A Summary of Invasive Species Risk Assessments, and Proposed and Existing Assessment Frameworks

Prepared by:

Frank J. Mazzotti and Venetia Briggs-Gonzalez
Department of Wildlife Ecology and Conservation
Fort Lauderdale Research and Education Center
University of Florida
3205 College Avenue
Fort Lauderdale, FL 33314

Prepared for:

Jennifer Eckles
Florida Fish and Wildlife Conservation Commission
#08347

Introduction

Today's extensive global trade and travel ensure that biogeographic barriers no longer function at keeping distinct flora and fauna separate between continents (Lowe et al. 2000; Mooney and Hobbs 2000). As a result, foreign species have the ability to become more vagile, prolific, and able to broaden distribution ranges that threaten integrity of native ecosystems. Foreign species are referred to by many terms, most common of which are alien, introduced, non-native, exotic, and invasive (Mack et al. 2000). An introduced species does not necessarily denote an invasive species, but the path from introduced to invader often involves a lag phase where an introduced species may go undetected, followed by a period of rapid growth and range expansion (Mack et al. 2000). An invasive species, as defined by the National Invasive Species Council (2006) is a species that is nonnative to the ecosystem under consideration and whose introduction causes or is likely to cause economic or environmental harm or harm to human health.

An estimated 10-20% of the vast number of introduced species that arrive at new locales are purported to become invasive (Williamson 1996, Arriaga et al. 2004). There are over 50,000 invasive species recognized in the United States alone, some of which are responsible for a wide range of problems from ecological damage to public health concerns, and often incur exceptionally high economic losses (Pimental et al. 2005, Williams and Grosholz 2008). Invasive species often undergo rapid exponential growth usurping space and resources vital for native species survival (Mack et al 2000). With over 21,000 threatened species in the world (IUCN Red List 2013) and 1,529 in the US (FWS 2014), a large proportion of species that are listed as threatened or endangered are considered to be at risk primarily because of impacts of invasive species (Wilcove et al. 1998, Pimental et al. 2005).

Invaders can drastically change food webs, alter hydrological systems, and affect ecosystem structure (Parker et al. 1999, Mooney and Hobbs 2000). Agricultural, forestry, and fishing industries are affected by invasive species in the form of pathogens and pests that reduce species health thereby diminishing yield at high costs (Ricciardi and Rasmussen 1999, Chornesky et al. 2005). A multitude of diseases are also brought in by invasive species and cross all taxa affecting plants, animals, and humans (Jenkins et al. 2007, Skerratt et al. 2007, Schleier et al. 2008, CDFA 2014). Combined detrimental effects that invasive species have had on the system require rigorous detection and enforcement to prevent further invasive species from becoming established and causing irreparable damage to ecosystems.

Prevention is always the best and least costly method of control and keeps an ecosystem free of invasive species (Leung et al. 2002, Rodgers, Figure 1). Once an introduced species is allowed to enter into a new area, small populations can begin to form in localized areas. At this stage, eradication, potential to remove all individuals from infested areas is still possible with time and effort. During the containment phase, an invasive species has rapidly reproduced and spread to large areas exceeding the possibility of eradication and increasing costly efforts must focus on

limiting boundaries of expansion. Beyond containment, a species has become widespread and abundant and efforts can only hope to curtail further population growth through management and to protect valued assets. Protection and management is the most expensive form of control and involves continual time investment (Rodgers, Figure 1). During the invasion process, there are important factors that affect probabilities at each stage. Socio-economic factors are proposed to be important at early stage of importation, release and/or escape; biogeographical and ecological factors affect the establishment stage. For invasion success, ecological and evolutionary factors such as ability to spread fast and having economic or ecological consequences are vital (Williamson 2006). There are stage-specific problems and challenges in the process of invasion, but precluding introduction of nonnative species into a system is the first step toward protecting native biodiversity and maintaining ecosystem integrity (Finnoff et al. 2007). Methods developed to target points of entry for incoming species are needed for prevention of invasive species to be effective. Simultaneously, tools to evaluate and identify potential invasive species, as well as proposed areas of spread will need to be applied at initial stages of prevention (Kareiva 1996, Byers et al. 2002). Australia and New Zealand provide good models for shifting management emphasis from costly eradication and control programs to proactive prevention (Williams and Grosholz 2008).

Many live animals are intentionally and legally imported annually into the US, and governed by federal agencies. US Department of Agriculture is responsible for wildlife imports that pose risks to livestock and plants, Center for Disease Control has authority over human disease vectors, and US Fish and Wildlife Service is responsible for "injurious" wildlife listed under the Lacey Act (1900). Lacey Act is the country's oldest wildlife protection statute instated in 1900 and amended in 2008 to reinforce state, federal, tribal, and international wildlife protection laws and requires wildlife shipments to be accurately labelled and illegal trafficking to be persecuted. Illegal trade includes live specimens and wildlife parts (feathers, eggs, skins, horns, etc.,) that are often mislabeled or concealed and transported commercially or by individuals. This illegal wildlife trade is continuously fueled by collectors and dealers willing to pay exorbitant prices to sustain the market (Anderson 1995). In addition to Lacey Act, several federal statutes prohibit trade of protected wildlife and wildlife parts, including Endangered Species Act (1973), and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES 1993). Other statutes include, but are not limited to Migratory Bird Treaty Act (1988), Marine Mammal Protection Act (1988, 1993), and African Elephant Conservation Act (1988, 1993) prohibit specific wildlife trade and impose penalties for violations.

Despite statutes and regulations, the greatest challenge to wildlife protection has been lack of coherent policies to address species trade, lack of implementation of regulations, inadequate funding for research and management, and absence of a screening process that accounts for cross-border wildlife trade (Simberloff et al. 2005, Jenkins et al. 2007). As such the "broken screens" of inefficient regulations and lack of implementation allow for a vast majority of non-

native species to enter the US unchecked at borders, or checked and permitted without cause (Jenkins et al. 2007). Illegal wildlife trade contributes to decline of global biodiversity, is characterized by high mortality rates of live specimens, aids in transmission of disease, and introduction of injurious pest species (Anderson 1995). To effectively combat these growing issues, wildlife trade must be monitored and risk assessments evaluating threats posed by new species need to be implemented. Risk assessment explores characteristics of a species to determine threats and potential for invading new areas (Burgman et al 1993); and provides necessary information for proper regulations (Ruesink et al. 1995), however, risk assessments can only be implemented at entry stage of invasion (Andersen et al 2004, Rodgers, Fig. 1). Risk of spread can be assessed but it is more strategic to be able to prevent a potential invasion instead of planning how to manage an established invasion (NISC 2003, Finnoff et al. 2007). Risk assessment is an objective evaluation that forces one to think of unintended effects of a species before being persuaded by its potential benefits (i.e., beauty, profit) (Ruesink et al. 1995). Consequently, there may be substantial utility to adopting a policy that keeps all nonnative species out of the country until they have been evaluated and are demonstrated to be safe (Ruesink et al. 1995).

In a first effort of its kind, the complete list of US animal imports were screened using a global database search to identify risky species. Consortium on Conservation Medicine and Defenders of Wildlife identified 2,241 nonnative animal imports using US Fish and Wildlife Service data from 2000 to 2004 and evaluated each species based on known threats from other countries (Jenkins et al. 2007). Collaborating scientists agreed that the single best predictor of invasiveness of a nonnative species in a given location is if it already has invaded somewhere else (Reusink et al. 1995, Jenkins et al. 2007). Of identified species, reptiles (N = 799), birds (N = 653), and invertebrates (N = 579) comprised the largest proportion of species imports, but amphibians were the most imported animal with over 23,780,548 individuals imported during the five year period. Several animals were only identified to class level (N = 340) or could not be reviewed because of lack of information, but 13% of all imports were termed "risky species" (Jenkins et al. 2007). Though a "coarse screening" process, this report provided a useful tool for evaluating species before they are permitted for import into the US. Here, we review history of risk assessments and summarize proposed and implemented methods for evaluating threats presented by a novel species.

History

Ecological risk assessments originated with inception of National Environmental Policy Act (NEPA) of 1969 which was designed to address public concern regarding environmental degradation. NEPA required federal agencies to conduct environmental impact assessments, and established the Council on Environmental Quality, but despite original objectives, NEPA produced a series of incomplete, outdated reports that were largely not peer-reviewed raising

concerns about scientific credibility of NEPA's assessments (Schindler 1976). Primary concern in integrating ecological risk assessment into NEPA's process was that ecological risk assessments would merely become a new name for traditional environmental impact assessments (Schindler 1976, Bartell 1998). While ecological risk assessments were integrated into NEPA's process, it became evident to outline the next transition in environmental assessment capabilities. Operationally linking ecological risk assessment methods with formal decision models appeared as a worthwhile objective in beginning this transition (Bartell 1998). This presented opportunities for environmental impact assessors to team up with ecologists to address basic questions of "What can go wrong?" "How likely is it to happen?" and "So, what if it does?"(Kaplan and Garrick 1981). As such, an ecological risk assessment is a process of estimating probabilities of often negative specified ecological events and evaluating subsequent consequences using a quantitative approach (Bartell 1996, Bartell 1998). Human health industry (NRC 1983) served as a model for ecological risk assessment and as needs for baseline risk assessments were required symposia, workshops, funding, and simulation models stimulated in-depth research for assessing ecological risk across taxa (Bartell 1998) using guidelines put forth by USEPA framework (1992, 1996).

Initial studies were aimed at understanding general schemes of how species invade, various stages of invasion (arrival, establishment, spread, and persistence), and different types of models associated with each phase (Mollison et al. 1986). Once stages of invasion were understood, research focuses turned to invasive abilities of species. Researching invasibility allows for prioritizing which species to address first for control/intervention (Byers et al. 2002). Earlier studies highlighted pathways species use to invade and marine systems made for good examples of how corridors can be affected by environmental changes and presented some difficulties in predicting invasions (Carlton 1996). Studies were based on aquatic species, particularly in the Great Lakes system that had been highly susceptible to invasions with extent of transoceanic boat traffic. Populations of zebra mussel, *Dreissena polymorpha*, one of many species introduced from Europe were already established when invasion studies began, thus, research focused on their distribution and how their spread could help in predicting future invaders (Ramcharan et al. 1997, Ricciardi and Rasmussen 1998, Ricciardi and Maclsaac 2000). Zebra mussel studies transitioned to exploring areas at risk for invasions (Riccardi 2003) and provided a better understanding of ecosystem effects of a species, and outlined necessary information for assessing risk of other species (Ricciardi 2001). Use of recreational boats as a mode of invasion into other inland lakes near the Great Lakes system was investigated (Johnson et al. 2001) and prompted spread of awareness about precautionary boat use and preserving lake systems.

Pioneering work on zebra mussels led to fish species targets and risk of introduction into the Great Lakes and models for risk assessment (Kolar and Lodge 2002). Here species that would cause most damage were pinpointed and prevention measures were proposed (Kolar and Lodge 2001, 2002). Other taxa were added to invasive species lists and included crayfish (Wilson et al.

2004), frogs (Tinsley and McCoid 1997), and bivalves (McMahon 2000, Zaranko et al. 1997). Subsequently other studies explored steps to take once an invader was established. Secondary spread prevention (Keller et al. 2007) and imposing traffic regulations emerged as solutions to invasion problems (Orr 2003, Vander Zanden and Olden 2008). Research exploring solutions to invasions have been critical to directing invasive species work because preventing introduction is the first major challenge (Keller and Lodge 2007).

Aquatic studies transitioned from Great Lakes research to include global cases, many of which continued to explore species with establishment potential and associated risks (Branch and Steffani 2004, Moyle and Marchetti 2006, Colnar and Landis 2007). Central to these continuing studies was need for regulation of transportation of aquatic species (Floerl et al. 2005). Cost of these species invading was a driving force in support of increased regulations. Numerous studies measured costs associated with invasive species (Pimental et al. 2000, Buhle et al. 2005, Pimental et al. 2005, Burnett et al. 2007) as added support that prevention efforts were optimal to control efforts (Keller et al. 2007, Burnett et al. 2008). However, despite obvious costs, there has been an inherent human preference for control measures over prevention efforts (Horan et al. 2002, Leung et al. 2002, Finnoff et al. 2007). Preference to use control measures coupled with technological limitations are what determine what actions have been and will be taken to aid in the ongoing crisis of invasive species (Margolis et al. 2005, Finnoff et al 2007, Sims and Finnoff 2013).

As aquatic studies developed further, research on insects started to surface, focusing on pest management. Investigating population dynamics of insect species was key to determining establishment stage of invasion and understanding that size of original colony greatly influenced success of invasion (Grevstad 1999). Holway and Suarez (1999) studied fire ant colony behavior as a way to explore effects of animal behavior on invasion capability. Specific behavioral traits are suited for different stages of invasion, i.e., high dispersal ability, omnivory, gregariousness, and asexuality are usually associated with an enhanced probability of colonization and establishment, but may have no influence on competitive ability, or rate of spread after establishment (Holway and Suarez 1999). Species biological data began to be incorporated in assessing species risk. Similarly, by using trade routes and historical data of establishment rates of invaders to predict future invasion rates there was an improved ability to forecast biological invasions (Levine and D'Antonio 2003), and illustrating that resources are better spent on prevention tactics rather than control efforts (Leung et al. 2002). However, because insect invaders can be introduced via a variety of hosts, it has been difficult to design preventative regulations to controlling insect invasions, thus pest management has historically been more prevalent (Bartell and Nair 2004, Evans et al. 2013).

Plants, as a group, have been studied as pests as well as ecological invaders and early studies began with what affects invasiveness, various steps of invasion, predicting invasions (Reichard

and Hamilton 1997), and errors of predicting invasions (Heger and Trepl 2003). Accounting for errors in and finding ways to lower error rates would be vital to obtaining accurate prediction estimates (Heger and Trepl 2003). Invasive plants have ability to spread quickly, largely due to dispersal mechanisms, thus calculating invasion speeds can be a helpful variable when assessing species' invasibility (Neubert and Caswell 2000, Neubert et al. 2000). Unveiling risky species is very important, however, knowing areas at risk can allow for focused prevention and preparation for an invasion (Apte et al. 2000, Andersen et al. 2003). A case study on buffel grass (*Cencrus ciliaris*) in Mexico identified risky areas that were suitable for invasion using spatial modeling validated by a case study in an area of known distribution (Arriaga et al. 2004). Several climate match studies followed providing information on areas at risk and accounting for different stages of invasion (Williamson 2006, Bomford et al. 2008, Bates et al. 2013). Niche-based models, delved deeper and used observations of species in native ranges and associated climatic variables to predict a species potential to invade new areas with similar climatic conditions (Broennimann et al. 2007, Beaumont et al. 2009), however this does not preclude a species' ability to spread into areas that are climatically different than their home range (Apte et al. 2000, Broennimann and Guisan 2008, Wearne et al. 2013). Studies on risky species were less frequent but Daehler et al. (2004) proposed a three-part scoring system for experts to identify invasive plant pests and rank species by risk.

More recent areas of invasive species interest have focused on wildlife, particularly with increased animal trade. "Broken Screens" Report (Jenkins et al. 2007) has illustrated poor regulations in place, and when coupled with negligence animal species are a real threat to native fauna (Drake and Williamson 1986, Levine and D'Antonio 2003). Invasive wildlife studies included work done with birds (Herring and Gawlik 2007, Zwiernik et al. 2007), mammals (Watari et al. 2011, Corin 2014, Murphy et al. 2014), and reptiles and amphibians (Bomford et al. 2005, Kraus 2007, Bomford et al. 2008, Fujisaki et al. 2009, Krause 2009, Kraus 2011, Krysko et al. 2011, Meshaka 2011). Invasive mammalian species have been responsible for significant environmental and economic damage but because populations were established studies have largely been aimed at control efforts (Blackie et al 2014). Reptiles and amphibians, however, have become more visible in risk assessment studies that attempt to eradicate, prevent, and predict exotic species.

Assessments of introduced amphibians and reptiles began with identifying modes of introduction. Intentional human introduction via pet trade and accidental import in cargo shipments were primary pathways for species introductions (Kraus 2003). Additional modes of introduction were for human consumption, for biocontrol, for aesthetic purposes and accidental introductions in nursery trade (Krause 2003). With identification of pathways of introduction, research moved into assessment based studies in live animal trade (van Wilgen et al. 2010), global impacts of invasive herpetofauna (Kraus 2009, 2010) and designing rapid response methods to invasive herpetofauna (Kraus and Duffy 2010). Hawaii and Australia provided

examples of rising exotic species invasions and research focused on risk assessment models suitable for taxon groups (Bomford 2003, Bomford et al. 2005, Bomford et al. 2008). Potential preventative measures for exotic herpetofauna were put forward (Burnett et al. 2008, Chiavernao et al. 2014) and use of a scoring system to rank invasiveness of a species began to be implemented in modelling species risk (Bomford et al. 2005, Bomford et al. 2009). Models will be discussed in methods section.

Performing risk assessments is fraught with social and political issues affecting efficacy of management and prevention (Margolis et al. 2005, Simberloff 2005). One way to regulate transfer of species among countries is to impose new trade tariffs (Margolis et al. 2005), though difficult to achieve, development of risk assessment frameworks and models can help aid in policy initiatives (Horan et al. 2002, Simberloff et al. 2005, Keller and Perrings 2011, Rickhus 2013). It will continue to involve much discussion to influence political views to be more open to cooperate with management and prevention plans with proof of economic benefits of risk assessment plans. Though many introduced species have had positive economic effects, costs of invasive species either as inflicted damage or costs of removal or control are exorbitant (Burnett et al. 2007). There is a general consensus that it is more cost-effective to invest in prevention methods, however implementing such prevention methods is an often non-preferred risk (Leung et al. 2002, Finnoff et al. 2007). Here we present proposed, and in some cases, implemented methods of risk assessment of exotic species.

Methods

Federal agencies, USDA, FWS, and EPA have applied risk assessments to introduced species to regulate species importation (Simberloff 2005). Proposed frameworks and guidelines on conducting ecological risk assessment present relevant components of the process that identify risk and effects, outlines expected outcomes (USEPA 1998), and involves necessary partnerships (Presidential/Congressional Commission 1997). A general strategy for risk analysis adapted from ecological risk assessment developed by USEPA (1992, 1998) and applied to invasive species include 1). identifying the problem, 2) analysis of biological data of species, 3) characterizing risk accounting for potential spread, impacts and costs, and 4). risk management by evaluating containment potential and associated costs (Stohlgren and Schnase 2006, Table 1).

Qualitative evaluation frameworks use professional judgement to assign species to risk ranking categories such as low, medium, and high risk based on biological characteristics, often combined with climate information (USEPA 1998). Qualitative assessment often involves a series of yes/no questions where answers for each question have a numerical value (Yes = 1, No = 0); values are added and the final number is the score used to determine species rank for risk (Bomford et al. 2005), or a value is assigned to each parameter using a ranking system (1-5, lowest-highest likelihood) relative to a comparative group and scores are tallied for an overall value (Reed et al. 2012). Using decision theory, appropriate use of a screening system to predict

successful invasion is evaluated (Smith et al. 1999) and has been implemented in assessing species risk (Blundell et al. 2003, Colnar and Landis 2007, Reed et al. 2012). Species risk, produced from a ranking system can also be statistically compared for a semi-quantitative approach (Daehler et al. 2004, Bomford et al. 2005, Ricciardi and Cohen 2006, Corin 2014). Quantitative techniques involve case studies or a compilation of previous studies quantifying cause and effect of raw data, and model simulation that predict species spread and associated effects (Arriaga et al. 2004, Andersen 2005, Reed 2005, Romanuk et al. 2009, Jones et al. 2013, Chiaverano and Holland 2014,). Relevant papers were reviewed and information on how each risk assessment was conducted is presented (Table 2).

A multitude of biological parameters have been used to assess a species' risk and generally include life history data, such as reproductive rates, longevity, dispersal size and rate, survival rates and genetic information (see Table 3 for species traits considered for risk analysis compiled from Reusink et al. 1995, Fujisaki et al. 2010, Reed et al. 2012). It should be noted that parameters that make a species a successful invader, are not necessarily accurate predictors of invasion (Williamson 2006). Phylogenetic information of target species and related species have been implemented in analyses and in some cases generated using genetic algorithm for rule-set production (GARP, Lodge et al. 2006). Climate data of native and potentially invaded ranges typically involve rainfall and temperature variables. These data are either statistically analyzed or entered into a climate matching system using programs such as CLIMATE, CLIMEX 3.0, and other emerging model-based programs (Peterson and Vieglais 2001, Arriaga et al. 2004, Bomford et al. 2009, Fujisaki et al. 2010). Climate matching systems use climate data to determine whether an area may have suitable conditions for an invasive species based on native or current species range. Use of determining effective population size of a species is also modelled using Population Viability Analysis (PVA, Andersen 2005). Niche-modelling that accounts for other environmental variables have also been incorporated to predict where invasive species may be able to spread to (Beaumont et al. 2009). Despite a variety of frameworks proposed or in place, the underlying function is to address: 1) factors that determine rate of entry, 2) biology and ecology of species, 3) availability of habitat and environmental factors that promote establishment in different geographical regions, 4) population dynamics of species, and 5) implications of uncertainties of risk estimates and risk reduction (Arriaga et al. 2004, Bartell and Nair 2004). These methodologies provide a baseline for assessment and prevention of introduced species that may become invasive under optimal environmental conditions.

In lieu of preventative measures to keep an invasive species from entering a novel area, species biological data have been used to assist with containment and management strategies of established species (ANSTF 2010) that account for original population size (Grevstad 1999), speed of spread (Neubert and Caswell 2000, Riccardi and Cohen 2006), and in some cases, targeting different life stages (Hastings et al. 2006) and adverse impacts once established (Fujisaki et al. 2010). Effective risk assessment will occur at prevention stages of invasion

(Rodgers, Figure 1) and when that is not possible data can be used to reduce impact of invasion and associated ecological and economic damage.

Summary

- Invasive species is a species that is nonnative to the ecosystem under consideration and whose introduction causes or is likely to cause economic or environmental harm or harm to human health
- Stages of invasion include arrival, establishment, spread, and persistence
- Invasion curve illustrates methods of control: prevention, eradication, containment, and asset based protection and long term management
- Prevention is least costly method of control
- Risk assessment uses species characteristics to determine threats and potential for invading new areas at entry stage of invasion
- "Broken Screens" report used US FWS animal import records to conduct a coarse screening process to identify risky species
- Risk assessments began with NEPA
- Risk assessments estimate probabilities of negative events and evaluate consequences using decision models and quantitative approaches
- Risk assessments based on aquatic species in Great Lakes
- Invasion studies used species distribution and spread to help predict future invasions
- Studies measured costs of invasive species and proposed transportation regulations
- Insect species difficult to prevent, hence pest management is most used
- Plant studies incorporated spatial modelling, climate matching, and niche-based models to identify areas at risk of invasion
- Amphibian and reptile species introduced via pet trade, for human consumption, biocontrol use, aesthetic purposes, and with nursery trade
- Rank scoring system used for invasive herpetofauna
- Risk assessment: identifies problem, analyzes species bio-data, evaluates risk, proposes risk management
- Risk assessments can be performed using qualitative, semi-quantitative, and quantitative frameworks
- Qualitative framework uses professional decision rules and ranking to assign species risk
- Semi-quantitative framework statistically analyzes decision rule to assess species risk
- Quantitative frameworks uses raw data from case studies or compilations and model simulations to evaluate species risk
- Biological species data (life history, reproductive data, survival, population dynamics, and genetic information) used to evaluate species risk
- Phylogenetic information, climate range data, effective population size, and niche data used to identify and predict susceptible areas at risk of invasion

Future Directions

In an effort to develop a risk assessment protocol to prevent the introduction or establishment of nonnative wildlife in Florida, biological profiles for invasive nonnative reptiles will be updated and new biological profiles will be created for additional risky species. Using available data of ecological correlates to identify potentially invasive species a coarse scale screening process using decision rules and professional expertise will be conducted for nonnative species currently present or in the process of being imported/introduced into Florida. Data will be analyzed in a semi-quantitative approach with plans toward developing finer scale analyses using appropriate quantitative techniques accounting for climate and niche variables in native species range and identifying potential areas at risk to invasion by nonnative species. Components necessary to conduct the risk assessment process will be evaluated and effective frameworks for implementation will be presented. The goal of the risk assessment process will be to identify risky species before they are introduced into Florida, to predict areas at risk, and to contain species spread beyond initial introduction. Risk assessment protocols will be used toward effective invasive species preventative efforts, science-based early detection, and rapid response to address nonnative species introduction into Florida.

Figure 1. The invasion curve illustrating an increase in infested areas by invasive species and associated costs at each stage of the invasion process. From Leroy Rodgers, South Florida Water Management District (Adapted from Invasive Plants and Animals Policy Framework, State of Victoria, Department of Primary Industries 2010).

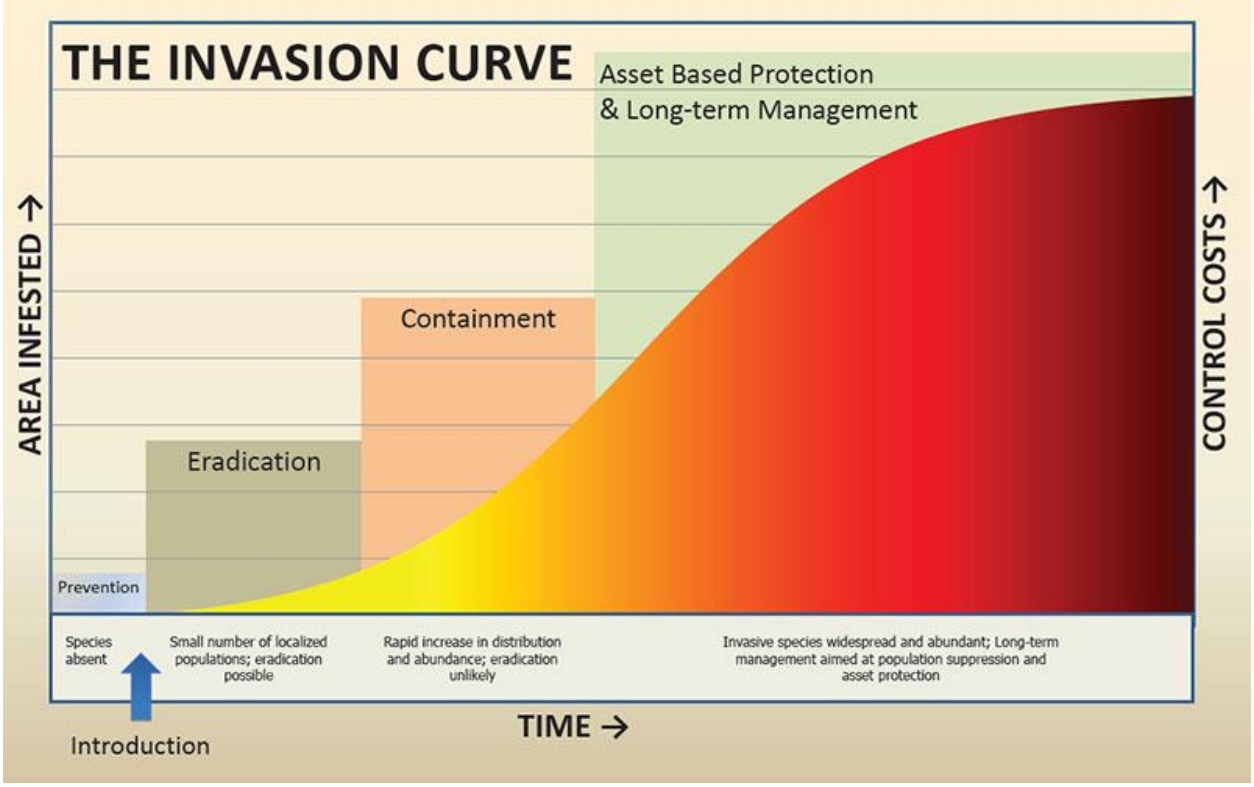

Table I. Generalized steps in risk analysis and specific information needed for risk analysis for invasive species adapted from Stohlgren and Schnase (2006).

Problem Formation
Scoping the problem
Defining assessment endpoints
Analysis
Information on species traits
Matching species traits to suitable habitats
Estimating exposure
Surveys of current distribution and abundance
Risk Characterization
Understanding of data completeness
Estimates of the "potential" distribution and abundance
Estimates of the potential rate of spread
Probable risks, impacts, and costs
Risk Management
Containment potential, costs, and opportunity costs
Legal mandates and social considerations
Information science and technology needs

Table 2. Biological and environmental parameters included in assessment of species risk and invasion. Compiled from Reusink et al. 1995, Fujisaki et al. 2010, Reed et al. 2012.

Species detection
Propagule pressure/introduction effort
Age at reproductive maturity
Adult body size
Juvenile survival probability
Adult survival probability
Maximum longevity
Fecundity
Clutch size
Generation time
Level of parental care
Dispersal size
Dispersal distance
Mobility
Rate of spread/vagility
Intrinsic rate of population growth
Functional population size
Possibility of parthenogenesis
Competitiveness
Gregariousness
Dietary breadth
Ability/inability to be controlled
Habitat compatibility
Habitat breadth or generality/native range size
Phenotypic plasticity
Vulnerability to predation
Response to human disturbance
Association with humans
Sale price/trade value
Species Manageability
Ability/proneness to escape
Venomousness
Prior establishment location
Prior establishment rate

Table 1. Exotic animal risk assessment research with extracted methodologies used. Frameworks with associated target variables and analyses are presented for each paper reviewed.

Framework	Species/Taxa	Variables	Analyses	Reference
Qualitative	Smooth shelled blue mussel (*Mytilus galloprovincialis)*	Data from worldwide distributions, climate	Species Identification (Nuclear DNA extraction)	Apte et al. 2000
	Nonindigenous species	Life history traits, and all known risks/facts of species	Directed Approach/Questionnaire	Byers et al. 2002
	Africanized honeybees (*Apis mellifera),* Bamboo, *Bambusa* sp.)	Natural and human disturbances, and competition from exotics	Hierarchical Framework	Blundell et al. 2003
	Mediterranean mussel (*Mytilus galloprovincialis*)	History, mode of dispersal, physiological performance, wave action preferences, influence on predators, effects of size and parasites, and effects on fauna	Invasion forecast based on set of predictors	Branch and Steffani 2004
	Feral pig *(Sus scrofa)*	Human values and ecological interactions	Multi-attribute utility analysis	Maguire2004
	Fish, mammals, amphibians, reptiles	Rate of establishment, rate of spread	Spearman's rank correlation of ranked impact	Ricciardi and Cohen 2006
	Giant reed (*Arundo donax*)	Location of individuals	Map comparison of previous years	Gallo and Waitt 2011
	Burmese python (*Python molurus bivittatus)*	15literature-based attributes (e.g., body size, reproductive potential, etc.,) of the species, and of vulnerable habitats relative to comparative group	Rank scoring	Reed et al. 2012
	Asian oyster (*Crassostrea ariakensis)*	Ecological characteristics (habitat and food, increases and decreases in resources)	Relative Risk Model, Weight-of-Evidence Approach	Menzie et al. 2013
Semi-Quantitative	Leaf-beetle (*Deuterocampta quadrijuga)*	Phylogenetic relatedness, biogeographic overlap, and ecological similarity	Centrifugal Phylogeny	Briese and Walker 2002
	Exotic vertebrates	Life history traits, and all known risks/facts of species	VPC Threat Category/Questionnaire	Bomford 2003
	Parasitoids, Predatory insects, Predatory	Potential establishment, ability to disperse, host range, and	Multiple Class Ranking System in Risk Categories	Van Lenteren et al. 2003

	mites, and Entomopathogens	direct/indirect effects on non-targets		
	~200 Plant species	Life history traits, and all known risks/facts of species	Modified Weed-Risk Assessment Questionnaire, and Decision Tree	Daehler et al. 2004
	Exotic reptiles and amphibians	Number of release events, climate match, history of establishing exotic populations elsewhere, taxonomic group, and life history traits	Multiple Class Ranking System/Predictive Risk Assessment	Bomford et al. 2005
	Exotic marine species	Fouling ranks and predictor variables (general information and vessel maintenance and travel history)	Classification Tree, and Ordinal Rank Scale	Floerl et al. 2005
	23 species of boas, pythons, and related snakes	Body size, fecundity, climatic variables of native range (latitude, elevation, temperature), Commercial variables (trade records)	Ecological and Synthetic Models	Reed 2005
	Camel (C*amelus dromedaries)*	Life history traits, and all known risks/facts of species	VPC Threat Category/Questionnaire	Corin 2014
Quantitative	*Bacillus cereus* UW85	Frequency of clusters in soil and rhizosphere habitats, bacterial communities from various habitats, and clusters most useful in discriminating among communities	Discriminant Analysis	Gilbert et al. 1996
	Theoretical asexual species reproducing during discrete time periods	Demographic stochasticity (population size, number of offspring per individual, extinction and establishment probability) and fluctuating environments	Poisson Branching Process Model	Haccou and Iwasa 1996
	Pine Species	Life history characteristics (mean height, maximum height, minimum juvenile period, mean longevity, mean seed mass, seedwing loading index, avg. percentage of germination, mean interval between large seed crops, degree of serotiny, and fire tolerance index)	Discriminant Analysis	Rejmanek and Richardson 1996
	Acacia saligna	Presence in plant communities, and	Principal Component Analysis	Holmes and Cowling 1997

	community composition of seed-banks		
Woody Plant Species	Native range, invasiveness and Life History characteristics (Leaf longevity, polyploidy, reproductive system, vegetative reproduction, minimum juvenile period, length of flowering period, flowering season, length of fruiting period, fruiting season, dispersal mechanism, seed size, and seed germination requirements)	Discriminant Analysis and Classification, Regression Trees (CART), and Decision Tree	Reichard and Hamilton 1997
Mosquito (*Aedes albopictus*)	Realized per capita rate of population change, competition between species, mean masses of adult individuals-sex combination	Finite rate of increase, Kruskal-Wallis test, ANOVA	Juliano 1998
Chrysomelid beetles *(Galerucella pusilla and Galerucella calmariensis)*	Population establishment and population growth rate	Multiple logistical regression	Grevstad 1999
teasel (*Dipsacus sylvestris*) and *Calathea ovandensis*	Population growth and rate of spread	Discrete-time model (couples matrix population models with integrodifference equations	Neubert and Caswell 2000
Brown mussel (*Perna perna)*	Population-level genetic diversity	Wright's hierarchical F-statistics, Hardy-Weinberg equilibrium, and Net's genetic distance	Holland 2001
Cattle egret (B*ubulcus ibis),* House finch (*Carpodacus mexicanus),* Asian longhorn beetle (*Anoplophora glabripennis),* and Japanese white-spotted citrus longhorn beetle (*A. malasiaca)*	Native distribution, geographic themes (aspects of vegetation, precipitation, temperature), ecological factors	GARP, Chi-square	Peterson and Vieglais 2001
Pea aphid (*Acyrthosiphon pisum*), and Parasitoid	Levels of resistance and virulence, as well as local adaptation	Mixed linear model (PROC MIXED)	Hufbauer 2002

wasp (*Aphidius ervi*)			
Alien fishes in the Great Lakes	13 life history characteristics, 5 habitat needs, 6 aspects of invasion history, and human use.	Discriminant Analysis, CART	Kolar and Lodge 2002
Zebra mussel (*Dreissena polymorpha)*	Ecological (rates of recruitment, growth and survival structured by age or size, and seasonality) and Economic processes (reduced water intake efficiency caused by fouling)	Stochastic Dynamic Programming	Leung et al. 2002
Native and nonnative flora of Argentina (*Gleditsia triacanthos, Lithraea ternifolia, Ligustrum lucidum, Fagara coco)*	Life history traits considered determinant of plant spread	Interacting Multiple Cellular Automata (IMCA)	Marco et al. 2002
Spiny pocket mouse, (*Heteromys anomalus*), the small bodied rodent, *Microryzomys minutus*, and the passerine bird (*Carpodacus mexicanus*)	Non-random associations between environmental characteristics (elevation, slope, aspect, soil conditions, geological ages, geomorphology, coarse potential vegetation zones, and a series of coverage for solar radiation, temperature, and 18recipitation) of localities of known occurrence versus those of the overall study region	GARP	Anderson et al. 2003
Gum Arabic tree *(Acacia nilotica)*	Climatic preference of the species and climate conditions (averages of rainfall, daily minimum and maximum air temperature, relative humidity, and soil moisture)	CLIMEX	Kriticos et al. 2003
Established Exotic Insects	Trade, and number of exotic species invasions	Log-Log Species-Area Model, Log-Linear Species-Area Model, Michaelis-Menten Model	Levine and D'Anotonio 2003
Zebra mussel (*Dreissena polymorpha*)	Invaded habitat types, impact on benthic invertebrate abundance and diversity, invader abundance and environmental variables	Regression analysis, Empirical Modeling	Ricciardi 2003
Buffel grass	Environmental and geological	GARP, chi-square, Kappa scores,	Arriaga et al. 2004

(*Cenchrus ciliaris)*	factors: digitized land-use and vegetation cartography, climatic information (types of climate, total annual rainfall, and digitized cover of minimum and maximum absolute temperatures), and digitized edaphic information	ArcView Spatial Analyst Extension	
Asian longhorn beetle (*Anoplophora glabripennis)*	Propagule pressure (exposure) and risk of establishment	Stage-based stochastic maxtrix population model	Bartell and Nair 2004
Cladoceran zooplankter (*Bythotrephes longimanus*)	Mate limitation and demographic stochasticity	Allee effect for continuously sexually reproducing and seasonally parthenogenetic species	Drake 2004
Dreissena polymorpha	Environmental and Geological Factors (average annual temperature, bedrock geology, elevation, flow accumulation, frost frequency, maximum temperature, minimum temperature, precipitation, slope, solar radiation, and surface geology)	GARP	Drake and Bossenbroek 2004
Scotch broom (*Cytisus scoparious)*	Population growth and rate of spread	Discrete-time Model	Neubert and Parker 2004
Insect, and plant species	Life history traits (age, size, life-cycle stage,) and stochasticity	Population Viability Analysis	Andersen 2005
Theoretical herbivorous insect	Movement behavior, oviposition events, native/nonnative plants	Individual-based model	Andersen et al. 2005
Oyster drills (*Ocinebrellus inornatus*)	Life history traits (reproduction, growth, and juvenile/adult survival) and rate of increase	Population Elasticity Analysis	Buhle et al. 2005
Egg parasitoid (*Trichogramma ostriniae*)	Babitat fidelity, ability to penetrate non-target habitats, and ability to locate and parasitize eggs	Precision Tree Analyses	Wright et al. 2005
Smooth cordgrass (*Spartina alterniflora)*	Survival, growth rates, and reproduction	Linear Model of Population Viability Analysis	Hastings et al. 2006
Spotted knapweed (*Centaurea maculosa*)	3 subsets of occurrence data (from Europe, western North America, and both) and climate (19 original	BIOMOD framework with Principal Component Analysis (PCA), Reciprocal Modelling	Broenniann et al. 2007

	WORLDCLIM bioclimatic variables)	Analyses using eight techniques (Artificial Neural Networks–ANN, Boosted Regression Trees-BRT, Classification Tree Analyses-CTA, Generalized Linear Models-GLM, Generalized Additive Models-GAM, Multivariate Adaptive Regression Splines-MARS, Mixture Discriminant Analysis-MDA, and Random Forest-RF)	
Shrubby tree (*Miconia calvescens*)	Population and time derivative, population growth, number of removals, time needed for removals, marginal cost for removals, and damages incurred at population	Deterministic Model	Burnett et al. 2007
European green crab (*Carcinus maenas)*	Source of individuals to risk, risk to selected biological endpoints, habitats, and sub-regions	Modified Relative Risk Model incorporating a Hierarchical Patch Dynamic Paradigm	Colnar and Landis 2007
Theoretical population of Zebra mussel (*Dreissena polymorpha*)	Abundance, probability of invasion, cost/damages to production, firm adaptation, prevention, and control	Integrated Bioeconomic Model	Finnoff et al. 2007
Cyanophyte (*Lyngbya majuscula*)	Environmental Factors (rain, number of dry days, ground water, air, point sources, land run off, dissolved organics, dissolved iron, dissolved phosphorus, dissolved nitrogen, turbidity, bottom current climate, particulate matter, sediment nutrient climate, wind speed, wind direction, tide, light quantity, light quality, light climate, temperature, available nutrient pool, and bloom initiation)	Bayesian Network (BN)	Hamilton et al. 2007
Spotted knapweed (*Centaurea maculosa*)	3 subsets of occurrence data (from Europe, North America, and both) and climate data (mean annual temperature, annual sum of	BIOMOD framework with Generalized Linear Models (GLM), Generalized Additive Models (GAM), Regression Trees,	Broennimann and Guisan 2008

	precipitation, mean annual daily temperature range, minimum temperature, maximum temperature, total precipitation of the wettest quarter, total precipitation of the driest quarter, and potential evaporation	and Random Forest (RF)	
Brown tree snake (*Boiga irregularis*)	Population, unit cost of removal, damage inflicted, avoidance expenditure, population growth, harvest level, and added individuals to the population	Deterministic Model	Burnett et al. 2008
Sacred Ibis (*Threskiornis aethiopicus)*	Distance to nearest neighbor and distance to body mass aggregation edge	Predictive Logistic Regression Model	Herring, G., and D.E. Gawlik. 2008
468 invasive species in the US (crustaceans, fish, various invertebrates, mammals, and plants)	Severity of invasion (invasive potential, distribution, and ecological impact), taxonomic group, and the continental origin of the invader,	Chi-square tables	Mueller and Hellmann 2008
Hawkweed *(Hieracium aurantiacum, Hieracium murorum and Hieracium pilosella)*	Climatic Niches (temperature, rainfall, and seasonality and variability of each) of native and invasive areas	Principal Component Analysis, Ecological niche models (ENMs), Regression analyses, Classification methods, Surface Range Envelope, Receiver-Operating Characteristic (ROC) Curve, Cohen's kappa	Beaumont et al. 2009
596 species of alien Amphibians and Reptiles	Environmental Factors (temperature and rainfall) and Success of Invasion	CLIMATE, Generalized Linear Mixed Model, ROC curves, Generalised Additive Mixed Model	Bomford et al. 2009
3 crocodilians, 10 lizards, 10 snakes, and 10 turtles	Taxonomic order, maximum temperature match between a species native range and Florida, animal sale price, and manageability	Discriminant Analysis, Logistic Regression, Recursive Partitioning and Regression Trees (RPART)	Fujisaki et al. 2010
Fresh and marine fish, mollusks, echinoderms, bryozoans, tunicates,	Geographical range extent and heat tolerance with invasion success	BIOMOD framework with Linear modelling and Maximum-likelihood	Bates et al. 2013

ascidians, arthropods, and annelids			
Theoretical populations of diploid sexual species	Phylogenetic distance and establishment success	Quantitative Genetic Framework	Jones et al. 2013
Asian oyster (*Crassostrea ariakensis*)	Pathways of diploid introduction (probability of establishing reproductive individuals) and, the number of co-occurring reproductive individuals	Multi-step predictive model, and a coupled hydrodynamic and larval transport model	Methratta et al. 2013
Jackson's chameleon (*Trioceros jacksonii xantholophus)*	Shell digestion and condition, Passage rates	Mann-Whitney, t-tests, One-way ANOVA, Tukey test, and Pearson Correlation	Chiaverano and Holland 2014
Jackson's chameleon (*Trioceros jacksonii xantholophus)*	Cumulative distance, total net displacement, home range, and home range overlap	One-way ANOVAs	Chiaverano et al. 2014