goals and objectives associated with existing activities and decisions. Reported concerns emphasize not only how climate change will exacerbate existing problems, but also how it may enhance conditions suitable for species not previously established. The following is a list of concerns reported by states:

- AIS range expansions;
- Identification of species that are more likely to establish under changing conditions and modification of management priorities accordingly;
- Prediction and assessment of conditions that may lead to invasion (e.g., warmer temperatures, disturbed ecosystems and native species, increased nutrient availability, modified precipitation regimes, and erratic weather patterns);
- Overwintering capabilities for invasive species;
- Increased propagule pressure and vectors;
- Increased growth rates;
- Unanticipated interactions between climate change and invasive species;
- Effects of climate change on the success of control efforts; and
- Effects on ecosystem services from increased invasions (e.g., water supply, recreation, etc.).

While state management staff generally recognize that climate change is an important issue, most states have not begun to incorporate climate change information into their ongoing AIS programs, activities, or plans, and few programs make concrete decisions based upon predicted climate change impacts. Additional challenges not reported by states—which may also highlight the nascence of the issue for many state managers—include the potential effects of changes in climate on control methodologies and costs, organizational management and authority, and communication of the problem to the public, among others.

Although not every state operates a comprehensive AIS program, consideration of the effects of climate change is still essential to the success of management efforts. Because states' resources for invasive species management are often scarce, they must be invested in management activities that will prevent, control, and eradicate species in as efficient a manner as possible. Incorporating climate change information when planning and implementing prevention, control, and eradication activities will help maintain the manager's ability to successfully carry out these activities. Adapting AIS management practices will not only allow for states to better prevent and control AIS invasions under changing conditions, but will also maximize the effectiveness and efficiency of each state dollar spent on such activities.

2.2. MANAGEMENT PLANS AS BLUEPRINTS FOR ACTION

Congress passed the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990 (NANPCA) to address the national problem of AIS. Section 1204 of NANPCA allows governors to submit management plans that identify areas and activities that would benefit from technical, enforcement, or financial assistance in order to eliminate or reduce the environmental, public health, and safety risks associated with AIS. Once these management plans are approved by the Aquatic Nuisance Species Task Force, states or regions are eligible to receive federal funding to assist with prevention and control activities. To date, seven state AIS plans have been approved: New York (1993), Michigan (1996), Ohio (1997), Illinois (1999), Indiana (2003), Wisconsin (2003), and Pennsylvania (2007). In FY 2006, Congress appropriated more than $1,075,000 of cost-share funding for these seven states to implement their plans. Several other states also have AIS plans in various stages of development.

Management plans are often organized into the following categories of action:

- Leadership and coordination;
- Prevention;
- Early detection and rapid response (EDRR);
- Control and management;
- Restoration;
- Research;
- Information management; and
- Education and public awareness.

In addition to inventorying AIS-related management actions for all 50 states (see *Appendix A: Aquatic Invasive Species Programs and Activities*), we also reviewed completed state and regional AIS management plans and assessed how they consider climate change specifically, as well as how they provide for adaptation of strategies and actions under changing conditions more generally (see *Appendix B: State Aquatic Invasive Species Management Plan Summaries* and *Appendix C: Regional Aquatic Invasive Species Management Plan Summaries*). Plans are not universal to all 50 states and existing plans are in various stages of both development and implementation. Furthermore, some states operate a multitude of AIS management activities and programs in the absence of a plan. However, an assessment of state plans provides a logical starting point for understanding how states are anticipating and responding to predicted effects of changes in climate.

2.3. RESEARCH RESULTS: STATE PLANNING FOR CLIMATE CHANGE AND AQUATIC INVASIVE SPECIES

In total, we reviewed 25 state plans, including 23 AIS-specific plans and 2 general invasive species management plans with a significant AIS focus. Several other states are currently developing AIS management plans, which were not included in this review. We also reviewed seven regional AIS plans.

Table 2.1 summarizes how each state's plan: (1) addresses potential impacts resulting from climate change, (2) demonstrates capacity to adapt to changing conditions, (3) provides monitoring strategies, (4) includes plans for periodic revision and update of the plan, and (5) describes funding sources/strategies for plan implementation. The assessment of 25 state plans and seven regional plans revealed that few plans consider climate change or changing conditions (see *Appendix D: Complete Criteria and Scoring for State Plan Consideration of Climate Change and/or Changing Conditions* for the full criteria and scoring). The majority of states' plans have management actions that, if conducted under different environmental conditions, may prove less relevant, less efficient, or less successful than they are under current conditions. However, some states, such as Alaska, Hawaii, and Washington, recognize that conditions may change over time and have built these considerations into their management actions. In addition, many state plans contain measures to periodically review and update management strategies and tasks, providing the opportunity to review the robustness of management plans in light of climate change and to amend plans where feasible.

While most state plans do not mention climate change or changing conditions, our assessment of these plans does reveal that states have at least some capacity to adapt their program or activities (Table 2.1). Most states (92%) scored a 1 or more in more than one of the five categories assessed. This represents a potential adaptive capacity across different parts of the program, which should make it easier for managers and decision makers to address potential program vulnerabilities to climate change. These results also illustrate which aspects of state programs can be modified more readily. For example, when scores are summed across states for each category and normalized by the number of questions assessed in each category, most of the adaptive capacity is in the ability of plans to be revised to incorporate new information and the fact that states have sources of funding to accomplish goals and activities (Table 2.1). Monitoring strategies is the next category where state plans exhibit substantial adaptive capacity. Relative to the other four categories, the category describing specific actions currently shows the least amount of adaptive capacity.

The highest scoring state was Washington with 17 points (Table 2.1). This plan scores highly in part because it acknowledges that species boundaries are influenced by climatic conditions, has a specific plan for using, managing, and updating monitoring data, and includes a timeline or benchmarks for updating the plan with new information (for detailed results on each state plan, see *Appendix B: State Aquatic Invasive Species Management Plan Summaries*).

2.3.1. Understanding and incorporating potential impacts resulting from climate change

Only the Virginia state AIS management plan includes a general discussion of climate change. Overall, 84% of the plans assessed do not mention climate change. However, most states (76%) acknowledge climatic boundaries of species, and some (40%) acknowledge the sensitivity of ecosystems to changing conditions. These results indicate areas where capacity exists in most states to begin to identify how these species may respond as climate changes at their current boundaries. Unfortunately, none of the plans currently identify climate change effects as potentially important research topics or mention the regional differences in projected climate changes.

2.3.2. Capacity to adapt to changing conditions

Table 2.2 provides an assessment of the capacity of each state's plan to adapt to changing conditions in its goals and strategies specifically designed to address: leadership and coordination, prevention, early detection and rapid response, restoration, research, information management, and education and public awareness. Across all of these topics just under half (48%) mention changing conditions, and this is generally implicit in the types of goals and strategies described that could be used to respond to any changes in the environment, including climate change. No state plan that was examined accounts for changing conditions in its restoration or information management goals and strategies—two critical aspects of a comprehensive AIS management plan—while many states do express the need for research and data to inform management decisions under changing conditions in their research goals and strategies. Of the plans that mention changing conditions under 'Research,' 20% of state plans mention research into changing conditions explicitly (scores of 2 or 3). Counting both implicit and explicit mention of changing conditions in these categories shows slightly higher capacities across states, although the research category still dominates (Table 2.3).

The goals and activities described by state plans in each of these sub-categories are likely to be affected by climate change. For example, prevention activities will be challenged as species move outside of known ranges. Modifications to how vectors and pathways are monitored may be necessary to capture these effects. One approach may be integrated vector management (Carlton & Ruiz 2005). The integrated vector management framework distinguishes cause, route, and vector for an invasion, including the biological and anthropogenic dimensions. This breakdown into the components is useful for analyzing where climate change may interact with vectors in order to formulate appropriate management responses.

2.3.3. Monitoring strategies

Although no plan includes a provision for monitoring changing environmental conditions, most plans (80%) have clear strategies for using, managing, and updating monitoring data. These results show a high capacity to modify activities associated with monitoring to include information on climate change effects.

While many of the plans reviewed are able to incorporate new management data, climate change may pose additional challenges with respect to the spatial and temporal scales of monitoring (Hellmann et al., *in review*). Providing feedback from researchers about changing conditions to managers would be valuable in order to adapt management activities. Thus, regional coordination, links between research and implementation, and decisions about the scale of monitoring could be included in invasive species management plans to build on their existing capacity.

2.3.4. Plan revisions and funding

Most of the state plans (64%) include language about periodic revisions, which indicates a high capacity to include new information and update goals and activities. Thus, these revisions may include information about climate change effects in the future. Although only 16% of states reviewed (*i.e.*, Missouri, Oregon, South Carolina, and Wisconsin) specify a source for 100% of the required funding for their actions, most state plans (64%) do identify some funding associated with their goals and activities. This indicates an overall high capacity for states to accomplish tasks in management plans. Combined with periodic revisions, this demonstrates that many of these states could accomplish activities that may ameliorate climate change effects on their invasive species programs.

2.3.5. Conclusions about adaptive capacity as illustrated in state plans

Our examination of 25 state plans' capacities to adapt to changing conditions shows that few states have developed strategies and associated tasks that specifically address climate change or consider potential changes in environmental conditions in general. While this is not a surprising finding, since states currently are not mandated to consider climate change effects, management plans could incorporate more strategies to increase a state's capacity to adapt to changing conditions. This analysis highlights that some capacity exists to deal with the additional stressor of climate change, particularly through revisions of management plans, the ability to fund specific activities, and existing monitoring strategies. These results provide managers and decision makers with information on what aspects of management plans can be readily revised to incorporate climate change information and where adaptive management approaches may be most beneficial.

The following sections summarize how state AIS management activities, including leadership and coordination, prevention, control, restoration, and information management, may be adapted to address the predicted effects of climate change. The options presented are intended as examples that managers and decision makers can consider when modifying AIS management plans to incorporate effects due to climate change. To learn more about specific, individual state and regional AIS management plans and how they can be revised to incorporate climate considerations and adaptive management procedures, see *Appendix B: State Aquatic Invasive Species Management Plan Summaries* and *Appendix C: Regional Aquatic Invasive Species Management Plan Summaries*.

Table 2.1. How 25 state plans consider climate change and/or provide for adaptation of strategies and actions under changing conditions.* States are listed in descending order. Possible total score is 51.

	Understanding and incorporating potential impacts resulting from climate change (out of 15 total points)	*Capacity to adapt to changing conditions (out of 21 total points)*	*Monitoring strategies (out of 9 total points)*	*Plan includes strategy for updating and incorporating new information out of 3 total points)*	*Plan identifies dedicated funding source for implementation out of 3 total points)*	*Score*
Washington	3	3	6	3	2	17
Alaska	4	4	5	2	1	16
Hawaii	4	3	6	1	0	14
Kansas	0	3	6	3	2	14
Connecticut	3	4	2	1	2	12
Indiana	3	2	3	3	1	12
Louisiana	6	1	3	0	2	12
Missouri	3	0	6	0	3	12
Massachusetts	5	0	3	0	2	10
Montana	1	3	0	3	2	9
North Dakota	3	1	2	1	2	9
Oregon	3	0	0	3	3	9
Iowa	1	0	3	2	2	8
Maine	5	0	0	3	0	8
Wisconsin	1	0	3	1	3	8
Virginia	4	0	0	3	0	7
Arizona	1	2	3	0	0	6
Illinois	2	2	2	0	0	6
South Carolina	0	0	1	2	3	6
Ohio	1	2	1	1	0	5
Texas	0	0	5	0	0	5
Michigan	1	0	3	0	0	4
New York	0	0	3	0	1	4
Pennsylvania	0	0	0	2	1	3
Idaho	1	0	0	0	0	1

** To view the complete set of criteria and scoring for each state, see *Appendix D: Complete Criteria and Scoring for State Plan Consideration of Climate Change and/or Changing Conditions.*.

Table 2.2. How 25 state plans account for changing conditions in their goals and strategies.* Possible total score is 24. States are listed alphabetically.

	*How plan accounts for changing conditions in its goals and strategies for...***							
	…leadership and coordination	*…prevention*	*…EDRR*	*…control and management*	*…restoration*	*…research*	*…information management*	*…education and public awareness*
Alaska	1	1	0	0	0	1	0	1
Arizona	0	1	0	0	0	1	0	0
Connecticut	1	1	0	1	0	1	0	0
Hawaii	0	0	1	0	0	1	0	1
Idaho	0	0	0	0	0	0	0	0
Illinois	0	0	0	0	0	2	0	0
Indiana	0	1	1	0	0	0	0	0
Iowa	0	0	0	0	0	0	0	0
Kansas	0	0	0	0	0	3	0	0
Louisiana	0	0	1	0	0	0	0	0
Maine	0	0	0	0	0	0	0	0
Massachusetts	0	0	0	0	0	0	0	0
Michigan	0	0	0	0	0	0	0	0
Missouri	0	0	0	0	0	0	0	0
Montana	0	0	0	0	0	3	0	0
New York	0	0	0	0	0	0	0	0
North Dakota	0	0	0	0	0	1	0	0
Ohio	0	0	0	0	0	2	0	0
Oregon	0	0	0	0	0	0	0	0
Pennsylvania	0	0	0	0	0	0	0	0
South Carolina	0	0	0	0	0	0	0	0
Texas	0	0	0	0	0	0	0	0
Virginia	0	0	0	0	0	0	0	0
Washington	0	0	0	0	0	2	0	1
Wisconsin	0	0	0	0	0	0	0	0

** *Scoring:* 0 = none; 1 = implicitly (i.e. includes goals and strategies that can be used to account for changing conditions, but does not specify changing conditions as part of their purpose); 2 = yes, explicitly, in passing; 3 = yes, explicitly, and specifies associated goals and/or action items

* To view the complete set of criteria and scoring for each state, see Appendix D.

Table 2.3. Percent of plans implicitly or explicitly accounting for changing conditions

Plan chapter	*Percent of plans*
Leadership and coordination	8 %
Prevention	16 %
EDRR	12 %
Control and management	4%
Restoration	0 %
Research	40 %
Information management	0 %
Education and public awareness	12 %

2.4. ADAPTING STATE PROGRAMS, ACTIVITIES, AND PLANS TO INCORPORATE CLIMATE CHANGE CONSIDERATIONS

In the sections below, we discuss how state programs, activities, and planned action items related to each category of activity may be susceptible to the projected effects of climate change, and we make recommendations for how management plans and strategies could be adapted to account for and remain robust under changing conditions.

2.4.1. Adapting Leadership and Coordination Activities

Coordination among federal, state, and local agencies, conservation organizations, and key members of the private sector allows for comprehensive and complementary coverage and implementation of state AIS plans and programs, as well as more efficient identification of priority issues and concerns (ELI, 2002). To facilitate coordination and provide leadership on AIS issues, many states have established invasive species councils, from Maryland to Arizona to Hawaii. While some states rely on general invasive species councils to address AIS, others have established AIS-specific councils. Many states have also hired state agency staff to coordinate state (or agency) management tasks among agencies, conservation organizations, landowners, and other stakeholders. Finally, state AIS plans, often created under the leadership of a state council, play a fundamental role in guiding state AIS management strategies and management actions.

As state leaders in AIS management, invasive species councils are in an excellent position to begin to address climate change. Councils may consider holding meetings or workshops to: (1) understand the scope of the climate change problem and its potential effects on AIS; (2) modify the design, if necessary, of current management actions and plans to incorporate existing climate change information; and (3) identify further informational and leadership needs. For example, states will need to know:

- How environmental conditions may change;
- Which species may become threats under projected future conditions;
- Which systems may become vulnerable to invasion due to changes in temperature, nutrient availability, water quality or quantity, and/or changes in ecological community composition;

- How vectors will be influenced by changes in climate;

- How management actions, such as control methods, may be affected by changes in the environment; and

- What research is needed to better inform management strategies.

State councils (or agency staff in the absence of a council) would benefit from sharing climate-related concerns and data with other states to address regional species of concern due to shifts in climate. For example, neighboring states could be alerted to encroaching species, changing vectors, and modified control strategies when possible. Lists of potential invaders could be created and distributed among neighboring states when possible.

State councils may also play a role in coordinating cross-program integration for strategies and tasks that involve more than one state agency, or more than one division within agencies, particularly those aspects that may involve multiple media.

Not every state will have the resources to develop an organized, systematic approach to address climate change. In these states, agency staff and coordinators may begin incorporating climate change information by: reviewing current prevention, control, and eradication activities, as well as planned action items, for their potential vulnerability to climate change; identifying information needs; and modifying strategies where feasible and when climate information is available from the growing body of related literature or from knowledgeable practitioners and researchers.

2.4.2. Adapting Prevention Activities

Prevention measures are implemented to avoid the introduction and establishment of invasive species and are widely recognized as the most effective and cost-efficient tools for combating invasive species because their associated costs far outweigh the potentially devastating environmental and economic costs of invasion (Keller et al., 2007; Leung et al., 2002; NISC, 2001; Wittenberg and Cock, 2001). States with limited resources may maximize the use of scarce invasive species dollars by investing in prevention efforts.

Numerous strategies and measures may be used to prevent the establishment of potentially harmful AIS, including: monitoring, mapping, and/or surveys to identify and mitigate invasive species threats; regulation of certain species, (e.g., introduction, import, or release requirements); quarantines; early detection and rapid response (EDRR) protocols and emergency powers to quickly identify and address new infestations; and education to increase public awareness regarding particular species and/or pathways.

Many state AIS prevention efforts are specific to species that have been identified as imminent threats, while other activities focus on managing and responding to common AIS pathways, such as ballast water, recreational boating, water gardening, or aquaculture. For example, the New Hampshire Department of Environmental Service's Weed Watcher Program trains volunteers to inspect recreational boats and other recreation-related gear to prevent introduction of aquatic invasive plants. Often, states will conduct a combination of prevention measures to address species or pathways. The Maryland Department of Natural Resources - Fisheries Service, for example, seeks to prevent the spread of snakeheads by circulating posters that ask anglers to kill and report all snakeheads, compiling regional data for captures in the Potomac River, and annual monitoring that includes seine, electrofishing, and gillnet surveys. Maine's Department of Environmental Protection and Department of Inland Fisheries and Wildlife conduct aquatic invasive plant prevention along common pathways. The agencies jointly inspect watercraft, trailers, and outboard motors at or near the state borders and at boat launching sites, regularly patrol waters and roads, and enforce violations such as launching a boat or transporting a vehicle on public roads with plants attached.

Prevention activities typically focus on species that are already known to cause impacts. Climate change, however, may enhance environmental conditions for some species with the following consequences: (1) new species are now able to survive in these locations; (2) known invasive species expand their range into new territories; and (3) species that are currently not considered invasive may become invasive and cause significant impacts. Monitoring and survey efforts may be used to identify species that are encroaching as a result of expanding ranges. Monitoring efforts may need to be modified to focus on weakened or changing ecosystems that are more vulnerable to invasion. As temperatures warm, precipitation regimes fluctuate, and nutrient flows change, ecosystems may lose their ability to support a diverse set of native species, becoming more vulnerable to invasion as new resources become available; however, managers should not assume that pristine, species-rich environments are immune to invasion (Melbourne et al., 2007; Byers and Noonburg, 2003; Davis et al., 2000).

Vectors also may be influenced by changes in climate and should be evaluated for their ability to transmit species under changing conditions. For example, seaways may remain open for longer periods during the year due to warming temperatures; thus, shipping and boating traffic, a major vector for species such as the zebra mussel, also may increase. To begin to address these concerns, pathway analysis and species prediction models should be modified to include climate change parameters. Inspection and border control agencies may need to be alerted to new invasive threats and related inspection priorities may need to be re-assessed in light of these impending threats and pathways. Import/introduction/release requirements should be based on risk assessments that account for how changing conditions will affect invasibility. For example, species such as the water hyacinth may become a greater threat under climate change scenarios, and import/release standards should be revised accordingly. Climate changes resulting in increased storm surge and flooding may increase the risk of species escape from aquaculture facilities. In light of these changes, aquaculture facilities may be required to take additional precautionary measures against escapes or establishment (e.g., use only triploids, stock only one sex, or use sterile hybrids) or to use only native species. Finally, ongoing land and water management activities must be re-evaluated for their potential to provide new invasion pathways. For example, waterway engineering should examine passage between water bodies that were historically separated, create barriers to passages, and consider AIS before re-filling or reconnecting waterways.

2.4.3. Adapting Early Detection Rapid Response Activities

Early detection and rapid response (EDRR) refers to efforts that identify and control or eradicate new infestations before they reach severe levels. Because even the most effective barriers to entry will at some point be breached, EDRR is an important element in preventing and controlling invasive species problems. In addition to monitoring and/or mapping to detect infestations, EDRR efforts may include emergency powers for state agencies to implement control measures quickly and restoration to decrease vulnerability to re-establishment of the invading species. Comprehensive EDRR plans identify participating and lead agencies, potential regulatory requirements for control, and other EDRR protocols.

The effectiveness of EDRR efforts may be improved by monitoring not only for the establishment of new infestations, but also for changing conditions in order to better predict which systems may become vulnerable to invasion. To address the potential effects of climate change, continued and new monitoring will be necessary to update information systems with data that allow evaluation of those effects (Lee et al., *in review*). Adapting monitoring may mean sampling at different temporal or spatial frequencies, or using different sampling techniques (Lee et al., *in review*). For example, monitoring to detect range changes may require sampling the distributional and altitudinal edges of species ranges (Lee et al., *in review*).

2.4.4. Adapting Control and Management Activities

Control and management measures vary widely among states and depend on the species being targeted, the infested ecosystem, availability of resources, and the severity of the infestation, among other factors. Control techniques may be biological, chemical, or mechanical, or a combination thereof. For example, the Colorado Department of Agriculture's Aquatic Plants Management Program operates several control projects throughout the state, including both manual removal and chemical treatments. EDRR is also an important element of invasive species control strategy (see *Section 2.4.3. Adapting Early Detection and Rapid Response Activities*).

Changing conditions such as warmer waters, extreme weather events, salt water intrusion, and/or changes in water chemistry may affect the success of "tried and true" biological, chemical, or mechanical control measures. For example, if a biocontrol agent is introduced, managers must be aware of the conditions under which the biocontrol species may fail—or conditions under which they may thrive beyond control—and cross-reference those parameters with predicted changes in the ecosystem. Changes in temperature and precipitation may affect biocontrol and invasive species differently, either increasing or decreasing the effectiveness of the biocontrol agent (Bryant et al., 2002). For example, saltcedar leaf beetles (*Diorhabda elongate*) may be less effective at controlling Tamarisk (*Tamarix ramosissima*) in warmer temperatures, while the alligatorweed flea beetle (*Agasicles hygrophila*) may become more effective in controlling alligatorweed (*Alternanthera philoxeroides*). Similarly, herbicides and other chemical control measures may also be affected by temperature, water chemistry, and other climate-related changes in the ecosystem (Ziska et al., 1999). Finally, mechanical control may no longer be feasible when warmer winter temperatures allow invasive species to spread that are currently limited by hard freezes or ice cover and occur in limited areas. A re-evaluation of appropriate control measures may be necessary in order to make efficient use of state investments in AIS management.

2.4.5. Adapting Restoration Activities

Restoration of natural systems is critical to preventing re-introduction of an invasive species once it has been eradicated or controlled. Because healthy ecosystems can be less vulnerable to invasion (Vitousek et al., 1996), restored ecosystems also may be less vulnerable to future invasions, thus providing some insurance to investments in invasive species prevention, EDRR, and other control measures. One example of this use of restoration is Massachusetts' AIS Management Plan that calls for reintroducing native species as part of a restoration program for lakes and ponds (Massachusetts Aquatic Invasive Species Working Group, 2002).

Given that climate change is predicted to alter native species and habitats and other ecosystem attributes, restoration designs should emphasize restoration of ecosystem processes (e.g., sediment and nutrient transport, export of woody debris, river-floodplain connections, etc.) that were originally disrupted and may have facilitated the establishment of AIS. Restoration projects should consider which native species may thrive in, or at least tolerate, future climate change conditions and avoid those species that may not be as well suited to future conditions. Restoration plans that consider the effects of sea level rise and the increased occurrence of extreme weather events are likely to produce projects that remain effective under future climates. For example, state coastal restorations are expected to be at risk from climate change, because water levels are critical in marsh restorations, and sea level rise could render many current saltwater marsh restorations useless if this effect is not considered in plans. Based on these factors, states may modify long-term restoration strategies in order to make habitats more robust and less vulnerable to potential invasions as conditions change.

Restoration of natural regimes and ecosystems are an effective management tool to control invasive species, and climate change effects are considered at the outset. In some cases tools such as controlled burns may become more limited if climate change exacerbates regional air quality issues and burning permits therefore cannot be obtained (Hellmann et al., *in review*). A similar issue may exist in simulating natural flood regimes through dam releases. The southwestern U.S. is predicted to become drier, reducing overall water availability (Seager et al., 2007); however, in regions with increased precipitation, this management tool may become more viable (Hellmann et al., *in review*).

2.4.6. Adapting Information Management Activities

No state has adopted a formal information management system that documents, evaluates, and monitors impacts from invasive species (NISC, 2001). States that are considering the development of an information management system will have to support rapid and accurate discovery of data, correlate and synthesize data from many sources, and present the results of data synthesis that meets the needs of users. In addition to data on species movement and establishment, information on ecosystem conditions – e.g., water temperatures, chemical composition, and salinity levels where applicable – should also be monitored and evaluated to fully assess invasive species threats in the context of a changing climate. Any existing or planned information systems for AIS should incorporate information on climate change and its effects on invasive species and have the ability to be updated with monitoring information in order to assess the occurrence of effects (Lee et al., *in review*). Furthermore, as more information on effects of climate change on AIS becomes available, information systems will need to have the capacity to be updated. Then more targeted research may be done that can provide more specific recommendations for AIS management in a changing climate (see also Section 3).

2.4.7. Adapting Public Education Activities

Many states conduct public awareness campaigns to inform the public, decision-makers, and other stakeholders about ways to prevent the introduction and spread of invasive species. For example, Nevada's Lake Tahoe Basin Weed Coordinating Group posts signs and distributes information to boaters on boat cleaning and disseminates flyers to alert them about potential AIS spread. Similarly, the Utah Department of Natural Resources' Division of Parks and Recreation and Division of Wildlife Resources educate boat drivers from areas of known zebra mussel infestations, encourage and fund boat washing, and inspect a percentage of boats for infestations. The program also posts public alert signs at major recreational waters, includes AIS information inserts in boat re-licensing packets, and prints and distributes AIS brochures.

State AIS outreach campaigns can use their existing efforts to educate the public about new invasive species threats due to climate change. For example, they may utilize monitoring information to identify invasive species that may be encroaching as a result of climate changes. States also may design education and awareness campaigns around those species (and their vectors) whose impacts are expected to increase due to climate change.

2.5. EXAMPLE MANAGEMENT RESPONSES TO CLIMATE CHANGE

States conduct management activities that target a wide variety of AIS. AIS problems commonly reported by state managers include: zebra mussel (*Dreissena polymorpha*), purple loosestrife (*Lythrum salicaria*), hydrilla (*Hydrilla verticillata*), water chestnut (*Trapa natans*), crayfish (*Astacoidea* [family]), giant salvinia (*Salvinia molesta*), mute swan (*Cygnus olor*), quagga mussel (*Dreissena bugensis*), snakehead (*Channidae* [family]), nutria (*Myocastor coypus*), New Zealand mud snail (*Potamopygus antipodarum*), water hyacinth (*Eichhornia crassipes*), common reed (*Phragmites australis*), Eurasian water milfoil (*Myriophyllum spicatum*), Golden Algae (*Prymnesium parvum*), salt cedar (*Tamarix ramosissima*), apple snail (*Pomacea canaliculata*), Brazilian elodea (*Egeria densa*), reed canary grass (*Phalaris arundinacea*), tall whitetop (*Lepidium latifolium*), sea lamprey (*Petromyzon marinus*), Japanese knotweed (*Fallopia japonica*), white perch (*Morone americana*), rice eel (*Monopterus albus*), coontail (*Ceratophyllum demersum*), curly leaf pondeed (*Potamogeton crispus*), water primrose (*Ludwigia hexapetala*), and Asian carp species such as grass carp (*Ctenopharyngodon idella*), bighead carp (*Aristicthys nobilis* or *Hypophthalmichthys nobilis*), silver carp (*Hypophthalmichthys molitrix*), black carp (*Mylopharyngodon piceus*), and common carp (*Cyprinus carpio*).

This section discusses four common AIS that are current priorities for many states and examines how climate change may affect these species. Although there are many other species from which to choose that are also high priorities, many of the management activities and potential responses to climate change may be transferable from these examples. Each example illustrates how climate change can both positively and negatively affect current management and control activities. Changes in the distribution of these invasive species will be positive in locations where the environment becomes less suitable, but negative in terms of impact and expense in areas experiencing new invasions. These species responses illustrate the need for monitoring and the sharing of monitoring data in coordinated information systems nationally.

While the complexities and uncertainties associated with climate change effects on AIS underscore the need for monitoring, coordinating information resources, and engaging in further research, some actions can be taken now to adapt invasive species management to this additional challenge using existing information.

2.5.1. Zebra Mussels

The zebra mussel (*Dreissena polymorpha*) population has expanded from its point of introduction in the Great Lakes in 1988 to its current range that includes rivers and lakes in 23 states, most recently invading aquatic ecosystems in Nevada (NISIC, *at* http://www.invasivespeciesinfo.gov/aquatics/zebramussel.shtml). Zebra mussels form dense aggregates on hard substrates, altering invaded ecosystems by consuming native phytoplankton and other species in the water column and significantly reducing biomass. This not only adversely affects the consumed species, but it also alters food web patterns and changes water properties by increasing water clarity and light penetration. Often zebra mussels settle in and on water supply pipes for industrial and agricultural facilities, constricting flow and damaging equipment. Taken together, the zebra mussel and the quagga mussel (*Dreissena bugensis*) (another Great Lakes invader that causes similar impacts and whose range is expanding) are estimated to cause $1 billion in damages and costs annually (Pimentel, 2003).

Currently, there have been almost no successful mechanisms to selectively eradicate zebra mussels once a population has been established in a water body.[1] Therefore, prevention is the key tool to decreasing zebra mussel invasions. Zebra mussels spread by passive transport, in ballast and bilge water, and by attachment to boat hulls and other equipment. Important prevention measures include inspecting and washing boats and dumping live bait and bilge water onto land. Because of the possibility of spread by recreational boaters and anglers, education and outreach are also important prevention tools. The 100th Meridian Initiative is one example of an interstate cooperative program that seeks to prevent the zebra mussels spread through education (see http://www.100thmeridian.org/). This organization posts signs and brochures along highways and at boat ramps to teach the importance of cleaning and inspecting boats.

[1] The Virginia Department of Game and Inland Fisheries eradicated zebra mussels from Millbrook Quarry by injecting twice the amount of potassium needed to kill zebra mussels over a three week period in the winter of 2006, four years after the first report of zebra mussels was submitted to the agency. For more information see: Virginia Department of Game and Inland Fisheries. Millbrook Quarry zebra mussel eradication. Available online at http://www.dgif.state.va.us/zebramussels/[accessed June 6, 2007].

Several states also have boat inspection sites, put out news releases, give presentations, educate divers, and train port of entry personnel. For example, Missouri uses a variety of measures, such as working with bait shops to spread their message and installing Traveler Information Stations to advise boaters to clean their boats.

Climate change is predicted to increase periods of warm weather (IPCC, 2007), which could mean that freshwater lakes and streams in the northern U.S. may be available for recreation for longer periods of the year. This would, in turn, extend the period of time during which recreational boaters and anglers could disperse zebra mussels in the northern U.S. Efforts such as those undertaken by the 100th Meridian Initiative may increase in importance, especially in the northern U.S. regions that are not yet infested with zebra mussels.

While higher latitudes and altitudes in the U.S. and Canada may become more suitable for zebra mussel invasion, habitats at the southern extent of its range may become less suitable. As temperatures rise, so do metabolic rates in zebra mussels. Unlike some species, zebra mussels have little capacity for metabolic adjustment to temperature change (Alexander et al, 1994). As turbidity increases, zebra mussel oxygen consumption drops, which may be due to increased undigestible particles clogging gills. Based on these results, Alexander et al. (1994) hypothesized that the most stressful conditions for zebra mussels would be high temperature and high turbidity conditions. Climate change may lead to these high temperature conditions in low altitude and latitude rivers and lakes in the U.S., making these habitats less suitable for zebra mussels; if these changes are combined with increased turbidity from altered precipitation and/or land use patterns, conditions may become too stressful for zebra mussels in these habitats. In addition, annual and several disturbances that result in die off of adults and decreased recruitment of one-year old juveniles has been shown to stabilize zebra mussel populations (Strayer and Malcom, 2006). If changes in hydrology due to climate change include more intense flooding, this type of population stabilization that limits population size may occur more frequently, versus a more cyclic dynamic that can include very high densities. Management of more stable populations may be easier and impacts also may be more stable (Strayer and Malcom, 2006).

2.5.2. Purple Loosestrife

Purple loosestrife (*Lythrum salicaria*) is a wetland plant with purple flowers that was introduced into the U.S. as early as the late 1700s and was well-established by the 1830s in New

England (Cox, 1999). Until the 1930s, purple loosestrife was not a major pest. It was during the 1930s that purple loosestrife became invasive with massive monocultures outcompeting native marsh vegetation and spreading across the U.S. Today, it is present in at least 40 states (NISIC, *at* http://www.invasivespeciesinfo.gov/aquatics/loosestrife.shtml).

Purple loosestrife requires temperatures in the range of 15 to 20°C to germinate, is shade intolerant, and is unable to invade saline wetlands (USFWS, 1996). Seeds, of which an adult plant can produce up to 2.5 million per year, are transported mainly by water but also can spread by attachment to moving birds, animals and people (Blossey, 2002). Approximately $45 million is spent each year to control the purple loosestrife invasion (Pimentel et al., 2000). Despite heavy investment in control, conventional control techniques do not work well. Because of its wide environmental tolerance, many control techniques such as water drawdowns and physical removal are unsuccessful and may destroy native vegetation (Pimentel et al., 2000). Biological controls may provide the best mechanism to control purple loosestrife. For example, four species of beetles have been introduced to control purple loosestrife with demonstrated success in significantly reducing purple loosestrife biomass (Blossey, 2002).

Climate change may in some instances enable further expansion of purple loosestrife and in other instances limit its success. As temperatures warm at higher altitudes and latitudes, conditions may become suitable for purple loosestrife seeds to germinate. However, purple loosestrife is already a successful invader in most U.S. states and in nine Canadian provinces, so it may only be polar regions and high altitude environments that should be carefully monitored for continued expansion. Climate change may also adversely affect purple loosestrife success in some coastal areas. Purple loosestrife is unable to grow in saline wetlands. As sea level rises and freshwater marshes become inundated with salt water, purple loosestrife may decline. However, this could be a hollow victory, as such a disturbance is also likely to severely impact native freshwater marsh species. Climate change may also limit the effectiveness of biocontrol species if temperature tolerances do not match. However, existing data demonstrates that two of the biocontrol species, *Galerucella calmariensis* and *G. pusilla*, exist throughout the native range of purple loosestrife (Blossey, 2002) and are likely to respond similarly to climate change.

2.5.3 Water Hyacinth

Water hyacinth (*Eichhornia crassipes*) is a tropical aquatic plant native to Brazil that has invaded many countries (Charudattan 2001). Considered one of the most problematic weeds in the world, it is highly invasive in southern states, Hawaii, and California (Ramey 2001). As a floating weed, water hyacinth grows quickly, faster than any other saltwater, freshwater, or terrestrial vascular aquatic plant (Masifaw et al. 2001; Toft et al. 2003). Forming thick mats, water hyacinth rapidly over takes water bodies and significantly blocks water ways (Pimental et al. 2000; Charudattan 2001).

Water hyacinth is also relatively cold tolerant and can survive in open waters (Charudattan 2001). However, it cannot withstand cold winter temperatures in more northern states. Water hyacinth has covered extensive areas in states such as Florida and California. Control efforts are intensive and expensive. Florida spends $15 million a year on three aquatic invasive plants including water hyacinth (Charudattan 2001). Florida also mandated a coordinated control effort for water hyacinth including biochemical and chemical control measures and surveys, which has been very successful at controlling water hyacinth. Biocontrol methods involving weevil species also have proven successful in other parts of the world such as Lake Victoria, Africa. Prevention, early detection, and regional coordination are critical for preventing aquatic weed invasions including water hyacinth (Charudattan 2001).

Climate change impacts may enable both the spread and establishment of water hyacinth within states as well as into more northern states. Increased rainfall and hurricane intensity could result in more frequent and intense flooding events, which can facilitate its dispersal (Michener et al. 1997). Water hyacinth are able to survive these types of extreme events and can reestablish and colonize both in up- and down-stream systems (Center and Spencer 1981). The increased frequency and intensity of disturbance events may create unsuitable conditions for native species, making ecosystems even more vulnerable to invasion by water hyacinth and enabling its spread. Changes in water temperatures in more northern states also may enable the spread and establishment of water hyacinth, which is already present in some northern states but unable to survive winter temperatures (Ramey 2001). Of particular concern are nurseries in northern states that sell water hyacinth for water gardens, because plant escapes are a common mechanism of spread (Charudattan 2001). These nurseries may become a viable pathway for water hyacinth as conditions in northern states become more suitable for water hyacinth survival.

2.5.4. Common Reed

Phragmites australis, the common reed, is prevalent on the Atlantic Coast and is rapidly spreading westward and northward. It is native to some regions of the United States, but the invasive strain is believed to have been introduced from Europe in the late 1800s (Blossey et al., 2002). It is most abundant on the Atlantic coast and is expanding in the Midwest. For example, Wilcox et al. (2003) mapped *Phragmites* coverage over nine different years using aerial photos in the Great Lakes region. GIS maps show that its distribution was dynamic from 1945 to 1999, but that it increased exponentially from 1995 to 1999. The authors believe expansion will continue quickly through the Great Lakes.

Phragmites control activities are important for wetland restoration projects. Methods to control *Phragmites* include biocontrol, flooding, non-specific herbicide control, cutting, and or burning (Ailstock et al., 2001). Most states carry out herbicide applications in conjunction with other management techniques, such as mechanical removal, burning, or induced tidal flooding. Ohio, Delaware, and Virginia have had success applying herbicides aerially, and other states are considering this method. Several states carry out herbicide control measures on private lands through cost-sharing programs or through financial and technical assistance. Virginia has mapped *Phragmites* distribution within the state and uses this information to prioritize control and management actions.

Climate change may affect *Phragmites* control. *Phragmites* can tolerate brackish but not saline water (Asaeda, 2003), and therefore sea level rise may help control this species and increase restoration success of some coastal wetlands. As with purple loosestrife, areas predicted to be both inundated by saltwater and experience increased frequency of saltwater intrusion due to climate change may not be priority target areas for control actions. However, *Phragmites* populations also increase with higher-than-average ambient air temperatures (Wilcox, 2003), and thus other wetland areas may need to increase their control activities.

3. INFORMATION AND RESEARCH NEEDS AND GAPS

A comparison of information available in the scientific literature with the needs of decision makers and state invasive species managers reveals that there is a significant need for scientific, multi-factor, long-term studies to more fully understand the interactions between climate change and invasive species. There are also some specific data needs that could be addressed quickly to adapt management practices in a changing climate. Section 3.1 outlines the immediate information needs of invasive species managers to begin addressing the effects of climate change. Section 3.2 discusses scientific research needed to develop a more comprehensive understanding of the interactions between climate and invasive species under changing conditions.

Information needs for managers were determined based on three sources: (1) a synthesis of comments from an EPA-sponsored meeting attended by researchers and state invasive species managers in June 2006, entitled "Assessing Gaps and Needs for Invasive Species Management in a Changing Climate," (2) our 50-state inventory of AIS management programs (see *Appendix A: Aquatic Invasive Species Programs and Activities*) and activities, and (3) a review of state and regional AIS management plans (see *Appendix B: State Aquatic Invasive Species Management Plan Summaries* and *Appendix C: Regional Aquatic Invasive Species Management Plan Summaries*). Research needs on invasive species and climate change interactions also are drawn from the workshop and the 50-state inventory as well as a review of scientific literature on the effects of climate change on invasive species.

3.1. INFORMATION NEEDS FOR STATE MANAGERS

This section summarizes the information needed by state AIS managers to adapt management practices under changing conditions. Information needs are discussed according to several corresponding chapters in the National Invasive Species Management Plan: Leadership and Coordination, Prevention, Early Detection and Rapid Response, Control and Management, Restoration, and Information Management.

3.1.1. Information Needs for Effective Leadership and Coordination in a Changing Climate

Leadership and coordination within and among states and regions on invasive species and climate change issues are essential not only for improving effectiveness of management efforts, but also for increasing awareness and understanding of these issues more generally. The need for better communication among states is a common concern among managers. For example, managers in Georgia have identified a need for interstate communication to prevent people from traveling across borders with illegal invasive species. This type of communication will be even more important as conditions change. Sharing information such as monitoring data among and within states and regions will help improve prevention and early detection efforts. Invasive species councils will be crucial to this effort; however, additional mechanisms and institutions would facilitate leadership and coordination on climate change and AIS issues at both state and regional levels.

Information needs and research questions for leadership and coordination under a changing climate may include the following:

- Identify AIS and climate change leaders in each state to promote the importance of considering AIS and climate change.

- Understand how states are already cooperating on climate change or invasive species issues by examining existing channels (e.g., invasive species councils) to share information on AIS and climate change and other mechanisms to facilitate the transfer of information (e.g., regular meetings, workshops, distribution lists, databases).

- Identify which structures, institutions, and/or policies work best across agencies and allow flexibility under changing conditions (e.g., flexibility in numbers or types of people working on issues and flexibility within legal authorities).

- Understand the consistencies and inconsistencies among state laws that could affect the ability of state agencies to cooperate both within and among states, e.g., problems and solutions affecting multiple media managed by different divisions or agencies.

- Prioritization of invasive species issues and concerns, in light of changing conditions; and

- Identification of existing, applicable adaptive management strategies that may guide state efforts to begin addressing climate change considerations in AIS management

3.1.2. Information Needs for Effective Prevention Activities in a Changing Climate

Effective prevention methods are fundamental to stemming the tide of AIS. Prevention strategies will need to be adapted based on predicted and observed climate change impacts. Thus, managers will need climate information as it relates to pathways, prediction, risk analyses, and monitoring.

3.1.2.1. *Information Needs Related to Pathways*

Information on the effects of climate change on vectors and pathways will help state AIS managers prioritize monitoring, inspection, education, and regulatory efforts. Massachusetts, for example, is particularly concerned about aquatic plants sold by nurseries that could escape and become established as water temperatures increase. However, identifying AIS pathways can be challenging, especially in light of anticipated climate changes.

Information needs and research questions for pathways and vectors under a changing climate may include the following:

- Identify new pathways that will emerge under climate change conditions.

- Identify species that will become invasive as conditions change in order to help target pathway analyses.

  - For example, extended warm temperatures in some areas due to climate change may result in an increase in recreational fishing, which could lead to a rise in boat traffic (an important AIS vector). Understanding the AIS implications of the emergence of these pathways, such as an increase in water hyacinth or zebra mussel introductions, and behavioral responses will be important information for managers adapting prevention and monitoring strategies.

- Determine how pathway/vector analyses can be modified to account for climate change and provide accurate predictions.

- Incorporate climate change information into models and systems that predict changes in pathways and transfer mechanisms.

3.1.2.2. *Information Needs Related to Prediction Models and Risk Analyses*

In addition to vectors, managers need to understand how species and habitats will respond to climate change (e.g., range expansion, ability for species to establish, habitat vulnerability to invasion). Risk analyses and prediction models could increase in accuracy by incorporating climate change parameters.

Information needs and research questions for prediction models and risk analyses under a changing climate may include the following:

- Determine how existing invasive species prediction models may be modified to incorporate climate change data (e.g., water temperature, timing of precipitation, dissolved oxygen content, sea-level rise).

- Develop new models to improve predictions of species responses to climate changes in order to provide managers with some expectations for ecosystem changes.Consider habitat alterations caused by climate change, especially thresholds in aquatic habitats, and the interactions between species' adaptive capacities, their shifting climate envelope, and the shifting landscape that will lead to new potential distributions.

- Establish baseline datasets in order to allow quantitative statistical analysis across global change scenarios.

- Identify AIS not yet found in northern climates whose temperature tolerances would allow them to overwinter as northern climates become milder.

- Research how the conditions that may lead to invasion (e.g., disturbed habitat, decreased native biodiversity, altered light availability) may be affected by climate change. Research will need to focus on both species and habitat characteristics.

- Identify mechanisms to integrate climate change parameters (e.g., water temperature, dissolved oxygen content, sea level rise) into risk analyses to more accurately determine the threat of a species establishment and spread within an area.

- Assess the risk that non-native species currently allowed into the U.S. may become invasive and/or expand their ranges in response to climate change.

3.1.2.3. *Information Needs Related to Monitoring*

Monitoring efforts will need to be adapted to ensure effective identification of potential new AIS, as well as existing AIS present at low levels.

Information needs and research questions for monitoring under a changing climate may include the following:

- Develop, establish, and fund strategically placed and comprehensive monitoring systems.
  - Integrate or coordinate monitoring systems among states.
  - Design monitoring systems to incorporate the potential effects of climate change.
  - Establish monitoring baselines to detect changes.
- Use research on encroaching species, climate change impacts on ecosystems, and new pathways that may emerge as a result of climate change to determine priority pathways, areas, and species to monitor.
  - For example, if pathway monitoring efforts in a state focus primarily on aquatic plant imports, but recreational boating and fishing are expected to increase as temperatures stay warmer for longer periods, then monitoring efforts and techniques may need to be developed that focus on boat inspections and bait usage.
- Use information on how habitats and ecosystems will respond to climate change (i.e., become more vulnerable to invasion) to help identify priority areas for monitoring.
- Use information on how species ranges and distributions will respond to climate change (i.e., become more vulnerable to invasion) to help identify priority areas for monitoring.
- Modify monitoring methods to identify effects from climate change and possibly distinguish between climate variability (e.g., drought cycles) and long-term climate change
- Develop a core set of indicators for state managers to use when monitoring for AIS under changing conditions.

3.1.3. Information Needs for Effective Early Detection and Rapid Response in a Changing Climate

Research to inform coordination and prevention also will help improve early detection and rapid response (EDRR) efforts under climate change conditions. However, additional research needs specific to EDRR also exist:

- Evaluate existing state EDRR capabilities (i.e., quarantine authority, emergency powers, border control capacity) in order to determine effectiveness in addressing invasive threats resulting from changing conditions.

- Develop an effective EDRR system (if existing system is insufficient) that anticipates barriers and deals with them before any new species arrives, so response can be swift and effective. The system will need to include successful mechanisms for inspections and response. An EDRR system designed in this way will be better prepared to detect potential invaders that may be more prevalent as conditions change.

- Collect information on altered species ranges and/or pathways under climate change to help identify where to target early detection monitoring efforts.

- Ensure priority lists of AIS are updated regularly to reflect changes in species as conditions change.

- Develop rapid response protocols for species that are predicted to become more invasive under a changing climate.

3.1.4. Information Needs for Effective Control and Management in a Changing Climate

Control and management practices also will need to account for climate change to ensure effective and successful control and eradication of AIS. There is already growing recognition by state managers of the need for more research on control methods and technologies for a wide range of species, such as zebra mussels, Eurasian water milfoil, *Phragmites,* apple snails, etc. Thus, as a part of the process to identify appropriate control techniques for specific species, scientists and managers also should study how climate change may impact these control methods.

Information needs and research questions for control and management under a changing climate may include the following:

- Research the performance of biological, chemical, and mechanical controls under various climatic conditions (e.g., increased temperatures, hydrology changes, and altered water chemistry).

- Determine which biological or chemical control methods will be most adaptable, or will remain robust, under climatic variability and change.

- Identify existing mechanical controls that adequately consider climate change.

- Develop guidelines on how climate change may affect different biocontrol species.

3.1.5. Information Needs for Effective Restoration in a Changing Climate

Managers also will need climate information to ensure restoration plans are adequately designed to re-establish ecosystem processes and be successful over the long-term. Information needs and research questions for restoration under a changing climate may include the following:

- Research how to best restore ecosystem processes in invaded areas, such as sediment and nutrient transport, and how restoration of these processes could be affected by climate change (e.g., how salinity, nutrient, and hydrological regime changes may impact the system's nutrient transport capabilities).

- Use research results to select plants that are adapted to future climates.

- Conduct studies to understand the types of feedbacks that may exist between climate change factors and invasibility so that restoration plans can adequately account for climate change conditions. For example coastal marsh restoration is dependent on water levels. With sea level rise, marsh restoration projects could be destroyed.

3.1.6. Information Needs for Effective Information Management in a Changing Climate

An information system that documents, evaluates, and monitors AIS impacts will be imperative to prevention, early detection, and control efforts. An information management system must include distribution and establishment data, and correlate and synthesize data from many sources. Although various states have networks of AIS distribution data, such as the Delaware Invasive Species Tracking System, additional research is needed to determine if these existing systems could support these additional information management system functions or if new systems will need to be created. In adapting current databases or developing new information management systems, climate change data (i.e., water temperature, salinity levels, and other hydrological parameters) will need to be included to make the system more robust and accurate. This information management system also must be easily accessible and available to state managers and others working on the ground on AIS issues. Systems will need to be made dynamic and updatable to reflect changes in species distributions and establishment success that may be caused by climate change (Lee et al., *in review*).

3.1.7. Information Needs for Effective Public Education in a Changing Climate

Public education activities will need to include information on climate change and its likely effects on aquatic ecosystems and AIS. These activities could also be used to highlight how states are preparing to deal with these effects and what additional actions may be needed.

3.2. RESEARCH NEEDS ON AIS AND CLIMATE CHANGE

In Section 3.1 above, we discussed the immediate information and data needs of conservation managers to begin addressing climate change conditions. Below we address broader scientific research needed to develop a more comprehensive understanding of the interactions between climate and invasive species under changing conditions. These needs are derived from a synthesis of the June 2006 workshop, "Assessing Gaps and Needs for Invasive Species Management in a Changing Climate," and the literature research conducted to develop this report. These research needs are necessarily broad in scope, demonstrating the paucity of information on climate change and invasive species interactions. For all research needs, however, climate change data will be most useful when it is tied to specific regions, and thus, to AIS that occur in those areas. For example, research on the impacts of climate change in western North America projects that earlier snowmelt due to increasing temperatures will impact stream flow (Stewart et al. 2004), an impact that will be important when identifying how AIS may respond to climate change in that region. However, regional climate change modeling and smaller scale projections of effects on specific watersheds are the current edge of scientific research; therefore, more detailed assessments of effects on specific AIS in specific places is not yet possible.

3.2.1. Climate Change Impacts on Invasive Species

Research is needed on the effects of climate change on invasive species in all aspects of the invasion pathway, including:

3.2.1.1. *Pathways and Vectors*

- Effects of climate change on AIS pathways and vectors, including new pathways and changes in existing pathways.

3.2.1.2. *Establishment and Spread*

- Ecosystem feedbacks between climate change and conditions favorable to AIS establishment and spread.

- Effects of climate change on current high priority invasive species, both positive and negative, in terms of changing distributions and impacts.

- Effects of carbon dioxide (CO_2) on freshwater ecosystems and AIS.

- Effects of changing precipitation patterns, such as flood and drought frequencies, on AIS establishment, habitat availability, and spread.

- Effects of increasing temperature on AIS establishment, habitat availability, and spread.

3.2.1.3. *Ecosystem Susceptibility*

- Climate change effects on the susceptibility of aquatic ecosystems to invasion by AIS

    - For example, conduct studies of the complex interactions among factors affecting species distribution and to determine whether climate change will increase susceptibility of habitats and regions to invasions, including assessment of positive interactions among non-native species and circumstances under which biodiversity may provide a barrier to invasions;

- Restoration and resilience effects on the susceptibility of ecosystems to invasion by AIS in the face of climate change.

- Studies of ecosystems recovering from disturbed states to understand the impacts of AIS on native species under changing climatic conditons.

- Climate change effects on different types of coastal and ocean currents and resulting effects on the spread and distribution of AIS and their impacts to coastal ecosystems.

3.2.2. Interacting stressors

Additional research questions on other stressors (e.g., land use change, overfishing, pollution, etc.) that interact with climate change, and the corresponding effects on invasive species, also need to be addressed, including:

- Studies on the relationship between other stressors, climate change and invasibility.
- How increasing temperatures, water quality problems resulting from pollution, and AIS may interact and the feedbacks that may occur among these factors.
- How changing precipitation patterns, water quality problems resulting from pollution, and AIS may interact and the feedbacks that may occur among these factors.
- How interactions between climate and land use change may affect distribution, spread, establishment, and impacts of AIS.
- How development patterns may change under climate change and resulting effects on AIS.
- How climate and overfishing impacts interact to affect AIS.
- How other factors may facilitate the establishment and spread of AIS under climate change.

Recommendations for research in scientific literature on AIS and climate change interactions highlight the need for additional basic research on this subject. Mack (2000) notes that research on just invasive species dates back only a few decades and more research is needed particularly on the epidemiology of invasive species so that predictions may be more accurate. This information will also be important for understanding how invasive species may respond to changing conditions. Dukes and Mooney (1999) identify a need to study climate change impacts on invasive species distribution, while Byers (2002) suggests studying the impacts of non-indigenous species on native species as the system recovers from a disturbed state to more natural conditions. These examples demonstrate that we still need to conduct a significant amount of research on invasive species and climate change in order to address many of the information needs of managers.

3.2.3. Climate Change and Invasive Species Distribution Models

Models of invasive species introductions, distribution and spread, and establishment are key tools for both understanding the invasive species problem and designing effective prevention and control techniques. Numerous types of models have been developed. In many cases, authors recommend that invasive species managers be cognizant of specific factors (e.g., species interactions, climatic factors, spread vectors) in ecosystem management. Some offer clear, ready-to-use models and strategies for conservation managers. However, most models of species invasion currently do not explicitly account for climate change; this represents an important action that will need to be addressed as part of the research needs discussed in sections 3.2.1 and 3.2.2, primarily in that scientists need to begin to build climate change variables and scenarios into models. Initial steps include integrating climate change-related parameters such as salinity variations, temperature changes, and soil chemistry into these models. Their outputs will help managers to better target and prioritize their prevention, monitoring, early detection, and rapid response programs under changing conditions. This section discusses some of the existing invasive species distribution models and how climate change information may be incorporated into them. *Appendix E: Models for Exotic Species Introduction, Establishment, Spread, an Invasion* provides additional examples.

3.2.3.1. *Models to Assess Climate Change Impacts on Species Distributions*

Numerous ecological models have already been developed to specifically address climate change impacts on species distributions, but these models are generally not applied to invasive species. One of these types of models, the bioclimatic envelope model, is used to identify correlations between species' distributions and climate change factors to determine a species' climatic boundaries. Based on this information, models predict how species' distributions may change under predicted climate changes (Pearson and Dawson, 2003). Discriminant analysis is one example where climate change impacts on invasive species have been evaluated explicitly. Mandrak (1989) uses discriminant function and principal component analyses to compare ecological characteristics of possible invading species to recently invading species to determine potential invaders' response to climate change. Carnutt (2000) used multiple discriminant analyses to identify connections between climate variables and plant distributions to predict plant invasions.

Ecological niche models also are used to predict potential species invasions. These models assume (1) a species distribution is limited by its ecological niche, and (2) a species can only disperse to an area with similar ecological characteristics (Peterson, 2003). One example of an ecological niche model is GARP (Genetic Algorithm for Rule-set Production), which can incorporate temperature as one of its environmental variables and has been used to predict invasive species distributions (Peterson & Vieglais, 2001; Stockwell & Peters, 1999; Stockwell and Noble, 1992; Kluza & McNyset, 2005). Since temperature can be included as a predictor of species distributions, it can be modified to examine changes in temperature over time. Several studies have used GARP to examine the potential effects of climate change on the distribution of species, including on the invasive Argentine ant and *Limnopurna fortunei*, a freshwater mussel native to southeast Asia (Roura-Pascual et al., 2004; Peterson et al., 2002; Peterson et al., 2001; Kluza & McNyset, 2005). These studies illustrate the potential usefulness of ecological niche models in projecting potential invasive species distributions under climate change. Integrating this information into other ecological niche models will help ensure that predictions are accurate under different climate change scenarios. An added challenge will be to use these models with appropriate projections of climate change effects in the aquatic environment.

3.2.3.2. *Models to Assess Invasive Species Distributions*

Most models of invasive species spread, distribution, and establishment are not designed specifically to incorporate climate change variables, but could be modified to account for these changes. For example, diffusion models are used to predict species dispersal patterns. Factors that affect dispersion are important to the accuracy of these models; thus, they should incorporate climate change factors, such as increased water temperatures and carbon dioxide and salinity levels, to determine how climate change may impact dispersal abilities and patterns. Zebra mussel dispersal relies heavily on boater movements (Buchan and Padilla, 2000). As temperatures stay warmer for longer periods of time, boat traffic may increase and move into new areas. Diffusion models will need to account for these types of climate-induced changes in dispersal to ensure their accuracy.

4. CONCLUSIONS, RECOMMENDATIONS, AND "NEXT STEPS"

Both invasive species and climate change are major ecosystem stressors. Furthermore, although not well understood, particularly in aquatic ecosystems, their interaction may exacerbate the effects of climate change on ecosystems, and likewise, climate change may enable further invasions. In order to design and conduct effective AIS management, state managers should consider the projected effects of climate change on AIS prevention, control, and eradication actions. This assessment underscores the need to consider climate change effects in every part of AIS management plans and programs in order to effectively address AIS threats.

Incorporation of climate change information is important for every state program, regardless of size or organization. Indeed, adapting AIS management practices will not only allow for states to better prevent and control AIS invasions under changing conditions, but will also maximize the effectiveness and efficiency of each state dollar spent on such activities. However, our review shows that, with few exceptions, states are not creating adaptive management strategies that incorporate climate change information.

The general lack of attention to the effects that climate change may impose upon AIS management activities and strategies may be attributed to a variety of reasons ranging from scarce funding to a lack of legislative mandate. However, research suggests that a significant factor may be the lack of data and information to inform AIS managers and decision makers in designing and implementing plans, programs, and activities. Indeed, many state plans include research tasks that incorporate changing conditions, thus reinforcing this perceived need for information. Scientific research, development of models and predictors, and data collection should be conducted in order to provide managers with the tools and information they need to conduct effective prevention, control, and eradication of AIS. Information needs include both immediate data needs and long-term research to better understand the complex interactions between climate change and aquatic invasions.

Below we summarize five recommendations, based on the preceding discussions that are designed to maintain and improve state AIS management programs and activities under a changing climate.

4.1. INCORPORATING CLIMATE INTO AIS LEADERSHIP AND COORDINATION ACTIVITIES

Invasive species councils, or lead state agencies in the absence of councils, could include climate considerations in management plans. This might be initiated by conducting facilitated meetings and/or workshops to identify specific management strategies and research needs to better inform management strategies. State councils also could work together to share information on climate-related data across regions. Additionally, existing AIS plans could begin incorporating climate considerations as they are being developed or updated. Coordination and information sharing among states will also facilitate the incorporation of activities that are adapted to climate change effects. Research and data are needed to inform each of these steps.

4.2. IDENTIFYING AIS THREATS UNDER CHANGING CONDITIONS

In order to effectively prevent invasions that might result from or be influenced by climate change factors, states should identify specific aquatic invasive threats, including new pathways and vectors, which may result as environmental conditions change. Coordination among states to share information on species and pathways will also aid prevention activities. Comprehensive monitoring systems need to be developed, established, and funded that can detect new AIS, new impacts, and range changes as a result of climate change. Furthermore, pathway analysis and species prediction models, regulatory requirements, and education efforts should be adjusted accordingly. Each of these steps could benefit from additional research that specifically addresses how current practices may need to change in light of climate change.

4.3. IDENTIFYING VULNERABLE ECOSYSTEMS UNDER CHANGING CONDITIONS AND DESIGNING RESTORATION TO WITHSTAND THESE CONDITIONS

Effective AIS prevention efforts must also include identification of ecosystems that may be more vulnerable to invasion under changing environmental conditions. Restoration of ecosystems is another important aspect to comprehensive prevention strategies, as robust habitats are less vulnerable to invasion. For these reasons, restoration should be designed to thrive under, or at least withstand, the changing conditions that are predicted to result from climate change. Both identifying vulnerable ecosystems and restoring ecosystems to become less vulnerable are activities that would benefit from additional research that includes climate change interactions.

4.4. IMPROVING CONTROL MEASURES UNDER CHANGING CONDITIONS

States should evaluate control measures for efficacy under the altered conditions that may result from a changing climate and adjust AIS management priorities and plans accordingly. Biological, chemical, and manual control methods may all be affected by climate change. More research is needed to identify these effects.

4.5. MANAGING INFORMATION UNDER CHANGING CONDITIONS

States designing AIS information management systems should account for changing conditions by collecting and tracking climate change data. Including this information, (e.g., water temperature, salinity levels, and water chemistry) will ensure robustness and accuracy of information management systems under changing conditions. Additional research and data collection will facilitate providing accurate information.

4.6. "NEXT STEPS" FOR RESEARCHERS AND MANAGERS

Although there is much to be done for states to begin to address climate change in AIS management, the importance of making a concerted movement is underscored by the discussions throughout this report. Clearly, state AIS managers have concrete informational and data needs; the research community, including universities, government agencies, nongovernmental organizations, and private groups, has the capability to address these needs, although specific support for all of these activities does not exist. However, even under the current circumstances, states have options for incorporating climate considerations into their current AIS efforts. Agency staff and AIS coordinators would receive valuable information from reviewing current prevention, control, and eradication activities, as well as planned action items, for their potential vulnerability to climate change; identifying specific information needs; and modifying current strategies where feasible and when climate information is available from the growing body of scientific literature or from knowledgeable practitioners and researchers.

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