Bioinvasions in a Changing World:

A Resource on Invasive Species-Climate Change Interactions for Conservation and Natural Resource Management

December 2014

Prepared for

The Aquatic Nuisance Species Task Force (ANSTF) and

The National Invasive Species Council (NISC)

By the *Ad Hoc* Working Group on Invasive Species and Climate Change

The *Ad Hoc* Working Group on Invasive Species and Climate Change

Co-chairs: Stanley W. Burgiel (NISC)
Thomas Hall (USDA Animal and Plant Health Inspection Service)

Working group members:

Noah Adams (U.S. Geological Survey)
Kevin Anderson (Puget Sound Partnership)
Elizabeth Bella (U.S. Fish and Wildlife Service)
Britta Bierwagen (Environmental Protection Agency)
Maria Boroja (U.S. Fish and Wildlife Service)
Elizabeth Brusati (California Invasive Plant Council)
Jeff Burgett (U.S. Fish and Wildlife Service)
LaDonna Carlisle (Bureau of Indian Affairs)
Ruark Cleary (Florida Fish and Wildlife Conservation Commission)
Dave Cleland (U.S. Forest Service)
John Darling (Environmental Protection Agency)
Robyn Draheim (U.S. Fish and Wildlife Service)
Darryl Forest (Department of Defense)
Sara Grise-Stahlman (Pennsylvania Sea Grant)
Sean Hart (Bureau of Indian Affairs)
Keith Hatch (Bureau of Indian Affairs)
Paul Heimowitz (U.S. Fish and Wildlife Service)
Jennie Hoffman (independent)
Tracy Holcombe (U.S. Geological Survey)
Doug Johnson (California Invasive Plant Council)
Denny Lassuy (North Slope Science Initiative)
Louanne McMartin (U.S. Fish and Wildlife Service)
Phil Moy (University of Wisconsin Sea Grant Institute)
Adrianna Muir (Department of Interior)
Richard Nelson (U.S. Fish and Wildlife Service)
Judith Pederson (MIT Sea Grant College Program)
Glenn Plumb (National Park Service)
Jim Quinn (University of California-Davis)
Jennifer Resnick (National Park Service)
Dolores Savignano (U.S. Fish and Wildlife Service)
Nick Schmal (U.S. Forest Service)
Linda Shaw (National Oceanic and Atmospheric Administration)
Bruce Stein (National Wildlife Federation)
Genelle Winter (Metlakatla Indian Community)
David Woodson (U.S. Geological Survey)
David Wooten (Bureau of Indian Affairs)
John Wullschleger (National Park Service)

For comments or questions, please contact:
Stanley W. Burgiel (stanley_burgiel@ios.doi.gov) or
Thomas Hall (thomas.c.hall@aphis.usda.gov)

Contents

Introduction

Independently, invasive species and climate change are two of the most significant issues voiced by natural resource managers concerned about the health of ecosystems. The globalization of trade and transport is accelerating the risk of introducing potentially invasive species as they are moved both unintentionally and for deliberate purposes. Trade and travel continue to be the major drivers of invasive species introductions (Levine and D'Antonio 2003, Lodge et al. 2006) and may present a more immediate threat than climate change (Stohlgren et al. 2014). At the same time, climate change poses a threat for the long-term. Forecasts predict an average increase in temperature of at least 2° Celsius by the end of the century with changes in precipitation, sea level rise, ocean acidification, as well as impacts on ecosystem functioning ranging from fire regimes to hydrological processes and (Karl et al. 2009, IPCC 2013). This trend is evident and ongoing in the United States, where most regions have seen significant warming over the past few decades (Melillo et al. 2014).

Beyond ecological effects, the measurable economic costs from these stressors are significant. The global costs of invasive species are estimated at over $1.4 trillion annually – 5% of the global economy – with impacts across a wide range of sectors including human health and safety (Pimentel et al. 2001, 2005).[1] Climate change has similar potential for economic impacts to agriculture, aquaculture, transportation and tourism with the Stern Report calculating the annual costs at 5% of global domestic product for the present and near future (Stern 2006).

These estimates provide a sense of the magnitude of the issues, even if the accuracy or precision of the numbers is debatable. Combining the threats of invasive species with those posed by climate change can magnify the intensity associated with both issues. Climate change may reduce the resilience of ecosystems to resist biological invasions, while biological invasions can similarly reduce the resiliency of ecosystems and economies to the impacts of climate change. Beyond that, the interactions among the drivers of change become significantly more complex due to the interplay of diverse phenomena like severe climatic events, changing precipitation patterns, and coastal erosion exacerbated by invasive species.

Recognizing these trends, in 2012, the Aquatic Nuisance Species Task Force (ANSTF), along with the National Invasive Species Council (NISC), recommended the establishment of a working group charged with

1) identifying and providing a platform for disseminating existing management strategies, tools and resources related to invasive species-climate change interactions; and
2) identifying knowledge gaps and providing recommendations for future research needs.

This document is intended to be a guide to the methods, resources and assistance available for dealing effectively with invasive species and their interface with climate change at the site level, and to inform policy-making and planning at larger geographic scales.

This recommendation comes amid a growing field of activity from local municipalities to federal agencies focused on climate change adaptation, supported by a range of scientific research and government initiatives, including the President's Task Force on Climate Preparedness and Resilience as well as the Priority Agenda-Enhancing the Climate Resilience of America's Natural Resources (Council on

[1] For the purposes of this report, 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." Further, an alien species is defined as, "with respect to a particular ecosystem, any species, including its seeds, eggs, spores, or other biological material capable of propagating that species, that is not native to that ecosystem." (NISC, Executive Order 13112)

Climate Preparedness and Resilience 2014), the national network of Landscape Conservation Cooperatives[2], the U.S. Geological Survey's (USGS) Climate Science Centers and the U.S. Department of Agriculture (USDA) Regional Hubs. The Invasive Species Advisory Committee (ISAC) to the National Invasive Species Council raised concerns about these issues in two white papers focused on initial opportunities for action as well as more specific attention to the marine environment (ISAC 2010, 2011). The National Fish, Wildlife and Plant Climate Adaptation Strategy, as well as the third National Climate Assessment, highlight the impacts and management needs for invasive species in the United States at the regional level (National Fish, Wildlife and Plants Climate Adaptation Partnership 2013, Melillo et al. [eds.] 2014). Additionally, the U.S. Environmental Protection Agency has focused more specifically on linkages to aquatic invasive species (EPA 2008). Similar discussions are ongoing at the international level within multilateral environmental and development institutions (World Bank 2009, Secretariat of the Convention on Biological Diversity 2009, Perry and Falzon 2014). This report aims to address one specific aspect of this issue, namely natural resource management, while contributing to the broader literature on invasive species and climate change.[3]

[2] The Landscape Conservation Cooperatives are a national network of self-directed partnerships between federal agencies, states, tribes, non-governmental organizations, universities, and other entities to collaboratively define science needs and jointly address broad-scale conservation issues, such as climate change in a defined geographic area (http://www.lccnetwork.org/Council).

[3] The intersection of invasive species and climate change has the potential to affect a number of sectors, such as human health and agriculture, but the focus herein is on natural ecosystems and their protection and management. For an analysis of the intersection between climate change and agricultural weeds, see Ziska and Dukes 2011.

I. Overview

This report is targeted at a broad audience of people interested in invasive species, climate change and natural resource management. It is structured to first provide a brief overview of the connections between invasive species and climate change before looking specifically at how these communities approach conservation and natural resource management. This document addresses the broader framework of invasive species management and climate change adaptation as tools to enhance and protect ecosystems and their natural resources in the face of these drivers of change. It is important to note that from a climate change adaptation perspective, invasive species management is one readily available tool as managers consider how they want to resist change or facilitate transformation. The report will then delve into the tools available to assess and manage the risks associated with invasive species under changing climatic conditions. It will conclude with a review of existing institutions and networks relevant to these management questions, as well as a discussion of available resources and recommended next steps.

The review of tools and methods will be of interest to managers working at specific sites and to individuals making strategic decisions at larger geographic scales. Policy-makers and government agencies at the local, state and national levels may be interested in the issues related to institutional coordination and recommendations, while the scientific and research community may focus on the application of assessment tools. Finally, the public as a whole may benefit from the overall focus on how the drivers of climate change and invasive species intersect and the potential ramifications these will have on the natural world.

Climate Change and Invasive Species: Basic Interactions

Separately, the issues of invasive species and climate change address a range of scientific uncertainties which are compounded when examining how these two drivers of change interact across the full range of ecosystems (including their services and species) and management responses. Recognizing that in many cases research is ongoing and that significant information gaps exist, this report synthesizes the available knowledge and tools particularly with regard to management of natural ecosystems. As background to the existing tools and resources, this section examines how climate change is affecting invasive species and their impacts, followed by how invasive species impact the ability of ecosystems to adapt to climate change.

The influence of climate change on invasive species distributions and impacts

A useful framework for conceptualizing invasive species-climate change dynamics is proposed by Hellman et al. (2008), which starts with the basic premise that climate change will alter biotic and abiotic conditions as well as human behavior (Figure 1). These factors directly influence the environmental constraints related to the colonization, establishment and spread of invasive species, as well as the human-mediated pathways of introduction. These in turn cause changes in species distributions, impacts and the effectiveness of management actions.[4]

[4] For additional information on the overarching intersection between climate change and invasive species, see Dukes and Mooney 1999, Hellman et al. 2008, Jarnevich and Stohlgren 2008, Pyke et al. 2008, Burgiel and Muir 2010, Mainka and Howard 2010, Hansen and Hoffman 2011 (particularly Chapter 12), and Ziska and Dukes 2014.

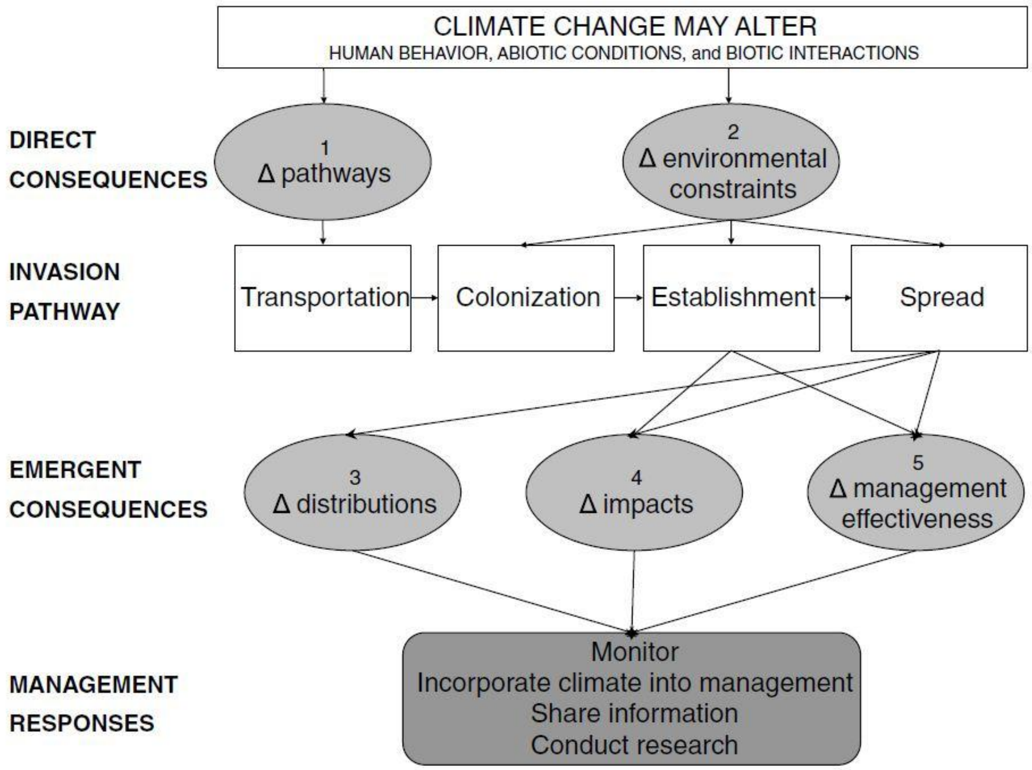

Figure 1. Associations across the invasion pathway, management responses, and the direct and emergent consequences for invasive species under climate change (Hellman et al. 2008).

The potential impacts from climate change on species and ecosystems are well documented, resulting from changes in temperature, carbon dioxide (CO_2) concentrations, hydrology (including precipitation, groundwater, soil moisture, soil chemistry, snow melt and ice cover), severe weather events, sea level rise, water salinity, and interactions with a range of ecosystem processes (Parmesan 2006, IPCC 2002, 2007, Secretariat of the Convention on Biological Diversity 2009, Karl et al. 2009, Bellard et al. 2012). These changing environmental parameters will affect how species move around, establish and impact ecosystems.

For example, changing conditions are likely to influence potential range shifts of native and non-native species and may facilitate further invasions. Several field surveys illustrate a correlation between invasion success and a warming climate across a range of taxa. Purse et al. (2005) describe the invasion of the midge-borne blue tongue virus into southern Europe in the late 1990s, an example of a vector-borne disease spreading as a result of climate change. Non-native hedgehogs in the Scottish Hebrides survive and breed better in warmer weather (Jackson 2007). Additionally, Ohlemuller et al. (2006) found that non-native plants flourished better than native species in warmer and dryer forest fragments. For some plants increased CO_2 levels improve their growth rates, and some plants exhibit evolutionary developments under higher CO_2 concentrations in test conditions (Grossman and Rice 2014). It is also critical to note that changing environmental factors may play a role in tipping the balance where a non-native species switches from being a benign presence to an invasive species with adverse impacts.[5]

[5] Note: these discussions on environmental constraints apply equally to non-native species and to invasive species (which are by definition non-native). This section will specifically focus on and use the term "invasive species,"

This section continues with an expanded discussion on the impacts of climate change on shifts in species' range, ecosystem transformations, weather-related movements and disturbance events, and pathways of introduction.

Range shift: Changes in environmental factors will impact suitable habitat – or climatic niches – currently supporting an invasive species leading to potential range shifts (Richardson et al. 2000 a, b, Hellman et al. 2008, Bellard et al. 2013). The concept of expanded, suitable invasion habitat is relevant both for areas that are already invaded, as well as for areas currently free of that species yet still vulnerable to introductions. The common perception is that species will migrate to higher latitudes (and altitudes) or deeper waters as those regions and waters warm. However, the picture becomes more complex as factors beyond temperature (e.g., hydrology, species' life-cycles, genetic traits, physiological characteristics, bioenergetics, inter-species interactions) are considered in determining a species' bioclimatic envelope.[6] A bioclimatic envelope is the range of climate regions in which a species occurs within its native range. It has been shown that species can occupy novel climatic regions in areas where they are invasive, that other climatic factors may outweigh temperature in determining species distribution changes, and that climate change can influence species distribution through changes in species interaction. Biological invasion and niche-based modeling needs to account for this potential (Broennimann et al. 2007, Gallagher et al. 2010).

While the focus of concern may be on the range expansion of invasive species, in some cases range contractions can occur to native and already established invasive species. A wide range of research exists on range shift. For example, Bradley (2009) and Bradley et al. (2009) reviewed: invasive plants in the western United States likely to expand their ranges, including yellow starthistle (*Centaurea solstitialis*) and tamarisk (*Tamarix spp*.); species likely to experience range expansion and contraction depending on local climatic variables, such as cheatgrass (*Bromus tectorum*) and spotted knapweed (*Centaurea biebersteinii*); and species predicted to contract in range, like leafy spurge (*Euphorbia esula*). Bertelsmeier et al. (2013) found that the range of suitable habitat for big-headed ant (*Pheidole megacephala*) could contract compared to its current potential range. In the marine realm, research suggests that warming

Hawaiian Honeycreepers and Avian Diseases

Climate change is impacting, and will continue to impact the range of habitat suitable for both native and invasive through changes in variables such as temperature and precipitation. In Hawaii, the interaction of threatened endemic honeycreeper species (Drepanidinae) and non-native avian pox (*Poxvirus avium*) and avian malaria (*Plasmodium relictum*) are indicative of the negative consequences of such range shifts. Introduced to Hawaii in the late 1800s / early 1900s, the two avian diseases transmitted by mosquitoes have had a significant impact on Hawaii's native forest birds. Honeycreepers have increasingly moved to higher elevations, where cooler temperatures have limited the spread of the mosquitoes and the avian diseases that they carry.

With rising temperatures, analyses predict that mosquito-free honeycreeper habitat will decrease, as they are limited to higher elevations. Additionally, changes in precipitation levels could limit the degree to which their favored forest habitats are similarly (un)able to respond to climate change. The end result could push remaining honeycreeper populations to extinction (Atkinson and LaPointe 2009, Benning et al. 2002, Burgiel and Muir 2010).

---

while recognizing that it equally applies more broadly to non-native species, including those that are currently benign yet could become invasive and vice versa.

[6] For example see, terrestrial plants - Ziska 2005; insects and crop pests – Bebber et al. 2013, Rice and Silverman 2013; livestock pathogens/insect pests – Perez de Leon et al. 2012; forest pathogens – Logan et al. 2003, Kliejunas et al. 2009, Kliejunas 2011; freshwater – Rahel and Olden 2008, Heikkinen et al. 2009; Marine - Harris and Tyrell 2001, Stachowicz et al. 2002, Compton et al 2010, Cote and Green 2012.

waters could favor the expansion of lionfish (*Pterois volitans*) into nearshore waters along the coastal shelf of North Carolina (Whitfield 2014).

These trends are also reflected outside the United States. Using a series of species distribution models, Bellard et al. (2013) identify three future hotspots of invasions, including Europe, northwestern North America and Australia/New Zealand, whereas decreasing invasive species pressure in other regions may provide new restoration opportunities. More specifically, Bertelsmeier et al. (2014) examined fifteen of the most invasive ant species worldwide and generally found that five species would likely increase their range, while the other ten species would decrease (although such results are obviously site specific).

A meta-analysis of existing studies by Sorte et al. (2013) found that in terrestrial systems, native and non-native species (primarily plants) had similar responses to environmental changes, whereas in aquatic systems temperature and CO_2 increases had a more detrimental impact on native species, primarily animals, than it did on invasive species. Thus, differences also exist between terrestrial and aquatic ecosystems. While this report covers all taxa and biomes, it should be noted that available research and tools are more developed in the area of terrestrial plants, which is reflected by the examples used throughout the paper. This also highlights the need to continue efforts in the aquatic realm as well as with terrestrial animals.

Overall, such research suggests that ecosystem types, along with their native and non-native species composition and vulnerability to new invasions, will respond differently to the range of climate-induced environmental variables. Microclimates and stratification or variation within broader ecosystem types may be better ways for resource managers to look at range contractions and expansions of native and non-native species.[7] Additionally, with shifting interspecies dynamics along with other phenological[8] or even genotypic changes[9] (e.g., Ayre and Hughes 2004, Aspinwall et al. 2013), the effectiveness of existing invasive species management measures will need to be reevaluated. This could include changes in the timing and level of pesticide applications and mechanical control methods to control invasive species. Additionally, biocontrol[10] may be an option to control an invasive species, but only after a thorough investigation into the efficacy of agents proposed to be used. Resource managers will need to reconsider their present management activities periodically as they address threats from new invasive species.

Recognizing that ecosystems and their species interactions and compositions are in flux with the changing climate, questions arise regarding the importance of the native *versus* non-native status of organisms. In some cases, native species may increasingly become pests due to changes in the historical processes for population suppression (e.g., cold temperatures, predators). The population explosion of

[7] Bioclimate predictions from models are improving with a new generation of algorithms, computer learning methods, and increased inclusion of additional and better data (e.g., Guo and Liu 2010) for climate and species enabling smaller-scale or downscaled predictions (Elith and Leathwick 2009, Lorena et al. 2011).

[8] Phenology is the study of the timing of recurring biological events. It has received increasing research attention leading to an emerging consensus that phenology can be viewed as an 'early warning system' for climate change.

[9] Genotypic refers to the normal genetic makeup of an organism or group of organisms with reference to a single trait, a set of traits or an entire complex of traits. Here, genotypic change refers to the potential change of the dominant genetic makeup of an organism in response to climate change.

[10] Biocontrol, short for biological control, is the introduction of a live organism in order to control another organism. Historically, a number of cases exist where biocontrol was used with poor and even counter-productive results. Current biocontrol work entails rigorous testing and risk assessment to ensure that released agents are host-specific to the target species.

the mountain pine beetle (*Dendroctonus ponderosae*) in western U.S. forests and the southern pine beetle (*D. frontalis*) in New Jersey are two examples. Clearly, such native species are increasingly of ecological concern and require appropriate consideration and management. Recognizing that, this report will specifically focus on the larger problem of species that are non-native with the potential for adverse impacts (Carey et al. 2012, Webber and Scott 2012).[11]

Ecosystem transformation: In many cases, invasive species transform ecosystems by altering their basic species composition or habitats. For example, cheatgrass in the U.S. West (Mack 1986, Bradley et al. 2009), buffelgrass (*Pennisetum ciliare*) in the southwestern desert (Bovey et al. 1986) and Old World climbing fern (*Lygodium microphyllum*) in southern Florida made habitat more prone to wildfires which in turn reinforce changes in those ecosystems (Burgiel and Muir 2010). These new fire-prone systems then independently impact carbon sequestration and the release of greenhouse gases. As invasive species can alter habitat vulnerability, similarly increased greenhouse gas emissions can affect both ecosystems and species with potential implications for invasive species. For example, increased CO_2 concentrations may favor some invasive plants over their native competitors.

From the perspective of ongoing climatic shifts, one of the most challenging issues is the process of ocean acidification.[12] If basic calcification processes are compromised, particularly in corals and bivalves, the broader range of species dependent on those keystone species will also be increasingly at risk (Fabricius et al. 2013). While the precise dynamics of the interplay between ocean acidification and invasive species are still unclear, research on particular species interactions is ongoing. For example, experiments have shown that Olympic oysters raised under acidified conditions were significantly smaller in size and were consumed at disproportionately greater rates by invasive snails than control populations (Sanford et al. 2014). Other researchers predict that the impacts of acidification on coral reefs could create openings for the growth and spread of algae and aquatic grasses, particularly those that are invasive, resulting in potentially dramatic shifts in those marine ecosystems (ISAC 2011). Ocean acidification can affect a range of marine systems as it decreases primary production, which can have a cascading effect on inter-linked species and habitats.[13]

For riparian areas, the composition of native *versus* invasive species can have significant impacts on water temperatures and availability. For example, in Appalachian stream systems loss of native hemlocks from the hemlock woolly adelgid (*Adelges tsugae*) and ash (*Fraxinus* spp.) from the emerald ash borer (*Agrilus planipennis*) has reduced shade cover resulting in higher water temperatures with consequent impacts on local microclimates and native insect biodiversity. Some invasive plants such as tamarisk and yellow starthistle can dramatically reduce local water availability (Stromberg et al. 2007). Additionally, Muhlfeld et al. (2014) attribute an increase in hybridization between native westslope cutthroat trout (*Oncorhynchus clarkii lewisi*) and non-native rainbow trout (*Oncorhynchus mykiss*) to climate change resulting in increased stream temperatures from higher ambient temperatures and more precipitation in winter. These studies and others illustrate that changes in temperature and species composition can lead to significant changes that can occur in riparian and aquatic ecosystems.

---

[11] It should also be noted that the definition of invasive species and specifically the native/non-native distinction in official policy documents and regulations will have ramifications for the scope of management actions, access to funding and potentially other legal questions.

[12] Oceans have absorbed half of the CO_2 made since the Industrial Revolution and have moderated the effects of greenhouse gases. As oceans absorb CO_2, they become more acidic. Thus, this is a clear human-caused result of greenhouse gas emissions.

[13] See http://www.princeton.edu/grandchallenges/energy/research-highlights/ocean-acidification/.

Finally, the spread of invasive, allelopathic[14] plants under climate change scenarios may also increase stresses on native plants, especially seedlings. For example, invasive allelopathic plants such as garlic mustard (*Alliaria petiolata*) should be analyzed in light of the relationship among invasive plants, nitrogen saturation and soil chemistry under different climate change scenarios (Prati and Bossdorf 2004, Stinson et al. 2006, Wolfe et al. 2008, Bowman et al. 2012, Jamieson et al. 2013).

Weather-related movements and ecosystem disturbance: In addition to shifting habitat ranges, invasive species may be moved into new areas by climatic events such as hurricanes or floods which are becoming more extreme or frequent (predictions are that hurricanes will become less frequent, but more intense). While some people consider such movements to be natural phenomena, resource managers will need to consider whether and how to address such risks in relation to existing invasive species and pathways of concern. While the exact magnitude that climate change will have on the number and severity of storms is debatable, the fact that these types of events can move invasive species is well documented (Gutowski et al. 2008). High winds, storm surges and flooding associated with extreme weather events such as hurricanes or typhoons[15] and severe rainstorms are known to move non-native species including insects, plants and fish. [16] Diez et al. (2012) provide a compelling analysis examining the role of extreme climatic events at each stage of the invasion process:

- Introduction/transport: strong winds and storm surges can move species into previously uninvaded locations;
- Establishment: extreme events can weaken ecosystems or create significantly disturbed areas that may facilitate successful establishment;
- Spread: invasive species already within an area can be further spread by winds and waters; and
- Impact: weather events may strengthen or compound the negative impacts of invasive species, for example extended drought or feedback interactions may alter fire regimes.

Extreme weather events can create disturbances in ecosystems that may make them more vulnerable to invasion. For example, mudslides, wind damage and ice storms could damage forest ecosystems making them ideal areas for invasion. Hurricanes, heavy rains, drought, wildfire, unusual movements of air masses and other extreme climatic events can equally weaken the resilience of ecosystems and expose new areas to invasion (Horvitz et al. 1998, Coulson et al. 2002, Hellman et al. 2008, Heller and Zavaleta 2009, Bhattarai and Cronin 2014). Damage from these events, especially where invasive species are present or invade as a result, may impact the ability of these ecosystems to regenerate from the damage caused by such events.[17] For example, invasive insects virtually eliminated the ability of the Micronesian cycad (*Cycas micronesica*) to withstand wind damage and regenerate following Typhoon Chaba in 2004 (Marler and Lawrence 2013). Additionally, the impacts of weather events can be exacerbated where invasive plants dominate the ground cover yet fail to provide adequate levels of root structure to bind and hold soils. The failure to secure the soil can lead to increased erosion and consequent impacts on stream turbidity and water quality. Beach vitex (*Vitex rotundifolia*) reduces the

[14] Allelopathy is the suppression of growth of a plant by a toxin released from a nearby plant of the same or another species.

[15] Hurricanes and typhoons are equivalent. Hurricane is the term used in the Atlantic, while typhoon is the word used for the same type of storm more often in the Pacific.

[16] In view of the ensuing section on pathways, some might consider this a "natural" pathway. For the purposes of this paper, discussion of pathways will focus on those that involve some form of direct human mediation responsible for the movement of a species. Such human intervention can be intentional or unintentional.

[17] These phenomena are generally in line with the intermediate disturbance hypothesis that examines the role that habitat disturbance plays in facilitating plant invasions (Catford et al. 2012).

capacity of coastal areas to diffuse the energy of incoming storms which contributes to the erosion of shorelines and dunes (Carter et al. 1999, Westbrooks and Madsen 2006). Similarly, species like nutria (*Myocastor coypus*) adversely impact wetland vegetation and its role in serving as an ecological buffer.

Pathways of Introduction: Biophysical effects from climate change and adaptation strategies will potentially open new or alter existing pathways for invasive species introduction. Biophysically, a changing environment presents new opportunities for transport of species with the inherent risk of introducing invasive species to new regions. For example, shrinking sea ice coverage in the Arctic may allow new northern transport opportunities and energy exploration, raising the risk of introductions through ballast water transfer, hull fouling on ships, and transports of drill platforms or other heavy machinery (Carmel 2013, Cressey 2007, Lassuy and Lewis 2013, U.S. Global Change Research Program 2013, Miller and Ruiz 2014). Climate change may give rise to the cultivation of new crops and feedstocks or the husbandry of different livestock and aquaculture which could open new pathways for introductions (USEPA 2013a). Additionally, construction activity (e.g., for energy development or hard infrastructure) is a well-documented source of disturbing habitats and inadvertently introducing or spreading invasive species through the movement of vehicles, material and waste (Joly et al. 2011, Padmanaba and Shell 2014).

Climate change mitigation activities may also present risks for the introduction and spread of invasive species.[18] Increased interest in biofuels has prompted debates over feedstock choice (Barney 2014), most notably the EPA's approval of giant reed (*Arundo donax*) and elephant grass (*Pennisetum purpureum*) – two known invasive species – as renewable fuelstocks under the Renewable Fuel Standard program (USEPA 2013b). Other proposed adaptation or mitigation measures include the use of non-native species to sequester carbon or prevent erosion and protect against storm surges.

Assisted migration, the deliberate movement of species to new areas to improve their chances of adapting to climate change or to enhance ecosystem structure, also presents inherent risks as such introductions may cause adverse impacts. Faced with depleted or endangered populations, resource managers might consider the movement of species to insure populations, cope with range lags or foster connectivity and

Biofuels Pathway

The United States currently produces 12 billion gallons of biofuels annually (Biofuels Interagency Working Group 2010). The Energy Independence and Security Act of 2007 (Public Law 110-140, Title II) set goals to increase production and use of biofuels as a way to meet the nation's energy needs and reduce greenhouse gas production. While most current biofuel production uses corn as a feedstock to produce ethanol, companies and researchers are investigating the potential of other plants as sources of biofuel feedstocks.

Concerns arise because some of the plants being used or considered for biofuel production are, or may become, invasive since the characteristics of good feedstocks for biofuels production (e.g., fast growing, tolerant of harsh environmental conditions, susceptible to few pests) and invasive plants overlap. The most notable example is EPA's approval of giant reed (*Arundo donax*) and napier grass (*Pennisetum purpereum*) as eligible cellulosic biofuel feedstocks under the Renewable Fuel Standard, despite the fact that both have already proven invasive in parts of the United States.

[18] This point is especially relevant for federal agencies, which by Executive Order 13112, are duty-bound not to "authorize, fund, or carry out actions that it believes are likely to cause or promote the introduction or spread of invasive species in the United States or elsewhere unless, pursuant to guidelines that it has prescribed, the agency has determined and made public its determination that the benefits of such actions clearly outweigh the potential harm caused by invasive species; and that all feasible and prudent measures to minimize risk of harm will be taken in conjunction with the actions." This would include climate change adaptation or mitigation measures that increase the risks associated with the introduction and spread of invasive species.

the ability for those species to adapt (McLachlan et al. 2007, Montserrat and Hulme 2011, Williams and Dumroese 2013). Such deliberate introductions need to consider the potential behavior of those species in their new environment, particularly if there is a risk of invasiveness. Additionally, managers must also consider the lag time needed for a species to adapt and expand its population,[19] as well as, how to minimize the risk of inadvertently moving associated "hitchhikers" such as parasitic or commensal organisms. Technical discussions between researchers involved in invasive species and reintroductions recognized some of the assisted migration issues and developed initial guidance to avoid potential problems (IUCN SSC 2012). Similarly, the development of conservation corridors to facilitate the natural migration of threatened species could serve as physical pathways for the movement and spread of invasive species (Resasco et al. 2014).

Finally, the relative risks of existing pathways for the introduction of invasive species may be exacerbated as a result of future climatic events. For example, flooding and storm winds could potentially allow the escape of potential invasive species from zoological gardens, aquaculture farms, pet shops, collapsed buildings or other structures where introduced plants and animals are being held. Another example is that consumers could purchase different landscape plants that will tolerate new climatic conditions due to changing hardiness zones. This could give rise to the importation of new plants from new international suppliers. Such dynamics could shift the risks posed by the pathway of invasive species introductions through the import of live plants (Bradley et al. 2012). This also suggests the need to examine existing biosecurity procedures for sectors whose business practices or merchandise are somehow affected by climate change.

The influence of invasive species on climate change and carbon sequestration

The broader scientific literature on invasive species and the previous section clearly identify increased vulnerability to other climate related stressors arising from impacts of invasive species on ecosystems, their functions and associated native species. Invasive species also adversely impact the ability of ecosystems to sequester carbon. For example, the invasion of Japanese stiltgrass (*Microstegium vimineum*) into forests of southern and eastern United States, as well as kudzu (*Pueraria lobata*) more broadly, is changing soil composition and its capacity to store carbon (Strickland et al. 2010, Tamura and Thayaril 2014). The large-scale transformation of other ecosystems has implications on carbon sequestration such as

Indirect Effects of Pest Management

An example of indirect change is the soybean aphid (*Aphis glycines*), which invaded North America sometime around 2000. Damage to the soybean crop from the aphid caused a sharp increase in the use of insecticides, which consequently led to a sharp increase in greenhouse gas emissions associated with product development, shipping, and application. From 2001 to 2006, greenhouse gases associated with this insecticide rose from below 1 to 40 million kg of CO_2 in the United States. It was also found that aphid densities below a certain threshold did not require spraying because biological control, namely lady beetles (Family Coccinellidae) would keep damage to below the cost of spraying. Once populations were significantly reduced, spraying declined as well (Heimpel et al. 2013).

[19] Lag time refers to the period of time that it takes a species from its initial introduction into a site to establish a self-sustaining population and then to spread and cause negative impacts. In some cases, non-native species have been present in an environment for decades before becoming invasive. One increasingly important question is the role that climate change may have in triggering that switch from benign to invasive. Crooks and Soulé describe three categories of explanations to characterize lag time including: 1) lags caused by the nature of population growth and range expansions; 2) environmental factors related to changes in ecological conditions that favor a non-native species; and 3) genetic factors related to the relative lack of fitness of a non-native species in a new environment (Crooks and Soulé 1999).

the conversion of woody shrublands by cheatgrass (*Bromus tectorum*) to fire-prone grasslands in the western United States (Bradley et al. 2009), forest dieback from a number of climate change-assisted forest pests (Logan et al. 2003) and drought (Breshears et al. 2005), and the decimation of coastal wetlands by nutria (ANSTF No Date).

In some cases, invasive species may positively affect carbon sequestration abilities as was found with the establishment and spread of Chinese tallow (*Triadica sebifera*) (Zou et al. 2006). The management question then becomes how to assess the relative benefits of CO_2 sequestration by an invasive plant like Chinese tallow versus the costs of its adverse ecological impacts. In considering climate change mitigation strategies involving the use of non-native species for sequestration purposes, it is critical to assess their potential to be invasive. Such issues will be further complicated by how native and invasive species, particularly plants, respond to increased CO_2 concentrations with regard to both growth rates and ability to sequester carbon (Zou et al. 2006).

These varying dynamics will require resource managers to look at situations on a case-by-case basis, often with the task of determining how to balance the trade-offs across adaptation actions, mitigation needs and the potential to compromise natural ecosystems.

II. The Context: Approaches to Climate Change Adaptation and Invasive Species Management

An understanding of the evolving context for management and conservation planning from a biological, social, and political standpoint is critical to developing effective responses to the combined threats of climate change and invasive species. Not only will this help resource managers identify priorities and utilize the tools identified in Section III, but it will also help facilitate communications across the disciplines of climate change and invasive species. This section starts with the perspective of climate change adaptation and conservation planning relevant to invasive species, and then proceeds to look at how the traditional invasive species management framework relates to climate issues.

Climate Change Adaptation and Conservation Planning

Climate change adaptation is an emerging field that focuses on preparing for, coping with, and responding to the impacts of current and future climate change (Stein et al. 2013a). Specifically, adaptation has been defined as "adjustment or preparation of natural or human systems to a new or changing environment which moderates harm or exploits beneficial opportunities" (USEPA no date).[20] Increasingly, the focus of attention at international, federal, state, and local levels on climate change activities has shifted planning to implementation (Bierbaum et al. 2013). Nevertheless, significant efforts to put concepts into practice have been achieved, including through the development of more rigorous design principles and implementation strategies (Adger 2005, Hansen and Hoffman 2010, Stein et al. 2013a). Indicative of this attention is recent Presidential Executive Order 13653 (November 2013) on climate preparedness and resilience. This Executive Order directs federal agencies to accelerate their efforts on adaptation, to reform policies that may increase vulnerabilities to climate-related risks, and to manage lands and waters to make them more resilient in the face of a changing climate.

While policymakers focused on climate change mitigation issues in the past such as reducing greenhouse gas emissions,[21] given the level of change already underway, climate change *adaptation* is also essential (Pielke et al. 2007). Indeed, the two approaches are complementary rather than competitive. Effective adaptation should be designed to ensure that natural systems are capable of continuing to fix and store carbon, which further supports climate mitigation goals.

In the shift toward implementation of climate change adaptation strategies in natural resource management, a legitimate concern has surfaced that all manner of conservation activities will be labeled, or relabeled, as "adaptation." From the perspective of invasive species, this is perhaps most likely to happen as a consequence of broad interpretations of certain adaptation principles and strategies.

The term "resilience," for example, is now frequently regarded as synonymous with adaptation. While the concept is intuitively appealing, the term resilience has multiple meanings (e.g., Holling 1996, Walker et al. 2004, Folke 2006), but is most commonly defined as a return to a particular functional state following a disturbance or the ability to maintain some level of functionality in an altered state. Thus, while the terms are related, resilience is not synonymous with adaptation. Among the most commonly discussed strategies for enhancing resilience is some variation of "reduce existing stressors" (Heller and Zavaleta 2009, West et al. 2009). However, caution is necessary to avoid overly broad

[20] For a broad overview on the state of climate change adaptation activities, see IPPC 2014a.

[21] Climate mitigation is focused on addressing the underlying cause of climate change through stabilizing and reducing the concentrations of greenhouse gases in the atmosphere. For a broad overview on the state of climate mitigation activities see IPPC 2014b.

Key Concepts for Climate Change and Conservation Planning

Conservation planning in the face of climate change entails assessing biogeographic variables in the context of socially and politically defined objects. This can include a focus on implementing solutions to mitigate climate change and/or adapting ecosystems and structures. Equally, natural resource managers need to have an understanding of how resilient their priority sites and species are as well as their key vulnerabilities. These are some of the key concepts and issues that will be further explored in this report:

Climate change adaptation: adjustment or preparation of natural or human systems to a new or changing environment which moderates harm or exploits beneficial opportunities.

Climate change mitigation: human intervention to reduce the human impact on the climate system, including includes strategies to reduce greenhouse gas sources and emissions and enhance greenhouse gas sinks.

Resilience: the capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.

Vulnerability: the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes.

EPA Glossary of Climate Change Terms (http://www.epa.gov/climatechange/glossary.html)

characterizations where virtually any existing conservation activity, including most invasive species-oriented activities, could be viewed as climate change adaptation.

The use of vulnerability assessments in adaptation planning is the key to developing effective adaptation strategies and documenting the link between actions and impacts (Glick et al. 2011). Given the emphasis on reducing climate-related vulnerabilities, having a clear understanding of how current and future climate is likely to affect the resources of concern, including invasive species, is at the core for developing effective and efficient strategies for reducing those vulnerabilities. The effect of climate change relative to invasive species can be viewed two ways. First, consider the perspective of how changing climatic variables are likely to positively or negatively affect a particular non-native, or already, invasive species. Secondly, consider the perspective of the consequences those effects may have on other species and the broader ecosystem. In this sense, the first is a direct effect on the non-native species and the second an indirect climate effect on other resources.

Climate change adaptation should be seen in the broader historical context of conservation and natural resource management as a way to address the effects of climate change on species and ecosystems in a thoughtful and rational manner. Using this perspective, Stein et al. (2014) developed guidance on "climate-smart conservation" to help practitioners put adaptation principles into practice. Four overarching themes frame this approach to climate change adaptation:

- Act with intentionality
- Manage for change, not just persistence
- Reconsider goals, not just strategies
- Integrate adaptation into existing work

Act with intentionality

Appropriate and relevant adaptation incorporates existing conservation approaches and actions, and requires the development and application of novel strategies. It is essential to determine which existing activities work under climate change, and when new approaches are required. Effective adaptation must be carried out in a purposeful and deliberate manner that explicitly considers the effects, or potential effects, of climate change on resources. Intentionality, a key component, requires that explicit consideration of direct and indirect climate impacts be considered during planning. Being deliberative and transparent includes documenting the process. This applies regardless of whether adaptation planning includes novel uses or traditional strategies.

Manage for change, not just persistence

The dominant paradigm in conservation is to maintain existing ecological conditions or attempt to restore a historical state (Cole and Yung 2010). Given the rapid pace of current and projected climate change, resource managers increasingly will be faced with changes exceeding the historical range of variability that previously bounded most management efforts. Accordingly, conservation in a climate-altered future will focus on preparing for and managing change (Millar et al. 2007, Stein and Shaw 2013).

Management approaches to climate change can range from resisting changes—to protect high value and climate-sensitive assets—to actively or passively facilitating changes. The goal for inevitable system transitions might be to retain desirable ecological attributes, rather than experience a complete collapse of ecosystem functions and services (Magness et al. 2012). One commonly used framework for adaptation responses to climate change consists of: 1) resistance; 2) resilience; and 3) realignment (Millar et al. 2007; Glick et al. 2011). Under this framework, resistance actions are intended to forestall impacts to species or systems, thus maintaining *status quo* conditions. Most current adaptation efforts focus on maintaining *status quo* conditions, whether through resistance-oriented strategies or by focusing on enhancing resilience with the expectation that the system will be better able to return to some conception of “normal” or at least a new realigned stable condition.

Resistance-oriented strategies for invasive species focus on preventing new invasions, limiting the spread of existing invaders into new areas, and using early detection and rapid-response approaches to eradicate new invasions before they become intractably established. In some cases, invasive species can either alter ecological functions and services or push systems across ecological thresholds, transforming those systems to new states or novel ecosystem types. This shift occurred in the transformation of sagebrush steppes to systems dominated by cheatgrass (*Bromus tectorum*) and the conversion of Pacific Northwest mudflat ecosystems into salt marsh by smooth cordgrass (*Spartina alterniflora*).

The emergence of “novel” or “no-analog” ecosystems as a consequence of climate change is a major theme in the adaptation literature (Hobbs et al. 2006, Williams and Jackson 2007). Although no-analog ecosystems are sometimes defined in terms of novel climates and mixes of species (both native and non-natives), many argue that existing anthropogenic ecosystems, including their non-native inhabitants, already constitute such novel ecosystems. Clearly, one of the central questions is how to manage these systems amidst differing opinions and preconceived ideas of normal and optimal social, environmental and economic benefits.

Reconsider conservation goals, not just strategies

As climatic conditions change, some conservation goals and management objectives may no longer be achievable. Successful adaptation to climate change will depend not only on adjusting strategies in an effort to meet current goals, but that underlying conservation goals and objectives be reevaluated and revised as appropriate (Hobbs et al. 2010, Glick et al. 2011). It must be recognized, though, that goals may change over time. Most adaptation efforts focus on modifying strategies to meet existing goals, but this “climate retrofit” approach will become increasingly untenable as climate change occurs and invasive species gain footholds in new areas (Stein and Shaw 2013). Meeting conservation goals under different climate change scenarios will have potential political, economic and environmental ramifications. Ideally, such goals should be formulated through a transparent process that also considers societal values.

As species ranges shift in response to changing climatic conditions, goals focused on maintaining particular assemblages of species in defined geographic areas become particularly problematic. As a result, a theme emerging from the adaptation literature is a shift from goals focused on maintaining "historical fidelity" in species composition to goals focusing on maintaining underlying ecological processes (Harris et al. 2006, Sandler 2012). It is also critical to use a landscape scale perspective for planning and prioritizing actions when considering shifts in habitats for native and invasive species. While plans may consider the landscape scale, management activities and objectives are often site-specific. Management activities and objectives for local areas may change over time, but landscape planning and analysis can assist in maximizing conservation benefits across a range of sites.

Related to setting goals to maintain ecological functions *versus* maintaining historic fidelity, is a debate about the value of defining conservation goals and management based on the origin of a species (i.e., native *versus* non-native) as opposed to setting goals and management objectives based on the functional attributes of an ecosystem (Tomimatsu et al. 2013). Another aspect of this dilemma is how to regard native species that are expanding into new regions due to changing climate. Are these "new-natives" truly native? Or should these new arrivals be regarded as non-native or invasive species to be eradicated or controlled? Perhaps no adaptation strategy has generated as much controversy as "assisted migration" or "managed translocation" (Ricciardi and Simberloff 2009, Schwartz et al. 2012). These issues raise similar questions regarding conservation practices for select species which may have unintended consequences for the new host environment.

Integrate climate change adaptation into existing work

For adaptation to be successful, climate considerations must be incorporated into a broad range of ongoing decisions and management actions. As a young science, the development of dedicated or stand-alone adaptation plans have often been tailored to better understand how climate change will impact a given area. Ultimately, the development and implementation of these plans must be mainstreamed with other ecological and management processes.

As an example, climate change considerations are increasingly being integrated into the assessment of a species' risk of invasiveness. One active area of research is using predictive species distribution models to understand where particular species may spread under future climatic scenarios. Climate matching has been used to assess the potential risk and spread of invasive snake species (Rodda et al. 2009, 2011). These types of models are starting to be used to help determine potential invaders to monitor as targets for early detection and rapid response efforts. (See the section on Tools and Methods for further details.)

The Framework of Invasive Species Management

As noted above, invasive species management is often cited as a climate change adaptation strategy by means of enhancing the resilience of native species, habitats, and ecosystems (Halpin, 1997; Lawler, 2009; West et. al., 2009). Heller and Zavaleta (2009) found that mitigating invasive species and other stressors was the third most frequently-recommended strategy for climate change adaptation among 112 journal articles published between 1975 and 2007. Identified strategies for invasive species are prevention, early detection with a rapid response to eradicate them, or, if they gain a foothold that will never likely be eradicated, control and management of them. Beyond technical feasibility, the choice of strategy also depends in large part on cost and available resources (Wilson et al. 2013).

Prevention

Prevention is cited as the most effective defense against biological invasions (NISC 2008). It is the only tactic that ensures an invasive species does not become an additional stressor to a vulnerable ecosystem. With or without climate change, preventing the human-assisted movement of invasive species (primarily via trade and transportation) is of principal importance in the management of invasive species. Preventing new invasions and controlling existing invasions can have value as climate change adaptation strategies, despite the risk of interpreting invasive species management too broadly.

Given the uncertainty of determining when a particular non-native species will become invasive, the most precautionary approach to prevention is thwarting the arrival of any non-native species. Typically this is impractical for technological, economic, and sociological reasons. Instead, the process of risk analysis for species and pathways can prioritize the extent and intensity of prevention efforts and associated investment of resources by targeting only those non-native species that present a potential risk.[22] Prevention tactics also depend on whether the pathway is based on intentional introductions of species where legal and regulatory ramifications may have greater bearing or is accidental in nature where technology and education may be more applicable.

Invasive Species Management

As part of the common body of practice, policy-makers, resource managers and researchers have generally accepted a hierarchy of action associated with the management of invasive species, namely: prevention, eradication and control.

Prevention is regarded as the optimal strategy as stopping the entry and establishment of an invasive species by its very nature means that their negative impacts and the costs of control are avoided.

Eradication is the second line of defense in cases where an invasive species is introduced and established. In some cases, small populations of an invasive species can be completely eliminated, thereby forgoing any future management costs.

Control becomes the fallback, where an invasive species population is too large or otherwise unfeasible to eradicate. Resource managers engage in longer-term control to limit the spread of an invasive species and/or protect priority resources. This entails ongoing management costs and activities.

Early detection and rapid response as well as restoration are activities that cut across this hierarchy. The use of targeted monitoring either along pathways of introduction or vulnerable sites helps to verify whether prevention efforts are effective. Early detection of a new introduction, thereby allows a rapid response to eradicate that incursion. Additionally, management actions to eradicate or control an invasive species require additional consideration of how to restore the site to ensure that native species thrive and to reduce its vulnerability to subsequent invasions.

Preventing the introduction of new invasive species preserves current levels of ecological resiliency. By contrast, invasive species control and management in the form of restoration may enhance an ecosystem's resilience, but not preserve it. Decision-making to prevent new invasive species *versus* managing existing ones becomes a critical question not just for conservation goals, but also with respect to available resources and management capacity. For example, in one area more ecological resilience might be provided over a few decades by reducing the density of an existing plant invasion than could be gained by preventing incursions of future invasive plants whereas the opposite could be true in another part of the United States, North America or the world. Tools to facilitate the decision-making process are available and critical to help plan in invasive species prevention (See the section on Tools and Methods).

Eradication, early detection and rapid response

Where prevention fails to stop the arrival of an invasive species to an ecosystem, early detection and a rapid response to eradicate that incursion can minimize harmful impacts before additional stress occurs to an ecosystem (Wittenberg and Cock 2001). Eradication is often only possible within a relatively short timeframe (figure 2) often because of the reproductive capabilities of the invasive species, which makes

[22] Risk analysis includes risk assessment (characterization of risks), risk management (evaluation of policies and interventions to reduce identified risks) and risk communication (transmission of risk assessment and management results to decision-makers and other stakeholders).

early identification and subsequent rapid response critical.[23] Climatic considerations can inform monitoring efforts for invasive species that are more likely to enter an area, thereby triggering rapid response efforts. Rapid eradication also depends on adequate preparedness – having the necessary methods, legal authorities, and resources to act on the detection before the invasion becomes entrenched. For this reason, eradication efforts should be considered within the broader, proactive conservation planning.

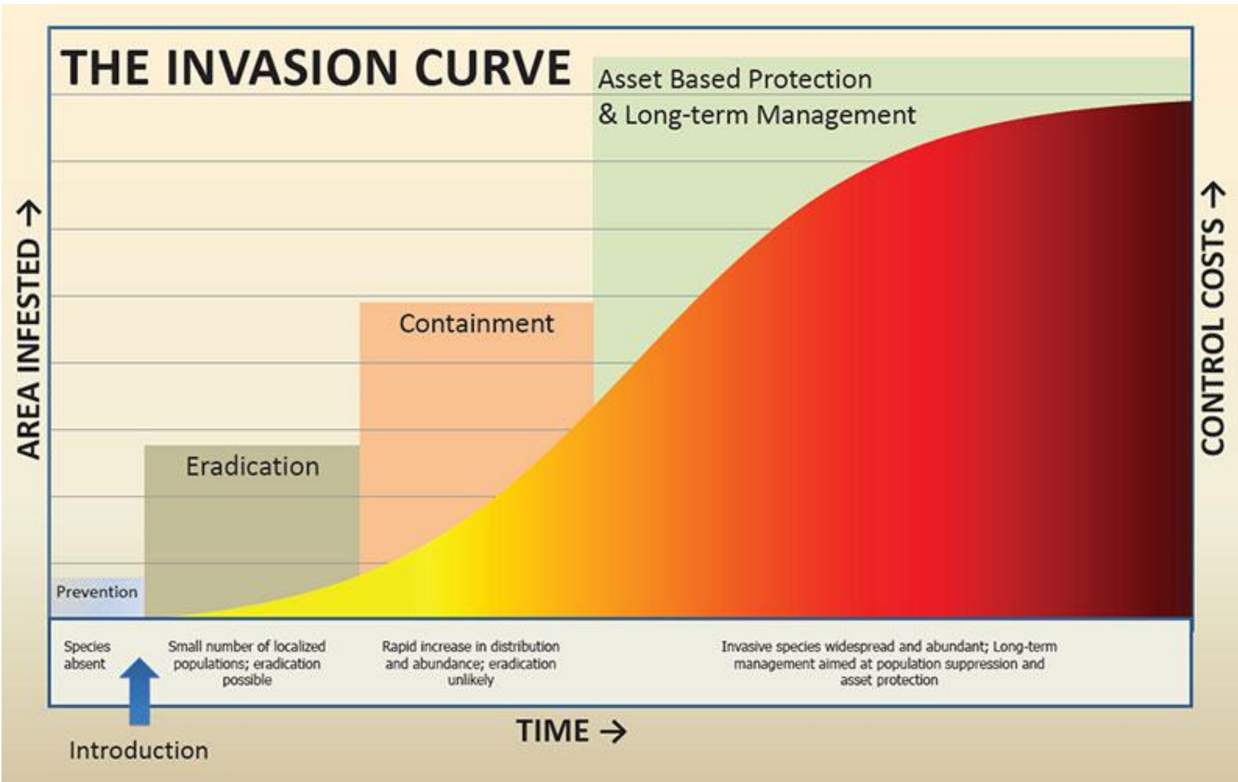

Figure 2: Phases of the Invasion Curve (Rodgers No Date)

Eradication of incipient populations is difficult, yet methods are continuously being refined. For example, successful eradications of rats (*Rattus* spp.), feral goats (*Capra hircus*), burros (*Equus asinus*), swine (*Sus scrofa*) and other species have been conducted on some islands and site-specific areas of larger land masses (Campbell and Donlan 2005, Carrion et al. 2007, 2011, Cruz et al. 2009, Parkes et al. 2010, Beauchamp et al 2011). Eradication of fruit fly outbreaks occurs along the Texas and Mexican border each year based on early detection systems (e.g., USDA 2002). Aquatic eradications have proven more difficult, but an exception is the successful removal of a highly invasive non-native marine seaweed (*Caulerpa taxifolia*), in two southern California locations in 2006; nicknamed the "killer algae," *Caulerpa* is a common aquarium plant and known invasive in other parts of the world (Merkel and Associates 2006).

[23] While eradication is generally contingent upon early detection of the invasive species and a rapid management response, in some cases such as terrestrial weeds there can be eradication opportunities for populations that have been established for significant periods but are still manageable. This can be due to the delay or lag time between the introduction of a non-native species and the point at which its population starts to dramatically increase with consequent adverse impacts.

Control

Once an invasive species has established and multiplied beyond a point where eradication is feasible, long-term control can still reduce that species' stress on the affected ecosystem. Reducing the extent or impact of existing invasive species may directly enhance ecological resiliency of the affected resource. This strategy can overlap with habitat restoration as a means of climate change adaptation given that invasive plant and animal control is an inherent tactic in most restoration projects. Limiting the impact of existing invasive species becomes more obvious as a climate change adaptation strategy when there is a direct relationship between the impacts of each stressor.[24] For example, the relatively high water consumption from tamarisk, an invasive tree also known as saltcedar (*Tamarix* spp.), causes ecological stress to water-limited riparian ecosystems (Nagler and Glenn 2013). Control of tamarisk, combined with native species revegetation, can provide resiliency to habitats where climate change is anticipated to aggravate drought conditions (Mainka and Howard 2010).

In contrast to eradication, long-term control can improve ecosystem functions of invaded areas, while also containing further spread and preserving ecological resiliency in nearby uninvaded areas. Primary strategies for invasive species control include physical methods (e.g., manual removal, prescribed fire, water level manipulation), mechanical treatment (e.g., mower, feller buncher), chemical treatment (e.g., pesticides), and biological tools (e.g., introduction of host-specific parasites). Future use of these management techniques also needs to consider climate-related impacts, particularly changes in environmental factors that may affect applications (e.g., pesticides) or biological changes within the target population (e.g., reproductive cycles and their timing). Additionally, it is important to consider where climate changes may actually facilitate invasive species control efforts. For example, changes in water availability may weaken invasive plant populations, which can create opportunities for native plant restoration. Additionally, the cost of management of an invasive species may be a determining factor in the decision-making process.

Climate change may exacerbate some exotic plant invasions, but may also reduce others. For example, droughts can promote invasions, such as by weakening resident native vegetation, but droughts also can reduce or eliminate some exotic plant populations. This can create opportunities for native plant restoration. Responses to climate change will vary by species and plans should build in flexibility to accommodate potential changes in biotic invasions as climate continues to change.

Finally, it is important to consider the role of research, modeling, and monitoring as secondary tactics that can enhance the effectiveness of invasive species management as a bona fide climate change adaptation strategy. Decision support models that integrate invasive species and climate impacts can help managers target limited resources to invasive species management tactics that provide the greatest ecological benefit. Monitoring ensures invasive species tactics create the desired effect and confirms relationships between the benefits of invasive species management and climate change impacts in situations where they overlap. Given the dynamic and unpredictable nature of biological invasions, ignoring these supporting functions undercuts the potential of invasive species management as a climate change adaptation strategy.

These frameworks for looking at invasive species management and climate change adaptation set the context for the discussion of available tools and methods in the next section.

[24] It should be noted that the impact of an invasive species on the adaptive capacity of a native species may also be indirect. For example, an invasive plant which grows faster than a native plant species under warmer conditions may cause negative impacts by overtopping and shading out the natives. The relationship here is indirect, as warming leads to faster growth of the invasive plant which then leads to shading out the natives.

III. Tools and Methods

The previous sections outlined the need to look at the interaction of climate change and invasive species and their implications for natural resource management. This approach includes looking at conservation goals and incorporating shifting ecological and biological parameters into decision-making processes. This section reviews some of the tools used to facilitate these efforts. Use of these tools and approaches can refine existing and future invasive species management, habitat improvement, water management and ecological restoration activities at a given site.[25] Management plans can then use these approaches to generate and incorporate knowledge about climate change predictions and anticipated responses by species and habitats into the planning process.

This effort focuses on how to manage invasive species within the context of a climate change adaptation framework. In contrast, a range of climate change adaptation tools is available to address issues like resilience, vulnerability and risk assessment, monitoring and land use planning, but they are beyond the scope of this effort (for general examples see Richardson and Otero 2012, Bours et al. 2014, Udvardy and Winkelman 2014; Czech et al 2014 specifically look at tools for National Wildlife Refuges; and USEPA (2014) has focused on risk-based adaptation plans).

Our discussion of management tools is organized by the categories of invasive species management which were outlined in the previous section: prevention and risk analysis, early detection and rapid response, and management and control. Listed tools may be applicable to more than one area (e.g., mapping tools could assist early detection and rapid response and control and management).

Prevention and Risk Analysis

Prevention and risk analysis depend on an intricate knowledge of species and habitats at a particular site or at the broader landscape-scale, and ultimately serve to reduce stresses on ecosystems by preventing entry or excluding invasive species from entering areas. Preventing the introduction of potentially invasive species requires an understanding of the pathways for introduction and the species that may intentionally or unintentionally be moved via those pathways. Risk analysis and its component parts (risk assessment, risk management and risk communication) serve as a key tool to identify potential threats, vulnerabilities, and areas of uncertainty associated with species or pathways. This approach is commonly used by the U.S. Fish and Wildlife Service when assessing if a non-native species should be considered injurious under the Lacey Act, thus prohibiting it from import into or transport within the United States.[26]

Assessments can include the identification of: non-native species with high risk or likelihood of becoming invasive, the potential impacts of climate change on these species, pathways of concern or that are subject to change, and suitable habitats for establishment and spread. Key questions might be: what are the vectors or pathways that would allow a species to enter into the country, region, state or watershed? What are the environmental constraints on a species establishing itself after arrival? What are the consequences of establishment such as its potential distribution, environmental and economic impacts, and cost-effectiveness of management options? For plants and plant products, risk analyses have been conducted to minimize the potential for plant pests to be introduced elsewhere (USDA 1996, Devorshak 2012, European and Mediterranean Plant Protection Organization [EPPO] 2014).

[25] For an interesting overview of decision tools applicable to the management of invasive species (and not specific to climate change) see Dana et al. 2013, and Miller and Morisette 2014.
[26] See http://www.fws.gov/injuriouswildlife/.

Pathway identification: Understanding the potential pathways that can introduce invasive species into new areas and how climate change can exacerbate this potential is crucial for any risk assessment. Commercial pathways include nurseries selling exotic ornamental plants, escaped exotic animals from pet stores and homes, exotic animals released (internationally or unintentionally) by pet owners[27], fishing bait releases, and shipments of live plants and animals that harbor pathogens or other exotic flora or fauna. Agricultural pathways include releases such as exotic species in aquaculture, domestic livestock gone feral or escapes from the live food industry. Transport is often associated with unintentional introductions, as invasive species may "hitchhike" on vehicles such as automobiles and boats moving from one location to another (Hulme 2009). For example, ballast water from ships is a pathway regulated by the EPA and the U.S. Coast Guard. Intentional introductions are also a concern, as seen with the historical introduction of animals such as swine and goats to supply food or some species of invasive, ornamental plants for horticultural purposes. Escapes and improper disposal of living organisms can introduce invasive species of plants and animals used in school science curricula.[28]

Experts also recognize that climate change itself will open new pathways or affect existing pathways for the movement of invasive species. Climate change may increase the risk in existing pathways by introducing species that could not survive earlier, but with a warmer environment are able to survive. For example, increased development and transport in the Arctic, selection of alternative feedstocks and even the choice of landscaping plants may all be associated with invasive species risks. Extreme climatic events such as hurricanes could blow in invasive species such as ticks (Perez de Leon et al. 2012). Additionally, facilities such as aquaculture ponds or net pen facilities that are vulnerable to flooding or severe weather events need to consider potential risks of escapes.

This report emphasizes the importance of evaluating pathways within the context of the geographic site or resource in question as it cannot identify potential changes in risk for all pathways. In this sense, Hazard Analysis and Critical Control Point (HACCP) plans are useful for looking at specific activities or operations to assess key areas of risk and the means to manage those risks (Britton et al. 2011) and need to include climate change variables to fully evaluate risks. HACCP is a preventative, management approach used to identify and control critical pathways within a process or practice that could spread invasive species to new locations. The HACCP planning process relies on principles such as self-monitoring, verification and record keeping to identify specific points in the activity pathway where non-target species can be removed. This results in minimizing the risk of the release or spread of an invasive species.

Risk assessment models: Risk assessment models identify high-risk species to help managers make informed decisions to minimize harm to native ecosystems. These evaluation processes use science-based tools to determine the invasive potential of species, including those, for example, that are proposed for imports. A risk assessment may be preceded by risk screening, which functions as a "first cut" to quickly identify species of concern. A risk screening typically categorizes species as a low, moderate, high or uncertain risk for establishment. Depending on the circumstances (e.g., species in trade or for cultivation in natural areas), screened species that are rated as high or uncertain risk may undergo a full risk assessment. Online tools and models are available for forecasting current risk and future range shifts in response to climate change. While many of these models are focused on

[27] Personal ownership via the pet trade was demonstrated as the principal pathway that resulted in the presence of all six large constrictor snake species in Florida that have been found in the wild or feral in the urban environment (Krysko et al. 2011).

[28] For a more comprehensive review of pathways addressing trade in living organisms, transport, and infrastructure and natural resource management, see ANSTF/NISC Prevention Committee 2014.

evaluating these species prior to their import or introduction, risk assessment can also be used to assess existing and potential impacts of species that are already present.

Risk assessment models may look at a variety of factors (e.g., history of invasiveness, climatic match, potential impact, particular traits of invasiveness), use quantitative and qualitative information and employ a range of questionnaires or statistical techniques. Despite these differences, models aim to be as accurate as possible using available information and as minimal information as necessary. Sometimes, there is little information available until an outbreak occurs. Decision makers may have different thresholds for accuracy and uncertainty, and tend to work with a model that suits their needs. While the initial development of tools were focused primarily on plants, risk assessment methods are increasingly being developed and applied to terrestrial and aquatic vertebrates, as well as invertebrates and pathogens.

Weed Risk Assessment	
The Australia Department of Agriculture developed the Weed Risk Assessment Process (WRP), a science-based quarantine risk analysis tool for determining the weed potential of proposed new plant imports. This model developed by Pheloung has served as the basis for development of other risk assessment models throughout the world (Pheloung et al. 1999).	http://www.daff.gov.au/ba/reviews/weeds/system & Pheloung et al. 1999
USDA APHIS has developed a weed risk assessment process that uses establishment/spread potential and impact potential in a logistic regression model to evaluate the invasive/weedy potential of a species (and Koop et al. 2011).	http://www.aphis.usda.gov/wps/portal/aphis/ourfocus/importexport?1dmy&urile=wcm:path:/aphis_content_library/sa_our_focus/sa_plant_health/sa_domestic_pests_and_diseases/sa_pests_and_diseases/sa_weeds/sa_noxious_weeds_program/ct_risk_assessments
California and Hawaii: Researchers in these two states have tested the Australia WRP model and used it to develop similar systems.	California Plant Risk Evaluation (PRE): http://www.plantright.org/research Hawaii: http://www.botany.hawaii.edu/faculty/daehler/wra/default2.htm
Aquatic plants: while the previous examples are mostly focused on terrestrial plants, the WRP model has also been tailored to address aquatic plants in a manner that incorporates climate change factors.	Gordon et al. (2012)
Animal Risk Assessment	
The U.S. Fish and Wildlife Service is developing a screening tool to rapidly assess the risks associated with aquatic animals primarily using their past history of invasiveness and a climatic match to the potential site for introduction.	http://www.fws.gov/injuriouswildlife/pdf_files/Standard_Operating_Procedures_01-08-14.pdf
The Freshwater Invasiveness Scoring Kit (FISK) was developed by the Centre for Environment, Fisheries and Aquaculture Science in the United Kingdom to assess risks associated with non-native, freshwater fish. Subsequent applications tailored the model to address freshwater invertebrates (FI-ISK), marine fish (MFISK), marine invertebrates (MI-ISK) and amphibians (AmphISK). The methodology is also being	http://www.cefas.defra.gov.uk/our-science/ecosystems-and-biodiversity/non-native-species/decision-support-tools.aspx

assessed in other countries including Australia, Canada, the United States and other parts of Europe (Copp et al. 2008, Lawson et al. 2012, Snyder et al. 2012, Vilizzi and Copp 2012, Almeida et al. 2013, Copp 2013).	
Science-based Tools for Aquatic Invasive Risk (STAIR) Assessment tools are being developed by a consortium of researchers in the Great Lakes to address risks associated with fish, plants, mollusks, amphibians, reptiles and crustaceans. The methodology considers traits from similar established invasive species to identify the most likely species traits contributing to their invasiveness.	http://www.iisgcp.org/topic_ais.html, http://www.michigan.gov/documents/deq/FENSKE_FINAL_25_Jan_2013_410830_7.pdf

Climate matching models: Climate matching models identify geographic areas that could be colonized by a potential invasive species based on a climate's similarity to a species' native range. Climate parameters (such as upper and lower temperature limits for growth, and threshold temperatures for cold and heat stress) determine survival thresholds to generate a potential distribution.

Climate Matching Models	
CLIMEX predicts the effect of climate change on species distribution by assessing biological parameters that limit species distributions and determine their seasonal phenology and relative abundance using climate information for a specific geographic region.	http://www.hearne.com.au/Software/CLIMEX/Editions
CLIMATCH is a web-based version of the CLIMATE model that can be used to predict the potential spread of invasive species.	http://data.daff.gov.au:8080/Climatch/
GARP (Genetic Algorithm for Rule-set Prediction) creates ecological niche models for species based on environmental parameters such as temperature, precipitation and elevation.	http://academic.research.microsoft.com/Keyword/55237/Genetic-Algorithm-for-Rule-Set-Prediction
RAMP (Risk Assessment Mapping Program) is being developed by the U.S. Fish and Wildlife Service to provide a climate suitability score for any species across North America using available spatial data in the online database GBIF.org (Sanders et al. 2012). The process uses ArcGIS to match the climate for a species in its native range with its potential non-native range in North America. RAMP outputs are a series of maps depicting a particular species' climate match across North America, and a list of climate-match score results. RAMP is currently undergoing peer review.	http://www.fws.gov/science/pdf/RAMP-Peer-Review.pdf
AquaMaps are computer-generated predictions of natural occurrence of marine species, based on the environmental tolerance of a given species with respect to depth, salinity, temperature, primary productivity and its association with sea ice or coastal areas.	http://www.aquamaps.org/main/home.php

Habitat suitability models (climate niche models): Like climate matching models, habitat suitability models identify geographic areas that could be colonized by invasive species. However, habitat suitability models go beyond climatic data to include environmental predictor layers from a study area, such as those derived from direct climate parameters, infrastructure layers or remote sensing data, with presence observations for a particular species. Statistical models analyze habitat requirements of the species of interest and predict its potential distribution based on habitat suitability. Model outputs assist land and natural resource managers by generating scenario maps that compare potential current and future habitat (see Elith et al. 2006 for the use of several models).

Habitat Suitability Models	
Methods for habitat modeling: statistical methods (boosted regression trees, logistic regression, multivariate adaptive regression splines), decision trees (random forest), software (Maxent), and expert input (Delphi Method).	In Alaska researchers used the Delphi Method incorporating literature reviews and expert surveys to model habitat suitability for invasive salt marsh cordgrasses (*Spartina spp.*) (Harney 2008). Forecasting stream water temperatures, flow rates and degrees of riparian management, Lawrence et al. (2014) developed a model to examine the interacting dynamics of native and non-native fish combined with restoration efforts for Chinook salmon (*Oncorhynchus tshawytscha*) rearing habitat in the Columbia River Basin.
The USGS Resource for Advanced Modeling (RAM) facility supports cooperative approaches for invasive species science to meet the urgent needs of land managers and the public by coordinating data and research derived from many sources.	http://www.fort.usgs.gov/RAM/

Eradication, Early Detection and Rapid Response (ED/RR)

The value of early detection is best realized with the establishment of a rapid response system. This may be a formal interagency team or a volunteer network of environmental groups and citizen scientists (preferably both). The sooner an invasive species can be detected *and* responded to, the more likely eradication will be successful. Critical areas for eradication and ED/RR include monitoring systems and detection tools, tools to report monitoring results, and tools to manage and map that data. Similarly, risk assessment tools, addressed in the prevention section, can help prioritize which species to watch for and/or how to best manage invasive species, which are already present.

Monitoring: A monitoring system must incorporate climate change as a planning variable. As environments are altered, invasive species may be found in areas where they were not originally expected. Species "watch lists" should include invasive species that are known to occur in a region but could move to an adjacent region in response to a change in climate. In many cases, the practices and tools associated with pathway identification and risk analysis can help inform early detection strategies in terms of prioritizing locations and species for observation.

Once an invasive species arrives, but *before* a population can become established, there typically is a small window of opportunity to eradicate the species. This requires a monitoring system that can detect arrivals at the earliest possible time. The most obvious example of this activity is conducted by agricultural inspectors and customs agents at ports-of-entry or inspection stations. ED/RR activities are critical not just at the national level, but can be strategically applied by states and at specific conservation sites.

Monitoring can employ a range of detection tools including visual surveys of locations, remote sensing, traps (e.g., for rodents or insects), and other physical means of capture or assessment (e.g., nets, electro-fishing). A new method to detect the presence of invasive species is environmental DNA (eDNA). Recent testing using eDNA methods includes Asian carps[29] in the Great Lakes, the Burmese python (*Python bivittatus*) in Florida, didymo or rock snot (*Didymosphenia geminate*) in the mid-Atlantic States and waters, and northern pike *(Esox lucius)* in lakes and water bodies on the Kenai Peninsula (Alaska Department of Fish and Game, pers. comm. 2014, Piaggio et al. 2014). eDNA techniques are especially useful for working with cryptic species or those that are otherwise difficult to identify (e.g., they might look similar to a native species), as well as species that are especially difficult to detect in very low numbers (also the time when eradication has the greatest chance of success). As costs decrease and portability increases, these tools (based on intensive sampling and laboratory testing) will become more viable at the site level.

Reporting: A number of tools are available to the public and land managers for reporting sightings of invasive species. One example is the *I've Got One* smart phone application developed by the University of Georgia and free to download (http://apps.bugwood.org/apps.html). Reporting tools usually interact with mapping software (see examples below) and used by agencies to monitor the occurrence and spread of invasive species. The Washington Invasive Species Council also has a smart phone app that allows people to report and map the State's priority invasive species (http://www.invasivespecies.wa.gov/report.shtml). The National Park Service also has an ED/RR app – IPAlert (http://nps.eddmaps.org).

Reporting incidences of invasive species is critical for a number of management actions. In the best case scenario, sightings of new invasive species can inform rapid response efforts. But decisions need to be based on accurate data. Thus, experts need to verify reports under a quality control process. Data collected over time on the locations of a particular invasive species can also assist control and management operations. If sufficient data is available, broader landscape management planning can incorporate findings into broader decision-making processes.

Mapping tools: Invasive species mapping tools are web-based programs that pinpoint locations of invasive species reports to identify known ranges or distributions. These tools are affordable, flexible, easy to use with no prior knowledge of GIS, include online data entry forms to include new invasion locations, and facilitate data entry from a wide variety of sources. Data can be searched, queried and downloaded in a variety of formats. Mapping tools facilitate implementation of ED/RR actions at relevant scales.

Mapping Tools	
The Early Detection and Distribution Mapping System (EDDMapS) is a web-based mapping system for documenting invasive species distribution which was started in 2005. Its goal is to maximize the effectiveness and accessibility of the immense numbers of invasive species observations recorded each year. EDDMapS combines data from other databases and organizations as well as volunteer observations to create a national network of invasive species distribution data that is shared with educators, land managers and conservation biologists.	http://www.eddmaps.org/

[29] Invasive Asian carps is a catchall for several species in the Great Lakes Region including bighead carp (*Hypophthalmichthys nobilis*), silver carp (*H. molitrix*), black carp (*Mylopharyngodon piceus*) and grass carp (*Ctenopharyngodon idella*).

iMapInvasives is a GIS-based, all taxa data management software tool designed for use by anyone who wishes to protect natural resources from the threat of invasive species. This resource is currently being utilized by seven U.S. states and one Canadian province with hopes to continue branching out to other states/provinces. iMapInvasives currently tracks over 4,600 invasive species, and contains over 300,000 records of invasive species occurrences. This effort promotes information-sharing and collaboration on the extent of invasions, survey efforts and treatment options.	http://www.imapinvasives.org/
CalWeedMapper is an online tool based on statewide mapping data for 200 invasive plants in California. CalWeedMapper provides users with recommendations for priority eradication and surveillance targets in their selected region. It also incorporates suitable range projections under future climate conditions.	http://calweedmapper.cal-ipc.org
The Great Lakes Aquatic Nonindigenous Species Information System (GLANSIS) is a regional database that includes a core list of species that are non-native in the Great Lakes basin, a list of those species that are expanding their range and a watchlist for priority non-native species not presently found in the Great Lakes.	http://www.glerl.noaa.gov/res/Programs/glansis/glansis.html
The National Exotic Marine and Estuarine Species Information System (NEMESIS) was developed by the Smithsonian Environmental Research Center and serves as a national database of marine and estuarine invasions and includes information on population status, site and pathway of introduction, and other relevant biological and ecological data particular to included invasive species.	http://invasions.si.edu/nemesis/
Sudden Oak Death Map tracks the spread of Sudden Oak Death in California, based on annual surveys and other forest diseases throughout North America.	http://oakmapper.org/
The USGS Nonindigenous Aquatic Species (NAS) Database serves as a repository for spatially referenced, biogeographic accounts of introduce aquatic species.	http://nas.er.usgs.gov/
The Center for Invasive Species and Ecosystem Health has designed a range of mobile applications ("apps") for identifying, monitoring and mapping invasive species.	http://apps.bugwood.org/apps.html

Rapid Response: While the terms early detection and rapid response are commonly used together in practice efforts frequently extend only to early detection and monitoring given a lack of resources or coordination to mount a rapid response. There are certainly exceptions to this with particular high profile species such as Asian longhorned beetle (*Anoplophora glabipennis*) or the siting of non-native species of carp in close proximity to the Great Lakes. Additionally, efforts have been underway to develop response frameworks and identify resources for rapid response actions at the national and state levels. For example, the interagency Council on Climate Preparedness and Resilience established by Executive Order 13653 calls upon the Department of Interior working with the National Invasive Species

Council and other federal agencies, states and tribes to develop a framework for a national ED/RR program. The program would include a plan for an emergency response fund to increase the capacity of interagency and inter-jurisdictional teams to respond to new invasions (Council on Climate Preparedness and Resilience 2014).

While the following examples are not all specifically tied to climate change, they are still useful resources for rapid response planning that may consider invasive species introductions due to climatic factors.

Rapid Response Tools	
Incident Command System (ICS) is an emergency response model that has been adapted to invasive species management efforts. ICS was initially developed in the 1970s to address shortcomings in government agency responses to fighting wildfires. It establishes a leadership and organizational structure to streamline operations, planning, logistics and financing/resources.	https://www.fema.gov/national-incident-management-system/incident-command-system-resources and https://www.osha.gov/SLTC/etools/ics/what_is_ics.html)
The APHIS Emergency Qualification System (EQS) is a central database containing each employee's emergency responder qualifications, personnel profiles and emergency contact information. This information is used to support APHIS emergency response and to alert employees of a potential emergency situation that may require action on their part. EQS is also utilized to locate individuals with particular skill sets, training or experience for dispatch in emergencies. All requests for resources (e.g., personnel) in emergencies are created and placed in the Resource Ordering and Status System (ROSS) using established ordering procedures. At the emergency location, an Incident Command System (ICS) is used to carry out management.	http://ross.nwcg.gov/

Control

Control focuses on addressing the risks associated with an invasive species that is already present at a particular site. This is generally the most costly stage of dealing with invasive species, especially for long-term projects. Planning must focus on the most appropriate and realistic goals, effective use of resources and strategic prioritization of the target invasive species for control. Management plans are instrumental for documenting processes in a transparent manner and should recognize the trade-offs across feasibility, available resources and long-term objectives. Planning efforts may be site-specific or encompass large areas and cover a single or multiple species, and should consider the influence of climate change on range expansion and the potential for introductions into new sites.

Control strategies differ according to the management objective (e.g., slow the spread, protect key resources) and may include outlier populations as well as the leading edge of expanding populations. In cases where multiple invasive species are present, managers need to consider their interactions to ensure that control of one invasive species does not exacerbate the impacts of another.

To incorporate climate change adaptation into an invasive species management plan, steps may include:

- Developing a matrix that cross-references available management tools with threats from climate change identified during the risk assessment process.

- Prioritizing species based on current versus future threats to ecosystems (e.g., terrestrial, freshwater, marine) in light of limits imposed by climate change (e.g., management of invasive species in freshwater systems are likely to be affected sooner than in terrestrial systems).
- Considering the interactive effects of projects involving the management of multiple species.[30]
- Assessing the efficacy of management tools (e.g., mechanical removal, chemical application, prescribed burning, water level manipulation, biocontrol) using expected scenarios for climatic change.
- Determining all potential pathways of introduction that may impact the particular site and species under management. This can also include eliminating all pathways or take steps to minimize the risk of introduction, and preventing the introduction of new specimens of the target invasive species that may reinforce existing populations or lead to re-invasion.

Control prioritization tools can help land managers choose which populations to control and which methods to use. These types of tools allow land managers to run multiple analyses with different combinations of species or management variables to understand how changing one variable can affect the outcome. They also assist with climate change adaptation by identifying parameters for the most effective strategies for addressing the top non-climate stressors (invasive species). Some of these tools also anticipate future environmental changes and incorporate them into strategies. However, many tools will need to be reassessed in the future to ensure they are still relevant and cost effective.

Control Prioritization Tools	
WHIPPET is a tool designed to prioritize from among a set of populations. It combines species data such as ecological impacts and reproductive ability with population data such as acreage, distance to dispersal vectors (roads or rivers), and location relative to important conservation habitat. It is currently available for California (Skurka Darin et al. 2011).	http://whippet.cal-ipc.org
Weed Search was developed by the University of New England (Australia) to perform weed eradication feasibility analysis. Users can determine how many populations are feasible to control based on an analysis of the cost of attacking each population relative to the user's available budget.	http://www-personal.une.edu.au/~ocacho/weedsearch.htm
USFS Template for Assessing Climate Change Impacts and Management Options (TACCIMO) provides landowners and managers with available research on threats to forests on a geographic basis. The search function currently includes research categories for exotic insect pests and invasive terrestrial plants.	http://www.taccimo.sgcp.ncsu.edu
The Center for Invasive Species and Ecosystem Health lists several control tools for a range of invasive species.	http://www.invasive.org/control/index.cfm

[30] Models that incorporate more than a single species are limited, yet they are critical for understanding the interactive dynamics in cases where multiple invasive species are present. These approaches generally look at combined or average effects from suitability model outputs to assess landscape vulnerability to invasions within particular management areas. Alternatively, they may predict landscape level habitat changes using vegetation-type layers as a species substitute. For more general, non-invasive species specific work on multi-species modeling and conservation work see Lawson et al. 2008.

IV. Institutional Coordination and Outreach

The goal of this section is to 1) identify ways to improve the effectiveness of coordination, communication, and partnerships between federal and state agencies, regional and local agencies, private and non-profit organizations, and advocacy groups working on climate change and invasive species issues; and 2) facilitate open and ongoing communication on the subject of climate change, climate change adaptation and invasive species. Ideally, it can be used by land managers to initiate actionable collaborations, provide information and develop educational opportunities. The goals of coordination and outreach vary, but can include:

- Increasing the rate of learning by sharing what's been tried and how it worked;
- Increasing the effectiveness of management actions by coordinating related efforts; and
- Improving monitoring of climatic changes and impacts, invasive species and management effectiveness by standardizing approaches and sharing resources.

Institutional Coordination

Collaboration among large numbers of individuals can be exceedingly difficult, even when they are working in the same organization and have a common interest. Consequently, when addressing vast or diffuse issues like climate change and invasive species, collaboration becomes far more difficult. These challenges are met partly by developing participant awareness to the need for expansive and inclusive cooperative efforts.

The disciplines of invasive species and climate change adaptation need to engage at the various levels of government and the non-governmental sector to provide the interagency coordination and education needs for conservation planners, policy makers, program administrators and land managers. These communities are not monolithic and internally uniform, but instead represent a range of skills. The development of this paper entailed working with those involved in scientific research and modeling, education and training, decision support, outreach and policy development as well as site management. The following rough categorization includes an indicative list of groups that should be involved in addressing these management discussions as they move forward.

Natural Resource Management: Arguably the most important group for this report, site managers and their networks are the responsible stewards for the lands and waters in question. They are essential in all stages from planning to implementation, as they have the most familiarity with the resources at stake, their value and the opportunities for and impediments to getting things done. Partnerships, particularly between those with field experience and those involved in research, tool development, and modeling, will be critical to understanding the "where, when and how" to manage invasive species in the face of climate change.

Examples:

- Federal, state and municipal agencies responsible for land and water management, forestry, wildlife, parks and recreation, and natural resources;
- National Marine Sanctuaries, National Estuarine Research Reserve System, marine fisheries commissions, fish habitat partnerships and other marine-based managers;
- Regional and state based organizations, such as invasive plant councils and the North American Invasive Species Management Association,
- Cooperative Invasive Species Management Areas (CISMAs) and Cooperative Weed Management Areas (CWMAs) and Partnerships for Regional Invasive Species Management (PRISMs in New York); and
- Public land trusts and private land-holders.

Inter-institutional Coordination: Entities responsible for developing broader strategies, coordinating activities and shaping the higher-level dialogue on natural resource management issues address the intersection of climate change and invasive species particularly as they relate to policy-making and resource allocation.

Examples:

- President's Council on Climate Preparedness and Resilience, Interagency Climate Change Adaptation Task Force and the Interagency Land Management Adaptation Group;
- Aquatic Nuisance Species Task Force (ANSTF) and its regional panels, Federal Interagency Committee on the Management of Noxious and Exotic Weeds (FICMNEW), Federal Interagency Committee on Invasive Terrestrial Animals and Pathogens (ITAP) and the National Invasive Species Council (NISC);
- National Fish, Wildlife and Plants Climate Adaptation Strategy, National Ocean Policy, National Arctic Strategy, Priority Agenda Enhancing the Climate Resilience of America's Natural Resources and their implementation working groups; and
- Regional and state-based planning efforts, such as the Pacific Northwest Regional Economic Conference, the Great Lakes Commission, regional governors' associations and state invasive species councils.

Research and Development: Research on climate change and invasive species perspectives and their interface are critical to developing adaptive strategies. Researchers and developers work at individual centers and regional and national networks and hubs. Researchers use their expertise to develop and apply models and risk assessment tools, collate and analyze data, conduct *in situ* and lab experiments using different climate parameters or management techniques, and analyze and translate research findings. In some cases, research centers could assist natural resource managers with modeling and other assessments, or provide training on how to select and use appropriate methods and tools.

Examples:

- Scientific networks: Landscape Conservation Cooperatives, USGS Climate Science Centers, USDA Regional Climate Hubs, NOAA Regional Integrated Science and Assessments Program, NOAA Sea Grant program, the Smithsonian Environmental Research Center (SERC), USDA-APHIS Wildlife Services National Wildlife Research Center, the North American Invasive Species Network;
- Programs with modeling expertise: UC-Davis Information Center for the Environment, Colorado State University/USGS collaboration on invasive species forecasting; and
- Training: USFWS National Training Conservation Center, USDA Cooperative Research and Extension Services.

Data and Information Resources: Accurate, reliable and easily accessible data underpin the ability of both managers and modelers to make realistic projections and decisions both in the short and longer-term. Data needs include, for example, climate and bio-geographical data for managed areas, biological and management information on non-native species, as well as a range of ecological, economic and socio-political information related to pathways, propagule pressure and other drivers of change. A few of the websites hosting data and information relevant to invasive species and climate change are listed below.

Data Resource Websites	
Climate.Data.gov	http://climate.data.gov
Climate Wizard	http://www.climatewizard.org

Intergovernmental Panel on Climate Change Data Distribution Centre	http://www.ipcc-data.org/
SERC Marine Invasions Research Lab – Online Databases	http://www.serc.si.edu/labs/marine_invasions/databases/index.aspx
USGS Biodiversity Information Serving Our Nation (BISON)	http://bison.usgs.ornl.gov/
USGS National Climate Change Viewer	http://www.usgs.gov/climate_landuse/clu_rd/nex-dcp30.asp
Information Resource Websites	
Climate Adaptation Knowledge Exchange	http://www.cakex.org/
Collaboratory for Adaptation to Climate Change	https://adapt.nd.edu/
USFS Climate Change Resource Center	http://www.fs.fed.us/ccrc/
US Global Change Research Program Resource Library	http://www.globalchange.gov/resources.html
Regional Resource Websites	
CalAdapt	http://cal-adapt.org
California Climate Commons	http://climate.calcommons.org
Great Lakes Environmental Assessment and Mapping Project (GLEAM)	http://www.greatlakesmapping.org
Great Lakes Coastal Resilience Planning Guide	http://greatlakesresilience.org

Outreach and Education

Making informed decisions regarding natural resource management, particularly for public lands and waters, involves a deliberative process that takes into account the public's broader views, values and priorities (NRC 2009). This entails engaging in a two-way process where the public can receive accurate information about the implications of climate change and invasive species, while ensuring mechanisms are in place to solicit and consider the public's views. Similarly, the environmental management community which often involves the general public, resource managers, and policy-makers can benefit from a broader understanding of these issues. This cross-pollination of ideas, research and management experiences across the climate change and invasive species communities advances knowledge of the junction between the two issues and effective protection of natural resources.

Outreach and education are frequently considered as an afterthought or a required task to appease prescribed public policy. Yet effective communication across a range of the involved public often leads to successful outcomes. An example is Great Lakes Climate which developed a range of outreach materials that address climate change in a broad range of sectors, including invasive species.[31]

Outreach and working across the range of relevant institutions and individuals, ensures the most appropriate and effective use of information and associated resources. Three broad approaches or models that can be used to communicate research and scientific information to policymakers include problem solving, interactive and enlightenment models (Weiss 1979).

[31] See http://climategreatlakes.com/resources-on-climate-change-for-community-outreach-professionals-invasive-species-management/.

Problem-solving model: This approach directly applies research to a particular problem faced by decision-makers through identification of the most appropriate information and tools. Specific examples include providing risk assessment tools to inform decisions regarding conservation priorities and threats, and checklists of noxious invaders or their non-invasive alternatives. These resources can be consulted before selecting species for climate change adaptation or mitigation plans.

Interactive model: This model uses the iterative process of policy development and decision-making to draw from a range of inputs and back-and-forth interaction with experts. It reflects the evolving nature of the scientific knowledge base regarding both climate change and invasive species management. An interactive approach facilitates ongoing communication and underlying relationships across site managers, decision makers and specialists. Here, the Landscape Conservation Cooperatives (LCCs) can be particularly effective with their ability to draw in a wide range of governmental, scientific and resource management experts focused on particular geographies. Such hubs can serve as catalysts for exchange of information on critical management questions.

Enlightenment model: In many cases, specific research results matter less than the broader conceptual and theoretical perspectives produced via research and debate used to inform decision-makers' thinking and public opinion. Shifts in thinking are particularly relevant, since climate change faces challenges to its validity and the role of humans in the process. In contrast, the invasive species community has fought for broader recognition in policy circles to garner the resources and regulatory frameworks necessary to address these problems. At a very general level, this report seeks to reinforce the connection between climate change and invasive species, establish the basis for future research collaboration and address resource management questions of mutual interest. By applying their educational role, universities and researchers not only develop topical information with direct application under the problem-solving model, but also reinforce shifts in the general public discussion. Similarly, broader planning efforts at the national, regional and state levels raise awareness about the relationships across climate change, invasive species and resource management.

V. Recommendations and Resources

Recommendations

Past studies have generated a multitude of recommendations on reducing negative impacts from invasive species and climate change as separate issues (Wittenberg and Cock 2001, Heller and Zavaleta 2007, Hansen et al. 2009, Heinz Center 2009, Tu 2009, The Nature Conservancy 2010). To the extent that reduction of either of these stressors increase resilience against the other, those recommendations are relevant to this report. However, this section focuses on interactions at the intersection of climate change and invasive species. These recommendations may be valid for a range of audiences from site and resource managers to government decision-makers for initiatives that can further support their work.

At the broadest level resource managers, researchers, and policy-makers need a basic understanding of the management paradigms for jointly addressing invasive species and climate change. This includes a clear understanding of the goals for conservation and management, which in turn determines the necessary strategies to address relevant issues such as ecosystem resilience, the management and use of particular species for adaptation purposes, and even how localized biogeographical changes may affect invasive species.

Two overarching messages foster synergies across these areas:

1. Target invasive species that increase vulnerability to climate change; and
2. Prioritize adaptation options that decrease the risk and impact of invasion.

The continuing evolution of science and management experience on both climate change and invasive species reinforces the need for managers and policy-makers to use adaptive management framework (Holling 1978, USDOI 2009, 2012).[32] Future work is also necessary to assess both existing capacity and needs at a range of levels.

Prevention recommendations

Incorporation of climate variables into individual species risk assessments is already used at the national level for a range of taxa. This practice needs to be expanded at the regional and local levels to better identify invasion risks associated with:

- Non-native species that are not yet established within a region, but have a high potential for introduction and major adverse impacts; and
- Special habitats (e.g., minimally invaded, high value, rare and unique) which may require a higher level of scrutiny due to their sensitivity.

Beyond the focus on individual species, further work on pathway risk assessments needs to incorporate climate change variables across a range of sectors such as transport, energy development, and food and fiber production. At the regional and local level, risk assessment methods must identify:

[32] Adaptive management is a process of "flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process" (National Research Council 2004).

- High risk pathways for new introductions into regions or sites that are undergoing anticipated changes;
- Hotspots for invasion within that area where non-native species may first be introduced (e.g., ports, transportation hubs and networks); and
- Vulnerable natural resources that may be potentially impacted by invasive species under climate change conditions.

Prevention planning should incorporate the modeling and risk assessment techniques while site level managers should consider using Hazard Analysis and Critical Control Points (HACCP) protocols and other prevention plans incorporating climate variables within their daily management practices and as a component to support longer-term conservation goals.

Eradication, early detection and rapid response recommendations

Regional and local level resource managers need to have detection methods for invasive species and coordinated response protocols readily available. These methods and response protocol need to be updated regularly to account for climate variables. The following recommendations should be in every regional or local managers tool box kit for invasive species.

- Monitoring and early detection programs can identify the introduction and spread of new species while tracking their relationship to changing climatic conditions. This is important for gradual or “natural” spread of invasive species, events occurring in the aftermath of severe weather and habitat degradation that increases vulnerability to invasions.
- Risk assessment of species and pathways that incorporate climate change variables can inform eradication and ED/RR efforts by prioritizing potential sites and problematic species.
- Climate related variables and assessments can identify areas that are particularly vulnerable to invasive species, potential hotspots for invasion and critical habitats in need of protection from invasive species.

Control recommendations

Resource managers at local to regional levels should have a prioritized list of invasive species that need to be controlled, recognizing that the list could change under different climate variables. Management of established invasive species can require significant resources, so managers should already have considered this prior to taking action. In addition, the following recommendations should be completed to account for climate change.

- The efficacy of control techniques (e.g., mechanical methods, pesticide applications and timing, biocontrol approaches) need to be reconsidered in the context of changing climates to ensure they remain effective.
- Modeling can inform managers about the potential expansion or contraction of established invasive species, their potential to impact priority conservation goals and aid in the allocation of management resources.

Institutional coordination and outreach recommendations

Managers should incorporate climate considerations into their ongoing invasive species outreach programs and vice versa and coordinate these with other institutions, especially for invasive species that cover more than just a site-specific level.

- At a broad level, researchers and managers working on the combined issue of invasive species and climate change need a central place to exchange information and experiences. This could take the form of a community of practice or information hubs linking site-level work to regional institutions such as the Landscape Conservation Cooperatives and the Aquatic Nuisance Species regional panels, among others.
- Policy-makers should be encouraged to support projects involving invasive species and climate change so that their junction can be researched and monitored. Where funding is designated solely for invasive species or climate change projects, efforts to look at the intersection of both issues should be supported, if possible.
- Local, state and regional efforts (e.g., cooperative weed management areas and state invasive plant councils) should be supported and integrated into broader landscape management efforts that also address climate change.
- The engagement of citizen scientists should be encouraged in a range of monitoring and educational activities.

Research and data recommendations

Underlying the successful application of climate models and risk assessment methodologies is the availability and accessibility of high quality data relating to the biophysical aspects of a particular geography as well as the biology and ecology of particular species. Baseline information to evaluate subsequent impacts from climate change and invasive species needs to include:

- Investment in development of detailed GIS layers for a variety of parameters at the local, regional and continental scales to improve prediction capacity for models that incorporate environmental variables. GIS layers for natural and physical predictor layers could include all possible details for an area such as hydrology, vegetation, sub-meter accuracy elevation, planned construction and road projects, etc.
- Research on the adaptive capacity of organisms under changing conditions and associated studies of evolutionary ecology of adapting populations (i.e., genotypic change in generations of species subject to changing climates). This could include research on genotypic variability (with or without phenotypic plasticity) within populations as an indicator of latent adaptability to changing conditions.
- Population and habitat assessments for evaluating long-term trends.

Special considerations for all recommendations

Potential conflicts could arise when management actions taken to address invasive species or climate change fail to consider interlinkages among ecosystem aspects. These types of conflicts include:

- Translocation and assisted migration of species improve the prospects of a species' survival by relocating it into a new range may introduce new risks of invasion.
- Connectivity can support the movement of invasive species as well as native species.

- The natural adaptive response of species shifts in distribution should be included in prioritization of control and eradication efforts, and considered in how harmful species (whether "non-native" or "native") are regarded in a policy and management context. This conflict arises because range expansion by native species may negatively affect new ecosystems.
- Some invasive species in local areas may actually reduce ecosystem vulnerability to climate change, which calls for careful consideration of ongoing eradication or control efforts. This may be applicable to situations where an invasive species is already well-established and cases where introductions of non-native species are proposed for restoration or habitat management purposes.
- Adaptation and mitigation actions may include the introduction and cultivation of species with special traits amenable for development as biofuels, food and fiber production. The risk of invasiveness needs to be balanced against potential benefits.

Resources

The previous sections, particularly those on tools and institutional coordination, provide a range of examples and potential informational resources. Beyond practical know-how, other resource questions relate to the availability of financial opportunities to support management work. This area depends on changing budget priorities interacting with other economic factors. Below is a list of websites and initiatives related to funding and resources.

National Websites	
National Disaster Resilience Competition	http://www.whitehouse.gov/the-press-office/2014/06/14/fact-sheet-national-disaster-resilience-competition
NOAA Climate Program Office – Grants and Projects	http://cpo.noaa.gov/GrantsandProjects.aspx
NOAA maintains an informal list of climate funding opportunities including federal agencies and foundations on the TNC Collaboratory site. Updates are semiannual and generally posted in January and July.	http://adapt.nd.edu and insert "Climate Funding Opportunities" in the site's search function
USDA Grant Partnership Programs for invasive species research, technical assistance, prevention and control and other invasive species funding information.	http://www.invasivespeciesinfo.gov/toolkit/grants.shtml
Wildlife Conservation Society Climate Adaptation Fund	http://www.wcsnorthamerica.org/ClimateAdaptationFund/tabid/4813/Default.aspx
Regional Websites	
Landscape Conservation Cooperatives	http://lccnetwork.org
Pacific-American Climate Fund	http://www.pgrd.org/projects/pacam/
USGS National Climate Change and Wildlife Science and Climate Science Centers regional scientific research funding	http://nccwsc.usgs.gov/ResearchFunds
Initiatives	
Great Lakes Restoration Initiative, Bay Delta Initiative, Gulf of Mexico Initiative, Everglades Initiative, Mississippi River Basin Health Watersheds Initiative, USDA Regional Conservation Partnership Initiative	

In closing, it is important to recognize that research and management experiences involving the intersection of invasive species and climate change will continue to evolve. By capturing the basic relations between the two issues along with an outline of recommendations and research priorities, this report can serve as a framework for cataloguing additional areas of work. The initial ANSTF recommendation calls for a platform to collate relevant information, which will be developed in the near future at http://www.invasivespecies.gov and supplemented by other relevant federal and non-federal sites.

Glossary of Key Terms

Climate change: any significant change in the measures of climate (e.g., temperature, precipitation, wind patterns) lasting for an extended period of time.

Climate change adaptation: adjustment or preparation of natural or human systems to a new or changing environment which moderates harm or exploits beneficial opportunities.

Climate change mitigation: human intervention to reduce the human impact on the climate system; it includes strategies to reduce greenhouse gas sources and emissions and enhancing greenhouse gas sinks.

Control: actions to contain or minimize the spread and/or impacts of an invasive species, usually used in cases where complete eradication is not feasible.

Early detection and rapid response: the process of monitoring for new introductions of invasive species in a site, and, if found, taking appropriate action to eradicate or control the population.

Eradication: the elimination of an established population of invasive species from a site.

Hazard Analysis and Critical Control Points (HACCP): a planning tool for reducing or eliminating the spread of unwanted species during specific processes or practices or in materials or products.

Invasive species: an alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health. An alien species is, with respect to a particular ecosystem, any species, including its seeds, eggs, spores, or other biological material capable of propagating that species, that is not native to that ecosystem.

Pathway: the means by which a human activity moves invasive species into a new area either intentionally as direct introductions into the environment or unintentionally as hitch-hikers on vehicles, plants and animals, or a range of other commercial goods and their packaging.

Prevention: the practice of stopping the establishment or movement of invasive species into a site, usually by managing pathways of introduction.

Range shift: an expansion, contraction or other alteration in suitable habitat to sustain a population of a species due to changes in climatic conditions.

Resilience: the capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy and the environment.

Risk analysis: a set of tools or process incorporating risk assessment, risk management and risk communication, which are used to evaluate the potential invasiveness and possible mitigation measures of a species and/or pathway for introduction and spread.

Vulnerability: the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. It is a function of the character, magnitude, and rate of climate variation to which a system is exposed; its sensitivity; and its adaptive capacity.

Definitions are drawn from the EPA Glossary of Climate Change Terms (http://www.epa.gov/climatechange/glossary.html) and NISC Executive Order, Management Plan and website (http://www.invasivespecies.gov).

References

Adger, W.N., N.W. Arnell and E.L. Tompkins. 2005. Successful adaptation to climate change across scales. Global Environmental Change 15:77-86.

Almeida, D., F. Ribeiro, P.M. Leunda, L. Vilizzi and G.H. Copp. 2013. Effectiveness of FISK, an invasiveness screening tool for non-native freshwater fishes, to perform risk identification assessments in the Iberian Peninsula. Risk Analysis 33 (8):1404-1413.

Aquatic Nuisance Species Task Force (ANSTF). No Date. Nutria. Prepared by S. Pasko, NOAA and A.M. Eich, USFWS. Available @ http://www.anstaskforce.gov/spoc/nutria.php. Last visited 11/7/2014.

Aquatic Nuisance Species Task Force (ANSTF) and National Invasive Species Council (NISC) Prevention Committee. 2014. Prevention and Pathways. (*in draft*). ANSTF/NISC: Washington, DC. Contact Stas_Burgiel@ios.doi.gov for copies of the draft.

Aspinwall, M. J., D. B. Lowry, S. H. Taylor, T. E. Juenger, C. V. Hawkes, M. V. Johnson, J. R. Kiniry and P. A. Fay. 2013. Genotypic variation in traits linked to climate and aboveground productivity in a widespread C_4 grass: evidence for a functional trait syndrome. New Phytologist 199:966-980.

Atkinson, C.T. and D.A. LaPointe. 2009. Introduced avian diseases, climate change, and the future of Hawaiian honeycreepers. Journal of Avian Medicine and Surgery 23(1):53-63.

Ayre, D. J. and T.P. Hughes. 2004. Climate change, genotypic diversity and gene flow in reef-building corals. Ecol. Letters 7: 273–278.

Bahattarai, G. P, and J. T. Cronin. 2014. Hurricane activity and the large-scale pattern of an invasive plant species. PLoS One 9(5): e98478. DOI:10.1371/journal.pone.00098478

Barney, J. N. 2014. Bioenergy and invasive plants: Quantifying and mitigating future risks. Invasive Plant Science and Management 7(2):199-209.

Beauchamp, A.J., M.D. Burt, and J. Jokiel. 2011. Eradication of feral goats (*Capra hircus*) from Makua Military Reservation, Oahu, Hawaii. Occasional Papers IUCN Species Survival Commission 42:280-284.

Bebber, D.P., M.A.T. Ramotowski and S.J. Gurr. 2013. Crop pests and pathogens move polewards in a warming world. Nature Climate Change. DOI: 10.1038/NCLIMATE1990

Bellard, C., C. Bertelsmeier, P. Leadley, W. Thuiller and F. Courchamp. 2012. Impacts of climate change on the future of biodiversity. Ecology Letters 15(4):365-377.

Bellard, C., W. Thuiller, B. Leroy, P. Genovesi, M. Bakkenes and F. Courchamp. 2013. Will climate change promote future invasions? Global Change Biology 19(12):3740-3748. DOI: 10.1111/gcb.12344

Benning, T.L., D. LaPointe, C.T. Atkinson and P.M. Vitousek. 2002. Interactions of climate change with biological invasions and land use in the Hawaiian Islands: Modeling the fate of endemic birds using a geographic information system. Proceedings of the National Academy of Sciences 99(22):14246-14249.

Bertelsmeier, C., G. M. Luque and F. Courchamp. 2013. Global warming may freeze the invasion of big-headed ants. Biological Invasions 15:1561-1572.

Bertelsmeier, C., G.M. Luque, B.D. Hoffmann and F. Courchamp. 2014. Worldwide ant invasions under climate change. Biodiversity Conservation. DOI:10.1007/s10531-014-0794-3

Bierbaum, R., J.B. Smith, A. Lee, M. Blair, L. Carter, F.S. Chapin, III, P. Fleming, S. Ruffo, M. Stults, S. McNeeley, E. Wasley and L. Verduzco. 2013. A comprehensive review of climate adaptation in the United States: More than before, but less than needed. Mitigation and Adaptation Strategies for Global Change 18:361-406.

Biofuels Interagency Working Group. 2010. Growing America's fuels: An innovation approach to achieving the President's biofuels target. Available @ http://www.whitehouse.gov/sites/default/files/rss_viewer/growing_americas_fuels.pdf. Last visited 11/7/2014.

Britton, D., P. Heimowitz, S. Pasko, M. Patterson and J. Thompson (eds.) 2011. HACCP: Hazard Analysis and Critical Control Point Planning to Prevent the Spread of Invasive Species. U.S. Fish and Wildlife Service and National Conservation Training Center. 86 pp.

Bours, D., C. McGinn and P. Pringle. 2014. Monitoring and evaluation for climate change adaptation and resilience: A synthesis of tools, frameworks and approaches. 2nd ed. SEA Change CoP, Phnom Penh, and UKCIP, Oxford, Eng. 87 pp.

Bovey, B. W., R.E. Meyer, M.G. Merkle and E.C. Bashaw. 1986. Effect of herbicides and handweeding on establishment of kleingrass and buffelgrass. Journal of Range Management. 39(6):547-551.

Bowman, W., J. Murgel, T. Blett and E. Porter. 2012. Nitrogen critical loads for alpine vegetation and soils in Rocky Mountain National Park. Journal of Environmental Management. 103:165-171. DOI:10.1016/j.jenvman.2012.03.002

Bradley, B.A. 2009. Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity. Global Change Biology 15:196-208.

Bradley, B.A., M. Oppenheimer and D.S. Wilcove. 2009. Climate change and plant invasions: restoration opportunities ahead? Global Change Biology. 103(6):1511-1521. DOI:10.1111/j.1365-2486.2008.01824.x

Bradley, B.A., D.M. Blumenthal, R. Early, E.D. Grosholz, J.J. Lawler, L.P. Miller, C.J.B. Sorte, C.M. D'Antonio, J.M. Diez, J.S. Dukes, I. Ibanez and J.D. Olden. 2012. Global change, global trade, and the next wave of plant invasions. Frontiers in Ecology and the Environment 10:20-28. DOI:10.1890/110145

Breshears, D.D., N.S. Cobb, P.M. Rich, K.P. Price, C.D. Allen, R.G. Balice, W.H. Romme, J.H. Kastens, M.L. Floyd, J. Belnap, J.L. Anderson, O.B. Myers and C.W. Meyer. 2005. Regional vegetation die-off in response to global-change- type drought. Proceedings of the National Academy of Sciences 102(42):15144-15148.

Broennimann, O., U. A. Treier, H. Müller-Shärer, W. Thuiller, A. T. Peterson, and A. Guisan. 2007. Evidence of climatic niche shift during biological invasion. Ecology Letters 10:701-709.

Burgiel, S.W. and A.A. Muir. 2010. Invasive Species, Climate Change and Ecosystem-Based Adaptation: Addressing Multiple Drivers of Change. Global Invasive Species Programme, Washington, DC and Nairobi, Kenya. 55 pp.

Campbell, K. and C. J. Donlan. 2005. Feral goat eradications on islands. Conservation Biology 19(5):1362-1374.

Carey, M.P., B.L. Sanderson, K.A. Barnas and J.D. Olden. 2012. Native invaders: Challenges for science, management, policy, and society. Frontiers in Ecology and the Environment. 10(7): 373–381. DOI:10.1890/110060

Carmel, S.M. 2013 The cold, hard realities of Arctic shipping. U.S. Naval Institute Proceedings Magazine 139(7)1.325. Available @ http://www.usni.org/magazines/proceedings/2013-07/cold-hard-realities-arctic-shipping. Last visited 11/10/2014.

Carrion, V., K. Campbell, C. Lavoie, F. Cruz and C.J. Donlan. 2007. Feral donkey (*Equus asinus*) eradications in the Galápagos. Biodiversity and Conservation 16(2):437-445. DOI:10.1007/s10531-005-5825-7

Carrion, V., C. J. Donlan, K.J.Campbell, C. Lavoie and F. Cruz. 2011. Archipelago-wide island restoration in the Galapagos Islands: Reducing costs of invasive mammal eradication programs and reinvasion risk. Plos One Article e18835. Publ. May 11.

Carter, J., A.L. Foote and L.A. Johnson-Randall. 1999. Modeling the effects of nutria (*Myocastor coypus*) on wetland loss. Wetlands 19(1):209-19.

Catford, J.A., C.C. Daehler, H.T. Murphy, A. W. Sheppard, B.D. Hardesty, D.A. Westcott, M. Rejmánek, P.J. Bellingham, J. Pergl, C.C. Horvit and P.E. Hulme. 2012. The intermediate disturbance hypothesis and plant invasions: Implications for species richness and management. Perspectives in Plant Ecology, Evolution and Systematics 14(3):231–241.

Cole, D.N. and L. Yung (eds.) 2010. Beyond Naturalness: Rethinking Park and Wilderness Stewardship in an Era of Rapid Change. Island Press, Washington, DC.

Compton, T.J., J. R. Leathwick and G. J. Inglis. 2010. Thermogeography predicts the potential global range of the invasive European green crab (*Carcinus maenas*). Diversity and Distributions. 16:243–255. DOI:10.1111/j.1472-4642.2010.00644.x

Copp, G.H. 2013. The Fish Invasiveness Screening Kit (FISK) for non-native freshwater fishes: A summary of current applications. Risk Analysis. 33(8):1394-6. DOI:10.1111/risa.12095

Copp, G.H., L. Vilizzi, J. Mumford, G.V. Fenwick, M.J. Godard and R.E. Gozlan. 2008. Calibration of FISK: An invasiveness screening tool for nonnative freshwater fishes. Risk Analysis. 29(3):457-67.

Cote, I.M. and S.J. Green. 2012. Potential effects of climate change on a marine invasion: The importance of current context. Current Zoology 58(1):1-8.

Coulson, S.J., I.D. Hodkinson, N.R. Webb, K. Mikkola, J.A. Harrison and D.E. Pedgley. 2002. Aerial colonization of high Arctic islands by invertebrates: The diamondback moth, *Plutella xylostella* (Lepidoptera: Yponomeutidae), as a potential indicator species. Diversity and Distributions 8:327–334.

Council on Climate Preparedness and Resilience. 2014. Priority agenda: Enhancing the climate resilience of America’s natural resources. Climate and Natural Resources Working Group.

Cressey, D. 2007. Arctic melt opens Northwest Passage. Nature 449: 267.

Crooks, J.A. and M.E. Soulé. 1999. Lag times in population explosions of invasive species: Causes and implications. Pp. 103-125. *In* Invasive Species and Biodiversity Management. O.T. Sandlund, P.J. Schei and A. Viken (eds.) Kluwer Acadamic Publishers, Norwell, MA.

Cruz, F., V. Carrion, K.J. Campbell, C. Lavoie and C.J. Donlan. 2009. Bio-economics of large-scale eradication of feral goats from Santiago Island, Galápagos. Journal of Wildlife Management 73(2):191-200.

Czech, B., S. Covington, T.M. Ericson, J.A. Ericson, C. Flather, M. Gale, K. Gerst, M. Higgins, M. Kaib, E. Marino, T. Moran, J. Morton, N. Niemuth, H. Peckett, D. Savignano, L. Saperstein, S. Skorupa, E. Wagener, B. Wilen and B. Wolfe. 2014. Planning for Climate Change on the National Wildlife Refuge System. U.S. Fish and Wildlife Service, National Wildlife Refuge System, Washingon, DC.

Dana, E.D., J.M. Jeschke and J. Garcia-de-Lomas. 2013. Decision tools for managing biological invasions: existing biases and future needs. Fauna & Flora International, Oryx 48(1):56-63. DOI:10.1017/S0030605312001263

Devorshak, C. (ed.) 2012. Plant Pest Risk Analysis: Concepts and Application. CABI, Cambridge, MA. 322 pp.

Diez, J.M., C.M. D’Antonio, J.S. Dukes, E.D. Grosholz, J.D. Olden, C.J.B. Sorte, D.M. Blumenthal, B.A. Bradley, R. Early, I. Ibáñez, S.J. Jones, J.J. Lawler and L.P. Miller. 2012. Will extreme climatic events facilitate biological invasions? Frontiers in Ecology and the Environment. 10(5):249–257. DOI:10.1890/110137

Dukes, J.S. and H.A. Mooney. 1999. Does global change increase the success of biological invaders? Trends in Ecology and Evolution 14(4):135-139.

Elith, J. and J. R. Leathwick. 2009. Species distribution models: ecological explanation and prediction across space and time. Annual Review of Ecological and Evolutionary Systems 40:677–697.

Elith J, C.H. Graham, R.P. Anderson, M. Dudík, S. Ferrier, A. Guisan, R.J. Hijmans, F. Huettmann, J.R. Leathwick, A. Lehmann, J. Li, L.G. Lohmann, B.A. Loiselle, G. Manion, C. Moritz, M. Nakamura, Y. Nakazawa, J. M. Overton, A.T. Peterson, S.J. Phillips, K. Richardson, R. Scachetti-Pereira, R.E. Schapire, J. Soberón, S. Williams, M.S. Wisz and N.E. Zimmermann. 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography 29:129-151.

European and Mediterranean Plant Protection Organization (EPPO). 2014. Efficacy of plant protection products. EPPO. Available @ http://www.eppo.int/PPPRODUCTS/ppp_standards/ppp_standards.htm. Last visited 11/10/2014.

Fabricius, K.E., G. De'ath, S. Noonan and S. Uthicke. 2013. Ecological effects of ocean acidification and habitat complexity on reef-associated macroinvertebrate communities. Proceedings of the Royal Society B. 281(1775). DOI: 10.1098/rspb.2013.2479

Folke, C. 2006. Resilience: the emergence of a perspective for social-ecological systems analyses. Global Environmental Change 16:253-267.

Gallagher, R. V., L. J., Beaumont, L. Hughes and M. R. Leishman. 2010. Evidence for climatic niche and biome shifts between native and novel ranges in plant species introduced to Australia. Journal of Ecology 98(4):790-799.

Glick, P., B.A. Stein and N. Edelson. 2011. Scanning the conservation horizon: a guide to climate change vulnerability assessment. National Wildlife Federation, Washington, DC.

Gordon D.R., C.A. Gantz, C.L. Jerde, W.L. Chadderton, R.P. Keller and P.D. Champion. 2012. Weed risk assessment for aquatic plants: Modification of a New Zealand system for the United States. PLoS ONE 7(7):e40031. DOI:10.1371/journal.pone.0040031

Grossman, J.D. and K.J. Rice. 2014. Contemporary evolution of an invasive grass in response to elevated atmospheric CO2 at a Mojave Desert FACE site. Ecology Letters 17:710-716. DOI:10.1111/ele.12274

Guo, Q. H. and Y. Liu. 2010. ModEco: An integrated software package for ecological niche modeling. Ecography 33:637-642.

Gutowski, W.J., G.C. Hegerl, G.J. Holland, T.R. Knutson, L.O. Mearns, R.J. Stouffer, P.J. Webster, M.F. Wehner and F.W. Zwiers. 2008. Causes of observed changes in extremes and projections of future changes in weather and climate extremes in a changing climate. Regions of focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. T.A. Karl, et al. (eds.) A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

Halpin, P.N., 1997. Global climate change and natural-area protection: management responses and research directions. Ecological Applications 7(3):828-843.

Hansen, L.J. and J.R. Hoffman. 2010. Climate Savvy. Washington, DC: Island Press.

Hansen, L., J. Hoffman, C. Drews and E. Mielbrecht. 2009. Designing climate-smart conservation: Guidance and case studies. Conservation Biology. 24(1):63-69. DOI:10.1111/j.1523-1739.2009.01404.x

Harney, J. 2008. Modeling habitat suitability for the invasive salt marsh cordgrass *Spartina* using ShoreZone coastal habitat mapping data in Southeast Alaska, British Columbia, and Washington State (CORI Project: 2008-06). Prepared for the Alaska Department of Fish and Game Sport Fish Division, Juneau, Alaska. Available @ http://www.shorezone.bluediamondserver.com/Portals/40/workspaces/Supporting_Doc/Harney-Spartina-Habitat-Suitability-Report-Dec08.pdf. Last visited 11/10/2014.

Harris, J.A., R.J. Hobbs, E. Higgs and J. Aronson. 2006. Ecological restoration and global climate change. Restoration Ecology 14(2):170-6.

Harris L.G. and M.C. Tyrrell. 2001. Changing community states in the Gulf of Maine: Synergism between invaders, overfishing and climate change. Biological Invasions. 3:9-21.

Heikkinen R.K., N. Leikola, S. Fronzek, R. Lampinen and H. Toivonen. 2009. Predicting distribution patterns and recent northward range shift of an invasive aquatic plant: *Elodea canadensis* in Europe. BioRisk 2:1-32. DOI:10.3897/biorisk.2.4

Heimpel, G. E., Y. Yang, J. D. Hill and D. W. Ragsdale. 2013. Environmental consequences of invasive species: Greenhouse gas emissions of insecticide use and the role of biological control in reducing emissions. PLoS ONE. DOI:10.1371/journal.pone.0072293.

Heinz Center, The. 2009. Strategies for Managing the Effects of Climate Change on Wildlife and Ecosystems. The Heinz Center: Washington DC.

Heller, N.E. and E.S. Zavaleta. 2009. Biodiversity management in the face of climate change: A review of 22 years of recommendations. Biological Conservation 142:14-32. DOI:10.1016/j.biocon.2008.10.006

Hellmann, J.J., J.E. Byers, B.G. Bierwagen and J.S. Dukes. 2008. Five potential consequences of climate change for invasive species. Conservation Biology 22(3):534-543.

Hobbs R.J., S. Arico, J. Aronson, J.S.Baron, P. Bridgewater, V.A. Cramer, P.R. Epstein, J.J. Ewel, C.A. Klink, A.E. Lugo, D. Norton, D. Ojima, D.M. Richardson, E.W. Sanderson, F. Valladares, M. Vilà, R. Zamora and M. Zobel. 2006. Novel ecosystems: theoretical and management aspects of the new ecological world order. Global Ecology and Biogeography 15:1-7.

Hobbs, R. J., D. N. Cole, L. Yung, E. S. Zavaleta, G. H. Aplet, F. S. Chapin III, P. B. Landres, D. J. Parsons, N. L. Stephenson, P. S. White, D. M. Graber, E. S. Higgs, C. I. Millar, J. M. Randall, K. A. Tonnessen and S. Woodley. 2010. Guiding concepts for park and wilderness stewardship in an era of global environmental change. Frontiers in Ecological Environment 8(9):483-490.

Holling, C. S (ed.). 1978. Adaptive Environmental Assessment and Management. International Inst. for Applied Systems Analysis. John Wiley & Sons, New York, NY. 377 pp.

Holling, C.S.1996. Engineering resilience versus ecological resilience. Pp. 31-45. *In*: P.C. Schulze, ed. Engineering within Ecological Constraints. National Academy Press, Washington, DC. 204 pp.

Horvitz, C.C., J.B. Pascarella, S. McMann, A. Freedman and R.H. Hofstetter. 1998. Functional roles of invasive non-indigenous plants in hurricane-affected subtropical hardwood forests. Ecological Applications 8(4):947-974.

Hulme, M. 2009. Why We Disagree about Climate Change: Understanding Controversy, Inaction, and Opportunity. Cambridge University Press, UK.

Intergovernmental Panel on Climate Change (IPCC). 2002. Climate Change and Biodiversity. IPCC Technical Paper. V.H. Gitay, A. Suarez, R.T. Watson and D.J. Dokken (eds). IPCC, Geneva, Switzerland. ISBN:92-9169-104-7. 77 pp.

----- 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.) Cambridge University Press, New York, NY. 976 pp.

----- 2013. Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.) Cambridge University Press: Cambridge, UK and New York, NY.

----- 2014a. Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.) Cambridge University Press: Cambridge, UK and New York, NY. Available @ http://ipcc-wg2.gov/AR5/images/uploads/WG2AR5_SPM_FINAL.pdf. Last visited 10/17/2014.

----- 2014b. Summary for Policymakers, In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.) Cambridge University Press: Cambridge, UK and New York, NY. Available @ http://report.mitigation2014.org/spm/ipcc_wg3_ar5_summary-for-policymakers_approved.pdf. Last visited 10/17/2014.

Invasive Species Advisory Committee (ISAC). 2010. Invasive Species and Climate Change. Approved by ISAC on 9 December 2010 for the National Invasive Species Council. Available @

http://invasivespecies.gov/ISAC/White%20Papers/Climate_Change_White_Paper_FINAL_VERSION.pdf. Last visited 10/17/2014).

----- ISAC. 2011. Marine Bioinvasions and Climate Change. Approved by ISAC on 16 June 2011 for the National Invasive Species Council. Available @ http://invasivespecies.gov/ISAC/White%20Papers/ISAC_Marine_Bioinvasions_WhitePaper.pdf. Last visited 10/17/2014.

IUCN Species Survival Commission (IUCN SSC). 2012. IUCN Guidelines for Reintroductions and Other Conservation Translocations. Adopted by SSC Steering Committee at Meeting SC 4 6 (9/5/2012).

Jackson, D.B. 2007. Factors affecting the abundance of introduced hedgehogs (Erinaceus europaeus) to the Hebridean island of South Uist in the absence of natural predators and implications for nesting birds. Journal of Zoology 271:210-217.

Jamieson, M.A., C. Quintero and D.M. Blumenthal. 2013. Interactive effects of simulated nitrogen deposition and altered precipitation patterns on plant allelochemical concentrations. Journal of Chemical Ecology. DOI:10.1007/s10886-013-0340-x

Jarnevich, C.S. and T.J. Stohlgren. 2008. Near term climate projections for invasive species distributions. Biological Invasions. 11:1373-1379. DOI:10.1007/s10530-008-9345-8

Joly, M., P. Bertrand, R.Y. Gbangou, M.C. White, J. Dubé and C.Lavoie. 2011. Paving the way for invasive species: Road type and the spread of common ragweed (*Ambrosia artemisiifolia*). Environmental Management 48(3):514-522. DOI:10.1007/s00267-011-9711-7

Karl T.R., J.M. Melillo and T.C. Peterson (eds.) 2009. Global Climate Change Impacts in the United States. U.S. Global Change Research Program. Cambridge University Press: Cambridge, UK and New York, NY.

Kliejunas, J.T. 2011. A risk assessment of climate change and the impact of forest diseases on forest ecosystems in the western United States and Canada. USDA Forest Service, Pacific Southwest Research Station. PSW-GTR-236.

Kliejunas, J.T., B.W. Geils, J.M. Glaeser, E.M. Goheen, P. Hennon, M.S. Kim, H. Kope, J. Stone, R. Sturrock and S.J. Frankel. 2009. Review of literature on climate change and forest diseases of western North America. USDA Forest Service, Pacific Southwest Research Station. PSW-GTR-225.

Koop, A.L., L. Fowler, L.P. Newton and B.P. Caton. 2011. Development and validation of a weed screening tool for the United States. Biological Invasions. DOI:10.1007/s10530-011-0061-4

Krysko, K.L., J.P. Burgess, M.R. Rochford, C.R. Gillette, D. Cueva, D.M. Enge, L.A. Somma, J.L. Stabile, D.C. Smith, J.A. Wasilewski, G.N. Kieckhefer III, M.C. Granatosky and S.V. Nielsen. 2011. Verified non-indigenous amphibians and reptiles in Florida from 1863 through 2010: Outlining the invasion process and identifying invasion pathways and stages. Zootaxa 3028:1-64.

Lassuy, D.R. and P.N. Lewis. 2013. Invasive species: human-induced. *In* Arctic Biodiversity Assessment, H. Meltofte, A.B. Josefson and D. Payer (eds.) Conservation of Arctic Flora and Fauna and Arctic Council. Available @ http://www.arcticbiodiversity.is/index.php/the-report. Last visited 10/17/2014.

Lawler, J. J. 2009. Climate change adaptation strategies for resource management and conservation planning. Annals of the New York Academy of Sciences 1162:79-98.

Lawrence, D.J., B. Stewart-Koster, J.D. Olden, A.S. Ruesch, C.E. Torgersen, J.J. Lawler, D.P. Butcher and J.K. Crown. 2014. The interactive effects of climate change, riparian management, and a nonnative predator on stream-rearing salmon. Ecological Applications 24(4):895-912.

Lawson, D.M., H.M. Regan and T.L. Mizerek. 2008. Multi-species management using modeling and decision theory applications to integrated natural resources management planning, Project No. 05-264. Department of Defense, Legacy Resource Management Program.

Lawson, L.L. Jr, J.E. Hill, L. Vilizzi, S. Hardin and G.H. Copp. 2012. Revisions of the Fish Invasiveness Scoring Kit (FISK) for its application in warmer climatic zones, with particular reference to peninsular Florida. Risk Analysis. 33(8):1414-1431.

Levine, J.M. and C.M. D'Antonio 2003. Forecasting biological invasions with increasing international trade. Conservation Biology 17:322-326.

Lodge, D.M., Williams, S., MacIsaac, H.J., Hayes, K.R., Leung, B., Reichard, S., Mack, R.N., Moyle, P.B., Smith, M., Andow, D.A., Carlton, J.T. and McMichael, A. 2006. Biological invasions: Recommendations for U.S. policy and management. Ecological Applications 16:2035-2054.

Logan J.A., J. Regniere and J.A. Powell. 2003. Assessing the impacts of global warming on forest pest dynamics. Frontiers in Ecology and the Environment 1(3):130-137.

Lorena AC, L. F. O. Jacintho, M. F. Siqueira,R. D. Giovanni, L. G. Lohmann, A.C. de Carvalho and M. Yamamoto. 2011. Comparing machine learning classifiers in potential distribution modelling. Expert Systems with Applications 38:5268-5275.

Mack, R. N. 1986. Alien plant invasion into the intermountain west: a case history. Pp. 191-213. *In* Ecology of Biological Invasions of North America and Hawaii. H. A. Mooney and J. A. Drake (eds.) Springer- Verlag: New York, NY.

Magness, D.R., A.L. Lovecraft and J.M. Morton. 2012. Factors influencing individual management preferences for facilitating adaptation to climate change within the National Wildlife Refuge System. Wildlife Society Bulletin. 36(3):457-468.

Mainka, S.A. and G.W. Howard. 2010. Climate change and invasive species: Double jeopardy. Integrative Zoology. 5:102-111.

Marler, T.E. and J.H. Lawrence. 2013. Phytophagous insects reduce cycad resistance to tropical cyclone winds and impair storm recovery. HortScience 48(10):1224-6.

Martin, J., P. Bertrand, R. ZY. Gbangou, M. C. White, J. Dube and C. Lavole. 2011. Paving the way for invasive species: Road type and spread of common ragweed (*Ambrosia artemisifolia*). Environmental Management 48(3):514-522.

McLachlan, J.S. J.J. Hellmann and M.W. Schwartz. 2007. A framework for debate of assisted migration in an era of climate change. Conservation Biology. 21(2):297–302. DOI:10.1111/j.1523-1739.2007.00676.x

Melillo, J.M., T.C. Richmond and G.W. Yohe (eds.) 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. DOI:10.7930/J0Z31WJ2. Available @ http://nca2014.globalchange.gov/. Last visited 10/17/2014.

Merkel and Associates. 2006. Final Report on Eradication of the Invasive Seaweed *Caulerpa taxifolia* from Agua Hedionda Lagoon and Huntington Harbour, California. Prepared for the Southern California Caulerpa Action Team. 13 pp. + appendices.

Millar, C.I., N.L. Stephenson and S.L. Stephens. 2007. Climate change and forests of the future: Managing in the face of uncertainty. Ecological Applications 17:2145-2151.

Miller, A.W. and G.M. Ruiz. 2014. Arctic shipping and marine invaders. Nature Climate Change. 4(6). DOI:10.1038/nclimate2244

Miller, B. W. and J. T. Morisette. 2014. Integrating research tools to support the management of social-ecological systems under climate change. Ecology and Society 19(3). DOI:10.5751/ES-06813-190341

Montserrat V. and P.E. Hulme. 2011. Jurassic Park? No thanks. Trends in Ecology and Evolution 26(10):496-7. DOI:10.1016/j.tree.2011.06.010

Muhlfeld, C.C., R.P. Kovach, L.A. Jones, R. Al-Chokhachy, M.C. Boyer, R.F. Leary, W.H. Lowe, G. Luikart and F.W. Allendorf. 2014. Invasive hybridization in a threatened species is accelerated by climate change. Nature Climate Change. DOI:10.1038/nclimate2252

Nagler, P. and E. Glenn. 2013. Tamarix and Diorhabda leaf beetle interactions: Implications for Tamarix water use and riparian habitat. Journal of the American Water Resources Association. 49(3):534-548.

National Fish, Wildlife and Plants Climate Adaptation Partnership. 2012. National Fish, Wildlife and Plants Climate Adaptation Strategy. Association of Fish and Wildlife Agencies, Council on Environmental Quality, Great Lakes Indian Fish and Wildlife Commission, National Oceanic and Atmospheric Administration, and U.S. Fish and Wildlife Service. Washington, DC.

National Invasive Species Council. 2008. 2008 - 2012 National Invasive Species Management Plan. Washington, DC.

National Research Council (NRC). 2004. Adaptive Management for Water Resources Planning. National Academies Press, Washington, DC.

----- 2009. Informing Decisions in a Changing Climate. Panel on Strategies and Methods for Climate-related Decision Support. National Academies Press.

Nature Conservancy, The. 2010. Climate Change and Conservation: A Primer for Assessing Impacts and Advancing Ecosystem-based Adaptation in The Nature Conservancy. The Nature Conservancy: Arlington, VA.

Ohlemüller R, E.S. Gritti, M.T. Sykes and C.D. Thomas. 2006. Towards European climate risk surfaces: The extent and distribution of analogous and non-analogous climates, 1931-2100. Global Ecology and Biogeography 15:395-405.

Padmanaba, M. and D. Shell. 2014. Spead of the invasive alien species *Piper aduncum* via logging roads in Borneo. Tropical Conservation Science7(1):35-44.

Parkes, J.P., D.S.L. Ramsey, N. Macdonald, K. Walker, S. McKnight, B.S. Cohen and S.A. Morrison. 2010. Rapid eradication of feral pigs (*Sus scrofa*) from Santa Cruz Island, California. Biological Conservation 143(3):634-641.

Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. Annual Review of Ecology, Evolution and Systematics. 37:637-69. DOI:10.1146/annurev.ecolsys.37.091305.110100

Perez de Leon, A.A., P.D. Teel, A.N. Auclair, M.T. Messenger, F.D. Guerrero, G. Schuster and R.J. Miller. 2012. Integrated strategy for sustainable cattle fever tick eradication in USA is required to mitigate the impact of global change. Frontiers in Physiology 3:1-17.

Perry, J. and C. Falzon. 2014. Climate Change Adaptation for Natural World Heritage Sites: A Practical Guide. World Heritage Paper Series No.37. UNESCO: Paris.

Pheloung, P.C., P.A. Williams and S.R. Halloy. 1999. A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. Journal of Environmental Management. 57:239-251.

Piaggio, A.J., R.M. Engeman, M.W. Hopken, J.S. Humphrey, K.L. Keacher, W.E. Bruce and M.L. Avery. 2014. Detecting an elusive invasive species: A diagnostic PCR to detect Burmese python in Florida waters and an assessment of persistence of environmental DNA. Molecular Ecology Resources 14:374-380.

Pielke Jr., R., G. Prins, S. Rayner and D. Sarewitz. 2007. Climate change 2007: Lifting the taboo on adaptation. Nature 445:597-598.

Pimentel, D., S. McNair, J. Janecka, J. Wightman, C. Simmonds, C. O'Connell, E. Wong, L. Russel, J. Zern, T. Aquino and T. Tsomondoa. 2001. Economic and environmental threats of alien plant, animal, and microbe invasions. Agriculture, Ecosystems and Environment 84:1-20.

Pimentel, D., R. Zuniga and D. Morrison. 2005. Update on the environmental and economic costs associated with alien invasive species in the United States. Ecological Economics 52:273-288. DOI:10.1016/j.ecolecon.2004.10.002

Prati, D., and O. Bossdorf. 2004. Allelopathic inhibition of germination by *Alliaria petiolata* (Brassicaceae). American Journal of Botany 91(2):285-88.

Purse, B.V., P.S. Mellor, D.J. Rogers, A.R.Samuel, P.P. Mertens and M. Baylis. 2005 Climate change and the recent emergence of bluetongue in Europe. Nature Reviews Microbiology 3:171-181.

Pyke, C.R., R. Thomas, R.D. Porter, J.J. Hellmann, J.S. Dukes, D.M. Lodge and G. Chavarria. 2008. Current practices and future opportunities for policy on climate change and invasive species. Conservation Biology 22(3):585-592.

Rahel F.J. and J.D. Olden. 2008. Assessing the effects of climate change on aquatic invasive species. Conservation Biology. 22(3):521-533. DOI:10.1111/j.1523-1739.2008.00950.x

Resasco, J., N.M. Haddad, J.L. Orrock, D. Shoemaker, L.A. Brudvig, E.I. Damschen, J.J. Tewksbury and D.J. Levey. 2014. Landscape corridors can increase invasion by an exotic species and reduce diversity of native species. Ecology 95(8):2033-2039.

Ricciardi, A. and D. Simberloff. 2009. Assisted colonization is not a viable conservation strategy. Trends in Ecology and Evolution 24:248-253.

Rice E.S. and J. Silverman. 2013. Propagule pressure and climate contribute to the displacement of *Linepithema humile* by *Pachycondyla chinensis*. PLoS ONE. 8(2). DOI:10.1371/journal.pone.0056281

Richardson, D.M., W.J. Bond, W.R.J. Dean, S.I. Higgins, G.F. Midgley, S.J. Milton, L.W. Powrie, M.C. Rutherford, M.J. Samways and R.E. Schulze. 2000a. Invasive alien species and global change: A South African perspective. Pp. 303-350. *In* Invasive Species in a Changing World. Mooney, H.A. and R.J. Hobbs (eds.) Island Press, Washington, DC.

Richardson, D.M., P Pysek, M. Rejmánek, M.G. Barbour, F.D. Panetta, and C.J. West. 2000b. Naturalization and invasion of alien plants: Concepts and definitions. Diversity and Distributions 6:93-107.

Richardson, G. and J. Otero. 2012. Land Use Planning Tools for Local Climate Change Adaptation. Government of Canada, Ottawa.

Rodda, G.H., C.S. Jarnevich and R.N. Reed. 2009. What parts of the US mainland are climatically suitable for invasive alien pythons spreading from Everglades National Park? Biological Invasions 11:241-252.

----- 2011. Challenges in identifying sites climatically matched to the native ranges of animal invaders. PLoS ONE 6(2):e14670. DOI:10.1371/journal.pone.0014670

Rodgers, L. No Date. Invasion Curve (diagram). South Florida Water Management District. Available @ http://www.naisn.org/generalinformation.html. Last visited 10/17/2014.

Sanders, S., C. Castiglione and M. Hoff. 2012. Risk Assessment Mapping Program (RAMP): Internally developed Python scripts for ArcGIS. Version 2.5. U.S. Fish and Wildlife Service.

Sandler, R. 2012. Global warming and virtues of ecological restoration. Pp. 63-79. *In* Ethical Adaptation to Climate Change: Human Virtues of the Future. Thompson A. and J. Bendik-Keymer (eds.) MIT Press, Cambridge, MA.

Sanford, E., B. Gaylord, A. Hettinger, E.A. Lenz, K. Meyer and T.M. Hill. 2014. Ocean acidification increases the vulnerability of native oysters to predation by invasive snails. Proceedings of the Royal Society B. 281(1778):1471-2954. DOI:10.1098/rspb.2013.2681

Schwartz, M.W., J.J. Hellmann, J.M. McLachlan, D.F. Sax, J.O. Borevitz, J. Brennan, A.E. Camacho, G. Ceballos, J.R. Clark, H. Doremus, R. Early, J.R. Etterson, D. Fielder, J.L. Gill, P. Gonzalez, N. Green, L. Hannah, D.W. Jamieson, D. Javeline, B.A. Minteer, J. Odenbaugh, S. Polasky, D.W. Richardson, T.L. Root, H.D. Safford, O. Sala, S.H. Schneider, A.R. Thompson, J.W. Williams, M. Vellend, P. Vitt and S. Zellmer. 2012. Managed relocation: Integrating the scientific, regulatory, and ethical challenges. BioScience 62:732-743.

Secretariat of the Convention on Biological Diversity. 2009. Connecting biodiversity and climate change mitigation and adaptation: Key messages from the Report of the Second *Ad Hoc* Technical Expert Group on biodiversity and climate change. Secretariat of the Convention on Biological Diversity: Montreal. Technical Series No. 41.

Skurka Darin, G.M., S. Shoenig, J.N. Barney, F. D. Panetta and J.M. DiTomaso. 2011. WHIPPET: A novel tool for prioritizing invasive plant populations for regional eradication. Journal of Environmental Management 92(1):131-139.

Snyder, E., N.E. Mandrak, H. Niblock and B. Cudmore. 2012. Developing a screening-level risk assessment prioritization protocol for aquatic non-indigenous species in Canada: Review of existing protocols. Fisheries and Oceans Canada, Canadian Science Advisory Secretariat: Research Document 2012/097.

Sorte, C.J.B., I. Ibáñez, D.M. Blumenthal, N.A. Molinari, L.P. Miller, E.D. Grosholz, J.M. Diez, C.M. D'Antonio, J.D. Olden, S.J. Jones and J.S. Dukes. 2013. Poised to prosper? A cross-system comparison of climate change effects on native and non-native species performance. Ecology Letters. 16(2):261-270.

Stachowicz J.J., J.R. Terwin, R.B. Whitlatch and R.W. Osman RW. 2002. Linking climate change and biological invasions: Ocean warming facilitates nonindigenous species invasions. Proceedings of the National Academy of Sciences. 99:15497-15500. DOI:10.1073/pnas.242437499

Stein, B.A. and M. R. Shaw. 2013. Biodiversity conservation for a climate-altered future. Pp. 50-66. *In* Successful Adaptation: Linking Science and Practice in Managing Climate Change Impacts. Moser S. and M. Boykoff (eds.) Rutledge Press, New York, NY.

Stein, B.A., A. Staudt, M.S. Cross, N.S. Dubois, C. Enquist, R. Griffis, L.J. Hansen, J.J. Hellmann, J.J. Lawler, E.J. Nelson and A. Pairis. 2013a. Preparing for and managing change: climate adaptation for biodiversity and ecosystems. Frontiers in Ecology and the Environment 11:502-510.

Stein B.A., P. Glick, N. Edelson and A. Staudt. 2014. Climate-Smart Conservation: Putting Adaptation Principles into Practice. Washington DC: National Wildlife Federation. Available @ http://www.nwf.org/climatesmartguide. Last visited 12/30/2014.

Stern, N. 2006. Stern Review: The Economics of Climate Change. HM Treasury: London, UK.

Stinson, K.A., S.A. Campbell, J.R. Powell, B.E. Wolfe, R.M. Callaway, G.C. Thelen, S.G. Hallett, D. Prati and J.N. Klironomos. 2006. Invasive plant suppresses the growth of native tree seedlings by disrupting belowground mutualisms. PLoS Biol 4(5):e140. DOI:10.1371/journal.pbio.0040140

Stohlgren, T.J., Resnik, J.R. and Plumb, G.E. 2014. Climate change and 'alien species in National Parks': Revisited. *In* Invasive Species and Global Climate Change. Ziska, L.H. and S. Dukes (eds.) CABI Publishing, Cambridge, MA.

Strickland, M.S., J.L. Devore , J.C. Maerz and M.A. Bradford. 2010. Grass invasion of a hardwood forest is associated with declines in belowground carbon pools. Global Change Biology 16:1338-1350. DOI:10.1111/j.1365-2486.2009.02042.x.

Stromberg, J.C., S.J. Lite, R. Marler, C. Paradzick, P.B. Shafroth, D. Shorrock, J.M. White and M.S. White. 2007. Altered stream-flow regimes and invasive plant species: The *Tamarix* case. Global Ecology and Biogeography 16:381-393.

Tamura, M. and N. Tharayil. 2014. Plant litter chemistry and microbial priming regulate the accrual, composition and stability of soil carbon in invaded ecosystems. New Phytologist 203:110-124.

Tomimatsu, H., T. Sasaki, H. Kurokawa, J. Bridle, C. Fontaine, J. Kitano, D. Stouffer, M. Velland, T. M. Bezemer, T. Fukami, E. Hadly, M. van der Heijden, M. Kawata, S. Kefi, N. Kraft, K. McCann, P. Mumby, T. Nakashizuka, O. Petchey, T. Roamnuk, K. Suding, G. Takimoto, J. Urabe and S. Yachi. 2013. Sustaining ecosystem functions in a changing world: A call for an integrated approach. Journal of Applied Ecology 50:1124-1130.

Tu, M. 2009. Assessing and Managing Invasive Species within Protected Areas. Protected Area Quick Guide Series. Ervin, J. (ed.) The Nature Conservancy: Arlington, VA.

Udvardy, S. and S. Winkelman. 2014. Green Resilience: Climate Adaptation + Mitigation Strategies. Center for Clean Air Policy: Washington, DC.

U.S. Department of Agriculture (USDA). 1996. Guideline for Plant Pest Risk Analysis of Imported Commodities. USDA-APHIS-Plant Protection and Quarantine, Commodity Pest Risk Analysis Branch. 191 pp. Available @ http://naldc.nal.usda.gov/naldc/download.xhtml?id=CAT10861158&content=PDF. Last visited 10/17/2014.

----- 2002. Fruit Fly Cooperative Control Program. Final Environ. Impact Statement 2001. USDA-APHIS-Plant Protection and Quarantine. 385 pp. Available @ http://www.aphis.usda.gov/plant_health/ea/downloads/fffeis.pdf. Last visited 10/17/2014.

U.S. Department of Interior (DOI). 2009. Adaptive Management: The U.S. Department of the Interior Technical Guide. Prepared by Williams, B. K., R. C. Szaro, and C. D. Shapiro. 2nd Edition, DOI, Washington, DC. 72 pp.

----- 2012. Adaptive Management: The U.S. Department of the Interior Applications Guide. Prepared by Williams, B. K. and E. D. Brown. Adaptive Management Working Group., DOI, Washington, DC. 120 pp.

U.S. Environmental Protection Agency (EPA). No Date. Glossary of climate change terms. Available @ http://www.epa.gov/climatechange/glossary.html. Last visited 10/17/2014.

----- 2008. Effects of Climate Change for Aquatic Invasive Species and Implications for Management and Research. National Center for Environmental Assessment, Washington, DC; EPA/600/R-08/014. Available @ http://www.epa.gov/ncea. Last visited 10/17/2014.

----- 2013a. Agriculture and Food Supply. EPA. Sept. 9. Available @ http://www.epa.gov/climatechange/impacts-adaptation/agriculture.html. Last visited 10/23/2014.

----- 2013b. Regulation of fuels and fuel additives: additional qualifying renewable fuel pathways under the renewable fuel standard program; final rule approving renewable fuel pathways for giant reed (*Arundo donax*) and napier grass (*Pennisetum purpureum*). 40 CFR Part 80 [EPA–HQ–OAR–2011–0542; FRL–9822–7]. RIN 2060–AR85

----- 2014. Being Prepared for Climate Change: A Workbook for Developing Risk-Based Adaptation Plans. EPA Office of Water, Climate Related Estuaries.

U.S. Global Change Research Program. 2013. Oceans and Marine Resources in a Changing Climate: Technical Input to the 2013 National Climate Assessment. Lead Authors R. Griifs and J. Howard. Report to National Climate Assessment Development Committee, March 1, 2012. Available @ http://downloads.usgcrp.gov/NCA/technicalinputreports/Griffis_Howard_Ocean_Marine_Resources.pdf. Last visited 10/17/2014.

Vilizzi, L. and G.H. Copp. 2012. Application of FISK: An invasiveness screening tool for non-native freshwater fishes, in the Murray-Darling Basin (southeastern Australia). Risk Analysis. 33(8):1432-1440.

Walker, B., C.S. Holling, S.R. Carpenter and A. Kinzig. 2004. Resilience, adaptability and transformability in social-ecological systems. Ecology and Society 9:5.

Webber, B.L. and J.K. Scott. 2012. Rapid global change: Implications for defining natives and aliens. Global Ecology and Biogeography. 21:305-311. DOI:10.1111/j.1466-8238.2011.00684.x

Weiss, C.H. 1979. The many meanings of research utilization. Public Administration Review. 426-431.

West, J.M., S.H. Julius, P. Kareiva, C. Enquist, J.J. Lawler, B. Petersen, A.E. Johnson and M.R. Shaw. 2009. U.S. natural resources and climate change: Concepts and approaches for management adaptation. Environmental Management 44:1001-1021.

Westbrooks, R.G. and J. Madsen. 2006. Federal Regulatory Weed Risk Assessment Beach Vitex (*Vitex rotundifolia L. f.*). Assessment Summary. GeoResources Institute and Mississippi State University, Whiteville, NC, US. Available @ http://www.northinlet.sc.edu/beachvitex/media/bv_risk_assessment.pdf. Last visited 10/17/2014.

Whitfield, P.E., R.C. Muñoz, C.A. Buckel, B.P. Degan, D.W. Freshwater and J.A. Hare. 2014. Native fish community structure and Indo-Pacific lionfish *Pterois volitans* densities along a depth-temperature gradient in Onslow Bay, North Carolina, USA. Marine Ecology Progress Series 509:241-254. DOI:10.3354/meps10882

Williams, J.W. and S.T. Jackson. 2007. Novel climates, no-analog communities, and ecological surprises. Frontiers in Ecology and the Environment 5:475-482.

Williams, M. and R. K. Dumroese. 2013. Preparing for climate change: Forestry and assisted migration. Journal of Forestry 111(4):287-297.

Wilson, J. R., P. Ivey, P. Manyama and I. Nänni. 2013. A new national unit for species detection, assessment and eradication. South African Journal of Science 109(5/6):1-13.

Wittenberg, R., and M.J.W. Cock (eds.) 2001. Invasive Alien Species: A Toolkit of Best Prevention and Management Practices. CAB International, Wallingford, UK.

Wolfe, B.E., V.L. Rodgers, K.A. Stinson and A. Pringle. 2008. The invasive plant *Alliaria petiolata* (garlic mustard) inhibits ectomycorrhizal fungi in its introduced range. Journal of Ecology. 96:777-83. DOI:10.1111/j.1365-2745.2008.01389.x

World Bank, The. 2009. Convenient Solutions to an Inconvenient Truth: Ecosystem-based Approaches to Climate Change. World Bank, Environment Department: Washington DC.

Ziska, L.H. 2005. Climate change impacts on weeds. Climate Change and Agriculture: Promoting Practical and Profitable Responses. Available @ http://www.climateandfarming.org/pdfs/FactSheets/III.1Weeds.pdf. Last visited 2/7/2014.

Ziska, L. and J. Dukes. 2011. Weed Biology and Climate Change. Wiley-Blackwell Publishing.

----- (eds.) 2014. Invasive Species and Global Climate Change. CABI, Surrey, UK.

Zou, J., W.E. Rogers, S.J. DeWalt and E. Siemann. 2006. The effect of Chinese tallow tree (*Sapium sebiferum*) ecotype on soil–plant system carbon and nitrogen processes. Oecologia. 150:272-281. DOI:10.1007/s00442-006-0512-2