Biosecurity under uncertainty: the influence of information availability and quality on expert decision-making for risk outcomes

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Submitted in fulfilment

of the requirements for the Degree of Doctor of Philosophy

University of Tasmania.

Launceston, Tasmania

March 2012

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STATEMENT OF CO-AUTHORSHIP

The following people and institutions contributed to the publication of the work undertaken as part of this thesis:

Chapter 2:

Dahlstrom, A., C. L. Hewitt, and M. L. Campbell. 2011. A review of international, regional and national biosecurity risk assessment frameworks. Marine Policy 35:208-217.

Dahlstrom, A (60%), Hewitt, CL (20%), Campbell, ML (20%)

Chapter 3:

Dahlstrom, A., C. L. Hewitt, and M. L. Campbell. 2011. Mitigating uncertainty using alternative information sources and expert judgment in aquatic nonindigenous species consequence assessment. Aquatic Invasions (in review).

Dahlstrom, A (60%), Hewitt, CL (20%), Campbell, ML (20%)

Chapter 4:

Dahlstrom, A., C. L. Hewitt, and M. L. Campbell. 2011. The role of uncertainty and subjective influences on consequence assessment by aquatic biosecurity experts. Biological Conservation (in review).

Dahlstrom, A (60%), Hewitt, CL (20%), Campbell, ML (20%)

- CL Hewitt and ML Campbell both contributed to the idea, its formalization and development, and assisted with refinement and presentation.

Chapter 5:

Dahlstrom, A. and C. L. Hewitt. 2011. Evidence of impact: low statistical power leads to false certainty of no impact for nonindigenous species. Nature (in prep).

Dahlstrom, A (80%), Hewitt, CL (20%)

- CL Hewitt contributed to the idea, its formalization and development, and assisted with refinement and presentation.

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ABSTRACT

Alongside climate change and habitat loss, aquatic nonindigenous species (ANS) introductions comprise a large and increasing contribution of the anthropogenic threat to environmental, economic, sociocultural and human health values worldwide. Biosecurity agencies aim to prevent and manage introductions using various tools, including risk assessment. Risk assessment can prioritize threats, but is frequently compromised by uncertainty, often due to information availability, quality and interpretation. Many risk assessment processes lack consistent and transparent treatment of uncertainty, particularly when biosecurity objectives warrant a precautionary approach.

This thesis aims to identify methods for managing uncertainty via an initial review of 14 existing national, regional and international biosecurity instruments. Results from this review found over half of the instruments explicitly included or mentioned precaution, and many instruments acknowledged the potential influence of subjective risk perceptions. Based on these outcomes, this thesis aims to: determine sources of uncertainty; understand the cognitive process of estimating consequence, and therefore risk under uncertainty; and provide transparent methods to reduce uncertainty that allow for precaution, using input from ANS experts in scientific and management fields. Finally, this thesis aims to examine how the frequentist statistical focus on low acceptable rates of Type I errors, most frequently applied in ANS impact research, influences findings of significant impact and the implications for management decisions.

Results of this thesis indicate that the scarcity of ANS impact information constitutes a primary source of uncertainty. When faced with knowledge gaps and other forms of uncertainty, experts tended to assume and assign lower consequence via a ‘hindsight approach’ (assume no impact without sufficient information), which stands opposite to precaution. To mitigate the effects of uncertainty, experts supported the use of alternative information sources, including non-empirical evidence. In practice, the provision of information and group discussion generally increased the consequence estimate, thus suggesting methods that allow functional and, if desired, precautionary consequence assessments despite high uncertainty. In situations of expected ‘low’ certainty, when information is available, my research indicated that an extremely high proportion of statistical analyses of impact had insufficient power to detect an impact, leading to ‘false certainty’ of no impact. This bias toward ‘missing’ impacts, again opposite to precaution, may further prevent appropriate management action.

The thesis concludes with a proposed framework that provides guidance for biosecurity-related research and management using an acceptable level of risk. It provides a transparent process and usable risk outcomes that: (1) integrate scientific process and management objectives; (2) are accountable for and unimpeded by uncertainty; (3) consider the assumptions used by the experts making the assessment; (4) can be adapted according to varying strengths of precaution desired by management; (5) follows World Trade Organization Sanitary and Phytosanitary (SPS) Agreement mandates; and (6) are feasible given time and budget constraints.

ACKNOWLEDGEMENTS

I wish to sincerely thank my supervisor Prof. Chad Hewitt and co-supervisor Prof. Marnie Campbell. I began my PhD with a project that promptly changed within a few weeks of my arrival. They provided me with the freedom to develop a new project, yet provided patient and invaluable guidance along the way that allowed me to arrive at its successful conclusion with some novel insights and appreciation for some of the social underpinnings of science. Their time and effort as mentors and, eventually, colleagues is most gratefully appreciated.

I am grateful to Dr. Greg Ruiz for providing me space at the Smithsonian Environmental Research Center (SERC) and also valuable input into my project during the first year of its development. A. Whitman Miller and Paul Fofonoff, also at SERC, provided useful feedback and collaboration.

I am grateful to the Australian Maritime College, a specialist institute of the University of Tasmania, for financial support via the John Bicknell Research Scholarship, which permitted my study in Australia. I also acknowledge the other sources of funding including the Australian Geographic Society and the University of Tasmania Graduate Research Candidate Conference Fund Scheme. I also thank the Human Research Ethics Committee (Tasmania) Network for ethics approval.

I wish to thank Jan Daniels and Mandy Norton for their kind assistance with all things administrative. I also wish to thank those individuals within each conference that facilitated organization of each workshop: Robyn Draheim (MBIC), Narelle Hall (AMSA), Lisa Carmody and Elizabeth Muckle-Jeffs (ICAIS) and Sonia Gorgula (NIMPCG). I owe the outcomes of Chapters 3 and 4 to all the participants who generously gave their time participating in the surveys and workshops, tirelessly putting up blue and red dots.

To my parents, my endless thanks. It is only as I grow older that I realize the sacrifices you made as individuals and as a couple to get me to where I am. I am sorry I ended up so far away, but thank you for letting me go. To my brothers, your humour and camaraderie have a special place in my heart – I look forward to larger doses in the future. To my friends back in 'merica, thank you for not forgetting me, down here at the end of the world, and always welcoming me back with big smiles and open arms when I manage a whirlwind visit (and a special thanks to those who ventured down here for a visit, long or short!) To my Tassie friends, thank you for welcoming me to the island and taming my obnoxious accent; you made these three years a joy. And to Tassie – I fell in love with your beautiful wildness like few other places I've been; they gave me peace and comfort when nothing else could. And to my partner in all things, Ben (GGB), thank you for your unfailing patience, love and ability to remind me what matters most in life.

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GLOSSARY OF TERMS RELEVANT TO THIS RESEARCH

Term	Definition
α (alpha)	The acceptable rate of Type I errors, or incorrectly rejecting the null hypothesis (Quinn and Keough 2002).
Alien species	Species that spread beyond their native range, not necessarily harmful, or species introduced to a new range that establish themselves and spread; similar terms include exotic species, foreign species, introduced species, non indigenous species, and non native species (Occhipinti-Ambrogi and Galil 2004, Jeschke and Strayer 2005).
ALOP (ALOR)	Acceptable Level of Protection (Acceptable Level of Risk). The level of protection deemed appropriate by the Member establishing a sanitary or phytosanitary measure to protect human, animal or plant life or health within its territory; also known as the acceptable level of risk (WTO 1995).
Ambiguity	The variability of (legitimate) interpretations based on identical observations or data assessments (Klinke and Renn 2002).
ANS	Aquatic Nonindigenous Species. Nonindigenous species (defined below) in marine, brackish or freshwater habitats.
Aquatic biosecurity	National, regional and international efforts to prevent, reduce, and manage the introduction of pests, diseases or unwanted organisms via entry and border surveillance, short-term response and long-term control of established pests.
Nuisance species	See *invasive species*.
Attitude	Evaluative reaction(s) to an object or behaviour that is based on beliefs about that object or behaviour and which is associated with behaviour toward the attitude object (Clayton and Myers 2009).
Availability heuristic	The tendency for events and outcomes to appear more probable when they come to mind more easily (Clayton and Myers 2009).
β (beta)	The acceptable rate of Type II errors, or incorrectly accepting a false null hypothesis (Quinn and Keough 2002).
Ballast water	The uptake and release of organisms during ballasting and de-ballasting operations (respectively), which are necessary to maintain trim, stability, propeller immersion, and safe levels of hull stress during travel or in port (Victorian Government 2006).
Biological control	The release of one species to control another (Carlton 2001).
Biological diversity or biodiversity	Used to describe species richness, ecosystem complexity, and genetic variation (Allaby 1998).

Glossary cont.

Term	Definition
Biological invasion or bioinvasion	A broad term that refers to both human-assisted introductions and natural range expansions (Carlton 2001).
Categorical descriptors	Categorical definitions of impact defined in a qualitative (e.g., low, medium or high) or quantitative manner. In semi-quantitative assessments, the definitions of consequence categories are often based on "threshold values", often in a combination of qualitative and numerical terms. Threshold values often include measures of magnitude, spatial extent of the impact (e.g. local, regional, or global), temporal scale of the impact (e.g. temporary or permanent), and resilience of the system to impact (e.g. the potential of the effected entity to recover). Each threshold description may contain several conditions, only one of which must be met in order to classify the impact to that category (Campbell 2005, 2008, Campbell and Gallagher 2007).
CBD	Convention on Biological Diversity. An international treaty to sustain the diversity of life on Earth.
Clean lists	A list of permitted species for introduction or import based on invasion history or characteristics (Ruesink et al. 1995, Simberloff et al. 2005); assumes guilty until proven innocent.
Cognitive bias	A patter of judgment that occurs when people rely on a limited number of heuristic principles that reduce the complex tasks of assessing probabilities and predicting values to simpler judgmental operations (Tversky and Kahneman 1974).
Community	Any grouping of populations of different organisms that live together in a particular environment (Allaby 1998).
Consequence (assessment)	The assessment (and related terms, e.g., 'core values', 'subcomponents' and 'categories') of potential impacts posed by a threat and which is combined with likelihood assessment to produce a risk estimate (Campbell 2005, 2008, Campbell and Gallagher 2007, Campbell and Hewitt 2008).
Consequence tables	The combination of categorical descriptions of consequence and associated threshold descriptions. The consequences of a species for each value area are then combined to give an idea of that species' overall consequence to a region (Campbell 2005, 2008, Campbell and Gallagher 2007, Campbell and Hewitt 2008).
Core value bias	Any difference in perceived consequence due to different valuation of the area of impact.

Glossary cont.

Term	Definition
Core values	The main value types against which impacts are assessed (e.g., Campbell 2008). They can include environmental, economic, social, cultural and human health. Environmental impacts of ANS can be ecological (abundance and distribution of organisms), biological (the organisms themselves), chemical (processes such as bioaccumulation of toxins) or physical (processes such as disturbance); qualitative or quantitative; structural or functional (Ward 1978). Economic impacts are effects on humans which alter their activities in ways that affect their incomes and expenditures of money (Fofonoff et al. 2003). Social impacts affect the values placed on a location or species in relation to human use for pleasure, aesthetic, and generational values (Campbell 2008). Cultural impacts affect aspects of the aquatic environment that represent an iconic or spiritual value, including those that create a sense of local, regional, or national identity (Campbell 2008). Human health impacts affect the value of a safe and healthy society shared equally across generations and socio-economic groups (Hewitt et al. 2010).
Cryptogenic species	Species that are neither clearly indigenous or nonindigenous (Carlton 1996a)
Decision theory	A multidisciplinary set of theories that describe the use of various principles in choosing one of multiple available options based on the perceived state of nature and potential consequences, often in an effort to maximize utility or rationality (Chernoff and Moses 1959).
Delphic process (modified)	A process used to make decisions and predictions in conditions of scarce and/or highly uncertain information inappropriate for traditional scientific methods, which uses expert revision of judgment based on input and opinion of other experts to reach consensus where possible and identify areas of disagreement where consensus is not possible, with a subsequent reduction in overall uncertainty (Webler et al. 1991). While the original process used anonymous expert input, a modified Delphic process uses expert input via group workshop process (Webler et al. 1991).
Dirty lists	A list of prohibited species for introduction or import based on invasion history or characteristics (Ruesink et al. 1995, Simberloff et al. 2005); assumes innocent until proven guilty.
DMURI	Decision Making Under Risk and Ignorance.
Ecological risk assessment	An evaluation of the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors (US EPA 1992).

Glossary cont.

Term	Definition
Economic valuation	Attempts to assign quantitative values to the goods and services provided by environmental resources, whether or not market prices are available. The economic value of any goods or services is generally measured in terms of what resource users or society at large are willing to pay for the commodity, minus what it costs to supply (Bonzon and Cochrane 2003).
Ecosystem	A discrete unit, or community of organisms and their physical environment (living and non-living parts), that interact to form a stable system (Allaby 1998).
Effect size	A statistical measurement of the difference between two populations that provides an estimate of the magnitude and direction of an effect (Nakagawa and Cuthill 2007).
Endpoints	The values affected by the hazard, which a risk assessment aims to protect and by which impacts are measured (US EPA Risk Assessment Forum 2003).
Environmental matching assessment	A risk assessment approach that compares environmental conditions including temperature and salinity between donor and recipient regions. The degree of similarity between the locations provides an indication of the likelihood of survival and the establishment of any species transferred between those locations (Herborg et al. 2007).
Epistemic uncertainty	Epistemic uncertainty stems from a lack of knowledge and can be ameliorated via additional research or similar efforts (Walker et al. 2003).
Expected utility	The expected utility of an act can be calculate once the probabilities and utilities of its possible outcomes are known, by multiplying the probability and utility of each outcome and then summing all terms into a single number representing the average utility of the act (Peterson 2009).
Hazard	An object or event that has the potential to cause harm under specific conditions that allow that risk to be realized; in order to assess the hazard, both the object (e.g. a vector, trade route, or species) and the conditions (e.g. the recipient port environment) are considered (Hewitt and Hayes 2002).
Heuristics	Heuristics are learned, declarative or procedural knowledge structures stored in memory (e.g., "rules of thumb", judgmental shortcuts, biases, educated guesses, intuitive judgments or simply common sense tools) that have been learned and internalized by the individual (e.g., ‘length implies strength’) to deal with an increasingly complex world, in which individuals are forced to make decisions using either an overwhelming or insufficient amount of information (Chaiken et al. 1989, Chen and Chaiken 1999).
Hindsight approach	In an ANS impact assessment context, when information is lacking or scarce, the assumption that a species is “innocent until proven guilty”.

Glossary cont.

Term	Definition
HSM	The Heuristic-Systematic Model attempts to explain how individuals make decisions under risk and ignorance (Trumbo 1999). The HSM identifies two methods by which people make judgments: systematic processing (a comprehensive analysis) and heuristic processing (a shortcut-based analysis; this occurs if an individual is unwilling or unable to take the time or make the effort to carefully consider the evidence) (Chen and Chaiken 1999, Trumbo 2002).
Hypothesis testing	see *NHST*
Impact assessment	Impact refers to the assessment of impacts to environmental, economic, social, human health, or cultural values caused by ANS, which contributes to the formal consequence assessment.
Import Health Standards	Legislative procedural documents established to ensure that the internationally agreed standard for quarantine and scientific evaluation are met, in order to reduce the unwarranted restrictions of trade when importing goods (Campbell 2009).
Incursion	See *Introduction*
Indigenous	A species that occurs naturally in an area; also known as native (Allaby 1998).
Information type/source	In this context, possible sources of knowledge for use in a consequence or risk assessment (e.g., harbour manager observations, grey literature, and experimental research).
Intentional introduction	A species that is brought to a new area, country, or bioregion for a specific purpose, such as for a garden or lawn; a crop species; a landscaping species; a species that provides food; a groundcover species; for soil stabilization or hydrological control; for aesthetics or familiarity of the species; or other purposeful reasons (Booth et al. 2003).
Introduced species	This terms means those species that have been transported by human activities, either intentionally or unintentionally, into a region in which they did not occur in historical time and are now reproducing in the wild (Carlton 2001). Similar terms include alien, exotic, foreign, nonindigenous, and non-native.
Introduction	The human mediated movement of an animal to an area outside its natural range (Hewitt et al. 2010).
Invasion	The expansion of a species into an area not previously occupied by it (Booth et al. 2003).

Glossary cont.

Term	Definition
Invasive species	Generally, this term refers to a subset of native or non-native plants or animals that are cause economic or environmental harm or harm to human health (Executive Presidential Order 1999). Commonly, widespread nonindigenous species that have adverse effects on the invaded habitat (Colautti and MacIsaac 2004). Similar terms include pest and nuisance.
Likelihood	In an aquatic biosecurity context, the probability of ANS incursion or establishment, described in qualitative, semi-quantitative or quantitative terms.
Maximin principle	A decision rule sometimes used in decisions under ignorance, which holds that one should maximise the minimal value obtainable in each decision. Hence, if the worst possible outcome of one alternative is better than that of another, then the former should be chosen (Peterson 2009).
National sovereignty	In this context, the WTO-provided right of any government to set the level of health protection it deems appropriate, but to ensure that these sovereign rights are not misused for protectionist purposes and do not result in unnecessary barriers to international trade (WTO 1998).
Native species	See *indigenous species*
NEMESIS	National Exotic Marine and Estuarine Species Information System; a database developed by the Smithsonian Environmental Research Center (SERC), http://invasions.si.edu/nemesis/
NHST	Null Hypothesis Significance Testing. The statistical evaluation of whether a set of results differs from a pre-identified null hypothesis, based on the probability (*p*-value) that the findings are unlikely to be within the population of the control (Nakagawa and Cuthill 2007).
NIMPIS	National Introduced Marine Pest Information System; a database developed by the Australian Government, http://adl.brs.gov.au/marinepests/
Non-native species	See *nonindigenous species*
Nonindigenous species	Species that have been transported by human activities – intentionally or unintentionally – into a region in which they did not occur in historical time (Hewitt et al. 2010). Similar terms include alien, exotic, and foreign.
Norms	Customary rules of behaviour that coordinate our interactions with others (Lewis 1969).
Ontological uncertainty	Stems from the inability to fully describe a variable and complex environment and cannot be eliminated (Walker et al. 2003).
Pathway	The vector, purpose (the reason why a species is moved), and route (the geographic corridor from one point to another) (Carlton 2001).

Glossary cont.

Term	Definition
Pest (IPPC)	Any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products (FAO 1997).
Population	A group of potentially inter-breeding individuals of the same species found in the same place at the same time (Booth et al. 2003).
Power analysis	A statistical procedure that uses sample size (n), significance criterion (α and β), effect size (ES) and σ (population standard deviation) to determine power (di Stefano 2003, Nakagawa and Cuthill 2007).
Power	The probability of correctly rejecting the hull hypothesis and the complement of the Type II error rate β, 1-β (Lehmann and Romano 2005, Nakagawa and Cuthill 2007).
Precaution	The stance that, "Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (United Nations General Assembly 1992). It often includes reversing the burden of proof, i.e., proving that an activity down not cause harm before proceeding. Often described in terms of the *precautionary principle* or *precautionary approach*.
Quarantine	Official confinement of regulated articles for observation and research or for further inspection, testing and/or treatment (IPPC Secretariat 2007).
Recognition heuristic	A "fast and frugal" heuristic by which individuals rank an object as more fitting of a criterion based on their recognition of it (e.g., ranking a city as greater in population based on recognizing its name) (Goldstein and Gigerenzer 2002).
Risk (decision theory)	A decision under risk occurs when the decision maker knows the probability and utility of all possible outcomes (Peterson 2009).
Risk (biosecurity)	The possibility that human actions or events lead to consequences that harm aspects of things that human beings value (Klinke and Renn 2002).
Risk analysis	A process comprised of risk assessment, risk management, risk communication, and risk policy (Byrd and Cothern 2000).
Risk assessment	The process of determining the probability (likelihood) and impacts (consequences) of that event (Hayes 1997).
Risk communication	A process that helps clearly express the risk to the relevant stakeholders and/or public (Byrd and Cothern 2000).
Risk management	A process that involves analysing and choosing the best options to reduce, eliminate or otherwise address the risk (Byrd and Cothern 2000).

Glossary cont.

Term	Definition
Risk matrix	Tables with vertical and horizontal headings that correspond to likelihood (aka probability, frequency, etc) and consequence (aka impact, severity, etc) in order to provide a risk estimate (e.g., Campbell 2008, Standards Australia 2009).
Risk perception	The multidisciplinary study of how and why people perceive risks, in recognition of the fact that this process occurs differently depending on the nature of the risk and the individual (Cohrssen and Covello 1989).
Risk policy	Risk policy surrounds the entire process of risk analysis, e.g., in developing guidelines for each component to improve the structure and process of risk analysis (Andersen et al. 2004).
Satisficing	A term from "satisfy" and "suffice", in which respondents choose not to expend energy making the optimal decision, instead merely making a choice that seems adequate (Krosnick 1999).
SIF	Subjective Influencing Factors. The values, attitudes, norms and biases that impact information processing and decision making within individuals and agencies responsible for estimating and managing risks.
Significance testing	see *NHST*
Species name bias	A difference in assessed consequence based on the species or genus name of the ANS.
Species	A group of organisms formally recognized as distinct from other groups; the basic unit of biological classification, defined by the reproductive isolation of the group from all other groups of organisms (Allaby 1998).
Species-specific assessment	A risk assessment approach that uses information on life history and physiological tolerances to define a species' physiological limits and thereby estimate its potential to survive or complete its life cycle in the recipient environment. That is, a comparison of individual species characteristics with the environmental conditions in the recipient port, to determine the likelihood of transfer and survival (IMO 2007).
SPS Agreement	Agreement on the Application of Sanitary and Phytosanitary Measures. A WTO framework that sets out the basic rules for food safety and animal and plant health standards, including measures taken to protect the health of fish and wild fauna, as well as of forests and wild flora. Sanitary and phytosanitary measures are defined as any measures applied: to protect human or animal life from risks arising from additives, contaminants, toxins or disease-causing organisms in their food; to protect human life from plant- or animal-carried diseases; to protect animal or plant life from pests, diseases, or disease-causing organisms; and to prevent or limit other damage to a country from the entry, establishment or spread of pests (WTO 1998).

Glossary cont.

Term	Definition
Subcomponents	A specific type of impact, within a core value, that has a unique unit, method and description for the measurement of consequence or impact.
Systematic measurement error	Error that results from biases or imperfections in collecting or interpreting measurements (Klinke and Renn 2002).
TPB	The Theory of Planned Behaviour is a modification of TRA that adds perceived behavioural control as an additional construct to determine the behavioural intention (Ajzen 1991).
TRA	The Theory of Reasoned Action posits that the attitudes and subjective norms surrounding an action combine to produce the behavioural intention (i.e., decision to perform an action) (Ajzen 1991).
Type I error	In an impact assessment context, incorrectly assigning an impact to a species.
Type II error	In an impact assessment context, incorrectly assigning no impact to a species.
Uncertainty (decision theory)	A decision under uncertainty occurs when the decision maker knows the utility of all possible outcomes, but not their probabilities (Peterson 2009).
Uncertainty	Any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system (Walker et al. 2003).
Unintentional introduction	An introduction of nonindigenous species that occurs as the result of activities other than the purposeful or intentional introduction of the species involved, such as the transport of nonindigenous species in ballast or in water used to transport fish, molluscs or crustaceans for aquaculture or other purposes (US EPA 2000).
Utility (decision theory)	The more an object is desired, the higher is its utility. Utility is measured on some utility scale, which is either ordinal or cardinal (Peterson 2009).
Values	General, stable, strongly held judgments or preferences for end states or ways of acting that serve as goals that apply across different contexts (Clayton and Myers 2009).
Vector	The physical means or agent by which a species is transported, such as ballast water, ships' hulls, boats, hiking boats, cars, vehicles, packing material, or soil in nursery stock (Carlton 2001).

Glossary cont.

Term	Definition
Vessel fouling	The association of aquatic organisms with objects immersed in salt water, including the hulls and ancillary gear of commercial and other vessels (AMOG Consulting 2001). Fouling species (including small fish, barnacles, mussels, sponges, algae, crabs, and sea squirts) foul ships via attaching to the wetted surface areas, or finding refuge within the matrix of the fouling community and protected nooks and crannies (e.g., sea chests) (AMOG Consulting 2001, Coutts et al. 2003).
WTO	World Trade Organization. An international organization dealing with the rules of trade between nations.

CHAPTER 1. GENERAL INTRODUCTION

Aquatic nonindigenous species

Within the suite of current environmental issues, aquatic nonindigenous species (ANS) remain one of the primary threats (Lubchenco et al. 1991, Bax et al. 2003). While climate change is the oft-cited driver of global change, nonindigenous species pose a serious threat in their own right (e.g., Ruiz et al. 1997, Carlton 2001, Hewitt et al. 2004a), as well as synergistically interacting with and augmenting the effects of climate change and other threats to biodiversity such as land use change, climate change, overexploitation, and pollution (Halpern et al. 2007). Damages imposed by introduced species will certainly effect the more 'ecocentric' values (such as biodiversity), but with impacts extending to human well-being – including food security, basic material for a good life, health, good social relations, and freedom of choice and action – they will threaten the very way we live (Millennium Ecosystem Assessment 2005).

While research and management initiatives to control and prevent aquatic invasions have only occurred for a few decades, human-mediated species introductions have occurred for thousands of years, with introduction rates accelerating during the last 200 years (Crosby 1986). The increasing rates of introductions are due to a variety of factors, including stressed ecosystems (Occhipinti-Ambrogi and Savini 2003) and increasing quantity and quality of vector-based transfer (current figures estimate over 10,000 species in transit at any given time) (Carlton 1999, Hulme 2009). Despite the thousands of documented ANS, these figures may underestimate actual numbers given uncertain systematics, confounding biogeography and insufficient sampling (Carlton 1996a, Ruiz and Hewiit 2002, Hewitt et al. 2004a).

Regardless of the potential for under-documentation of the species, the threat remains global; ANS have impacted every marine bioregion in the world (sensu the IUCN WCPA – Marine Plan of Action adapted from Kelleher et al. 1995) (Laffoley 2006; Figure 1.1). As a region with species arriving only recently, impacts to the Antarctic (IUCN Bioregion 1) by ANS such as *Hyas araneus* remain unknown (Tavares and Melo 2004). *Enteromorpha prolifera* degrades sandflat communities in the near-Arctic (IUCN Bioregion 2) (Bolam et al. 2000); *Hydroides dianthus* fouls infrastructure in the Mediterranean (IUCN Bioregion 3) (Galil 2000); *Hemigrapsus sanguineus* alters structure of rocky intertidal communities in the northwestern Atlantic Ocean (IUCN Bioregion 4) (Gerard et al. 1999); *Polysiphonia harveyi* fouls ropes and pontoons in northeast Atlantic marinas (IUCN Bioregion 5) (Maggs and Stegenga 1998); *Acartia tonsa* dominates communities in the Baltic Sea (IUCN Bioregion 6) (Leppakoski et al. 2002); *Perna viridis* displaces native species in the Caribbean (IUCN Bioregion 7) (Buddo et al. 2003); *Caulerpa racemosa* var. *cylindracea* spreads over substrate in the Canary Islands (IUCN Bioregion 8) (Verlaque et al. 2004); *Limnoperna fortunei* impedes water-treatment plants, industrial refrigeration systems and power stations in the South Atlantic (IUCN Bioregion 9) (Darrigran 2002); *Mytilopsis sallei* forms thick fouling communities on vessels in India (IUCN Bioregion 10) (Morton 1981); *Sparus aurata* may impact fisheries in the Arabian Sea (IUCN Bioregion 11) (Global Invasive Species Database, http://www.issg.org/database); *Salvinia molesta* degrades aquaculture and tourism in Lake Naivasha, Kenya (IUCN Bioregion 12) (Caspers 1976); *Oreochromis* spp. has contributed to the decline or extinction of several species in the Philippines (IUCN Bioregion 13) (Pullin et al. 1997); *Chthamalus proteus* forms almost 100% cover in some Hawaiian intertidal zones (IUCN Bioregion 14) (Zabin and Altieri 2007); *Corbula amurensis* has disrupted trophic interactions in the San Francisco Bay (IUCN Bioregion 15) (Alpine and Cloern 1992); *Pyromaia tuberculata* dominates Tokyo Bay, Japan (IUCN Bioregion 16) as the most abundant crab (Wahitani 2004); *Codium fragile* invasion threatens the persistence of *Gracilaria chilensis* farms in northern Chile (IUCN Bioregion 17) (Neill et al. 2006); and *Asterias amurensis* predates on commercially farmed bivalves in Tasmania (IUCN Bioregion 18) (Ross et al. 2002).

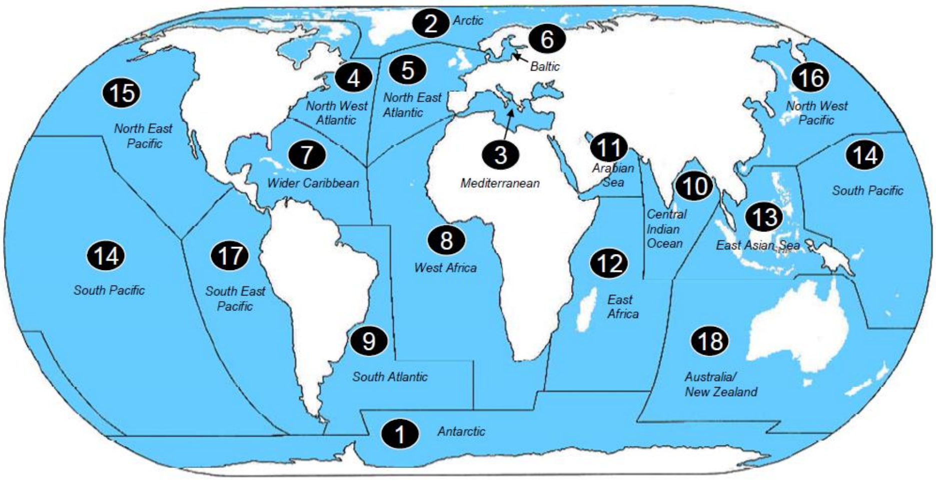

Figure 1.1. The global marine bioregions derived from an ecosystem-based approach (used by IUCN, based on Kelleher et al. 1995).

Within IUCN Bioregion 18, the effects of introduced marine species in all Australian bioprovinces (Figure 1.2) have been well documented (Hewitt et al. 1999, Hewitt 2002, Hayes et al. 2004, Hewitt and Campbell 2008, Neil et al. 2008). For example, *Bugula neritina* heavily fouls ports and harbours in the Solanderian province (Keough and Ross 1999); *Alexandrium minutum* produces paralytic shellfish poisons in the Peronian province (Hallegraeff et al. 1991); *Asterias amurensis* reduces survivorship of recently settled juveniles of the commercial bivalve *Fulvia tenuicostata* in the Flindersian province (Ross et al. 2002); and *Zoobotryon verticillatium* fouls ports and harbours in the Dampierian province (Wells et al. 2009).

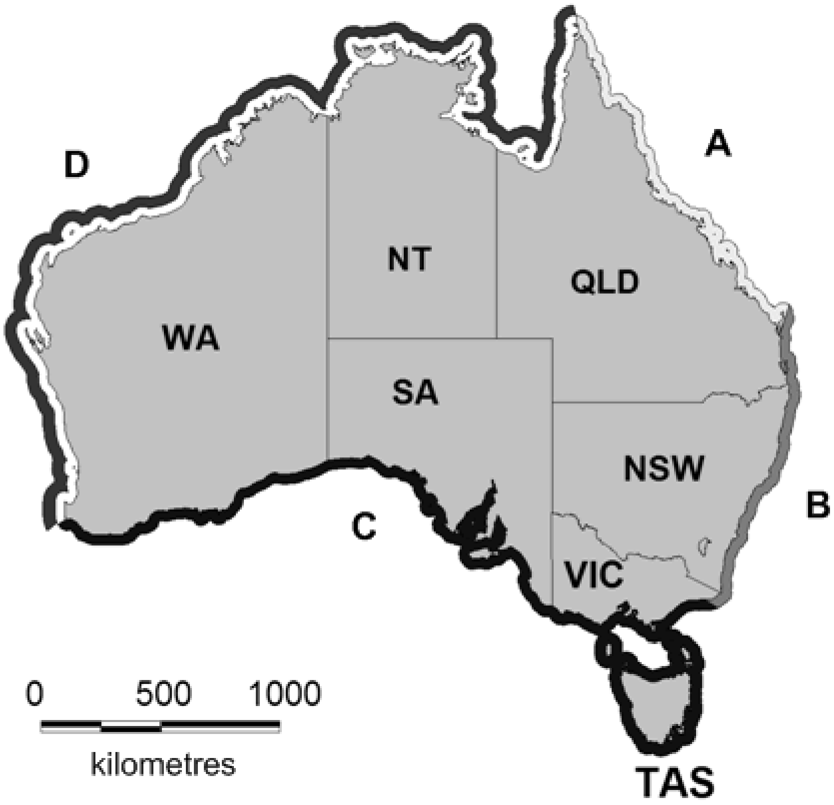

Figure 1.2. The four major biogeographic provinces of Australia: A Solanderian; B Peronian (includes Lord Howe and Norfolk Islands); C Flindersian; and D Dampierian (includes Cocos, Keeling and Thursday Islands and Ashmore Reef) (Campbell and Hewitt 2011, as adjusted from Poore 1995).

With the increasing number of introductions comes an increasing variety and magnitude of potential impacts from ANS. These impacts occur over a variety of values (environmental, economic, social, cultural and human health, hereafter referred to as 'core values'; Campbell 2008) and scales. In an environmental context, ANS can have negative effects at the species level (e.g., *Sargassum muticum* dominates the eelgrass *Zostera* via prevention of recolonization in Brittany, France; den Hartog 1997), community level (e.g., *Musculista senhousia* alters community assemblages via their mat-forming byssal threads in Tamaki Estuary, New Zealand; Creese et al. 1997); and ecosystem level (e.g., *Potamocorbula amurensis* decreases pelagic production within the San Francisco Bay through filtration of the phytoplankton bloom; Alpine and Cloern 1992). As ANS expand their relative ranges, similar suites of ANS are becoming the dominant species at local and regional scales, leading to a loss of community biodiversity and eventual 'biotic homogenization' (McKinney and Lockwood 1999). To make matters worse, ANS impacts can synergistically combine with other human-mediated impacts such as habitat destruction, pollution and climate change (Bianchi and Morri

2000), or facilitate the success of other invaders, increasing the overall impact and potentially leading to 'invasional meltdown' (Simberloff and Von Holle 1999). As eradication, or control of these species is extremely difficult, costly, and oftentimes impossible once established, prevention is not only more economically efficient, but also often necessary to prevent impacts from occurring (Mack et al. 2000). However, accurate prediction as to which species will establish, spread and have impacts in order to aid prevention measures remains generally unsuccessful (Carlton 1996b, Ricciardi 2003, Guo 2006), particularly given the lack of necessary information (Nyberg and Wallentinus 2005).

Despite the difficulties in identifying invasive ANS, measures to prevent these ANS are recognized as necessary given the potential severity of their impacts (Bax et al. 2003). These measures often focus on ANS vectors, as a limited number of vectors are responsible for the majority of unintentional introductions, namely ballast water and biofouling (Rigby et al. 2003, Hewitt and Campbell 2008). Ballast water (as a vector) refers to the uptake and release of organisms during ballasting and de-ballasting operations (respectively), which are necessary to maintain trim, stability, propeller immersion, and safe levels of hull stress during travel or in port (Victorian Government 2006, IMO 2011). Biofouling (i.e., vessel fouling or hull fouling) refers to the association of aquatic organisms with objects immersed in water, including the hulls and ancillary gear of commercial and other vessels, as well as sea chests (Coutts et al. 2003, Hewitt et al. 2004a, Hewitt et al. 2004b, Tavares and Melo 2004, Coutts and Dodgshun 2007). Fouling species and associated species (including small fish, barnacles, mussels, sponges, algae, crabs, and sea squirts) foul ships via attaching to the wetted surface areas, or finding refuge within the matrix of the fouling community and protected areas (e.g., sea chests) (Coutts et al. 2003). Once ANS enter ballast tanks or colonize a vessel, they are carried between ports and inoculation occurs via release (ballast water) or spawning and/or physical removal (of fouling), with subsequent opportunity for establishment, spread and impact (Hewitt et al. 2009).

While ballast water has been often cited as the primary vector for ANS transfer, biofouling has also been identified as a significant vector (Woods Hole Oceanographic Institution 1952, Cohen and Carlton 1995, Cranfield et al. 1998) that in some areas is responsible for more introductions than ballast water (Eno et al. 1997, Coutts 1999, Drake and Lodge 2007, Hewitt and Campbell 2008). For example, biofouling is potentially responsible for 78.3% of ANS in Port Phillip Bay, Australia (Hewitt et al. 2004a); 69% of introduced marine species in New Zealand (Cranfield et al. 1998); and over 50% of vessel-mediated introductions in the North Sea (Gollasch 2002). Biofouling species also have significant impacts on the marine environment, natural resources and industries (e.g. aquaculture, fisheries, tourism, commercial shipping, and marine infrastructure). In Australia, eradication and control of the black striped mussel, *Mytilopsis sallei*, alone resulted in costs over A$2.2 million and death of all other organisms in the treated area (Willan et al. 2000, Bax et al. 2002). Similarly, in the United States, damage from the zebra mussel, *Dreissena polymorpha*, and quagga mussel, *Dreissena rostriformis bugensis,* has exceeded US$1 billion (Pimentel 2005).

In addition to the overall increase in vector strength cited above, the risk of introductions due to biofouling may increase due to several factors. First, the *International Convention on the Control of Harmful Anti-fouling Systems on Ships* (enforcement initiated in 2008) bans the use of a common anti-fouling system (AFS), tributyltin (TBT). The absence of an effective and low-cost alternative AFS is likely to result in an increased level and diversity of fouling and introduction potential (Nehring 2001, Lewis et al. 2003), as hulls without TBT as an anti-foulant have shown to have greater biomass than control panels (Jelic-Mrcelic et al. 2006). Second, the 2007-2009 global economic recession has slowed or halted a significant amount of vessel traffic. During the first quarter of 2009, 10% of containerships and 25% of refrigerated vessels were taken out of service and anchored for months near Malaysia, Indonesia and the Philippines due to low anchoring fees (Floerl and Coutts 2009). This may increase the risk of ANS transfer as the economy improves and these vessels re-enter trading activity, as time spent at anchor allows for an increased accumulation of fouling species and can render AFS less effective (Coutts 1999). This is particularly relevant given that southeast Asia is an important trading partner with Australasia, Europe and the Americas, with a number of dominant shipping hubs (e.g., Singapore, Hong Kong, Tanjung Pelepas; Slack and Wang 2002, Lee et al. 2008). It is exacerbated by the cost and time commitments for dry-docking to properly remove the fouling and re-apply AFS. Many ships may undergo in-water cleaning, which has the potential to trigger a reproduction event or remove viable adult organisms with the potential to establish (Floerl and Coutts 2009).

Management of the ANS threat via aquatic biosecurity

Vectors such as biofouling are commonly managed under a suite of tools collectively known as aquatic biosecurity. Aquatic biosecurity involves national, regional, and international efforts to prevent, reduce and manage the introduction of pests and diseases in order to reduce the threat to core values (Hewitt et al. 2004b). This is done via entry and border surveillance and the provision for short-term response and long-term control of established pests (Hewitt et al. 2004b). Biosecurity responds to both intentional (e.g., bioterrorism) and unintentional (e.g., vessel-mediated ANS) threats (Hewitt et al. 2004b).

Elements of biosecurity include pre-border, border and post-border management (Hewitt et al. 2004b). Pre-border management involves understanding and predicting the relative risks presented by various pathways or species, then using this information to manage and minimize harm. Pre-border tools include vector-based activities such as ballast water exchange and hull cleaning before arrival, as well as tools often utilized by the receiving entity, including Import Health Standards and risk assessment (Hewitt 2003b, Hewitt et al. 2004b). Border management addresses the issue at the stage of arrival and includes treatment of fouling or ballast water, as well as education and outreach efforts to prevent future threats. Finally, post-border management depends on detection, eradication and control activities (Hewitt et al. 2004b). As prevention is often the most technically and economically feasible option, pre-border management, and particularly risk assessment, is often the focus of biosecurity efforts.

Risk assessment is an important tool in aquatic biosecurity for several reasons. Namely, risk assessment facilitates efficient and effective ANS management by allowing managers to determine the relative risk of various species, pathways, and vectors, and thus effectively allocate available resources (Andersen et al. 2004). In addition, risk assessment is required by the World Trade Organization (WTO) Sanitary and Phytosanitary (SPS) Agreement to justify national or regional biosecurity policies that may affect trade (e.g. the development or review of import standards, surveillance programs, and incursion responses) (Campbell et al. 2009). The SPS Agreement allows national sovereignty in setting the acceptable risk, but specifies that these policies (based on the associated risk assessments) must be science-based and transparent, minimize negative effects on trade, and make an attempt to cooperate and harmonize with other international standards (WTO 1995). Given the efficiency of prevention versus control or removal efforts (Bax et al. 2003), the use of risk assessment for aquatic biosecurity is often related to prevention measures such as: the development of Import Health Standards (Campbell 2009); the determination of likely species of concern or 'next pests' (e.g., Hayes and Sliwa 2003); and the assessment of which vectors and pathways present the greatest risk (e.g., GloBallast in Clarke et al. 2004, Hewitt and Campbell 2007).

Risk Assessment Background

Risk is present in many common actions and events and consequently, risk assessment often occurs informally to compare the potential negative and positive trade-offs of a threat (Tulloch and Lupton 2003). A formal risk assessment is an essential element of the decision-making process because it clearly defines the components of the decision involved (Williams et al. 2008). This helps take into account all potential impacts (National Research Council 1996a, Byrd and Cothern 2000), including those on core values that may have gone unrecognized without a formal impact assessment process. Risk assessment is also a valuable tool for managing threats efficiently by allowing managers to determine what risks are most significant, the magnitude of that significance, and using this knowledge to subsequently set management priorities (Byrd and Cothern 2000). Flexibly managing risk in this manner can save time and money, as it allows management to identify and respond to the highest-risk threats (Haugom et al. 2002).

Risk terminology and definitions vary according to differences in the context or field, the risk assessor's preferences, and the view of risk as a function of probability (the likeliness that an event will occur) or utility (a combination of the likelihood and impacts of that event) (Shrader-Frechette 1991, Byrd and Cothern 2000). These definitions include "the possibility of loss or injury" (Merriam-Webster 2011); "the probability of future loss" (Byrd and Cothern 2000); "effect of uncertainty on objectives" (Standards Australia 2009); and "a concept used to give meaning to things, forces, or circumstances that pose danger to people or to what they value" (National Research Council 1996a). For consistency, risk is defined within this thesis as the possibility that human actions or events lead to consequences that harm aspects of things that humans value (*sensu* Klinke and Renn 2002). Risk assessment is defined as the process of determining the probability (likelihood) and impacts (consequences) of that event (Hayes 1997).

Risk assessment is part of the risk analysis process, which is comprised of risk assessment, risk management, risk communication, and risk policy[1] (Byrd and Cothern 2000, Arthur et al. 2009). Risk management involves analysing and choosing the best options to reduce, eliminate or otherwise address the risk. This involves weighing a variety of options (including take no action, gather more information, or find methods to reduce the risk) and implementing the most effective option (Byrd and Cothern 2000, Andersen et al. 2004). Risk communication helps to clearly express the information and consequences surrounding the risk to the relevant stakeholders and/or public (Morgan et al. 2002). Risk policy surrounds the entire process of risk analysis and includes developing guidelines for each component to improve the structure and process of risk analysis (Andersen et al. 2004).

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[1] There is some debate on the respective use of "risk analysis" and "risk assessment". Most risk analysts use the definitions provided in Byrd and Cothern (2000), but some organizations (such as the U.S. Department of Defence) reverse the definitions so that risk assessment refers to the entire process (i.e. risk analysis, risk management, risk communication and risk policy). For the purposes of this thesis, "risk analysis" refers to the entire process and "risk assessment" refers to the process of determining the likelihood and consequence.

Types of risk assessments

Because of the wide variety of factors influencing risk assessment (e.g., discipline containing the risk, cultural values and desired outcomes) there is no standardized method or framework. However, certain cross-cutting concepts do exist; a comprehensive risk assessment process generally includes the following components: (1) identifying endpoints; (2) identifying hazards; (3) determining likelihood; (4) determining consequences; and (5) calculating risk (Standards Australia 2009).

1) Identifying endpoints. Assessment endpoints are the values (defined via a specific entity and its measurable attributes) potentially affected by a hazard that the risk assessment aims to protect (Sergeant 2002). For example, a biosecurity risk assessment may measure the risk of an ANS by its effects on biodiversity or water quality. The endpoints should be ecologically and managerially relevant, as well as susceptible to the hazard (Sergeant 2002). The choice of endpoints is a result of the assessor's values and subjective judgment; though each field may have suggested endpoints, there is generally no standardized list. Because of this subjectivity and dependence on political, social and other considerations, the endpoint(s) and acceptable levels of impact to the endpoint(s) should be externally established before the risk assessment is underway (Hayes 1997). In ecological and aquatic biosecurity risk assessment, this is a challenging process because the endpoints are often diverse, numerous and may include subcomponents[2] from each of the core values[3] (e.g., biodiversity within the environmental core value). However, establishing endpoints is a useful and necessary step to meet legal requirements, set limits for damage, serve as models for the creation of additional, situation-specific endpoints, further develop risk assessment frameworks, facilitate action by risk managers and set standards for monitoring (Suter 2000).

2) Identifying hazards. A hazard consists of an object or event that has the potential to cause harm under specific conditions that allow that risk to be realized. In order to assess the hazard, both the object (e.g. a vector, trade route, or species) and the conditions (e.g. the recipient port environment) are considered (Hewitt and Hayes 2002).

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[2] A specific type of impact, within a core value, that has a unique unit, method and description for the measurement of consequence or impact (Campbell 2005, Campbell and Gallagher 2007).

[3] The main types of values (i.e., things that are important to people, government, industry etc) that impacts are assessed against. These include environment, economic, social, cultural and human health factors (e.g., Campbell 2008).

3) Determining likelihood. Once the hazards are identified, risk assessment requires an estimation of an event's likelihood (e.g., the probability of ANS incursion or establishment). The likelihood is usually described in qualitative, semi-quantitative, or quantitative terms.

4) Determining consequences. The consequences are the impacts or effects of the hazard on a range of values (as defined by the assessment endpoints). The consequence assessment can include descriptions of the impact magnitude, frequency, spatial extent, and duration/reversibility. While generally negative, it should be established beforehand if the assessment is to include positive and negative, or negative only impacts. Consequence assessment requires understanding of the baseline conditions, analysis of the actual impacts, and a determination of the significance of the consequences (Westman 1985).

5) Calculating risk. For each core value, the likelihood estimates are considered against the consequence estimates to produce a final risk estimate. This is often done quantitatively or qualitatively using risk matrices. Risk matrices are tables with vertical and horizontal headings that correspond to likelihood (i.e., probability, frequency, etc) and consequence (i.e., impact, severity, etc) (e.g., Campbell 2008, Standards Australia 2009). Each cell of the table corresponds to a combination of these two factors (often coloured green, yellow and red) and provides a risk estimate that can be used to determine appropriate management actions (e.g., Table 1.1) (Cox 2008).

Table 1.1. Qualitative risk matrix (Standards Australia 1999)

	Consequences				
Likelihood	***Insignificant 1***	***Minor 2***	***Moderate 3***	***Major 4***	***Catastrophic 5***
A (almost certain)	High	High	Extreme	Extreme	Extreme
B (likely)	Medium	High	High	Extreme	Extreme
C (possible)	Low	Medium	High	Extreme	Extreme
D (unlikely)	Low	Low	Medium	High	Extreme
E (rare)	Low	Low	Medium	High	High

Ecological Risk Assessments

The initial application of risk assessment was in non-environmental fields (e.g., finance and insurance); the first environmental risk assessments were spurred by the Piper Alpha oil platform disaster of 1988, as well as the increasing attention to the threat of toxic chemicals on human health (Committee on the Institutional Means for Assessment of Risks to Public Health 1983). Ecological risk assessment began, informally, with the US *National Environmental Policy Act* (NEPA), which required the preparation of an environmental impact statement for any action that significantly effects the environment. Many of the early ecological risk assessment methods were based on those from chemical risk assessments, a model established by the US National Research Council in 1983 (Hayes 1997).

In 1990, the US Environmental Protection Agency (EPA) Science Advisory Board released *Reducing Risk: Setting Priorities and Strategies for Environmental Protection*, which recommended that the US EPA should consider the reduction of ecological risk as important as the reduction of human risk (Byrd and Cothern 2000). As a result, the US EPA used components from the chemical risk assessment framework to develop their *Framework for Ecological Assessment* (1992), which focused on ecosystem effects. While a first step in providing a risk assessment method for aquatic biosecurity, this framework is insufficient to serve as a standard framework to assess the risk from the wide range of environmental hazards. For example, the considerations for an aquatic biosecurity risk assessment will be different from many standard ecological risk assessments, e.g., highway construction through wetlands or nonpoint source air pollution (Hayes 1997).

In 1995, the Council of Standards Australia and Council of Standards New Zealand developed the first edition of the risk management standard AS/NZS 4360, which has been subsequently used by the Australian government (e.g., Commonwealth of Australia 1996) and forms the basis for the first international risk management standard, AS/NZS ISO 31000:2009 (Standards Australia 2009). AS/NZS ISO 31000:2009 are generic guidelines intended for adaptation based on the relevant objectives and projects across disciplines. In 2007 (updated in 2009), the Australian Department of Agriculture, Forestry and Fisheries (DAFF) released their Import Risk Analysis Handbook. The purpose of this handbook is to prevent or control the intentional import and subsequent establishment or spread of pests and diseases that could cause significant harm to people, animals, plants and other components of the environment (DAFF 2009), given the relevant obligations under the WTO SPS Agreement and risk assessment standards under the IPPC and OIE.

Aquatic biosecurity risk assessment frameworks

The differences between aquatic biosecurity and ecological risk assessments result from several characteristics of biological hazards: (1) biological stressors reproduce and multiply, which can lead to a time lag between when a species is introduced and when it imposes the full impact; (2) biological stressors disperse in a variety of ways that are more difficult to predict than chemical dispersal; (3) it’s difficult to predict biological interactions with biotic and abiotic ecosystem parts;

and (4) biological stressors have the potential to evolve and adapt (Suter 1993, Simberloff and Alexander 1994, Stohlgren and Schnase 2006).

Although most biosecurity risk assessments contain the same general components (likelihood and consequence), there is no standardized framework: each assessment requires decisions regarding the drivers, focus, likelihood and consequence considerations, and type of analysis (Campbell 2009).

- Drivers. The assessment can be quarantine-driven or impact-driven. A quarantine-driven assessment focuses on the likelihood component (assumes impacts are significant) and uses likelihood as the indicator of risk. Impact-driven assessments use a combination of likelihood and consequence to determine the highest risks (Campbell 2009).

- Focus. The focus of the assessment can be at the species, vector or pathway level. Species-focused risk assessments may be applied to intentional or unintentional introductions or translocations to help identify high risk ANS (Azmi 2010, Hewitt et al. 2010). Vector-focused risk assessments identify, within a vector (e.g., vessels or aquaculture gear), which activities or objects pose a risk. Pathway-focused risk assessments compare relative risk between vectors or “nodes” (e.g., ports, harbours or in-water cleaning stations) (Campbell 2009, Azmi 2010).

- Likelihood. To estimate the likelihood component, the assessment can choose from several methods, such as environmental matching or species-specific assessments. Environmental matching methods compare environmental conditions (e.g. temperature, salinity) between the donor and recipient ports or locations, under the assumption that high similarity will indicate a greater chance of successful organism establishment or spread (Hayes 2003). However, which environmental characteristics make the best predictors of these events is relatively unknown (Mack et al. 2000) and remains elusive despite significant effort to determine global characteristics of invasive species (Enserink 1999, Williamson 1999, Kolar and Lodge 2000). The species-specific approach selects a species or suite of species to assess via comparisons of the species’ life history and physiological traits to the environmental conditions in the recipient port or location (e.g., Kolar and Lodge 2002, Clarke et al. 2004, Gollasch 2006, Bomford et al. 2010). The environmental matching approach requires less data but can have a less conservative outcome than a species-approach (resulting in a finding of artificially low risk) because apparent environmental differences may be less than the data suggest or may not actually present a barrier to a species’ successful introduction, establishment or spread (Hayes 2003, UNEP/MAP-RAC/SPA 2008). For example, the water hyacinth, *Eichhornia crassipes*, was introduced to ornamental ponds in Florida, but has spread beyond what its native range (Amazon basin) would suggest, throughout much of the southeast US and as far north as the top of California's central valley (Mack 1996). Species-based assessments require greater amounts of data (e.g. species distributions, reproductive characteristics, physiological constraints and environmental preferences) and often have more conservative outcomes than an environmental-matching approach (resulting in a finding of artificially high risk) (UNEP/MAP-RAC/SPA 2008).

- Consequence. Of the two risk components (likelihood and consequence), more effort has been focused on the likelihood component, with consequence assessment receiving relatively little attention (Parker et al. 1999, Hayes et al. 2004). This is partially due to the scarcity of ANS impact data, and, when available, its existence in a form inaccessible or not easily digested by resource managers (Byers et al. 2002). Within consequence assessment, there are several major considerations: the choice of values to assess; how to measure the impact for each value and categorize the consequence to these values; the choice of assessment methodology; the influence of risk perception; the use of various information types; the management of uncertainty (ambiguity, knowledge gaps, systematic and random measurement error, and variability); and the use of precaution to address this uncertainty (Campbell 2008, 2009).

- Type. The assessment can be quantitative, qualitative or semi-quantitative (Hayes 1997).

  - Quantitative assessments place numerical probabilities or descriptors on the elements of the risk assessment. Subsequently, they have been viewed as more objective and accurate, with less potential for misinterpretation (Fiorino 1989). However, while these beliefs are potentially valid with sufficient information, they require large amounts of data, financial and other resources (Campbell 2009). While occasionally used in aquatic biosecurity (e.g., Stone et al. 1997, Hayes and Hewitt 2000), there is generally not enough information or resources to complete a quantitative analyses for ANS (Ricciardi 2003). While possible to complete a quantitative analysis with insufficient information, the results may not justify the effort (Morgan and Henrion 1990).

  - Qualitative assessments use categorical descriptors such as "low", "medium" and "high" to determine comparative levels of risk. They are relatively inexpensive, quick, simple, feasible (when little data is available), and more easily interpreted by those without risk assessment experience (Byrd and Cothern 2000). However, they are sometimes criticized for containing greater uncertainty due to the influence of subjective judgment and perception, and leading to difficulty in making management decisions, especially when resource trade-offs are necessary (Hayes 1997, Cox 2008).

- Semi-quantitative assessments combine qualitative and quantitative data to create categorical descriptors of likelihood (with associated probabilities expressed as a percentage) and consequence (with qualitative or quantitative descriptions of each level) to determine risk (Campbell and Gallagher 2007). Semi-quantitative assessments often use quantitative data, but represent the data and outcomes in a qualitative manner. Qualitative data can also be added to the assessment and would include situations where data has been captured and combined with stakeholder and expert perceptions and empirical data (Hewitt et al. 2010).

Uncertainty and false certainty

Uncertainty constitutes an inherent component of risk given the unknown characteristics of a threat and the associated predictive efforts of assessing the risk of that threat (Morgan and Henrion 1990, Yates and Stone 1992). Uncertainty is a concept with as many definitions as disciplines in which it occurs. Both uncertainty and the related fields of risk assessment lack a shared definition of uncertainty and related terminology (Walker et al. 2003). However, when describing the typology of uncertainty, a common delineation occurs between epistemic and ontological varieties (Walker et al. 2003, Cooney and Lang 2007). Epistemic uncertainty stems from a lack of knowledge and can be ameliorated via additional research or similar efforts (Walker et al. 2003). Ontological uncertainty stems from the inability to fully describe a variable and complex environment and cannot be eliminated (Walker et al. 2003).

In an impact assessment context, these two types lead to several specific sources of uncertainty, including: (1) knowledge gaps; (2) systematic and random measurement error (e.g., flawed measurements and uncertain or inappropriate models); (3) indeterminacy (unavoidable, stochastic behaviour between hazard and impact); (4) variability (the variety of impacts that the same hazard can have in different locations of time and space); and (5) ambiguity (e.g., different interpretations of the same data set) (Byrd and Cothern 2000, Klinke and Renn 2002).

Using the Walker et al. (2003) definition of uncertainty, “any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system”, another source of uncertainty is the ‘false uncertainty’. False certainty stems from interpretation error where the assumption of an outcome is overstated or overly simplified, such as the interpretation of a statistically non-significant result as inferring “no impact”, despite low power (i.e., a low probability of detecting an effect, given there is one). In an impact assessment context, this false certainty can obscure ANS effects on a native species, community or ecosystem due to insufficient sample or effect size or inappropriate experimental design, leading to Type II errors.

Uncertainty and risk management

Both reducible and irreducible forms of uncertainty have implications for risk management (Smithson 2008). Epistemic uncertainty, which can often be identified and addressed through additional research or including alternative forms of knowledge, undoubtedly presents a challenge to risk management (Walker et al. 2003). In an ANS risk assessment context, this includes understanding what forms of uncertainty exist and to what extent, finding ways to reduce this uncertainty that are acceptable to expert and stakeholder groups as well as international trade bodies such as the WTO, and finally, implementing these methods using the (often limited) resources available to aquatic biosecurity agencies. However, in situations in which uncertainty cannot be reduced, for reasons of an ontological or practical nature (such as time or other resource constraints), risk management is faced with a more difficult task. That is, making decisions despite extensive knowledge gaps, in which subjective expert and stakeholder judgment play a key role and controversy or disagreement are common (a state described by Kasperson as 'deep uncertainty'; Kasperson 2008).

Both expert judgment and precaution have been proposed as methods to mitigate uncertainty, with challenges associated with each (Stirling and Gee 2002, Teck et al. 2010). Expert judgment is used in many environmental contexts with general success in minimizing the effects of uncertainty in reaching a decision (e.g., Meyer and Booker 1990, Campbell and Gallagher 2007, Therriault and Herborg 2008, Donlan et al. 2010, Teck et al. 2010). However, it is susceptible to subjective factors that influence the cognitive decision-making process (i.e., heuristics and biases) (Smithson 2008). Precaution is a tool used in environmental management, positing that the presence of uncertainty shall not prevent measures to prevent or minimize significant harm (Peel 2005). The Convention on Biological Diversity (CBD) not only directs Members to use precaution, but also to "prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species" (CBD Secretariat 1992). This suggests that uncertainty within ANS risk assessment should be managed in a precautionary manner, i.e., assume "guilty until proven innocent" and implement measures to mitigate the threat (Campbell et al. 2009). However, the application of precaution is fraught with criticisms and viewed as "unscientific" by many individuals and regulating bodies, including the WTO (Tucker and Treweek 2005, Peterson 2006). In addition, due to the context-dependent application of precaution, there is no common prescription for how and when precaution should be applied (Peel 2005). Understanding when the use of expert judgment and the application of precaution are appropriate, and how they should be incorporated into the risk assessment process, presents significant challenges (Peel 2005).

Challenges for aquatic biosecurity risk assessment

In response to the general recognition of gaps, redundancies and inconsistencies in terminology, content, and process within measures on the prevention, early detection, eradication and control of invasive species, the CBD Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) reviewed relevant national, regional and international measures (Subsidiary Body on Scientific Technical and Technological Advice 2001). The review found gaps in regulatory frameworks for animals that are not pests of plants (or, are pests but of marine plants), as well as for the ballast water and hull fouling vectors (Subsidiary Body on Scientific Technical and Technological Advice 2005). The report also found varying levels of understanding, interpretations and application of precaution in the resolution of uncertainty (Shine 2006). This review of the regulatory framework suggests the presence of gaps and/or inconsistencies in aquatic biosecurity measures aimed at the ballast water and hull fouling vectors, and specifically, aquatic biosecurity risk assessment frameworks, at the national, regional and international level.

Challenges for aquatic biosecurity consequence (impact) assessment

While a relatively large number of articles have been published on the impacts of ANS, literature providing an impact assessment framework applicable in a marine biosecurity risk assessment context is lacking (Parker et al. 1999). That is, frameworks that can provide broad descriptions of varying impacts for a broad suite of species, account for uncertainty, and are easily integrated and prioritized to inform policy development or management action, are scarce (Parker et al. 1999). While several articles provide a framework to categorize a subset of potential impacts, they are often limited taxonomically, spatially or by impact type. For example, Ruiz et al (1999) completed an impact assessment that, while comprehensive in its treatment of nine types of environmental impacts (competition, habitat change, food-prey, predation, herbivory, hybridization, parasitism, toxicity and bioturbation) by 196 ANS in Chesapeake Bay, did not include other core values.

Aims, hypotheses and thesis structure

In the face of a growing ANS threat, scientists and managers look to risk management strategies to minimize or eliminate this threat (Hewitt and Hayes 2002). However, these are limited by the presence of significant gaps and inconsistencies in existing national, regional and international aquatic biosecurity risk assessments, as well as uncertainty within the knowledge and process used in the assessment (Dahlstrom et al. 2011). Policy and regulatory bodies require assessors to make decisions of consequence in the presence of significant uncertainty and scarce resources (resources necessary to ameliorate that uncertainty through additional research) (Hattis and Anderson 1999). As such, this thesis intends to identify these broad gaps and inconsistencies, then focus on the identification of uncertainty, how uncertainty affects expert judgment, methods to reduce this uncertainty (when possible) and (when not possible) outline measures for estimation of ANS consequence that are transparent and allow for varying degrees precaution. Understanding the implications of uncertainty, as well as effective measures to mitigate these implications, will lead to more successful risk-based management of ANS. This chapter reviews the increasing threat of ANS impacts juxtaposed against the uncertainty surrounding risk-based decision making. These considerations provide the foundation for the aims and structure of the following chapters.

To this end, in Chapter 2 (publication provided in Appendix A) I use thematic analysis to compare the various components of biosecurity risk assessment frameworks for 14 national, regional and international biosecurity instruments, including the risk definition, risk assessment principles, terminology, information type, likelihood and consequence considerations, core values and subcomponents, and mention of precaution and uncertainty. Based on the weaknesses discussed above, I expected the review to find variety in the content and sufficiency of both the descriptions and prescriptive directions for many of the framework components. The outcomes of this review are used to identify similarities, differences, and deficiencies in the frameworks and from these provide recommendations to improve the content and process of aquatic biosecurity risk assessment.

Despite significant sources of uncertainty in ANS management, such as knowledge gaps, confusing terminology and spatial and temporal variability, the review of biosecurity risk assessment frameworks found limited mention of how to address and mitigate this uncertainty. Where the frameworks do address uncertainty, they offer the use of expert judgment (often via the Delphic process) and precaution as potential solutions, but with limited guidance as to their implementation. As such, in Chapter 3 I survey ANS science and management experts to identify where and in what forms uncertainty exists and how it can be best addressed in a consequence assessment context. I also hold a 'mock' consequence assessment exercise using a subset of ANS to both determine the effects of uncertainty on consequence estimates, and test the functionality of a Delphic process in aiding such decision making under uncertainty. Experts were challenged to identify significant sources of uncertainty, particularly due to knowledge gaps, with moderate endorsement of precaution and limited endorsement of alternative information sources (such as using observational information) to make an assessment. I also anticipated that the Delphic process would decrease uncertainty. Based on the outcomes of the survey and consequence assessment, I present methods to facilitate the completion of consequence (and hence, risk) assessments in the presence of reducible and irreducible uncertainty in a manner that is supported by the experts providing the input, and thus in accordance with the science-based mandates of the WTO.

Chapter 4 explores the effect of uncertainty on the cognitive decision making process in a biosecurity risk assessment context via the relationship between uncertainty and consequence estimates observed in Chapter 3. This chapter also includes investigations into the effect of several other heuristics and biases affecting the perception of a species consequence on core values. Given that both normative decision theories and the use of precaution posit that decision making under uncertainty should maximize expected value via erring on the side of caution to avoid making Type II errors, it was anticipated that assessors would assign greater consequence when faced with irreducible uncertainty. However, descriptive models repeatedly find that uncertainty leads to the use of cognitive heuristics and biases. As such, I anticipated that several biases would differentially affect the estimates for several species, such as those from a genus well-known for severe impacts (e.g., *Caulerpa*) or those having economic impacts (e.g., *Bonamia ostreae*) as opposed to environmental impacts. Understanding the cognitive processes in, and influences on, expert decision making process will provide for a more transparent risk assessment process and facilitate the development of measures to mitigate or account for these influences (where appropriate).

In addition to the traditional forms of uncertainty addressed in Chapters 3 and 4, the false certainty arising from low-powered statistical analyses that find an insignificant statistical effect may have severe implications for biosecurity risk assessment and management. Chapter 5 uses algal and crustacean ANS impact studies to determine the prevalence of low power in risk and impact-based research. Given the traditional use of a null hypothesis that assumes no difference between treatments (central to significance testing methods), combined with the low acceptable rate of Type I errors (“false alarms”), I anticipated finding low power in many of the studies. Due to the implications of this potential outcome (i.e., high rates of Type II errors or “missing” an impact), I provide alternative impact assessment methods that incorporate the pre-determined acceptable level of risk and associated costs of each error type. These methods help align the respective needs and outcomes of biosecurity research and management, as well as improving the communication between the two sectors.

Chapter 6 synthesizes the outcomes of the previous chapters and provides implications for management efforts. It underscores the importance of a framework that can provide direction despite uncertainty and also incorporate policy mandates (such as acceptable level or risk) due to recent economic and political factors contributing to an increase in potential transfer of ANS. Present and growing global factors such as military expansion, local energy-related development, the global financial crisis, and regional trade agreements all lead to increased connectivity and hence increased risk of species introductions. The continued increase in the magnitude of globalization underscores the importance of developing a comprehensive risk assessment framework that can operate despite uncertainty. These factors highlight the importance of not only integrating scientific data when completing risk assessment, but also 'non-scientific' (e.g., economic and political) considerations into decisions of risk. I conclude with a model that provides transparent guidance for assessing consequence given both available and scarce information.

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Chapter 2:
Dahlstrom, A., C. L. Hewitt, and M. L. Campbell. 2011. A review of international, regional and national biosecurity risk assessment frameworks. Marine Policy 35(2) :208-217. doi:10.1016/j.marpol.2010.10.001

Chapter 3:
Dahlstrom, A., C. L. Hewitt, and M. L. Campbell. 2011. Mitigating uncertainty using alternative
information sources and expert judgment in aquatic nonindigenous species consequence assessment. Aquatic Invasions (in review).

Chapter 4:
Dahlstrom, A., C. L. Hewitt, and M. L. Campbell. 2011. The role of uncertainty and subjective influences on consequence assessment by aquatic biosecurity experts. Biological Conservation (in
review).

Chapter 5:
Dahlstrom, A. and C. L. Hewitt. 2011. Evidence of impact: low statistical power leads to false certainty of no impact for nonindigenous species. Nature (in prep).

CHAPTER 6. GENERAL DISCUSSION

Synthesis and implications for management

This research found two sources of information used in expert decision-making under uncertainty (personal opinion and available research) that influenced risk outcomes in a non-precautionary, or “hindsight” manner (nonindigenous species assumed innocent until proven guilty). This occurred despite the mention or endorsement of precaution by the majority of biosecurity risk assessments reviewed and views expressed by the experts surveyed. A non-precautionary outcome from expert-decision making occurred due to the assignation of low consequence when uncertain, potentially via a heuristic based on the scientific norm of assuming no impact without evidence (Figure 4.6). A non-precautionary outcome from the use of available research occurred due to the traditional statistical methods applied in the impact research. That is, the traditional focus on avoiding Type I errors led to a ‘false certainty’ of no impact when in reality, the low power led to potentially high rates of missing an impact.

The management implications of these findings are considerable. If uncertainty within ANS risk assessment is to be managed in a precautionary manner, as supported by experts and suggested by the Convention on Biological Diversity and others (Campbell et al. 2009), the response to scarce information and the treatment of available information requires a shift. To mitigate the non-precautionary tendencies in expert opinion ‘pre-assessment’, a modified Delphic process with a variety of available stakeholders may avoid the potential biases (identified in Chapters 3 and 4) and mitigate the effects of uncertainty on consequence estimates, as evidenced by the increase in consequence estimate after this process (Chapter 3, Figure 3.1). Specifically, to ensure a comprehensive assessment, the Delphic process should involve experts in a variety of core value areas, as the experts felt they were working at the edge of their expertise when asked to describe social and cultural impacts. Experts also supported using alternative information sources including empirical evidence from other regions or from similar species, as well as non-empirical evidence (Chapter 3). ‘Post-assessment’, managers can use the expert consequence estimates to make enlightened decisions, given awareness of the potential effects of the hindsight heuristic (assumptions of no impact without evidence). That is, group species into management quadrants by consequence and uncertainty (Chapter 4, Figure 4.8), so that those with high uncertainty and low consequence are left in the assessment (following expert indication that ANS have impact based on their nonindigenous status; Chapter 3) and treated with precaution. Risk assessors can also account for the effects of uncertainty and transparently apply precaution via expression of a range of risk outcomes using standard errors or a full span of the consequence estimates (Chapter 4, Figure 4.9). To mitigate non-precautionary outcomes resulting from the conventional uptake of available research, research to inform risk assessment can shift statistical focus on the conventional $\alpha=0.05$ to a focus on β, using the relative costs of each error type to then determine biosecurity spending (Chapter 5, Figure 5.4). That most experts (75-83%) indicated avoiding Type II errors as more important than Type I errors supports this shift (Chapter 3), as does other literature (e.g., Buhl-Mortensen 1996, Hewitt et al. 2006). The public source of most biosecurity-related funding for ANS research reinforces the importance of obtaining results useable for public benefit (i.e., risk assessment).

Given the outcomes of Chapter 2 to 5, I've developed a model for estimating species consequence given a range of information quality and quantity (Figure 6.1). Risk assessments do not occur in isolation, but are often completed as part of or due to political- and economic-related activity. As such, I use the concept of acceptable level of risk as a basis for the model to reflect policy obligations and also allow adaptability across agencies or countries. The increase in ANS numbers and impact types, budget limitations and global connectivity underscores the imperative for a risk assessment able to adapt to a variety of information sources, funding availability and policy backgrounds.

A response to uncertain risks, both new and old

While tempting to surrender hope of ANS prevention in the face of the ever-growing ease of vessel movement and the subsequent large and ever-growing threat and potential impacts of ANS, regional trade agreements may provide an opportunity for the regional coordination often been called for (Burgiel et al. 2006). For those individuals and organizations, a successful attempt at this coordination requires a clearly defined risk assessment framework (particularly for consequence assessment) that can be applied broadly.

Maguire (2004) suggests the use of a decision analysis framework analysis to help make decisions on invasive species management in situations of (1) uncertain outcomes of possible management actions; (2) many and potentially conflicting objectives for management; and (3) numerous stakeholders and their respective views. As such, and based on the outcomes of Chapters 2 to 5, I suggest a decision-making framework for ANS risk assessment under uncertainty (Figure 6.1; Table 6.1).

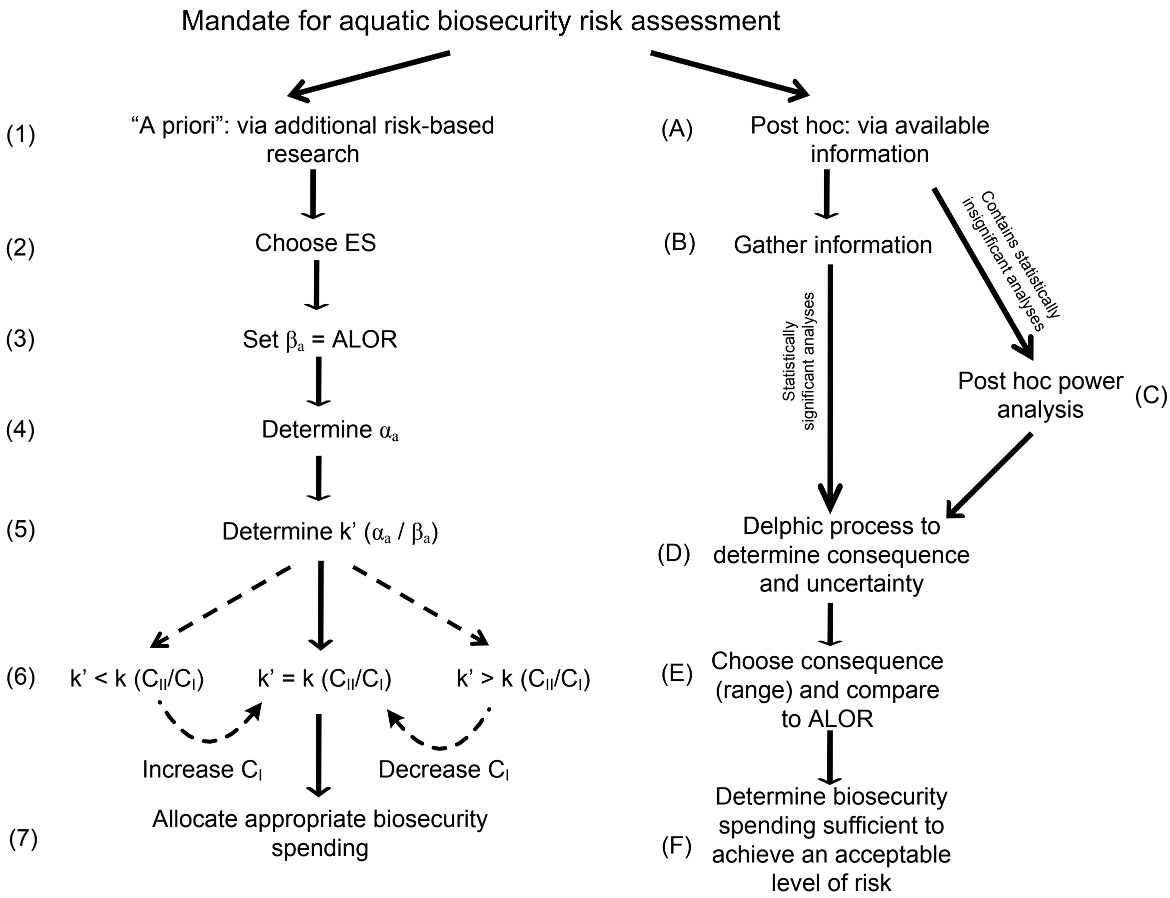

Figure 6.1. Proposed consequence assessment framework, given the mandate for a biosecurity risk assessment. ES = effect size; β_a = acceptable Type II error rate (β); α_a = acceptable Type I error rate (α); k' = ratio between acceptance criteria; and k=ratio between costs of Type II (C_{II}) and I (C_I) errors. Left side modified from Mapstone (1995). Additional description of each step provided in Table 6.1.

Table 6.1. Additional description of steps in the consequence assessment framework. The steps in *a priori* research and assessment use ALOR and costs of errors to determine appropriate statistical parameters and quarantine budget. The steps in *post hoc* assessment use available information, the Delphic process and the uncertainty consequence matrix to guide and optimize management decisions.

***A priori* research and assessment**	***Post hoc* assessment**
(1) Appropriate when proposing pre-assessment research on a threat and designing experimental parameters to reflect and test for the acceptable level of risk and/or impact. (2) Use consequence tables to translate qualitative description of risk/impact based on ALOR into semi-quantitative descriptors of effect size. (3) Choose acceptable level of β (e.g., if ALOR is very low, β=0.05). (4) Determine α based on *a priori* power analysis, based on effect size, feasible sample size and observed variation (e.g., from a pilot test). (5) k' represents the ratio between acceptable rates of Type I and II errors. (6) Determine k based on the costs of Type I and II errors. Adjust C_I until k = k'. (7) Use C_I to determine appropriate quarantine measures. If an increase in C_I sufficient to equal k' (and thus achieve the pre-determined experimental parameters) is not possible, the proposed policy or action responsible for the risk should be designated as unacceptable, and prohibited or modified accordingly.	(A) Appropriate in situations where time or other resource limitations require the use of existing information. (B) Gather all available information, including empirical research across geographic scales and for similar species, as well as alternative information sources such as observations or grey literature. (C) Studies with insignificant results should be scrutinized with *post hoc* power analysis and account for effect size and power. (D) Use the Delphic process to choose consequence and associated uncertainty levels, based on group discussion and gathered information. Potential assumptions and biases used in assigning impact (e.g., assuming no impact if unknown) should be discussed before beginning assessment. If appropriate as per risk policy, identify appropriate assumptions or other cognitive tools for participants to use when assigning impact (e.g., when studies present varying levels of impact, use that with the greatest magnitude). This process should not only include experts, but other relevant stakeholders as well (based on the core value under consideration). (E) Based on outcomes of assessment, use the consequence and uncertainty matrix from Chapter 4 to determine the consequence level. Risk policy should provide methods for how to choose this value (e.g., use highest, lowest, average, or mode assigned consequence). (F) If a budget necessary to reduce the risk is not available, the proposed policy or action responsible for the risk should be designated as unacceptable, and prohibited or modified accordingly.

This framework does several things necessary for use in a biosecurity context. It provides a transparent process and usable outcomes that: (1) integrate scientific process and management objectives; (2) are accountable for and unimpeded by uncertainty; (3) consider the assumptions used by the experts making the assessment; (4) can be adapted according to varying strengths of precaution desired by management; (5) follows WTO SPS Agreement mandates; and (6) are feasible given time and budget constraints.

1) Integrates scientific process and management objectives

When their potential application includes biosecurity- or trade-related policy, risk assessment outcomes must consider policy and management needs. Instead of the scientific analysis and management priorities remaining compartmentalized, an assessment that considers the respective objectives of both will provide an outcome amenable to both. For example, management often has difficulty making decisions under significant uncertainty (Jenkins 1996), including uncertainty due to interpretation of a risk assessment. If policy mandates a threshold level of risk or impact, communicating and developing an understanding of these parameters with the scientific community will allow for their integration into the assessment, thus providing (relatively) increased clarity for decision-making (Harlow 2004). Specifically, the framework must take into account the acceptable level of protection (or risk). For all its powers, science does not define terms like “acceptable” or “reasonable” (Crawford-Brown et al. 2004). Several agencies argue for the separation of risk assessment and risk management, but this research suggests that an *a priori* consideration of ALOR optimizes parameters such as statistical power and therefore reduces uncertainty (Figure 6.1).

An additional benefit of this integration is a transparent and supported process for setting and allocating items within a budget. Literature often focuses on tradeoffs between management activities based on cost-benefit analyses (Horan et al. 2002, Sharov 2004, Saphores and Shogren 2005, Fernandez 2008), but rarely integrates acceptable risk and uncertainty. This decision framework applies all of these factors in producing a suggested budget for management of the vector or species under consideration.

2) Accountable for and unimpeded by uncertainty

The sources of uncertainty challenging ANS risk assessment have been well-documented (Chapters 2 and 3), as has the importance of describing this uncertainty (Crawford-Brown et al. 2004). Due to this uncertainty, decisions to manage or ignore a vector with potential to introduce ANS are subject to error. Not only are the prices of these errors likely to be asymmetrical, with greater cost resulting from mistakenly ignoring a potential ANS (Buhl-Mortensen 1996), so too, are the distribution of those costs likely to be skewed, with the environment and public bearing much more than those responsible for the introduction (Maguire 2004). As such, there is a need for a framework that considers the cost of both types of errors and can provide outcomes despite uncertainty (given that an 'unknown' designation is not useful for management decisions and often interpreted as 'no risk').

3) Considers the assumptions used by the experts making the assessment

Those responsible for risk assessment often fail to consider the assumptions on which the experts involved base their judgments (National Plant Board 1999, Harlow 2004). Defining the assumptions resulting from experts' different worldviews will improve the risk assessment process (Harlow 2004) by identifying and (if appropriate) separating, or subjugating, these subjective influences in the decision-making process (Maguire 2004). The benefits include a more transparent and repeatable process and outcome, as well as a more harmonious and efficient discussion and interaction between the experts assessing the hazard.

4) Adaption according to varying strengths of precaution desired by management

Currently, most ANS management decisions are made based on the assumption that a species will not cause harm, unless sufficient evidence indicates otherwise – that is "innocent until proven guilty". The reason for the continued application of this dogma likely lies in the inertia gathered from a long history of use, as well as fiscal realities. The long list of species causing unpredicted environmental, economic, social, cultural and human health impacts would surely belie any claim that this is an optimal solution for environmental conservation (e.g., Williamson 1996, Mack et al. 2000). Indeed, the call for a reverse assumption, that is, "guilty until proven innocent", has been made repeatedly (Campbell 2001, Simberloff 2005), and primarily for the most anthropocentric of reasons: economic gain.

Despite arguments to the contrary, precaution in preventing ANS is often cheaper (Campbell 2001). Keller et al. (2008) tested the economic costs and benefits that would have been derived from choosing different thresholds to guide management of an invasive crayfish for several inland lakes, based on the net value represented by the difference between the cost of protecting a lake against the impact of the crayfish. They estimated the net value for several management strategies, that ranged from a low threshold of risk (most lakes were protected) to a high threshold of risk (few lakes were protected). They found low management thresholds produced financial gains of $32.8 million, a significantly greater total value over the 30-year time period than for any other policy (Keller et al. 2008). In addition, they suggested the net benefits of prevention efforts were likely underestimated for several reasons, including the benefits of management efforts would be greater than indicated because of the protection provided from other invasive species (Keller et al. 2008).

Economics notwithstanding, a degree of precaution will at least slow the human-induced degradation of ecosystems around the world by introduced species. Given the extensive services provided by these same ecosystems, such an effort will not only ensure our own survival but show at least some sign of respect for the non-human flora and fauna of the world.

5) Follows WTO SPS Agreement mandates

Available scientific evidence and economic analysis aside, any biosecurity activity that may impact trade must, for now, fall in accord with trade mandates, namely those of the WTO SPS Agreement. More often than not, precaution and the 'guilty until proven innocent' approach have been seen as failing in this respect (Campbell 2001). As such, the development of the framework provided included careful consideration of each of the relevant WTO principles and obligations to ensure the validity of any resulting biosecurity measure:

- National sovereignty. The framework allows Members to consistently and clearly apply their chosen acceptable level of protection (ALOP).

- Scientific principles and evidence. This is perhaps the most-oft cited principle in disputes of SPS measures, particularly those that may intend to apply some degree of precaution. Campbell (2001) states that to be 'science-based', a phytosanitary program should reflect the serious threat of ANS. The components and rationale for the framework provided (particularly those related to precaution) are based on input from scientific and natural resource management experts and reflect this threat. Bernstein (1983) supports the view that the rationality within scientific risk estimates is found in discussion between scientists of the content and process of the assessment.

- Harmonization. The review in Chapter 2 found insufficient guidance for Members to conduct a consequence assessment, particularly in conditions of uncertainty. This framework potentially provides a process for consistent consequence assessment across countries.

- Risk assessment. This process facilitates more effective and higher rates of completed risk assessments through flexible demands of time, resources and information.

- Transparency. This process clearly identifies the steps and their associated rationale, to allow a clear understanding by other Members.

6) Feasible given time and budget constraints

As a risk assessment is often the preliminary step necessary to trigger appropriate management efforts, a framework that doesn't require extensive resources is necessary for protection of threatened core values (Burgiel et al. 2006). Yet risk assessments under WTO standards are often expensive and time consuming (Lovell and Stone 2005). For example, risk assessments by US federal agencies can cost $500,000 (US Department of Agriculture 1991). The US Animal and Plant Health Inspection Service stated it considered solid wood packing material as one of the biggest threats in May 1998, but only released the risk assessment in late 2000, with an expected ruling five years after the threat was first recognized (Campbell 2001). In light of the increasing rates of trade, introductions and their synergies with other threats such as climate change, assessing the risk of trade policies must be achievable within shorter timeframes and limited budgets in order to keep up (Hulme 2009).

A risk assessment that is flexible in terms of required expertise, information and budget is particularly important for small island and developing countries and territories that often lack these resources (Mumford 2002, Burgiel et al. 2006), particularly given the increasing amount and variety of trade by these countries (Jenkins 1996). Despite a desire for biosecurity, the ability to become highly biosecure may just not be possible (Smith 1997). As a result of, and impetus to improving this situation, island ecosystems make up some of the most impacted and threatened in the world (Donlan and Wilcox 2008). Also contributing to the risk from ANS is the difference in imports as a percentage of GDP (given this factor's influence on invasion risk; Perrings et al. 2002): the average for island countries is 43%, continental countries 27%, and the overall average (of 26 countries) 32% (Dalmazzone 2000).

However, a risk framework amenable to developing or other limited-budget countries remains wanting (Harlow 2004). This lack of consideration has resulted in part from a 'lowest common denominator' of biosecurity protection that often fails to protect vulnerable countries (Burgiel et al. 2006). In addition to the environmental, economic and social injustice this represents, introduced species are a 'weakest link' phenomenon; one 'bioinsecure' country raises the risk for all (Perrings et al. 2000). Harlow (2004) has suggested that the limited ability by developing and island countries to develop and implement biosecurity policy in the face of rapid and significant increases in trade may require the application of precaution via methods that clearly show it is not mere protectionism – an approach afforded by the framework provided.

The provided framework may be subject to a variety of criticisms. Among these is the suggested change (increase) in the threshold of statistical significance, α. To this, I suggest a consideration of the different situations in which this α is applied (Crawford-Brown et al. 2004). In one, α is held as a standard for consistency and quality in drawing conclusions in peer-reviewed journals. Resulting Type I errors are often viewed as a necessary sacrifice for upholding reliable publishing criteria and their consequences are few. In the other, α is used as a standard for determining impact, upon which conclusions of consequence are made that will have repercussions in risk management decisions; Type I errors are realized in hindsight and their consequences can be severe (e.g., a devastating invasion). Given this discrepancy, I suggest the adjustment as to how, and by what measure, significance is determined, is appropriate.

I conclude that this framework: (1) integrates scientific process and management objectives; (2) accounts for and is unimpeded by uncertainty; (3) considers the assumptions used by the experts making the assessment; (4) can be adapted according to varying strengths of precaution desired by management; (5) follows WTO SPS Agreement mandates; and (6) is feasible given time and budget constraints. As these features can be applied for both *'post hoc'* and *'a priori'* risk assessment contexts, this framework provides a widely-applicable decision framework necessary to manage the ever-changing nature of aquatic introductions.

Future direction

The work from this thesis could be expanded in several directions. Some of the most currently relevant and potentially fundable ideas include: (1) exploration of how attitudes of terrestrial biosecurity and quarantine experts and agencies to uncertainty and precaution compare with these aquatic findings; (2) more in-depth power analysis of impact studies including a broader range of impacts and taxa examined; and (3) application of the experimental (specifically, statistical) approach described in Chapter 5 to actual field impact studies to determine improvements and usefulness.

At the very least, future ANS impact researchers must reconsider how they determine and display statistical outcomes. Given the small sample and effect size common to studies of nonindigenous species impacts, the focus on Type I errors and inattention to power is inappropriate. Studies funded via public monies should be required to discuss outcomes in terms of Type II errors and, in some cases, the acceptable level of risk or threshold consequences. This will ensure those unfamiliar with or simply forgetful of the assumptions used in frequentist statistical analyses (which include individuals in science, as well as policy) will properly consider the evidence and have the ability to apply it in a precautionary manner if desired. Alongside this, biosecurity risk assessments that include experts, particularly scientific experts, to inform risk outcomes, must take either pre- or post-assessment steps to account for the assignation of lower consequence due to uncertainty. While perhaps appropriate in other management areas, the high costs and irreversibility of Type II errors in biosecurity management actions necessitate a different, more precautionary, approach.

Conclusion

The outcomes of this thesis contribute to biosecurity risk assessment and management in several ways, primarily through closing the identified gap in existing frameworks around the treatment of uncertainty and precaution. The outcomes demonstrate that adding uncertainty estimates after making the consequence estimate may lead to under-management of ANS. The influence of uncertainty must be addressed up front, during the decision-making process, particularly if precaution is desired. A modified Delphic process that includes experts and stakeholders with a variety of backgrounds can assist in this process. In demonstrating that uncertainty does not always lead to higher consequence estimates, this thesis also adds to existing decision-making and risk perception research. Finally, the outcomes highlight that even when we have 'sufficient' evidence, its use at face value may not provide the full or correct picture due to low power or other considerations. In offering potential solutions and guiding frameworks, this thesis aims to provide useful means to a very important end: understanding both existing and novel ANS threats, in order to maintain the biotic and abiotic integrity of all shared values.

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Appendix A chapter 2 contains a published article and has been removed due to copyright or proprietary reasons

Chapter 2 :

Has been published as:

Alisha Dahlstrom , ChadL.Hewitt , MarnieL.Campbell A review of international, regional and national biosecurity risk assessment frameworks. Marine Policy 35 : pp. 208-217.

doi:10.1016/j.marpol.2010.10.001

Appendix B1: Table 1. Alternative information types considered by survey participants.

Primary literature: – Direct empirical evidence (laboratory) (e.g., controlled experiments with quantified impact) – Direct empirical evidence (field) (e.g. before-after-control-impact designs) – Extrapolation: experimental observations outside the region under consideration – Meta-analysis: Analysis of multiple data sets may be stronger than a single, controlled study due to the variety of information sources. A meta-analysis may also be necessary when time or other resources are insufficient to set-up and conduct a new experiment (Byrd and Cothern 2000)
Impacts that are published but do not cite experimental analysis
Expert judgment and opinion
Grey literature (e.g. websites, policy documents, databases, technical reports)
"Anecdotal" information (e.g. news stories, community newsletters)
Incomplete and/or unfinished scientific studies
Personal communications with scientists
Supported/verified observations (e.g. multiple reports from individuals knowledgeable about ANS management such as restoration planners, fisheries specialist, biosecurity managers, or park directors)
Unsupported/unverified observations (e.g. a single report from an individual knowledgeable about ANS management such as restoration planners, fisheries specialist, biosecurity managers, or park directors)
Lay knowledge (e.g. observational data from the experienced public such as port managers, long-term residents of a site, fishermen)

Appendix B1: Table 2. Precaution has many definitions, often grouped into three versions: weak, moderate and strong (Cameron 2006), as well as an unclear interpretation by the WTO.

Weak	The weak version is the least restrictive and *allows* preventive measures to be taken in the face of uncertainty, but does not *require* them (e.g., United Nations General Assembly 1992). To satisfy the threshold of harm, there must be some evidence relating to both the likelihood of occurrence and the severity of consequences. Factors other than scientific uncertainty, including economic considerations, may provide legitimate grounds for postponing action. However, not all forms require consideration of the economic costs of precautionary measures. Under weak formulations, the requirement to justify the need for action (the burden of proof) generally falls on those advocating precautionary action. No mention is made of assignment of liability for environmental harm.
Moderate	In moderate versions of the principle, the presence of an uncertain threat is a *positive basis* for action, once it has been established that a sufficiently serious threat exists. For example, the United Kingdom Biodiversity Action Plan states: "In line with the precautionary principle, where interactions are complex and where the available evidence suggests that there is a significant chance of damage to our biodiversity heritage occurring, conservation measures are appropriate, even in the absence of conclusive scientific evidence that damage will occur" (Gummer et al. 1994). Usually, there is no requirement for proposed precautionary measures to be assessed against other factors such as economic or social costs. The trigger for action may be less rigorously defined, e.g., as "potential damage", rather than as "serious or irreversible" damage as in the weak version. Liability is not mentioned and the burden of proof generally remains with those advocating precautionary action.
Strong	Strong versions of the principle differ from the weak and moderate versions in requiring action and reversing the burden of proof. Strong versions *justify or require* precautionary measures in the face of significant harm and some also establish liability for environmental harm on the side proposing the activity, which is effectively a strong form of "polluter pays". For example, the Earth Charter states: "When knowledge is limited apply a precautionary approach …. Place the burden of proof on those who argue that a proposed activity will not cause significant harm, and make the responsible parties liable for environmental harm" (Cousteau et al. 2000). Reversal of proof requires those proposing an activity to prove that the product, process or technology is sufficiently "safe" before approval is granted.
WTO	While the WTO's inclusion of precaution is still unclear (see Chapter 2), the SPS Agreement contains a clause that has been cited as a potential form of precaution; Article 5.7 states, "In cases where relevant scientific evidence is insufficient, a Member may provisionally adopt sanitary or phytosanitary measures on the basis of available pertinent information, including that from the relevant international organizations as well as from sanitary or phytosanitary measures applied by other Members" (WTO 1995). So while several arguments citing this as a method by which to incorporate precaution into SPS Standards, the WTO dispute settlement bodies have returned mixed verdicts as to the validity of this assertion.

Appendix B2. Internet survey as provided to participants.

Title: Development of an Aquatic Nonindigenous Species (ANS) Impact Assessment Framework

Introduction and Background

This survey is comprised of 32 multiple-choice questions, 3 open-ended questions, an optional comments section, and an evaluation section for 13 nonindigenous aquatic species. This survey should take 40 minute to complete. For each question, use the knowledge you already have about that item. If your knowledge is limited or you simply don't know, use your best judgment to answer the question. All responses will be kept confidential and results reported only in statistical form. Please remember that there are no right or wrong answers; I am simply interested in your opinions. Additional

Risk assessment combines the probability (likelihood) and impacts (consequences) of a threat (such as introduction, establishment, and/or spread of nonindigenous species. Risk analysis is the complete process of hazard identification, risk assessment, risk communication, risk management, and risk policy.

This survey includes questions on risk assessment, as well as questions on the use of precaution. In this survey, the term "precaution" should be taken as equivalent to the terms "precautionary approach" and/or "precautionary principle".

This survey is designed to provide responses that will improve the process and framework of impact assessment. Please answer the questions to the best of your ability. The information obtained from this survey is strictly confidential.

Questions

1. What is your participant number? (this is contained in introductory email)
2. In which country do you work?
    a. United States
    b. Canada
    c. Australia
    d. New Zealand
3. Please indicate your gender:
    a. Female
    b. Male
    c. Prefer not to answer
4. Please indicate your age:
    a. 18-25
    b. 26-35
    c. 36-45
    d. 46-55
    e. 56-65
    f. 65+
    g. Prefer not to answer
5. What is your highest level of education?

a. High school (secondary)
b. Undergraduate
c. Postgraduate by coursework
d. Masters by research
e. Doctorate

6. In what area of expertise was your highest level of education?
    a. Aquaculture
    b. Aquatic/Marine Biology
    c. Biology
    d. Ecology
    e. Economics
    f. Environmental Science
    g. Fisheries Science
    h. Natural Resources Management
    i. Oceanography
    j. Other: (please indicate area) __________________________
7. What taxonomic description best describes your background/speciality? (circle all that apply)
    a. Amphipod
    b. Ascidian/tunicate
    c. Barnacle
    d. Bryozoan
    e. Clam
    f. Copepod
    g. Crab
    h. Fish
    i. Gastropod
    j. Algae
    k. Hydroid
    l. Isopod
    m. Protozoan
    n. Worm
    o. Other: (blank)
    p. None of the above – ANS generalist
8. How long have you worked on aquatic nonindigenous species (ANS) issues?
    a. 0 – 2 years
    b. 2– 5 years
    c. 5 – 10 years
    d. 10-15 years
    e. More than 15 years: (please indicate number of years) _________
9. Does your work involve any of the following (check all that apply):
    a. Assessing likelihood of ANS entry, establishment, and/or spread
    b. Assessing impacts of ANS
    c. Communicating risk of ANS

    d. Managing risk of ANS
    e. Developing risk policy for nonindigenous species
    f. None of the above
10. How important are these next statements as a guiding principal in your life (not Important, important, extremely Important):
    a. Respecting the earth, harmony with other species
    b. Equality, equal opportunity for all
    c. A world at peace, free of war and conflict
    d. Protecting the environment, preserving nature
    e. Social justice, correcting injustice, care for the weak
11. For the following, please indicate whether you (Strongly agree, agree, disagree, strongly disagree):
    a. Humans are severely abusing the environment
    b. Nature will always possess unknowable mysteries
    c. It is important to have a sense of empathy and kinship with other forms of life
    d. The universe is a holistic, integrative system with a unifying life force
    e. Natural resources should be exploited for human use
    f. Wisdom and ethics are derived from interaction with other people
    g. The earth is like a spaceship with very limited room and resources
    h. The proper human role is to dissect, analyse and manage nature for one's own needs
    i. Humans should exercise dominion over nature in order to use it for personal and economic gain
    j. It is important for humans to be separate from and superior over other forms of life
    k. Human reason transcends the natural world and can produce insights independently of it
    l. The proper human role is to participate in the orderly designs of nature.
    m. If things continue on their present course, we will soon experience a major ecological catastrophe
    n. The so called 'ecological crisis' facing humankind has been greatly exaggerated
    o. The balance of nature is strong enough to cope with the impacts of modern industrial nations
    p. Nature is completely understandable to the rational human mind
12. In your opinion, how much of a threat are ANS, as compared to other threats to the environment:
    a. ANS are the greatest threat to the environment
    b. ANS are one of the biggest threats to the environment
    c. ANS are a moderate threat to the environment
    d. ANS are a low threat to the environment
    e. ANS are not a significant threat to the environment
13. For the following, please indicate whether you (Strongly disagree, somewhat disagree, somewhat agree, strongly agree):
    a. Technology can provide solutions to most challenges facing society
    b. Government safety assurances are not usually very accurate

c. Science is able to explain the natural world effectively
d. The potential gains outweigh potential risks to society from technological research and development
e. Government warnings of threat or risk are generally exaggerated
f. With enough time and money, research will continue to improve the quality of life
g. Risk assessments by private corporations are usually comprehensive and trustworthy
h. Environmental preservation is more important than economic growth
i. Science is able to predict future harms to the environment with high accuracy

14. Please indicate how you feel about the following statement: "There can be scientific uncertainty that is not recognized or cannot be defined (i.e. there are unknown 'unknowns')." (Strongly disagree, disagree, agree, strongly agree)
15. Please indicate which statement you most agree with:
    a. Science can provide answers to most research questions with 100% certainty
    b. Most research questions can be answered with high certainty
    c. Few research questions can be answered with high certainty
    d. No research questions can be answered with 100% certainty
16. Please indicate your opinion on the following statement: "Given enough time and money, research can reduce the uncertainties and knowledge gaps surrounding ANS and their impacts." (Strongly disagree, disagree, agree, strongly agree).
17. Please indicate which statement you most agree with:
    a. If ANS impact data contain significant amounts of uncertainty, any conclusions or decisions made based on the information are generally invalid
    b. Uncertainty in ANS impact analysis is unavoidable but can be managed to provide reliable results
    c. Uncertainty in ANS impact analysis can be avoided through proper identification and management of its sources
18. Please indicate your opinion on the following statement: "When analysing impacts of ANS, avoiding Type 2 errors (not assigning an impact when there actually is one) is more important than avoiding Type 1 errors (assigning an impact when there is actually not one)." (Strongly disagree, disagree, agree, strongly agree)
19. Please choose the statement that most closely reflects your opinion for an answer to the following question. If a statistical analysis of data for an observed pattern or impact yields an insignificant p-value, the data (please indicate which statement you most agree with):
    a. Should not be used when assessing impacts
    b. May be used with discretion if no other data is available
    c. Are valid to use when assessing impact (i.e. they may still be significant)
20. Please rank the importance of protecting each of the following values from threats by ANS, from 1 (most important) to 4 (least important):
    a. Environment/ecological values
    b. Social and cultural values
    c. Economic values
    d. Human health values

21. Do nonindigenous species have an impact due to their presence as a non-native component of the ecosystem?
    a. Yes
    b. No
22. If yes, do you agree with assigning a non- indigenous species "low impact" if there is an absence of impact literature for that non- indigenous species?
    a. Yes
    b. No
23. Before beginning this survey, were you familiar with the use of precaution (i.e. the precautionary approach and/or precautionary principle)?
    a. Yes, a clear understanding
    b. Yes, somewhat
    c. No, not really
    d. No, never heard of it
24. Which interpretation of precaution is used by your workplace?
    a. The presence of scientific certainty surrounding a threat of serious or irreversible damage **shall not prevent** the implementation of precautionary measures to prevent harm
    b. The presence of scientific certainty surrounding a threat of serious or irreversible damage is **a positive basis** for implementation of precautionary measures to prevent harm
    c. The presence of scientific certainty surrounding a threat of serious or irreversible damage **requires** implementation of precautionary measures to prevent harm
    d. The presence of scientific certainty surrounding a threat of serious or irreversible damage **allows provisional measures** to prevent harm until additional information necessary for a more objective assessment of risk is reviewed
    e. NA – my workplace does not use precaution
25. Which interpretation of precaution do you personally favour?
    a. The presence of scientific certainty surrounding a threat of serious or irreversible damage **shall not prevent** the implementation of precautionary measures to prevent harm
    b. The presence of scientific certainty surrounding a threat of serious or irreversible damage is **a positive basis** for implementation of precautionary measures to prevent harm
    c. The presence of scientific certainty surrounding a threat of serious or irreversible damage **requires** implementation of precautionary measures to prevent harm
    d. The presence of scientific certainty surrounding a threat of serious or irreversible damage **allows provisional measures** to prevent harm until additional information necessary for a more objective assessment of risk is reviewed
26. Should precaution be applied along a continuum, i.e. the more serious the potential impact, the more scientific uncertainty allowed before taking protective measures; conversely, the less serious the potential impact, the less scientific uncertainty allowed before taking protective measures?
    a. Yes

b. No

27. In general, what percentage of your work-related decisions involve precautionary measures?
    a. 0% of my decisions involve precautionary measures
    b. <10% of my decisions involve precautionary measures
    c. 10-25% of my decisions involve precautionary measures
    d. 26-50% of my decisions involve precautionary measures
    e. 51-75% of my decisions involve precautionary measures
    f. 76-100% of my decisions involve precautionary measures
28. The application of precaution is a necessary component in risk assessments to deal with the uncertainties present in the methods and information used. (Strongly disagree, disagree, agree, strongly agree)

29. How important is it to apply precaution for protection of the following categories? Please rank each category from 1 (the most important) to 4 (the least important):
    a. Environmental/ecological values
    b. Social and cultural values
    c. Economic values
    d. Human health values
30. Which of the following do you see as potential steps to integrate precaution into an ANS risk assessment (choose 3):
    a. Assume all cryptogenic species are nonindigenous; that is, if a species can't be determined to be native or not, assign non-native status
    b. Including public input regarding values and impact significance
    c. For nonindigenous species with unknown impacts, assign a "low" impact
    d. Use conservative estimates when developing and/or using model parameters
    e. In the final assessment, include even those species with low and/or unknown likelihood or low and/or unknown impact designation as possible risks
    f. If impacts for a particular nonindigenous species are unknown, use impacts from a similar species with known impacts
    g. When assessing impacts for a species using previously-documented impacts, use the impact of highest magnitude
31. Generalizing demonstrated impacts of ANS for future invasions is an uncertain process due to a variety of factors. What do you see as some of the biggest challenges to, and sources of uncertainty in predicting future impacts of nonindigenous species: (open)
32. When is it appropriate to use past impacts as predictors of future impacts for ANS?
    a. Most of the time
    b. Some of the time
    c. Rarely
    d. Never
33. Given the following combinations of evidence and uncertainty regarding the impacts attributed to an ANS, how would you rate the impact (assign no impact, assign low impact, assign moderate impact, assign high impact)
    a. **Uncertain observational/lay evidence** that the ANS would cause a serious negative impact

b. **Strong observational/lay evidence** that the ANS would cause a serious negative impact
c. **Uncertain experimental/scientific evidence** that the ANS would cause a serious negative impact
d. **Strong experimental/scientific evidence** that the ANS would cause a serious negative impact
e. **Uncertain observational/lay evidence** that an ANS **similar to that under consideration** caused a serious negative impact
f. **Strong observational/lay evidence** that an ANS **similar to that under consideration** caused a serious negative impact
g. **Uncertain experimental/scientific evidence** that an ANS **similar to that under consideration** caused a serious negative impact
h. **Strong experimental/scientific evidence** that an ANS **similar to that under consideration** caused a serious negative impact

34. When assigning impacts for nonindigenous species with absent or insufficient peer-reviewed impact data, it is appropriate to also include (choose all that apply):
    a. Incomplete and/or unfinished scientific studies
    b. Impacts that are published but do not cite experimental analysis
    c. "Anecdotal" information, such as news stories
    d. Personal communication with scientist
    e. Heuristic/expert observation/experience
    f. Lay knowledge (e.g. observational data from public such as port managers, long-term residents of a site, or fishers)
    g. Supported/verified observations (e.g. data from more than one person involved in resource management such as restoration planners, fisheries specialist, or park director)
    h. Unsupported/unverified observations
    i. Grey literature (e.g. websites, policy documents, databases, reports)
35. A precautionary approach to risk assessment would examine/include all potential sources of information (including non-scientific information)? (strongly disagree, disagree, agree, strongly agree)
36. A risk assessment that used all potential sources of information (including non-scientific information) would alter the quality of the assessment by what degree? 1 (risk assessment quality would be much lower) to 10 (risk assessment quality would be much higher):
37. For risk assessment, various international organizations mandate that risk assessors: "take into account available scientific evidence; relevant processes and production methods; relevant inspection, sampling and testing methods; prevalence of specific diseases or pests; existence of pest- or disease-free areas; relevant ecological and environmental conditions; and quarantine or other treatment." Based on this description, could the use of precaution in impact assessment be seen as an acceptable tool for risk assessment?
    a. Yes
    b. No
38. What do you see as the biggest challenges to understanding and describing impacts of ANS: (open)

39. Please add any additional comments you feel may assist in understanding your views on ANS impacts, risk, precaution, or uncertainty.

Appendix B3. Survey 2 and 3[17].

This survey contains questions similar to the second part of the first survey. You have been provided with information on a set of 10 species. For this survey, please use the provided information to do the following for each species (without consulting other sources, except from those provided):

- For each of the 4 value categories (economic, environmental, social/cultural, and human health), indicate the magnitude of impact and the uncertainty surrounding your choice (i.e. how sure you are that the impact magnitude is accurate).

- If you are aware of any specific types of impacts for each of the 4 main categories, please list those

- For each species, please explain (1) why/how you chose a particular impact magnitude for each of the four categories and (2) why/how you chose any specific types of impacts and their magnitude.

Please remember that there are no right or wrong answers; I am simply interested in your opinions. All responses will be kept confidential.

What is your participant number? ___

Species: *Caulerpa scalpelliformis*

Please respond to the following questions for the species, *Caulerpa scalpelliformis*, using the information given below and the paper (cited below) that was sent as pdf in email.

Species: *Caulerpa scalpelliformis*
Common group name: Green alga
Size: Fronds 20cm tall, 3 cm wide
Diet: Photosynthetic
Reproduction: Horizontal spread through stolons; reattachment of fragments; sexual reproduction poorly understood
Mobility: Sessile
Habitat: Up to 100 m depth in bays and estuaries; exposed and protected rock, sand, sea grass beds
Vector(s): Fisheries, aquarium or ornamental release
Native: Cryptogenic
Introduced: Cryptogenic, but distribution in Indian Ocean, Australia, Brazil
Impacts: See paper (provided):

[17] Questions only provided for first species, as they were identical for each species in both surveys.

Falca C and de Szechy MTM (2005) Changes in shallow phytobenthic assemblages in southeastern Brazil, following the replacement of Sargassum vulgare (Phaeophyta) by *Caulerpa scalpelliformis* (Chlorophyta). *Botanica Marina* **48**: 208–217.

1. To the best of your knowledge, please indicate this species' overall impact on environmental values:
    a. Negligible
    b. Low
    c. Moderate
    d. High
    e. Extreme

2. For the question above, what is the level of uncertainty surrounding your choice of impact?
    a. Negligible uncertainty
    b. Low uncertainty
    c. Moderate uncertainty
    d. High uncertainty
    e. Extreme uncertainty

3. For this species, please list any specific environmental impacts that you are aware of (e.g. loss of biodiversity):

4. For this species, please explain (1) why/how you chose the environmental impact magnitude and (2) why/how you chose the specific environmental impacts and their magnitude:

5. To the best of your knowledge, please indicate this species' overall impact on economic values:
    a. Negligible
    b. Low
    c. Moderate
    d. High
    e. Extreme

6. For the question above, what is the level of uncertainty surrounding your choice of impact?
    a. Negligible uncertainty
    b. Low uncertainty
    c. Moderate uncertainty
    d. High uncertainty
    e. Extreme uncertainty

7. For this species, please explain (1) why/how you chose the economic impact magnitude and (2) why/how you chose the specific economic impacts and their magnitude.

8. For this species, please list any specific economic impacts that you are aware of (e.g. clogs power plant intake pipes):

9. To the best of your knowledge, please indicate this species' overall impact on social and/or cultural values:
    a. Negligible
    b. Low
    c. Moderate
    d. High
    e. Extreme

10. For the question above, what is the level of uncertainty surrounding your choice of impact?
    a. Negligible uncertainty
    b. Low uncertainty
    c. Moderate uncertainty
    d. High uncertainty
    e. Extreme uncertainty

11. For this species, please list any specific social and/or cultural impacts that you are aware of (e.g. reduces enjoyment of beaches):

12. For this species, please explain (1) why/how you chose the social/cultural impact magnitude and (2) why/how you chose the specific social/cultural impacts and their magnitude.

13. To the best of your knowledge, please indicate this species' overall impact on human health values:
    a. Negligible
    b. Low
    c. Moderate
    d. High
    e. Extreme

14. For the question above, what is the level of uncertainty surrounding your choice of impact?
    a. Negligible uncertainty
    b. Low uncertainty
    c. Moderate uncertainty
    d. High uncertainty
    e. Extreme uncertainty

15. For this species, please list any specific human health impacts that you are aware of (e.g. vector for human pathogen):

16. For this species, please explain (1) why/how you chose the human health impact magnitude and (2) why/how you chose the specific human health impacts and their magnitude.

17. Please indicate your opinion for the following statements:
    a. The impacts of this species can be controlled.
       Strongly agree　　Agree　　Disagree　　Strongly disagree
    b. The impacts of this species can be mitigated:
       Strongly agree　　Agree　　Disagree　　Strongly disagree

18. In general, what is your level of concern about the impacts caused by this species?

Unidentified Gastropod Species

Common group name: Gastropod
Size: 50-80mm length, 25mm width
Diet: Suspension feeder
Reproduction: Sexual, internal fertilization
Mobility: Sedentary
Habitat: mud, sand or rock substrates from low intertidal to shallow subtidal
Vector(s): Aquaculture, ballast
Native: Europe (United Kingdom to the Netherlands)
Introduced: United States (Virginia to Maine)
Impacts:
No demonstrated impact, may affect invertebrate diversity and predation rates in soft-sediment benthic communities through modification of habitat structure due to high abundance of this species' shells.

Species: *Pterois volitans*

Common group name: Fish
Size: 15-30cm average, largest recorded at 43cm
Diet: Carnivore (crustacea and fish)
Reproduction: Dioecious, external fertilization, pelagic egg mass
Mobility: Highly mobile
Habitat: Variable: inshore lagoons to offshore reefs <50 m depth
Vector(s): Aquarium trade, ballast
Native: Western and South Pacific
Introduced: Atlantic Ocean from New York south to the Bahamas, Columbia
Impacts: See attached paper:
Albins MA and Hixon MA (2008) Invasive Indo-Pacific lionfish *Pterois volitans* reduce recruitment of Atlantic coral-reef fishes. *Marine Ecology Progress Series* 367: 233–238.

Species: Unidentified Ascidian Species

Common group name: Ascidian
Size: Cone-shaped, 120mm length
Diet: Suspension feeder (phytoplankton, zooplankton)
Reproduction: Hermaphrodite, no self-fertilization; external fertilization
Mobility: Sessile
Habitat: Artificial or natural substrates in low intertidal or subtidal areas
Vector(s): Fisheries, fouling, ballast
Native: Mediterranean
Introduced: Brazil
Impacts:
This is a prominent nuisance fouler in aquaculture, specifically mussel rope culture, oyster farms and suspended scallop ropes. Documented impacts include: dramatically reduced harvests of mussels and increased processing costs due to increased handling and hoisting effort of culture ropes made heavy due to this species.

Species: *Bonamia ostreae*

Common group name: Protozoan

Size: 2-5µm
Diet: This species is an oyster pathogen
Reproduction: Asexual
Mobility: Passive
Habitat: Oysters, particulary gills, mantle, and digestive gland
Vector(s):Shellfish aquaculture, fouling, ballast
Native: Cryptogenic
Introduced: Cryptogenic, but distribution in Europe (France, the United Kingdom, the Netherlands, Spain, Denmark, Italy), Morocco, Eastern Pacific (Washington and British Columbia), Western Atlantic (Maine)
Impacts: See attached paper:
Lallias D, Arzul I, Heurtebise S, Ferrand S, Chollet B, Robert M, Beaumont AR, Boudry P, Morga B, and Lapègue S (2008) *Bonamia ostreae*-induced mortalities in one-year old European flat oysters *Ostrea edulis*: experimental infection by cohabitation challenge. *Aquatic Living Resources* 21: 423-439.

Unidentified Algae Species

Common group name: Green alga
Size: Fronds 25cm tall
Diet: Photosynthetic
Reproduction: Vegetative (asexual) reproduction
Mobility: Sessile
Habitat: Rock and sand substrates in subtidal areas of bays and estuaries
Vector(s): Fouling, aquarium release
Native: Cryptogenic
Introduced: Cryptogenic but distribution in Indian Ocean, Australia, Brazil
Impacts:
Where introduced, this alga has spread rapidly. An increase in cover of this species on deep-reef habitat has been associated with a substantial decline in the cover of sessile invertebrates, predominantly sponges, colonial ascidians and bryozoans. Within 12 months of the appearance of the alga in one area, random photoquadrats revealed that it had reached an average cover of 57 ± 10%. Over the same period the average cover of sessile invertebrates declined from 49 to 21%; no such decline was observed in reference sites. This alga has an ability to rapidly expand across continuous reef, as well as an ability to establish on non-continuous reef. It has also been found that herbivores associated with the alga's habitat are highly unlikely to graze at sufficient rates to control the spread of this species.

Species: *Maoricolpus roseus*

Common group name: Gastropod
Size: 60-70mm length
Diet: Suspension feeder
Reproduction: Sexual, internal fertilization
Mobility: Sedentary
Habitat: Fine silts, muds, sand, gravel or shell substrates from low intertidal to 200m
Vector(s): Aquaculture, ballast
Native: New Zealand
Introduced: Australia
Impacts:

No demonstrated impact, may have role in decline of native gastropod species.

Unidentified Parasite Species

Common group name: Apicomplexa (parasite protist)
Size: 1µm
Diet: This species parasitizes Ateroidea (starfish) species
Reproduction: Asexual
Mobility: Passive
Habitat: Intracellular
Vector(s): Fouling, ballast
Native: Cryptogenic
Introduced: Cryptogenic, but distribution in France, the United Kingdom, Spain, and Portugal, South Africa, Eastern Pacific (Mexico to Washington), Western Atlantic (Rhode Island to Nova Scotia)
Impacts:
Recently, this species has been found in several Asteroidea (starfish) species throughout the parasites range, and further infection of additional species may be possible. The life cycle outside the host is unknown, though it has been possible to transmit the disease experimentally in the laboratory by cohabitation or inoculation of purified parasites. In the wild, the parasite occurs throughout the year but prevalence and intensity of infection tend to increase during warmer months. There are no outward signs of infection, but this parasite becomes systemic with overwhelming numbers of parasites coinciding with the death of the starfish. Effected starfish have high mortality rates (50-70%). Several of the effected species are ecologically important in their native range, and several local populations have experience complete or functional extinction. It has not been determined what ecological effects the potential loss of the effected starfish species will have.

Species: *Ciona intestinalis*

Common group name: Ascidian
Size: Cylindrical, 100-150mm length
Diet: Suspension feeder (phytoplankton, zooplankton, organic matter)
Reproduction: Hermaphrodite, no self-fertilization; external fertilization
Mobility: Sessile
Habitat: Artificial or natural substrates in low intertidal or subtidal areas in enclosed and semi-protected bays and estuaries
Vector(s): Fisheries, fouling, ballast
Native: Cryptogenic
Introduced: Cryptogenic, but cosmopolitan distribution
Impacts: See attached paper:
Ramsay A, Davidson J, Landry T, and Arsenault G (2008) Process of invasiveness among exotic tunicates in Prince Edward Island, Canada. *Biological Invasions* 10: 1311–1316.

Unidentified Fish Species

Common group name: Fish
Size: 20-25cm average, largest recorded at 36cm
Diet: Carnivore
Reproduction: Dioecious, external fertilization, pelagic egg mass
Mobility: Highly mobile

Habitat: bays and estuaries to shallow offshore reefs
Vector(s): Aquarium release
Native: South Africa
Introduced: Indonesia, Australia
Impacts:
This fish poses a threat to fishermen, divers, wildlife inspectors, in particular, but also to any individual near the fish's habitat, because it is venomous and people unfamiliar with the nonindigenous fish may not know this. This species can inject venom with multiple dorsal-fin, anal-fin, and pelvic-fin spines. This fish will not retreat under threat, but point their spines at the aggressor and swim forward rapidly to inflict a sting, most often to the individual's hand. Serious wounds have also resulted from handling of newly dead specimens. The sting leads to several hours of extreme pain, depending upon the amount of venom received. Other symptoms of the sting may include swelling, redness, bleeding, nausea, numbness, joint pain, anxiety, headache, disorientation, dizziness, nausea, paralysis, and convulsions. Without immediate care, the sting can lead to complications and eventual loss of motion in the affected area. The stings of this fish have been implicated in human deaths, though whether this was the sole cause is not certain.

Appendix B4. Ethics approval letter.

COPY

MEMORANDUM

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UTAS

HUMAN RESEARCH ETHICS COMMITTEE (TASMANIA) NETWORK

FULL COMMITTEE APPLICATION APPROVAL

18 August 2009

Professor Chad Hewitt
NC Marine Conservation and Resource Sustainability
Private Bag 1370
Launceston

Ethics Reference: H10726

Development of an Aquatic Non-indigenous Species (ANS) Impact Assessment Framework.

PhD Candidate: Ms Alisha Dahlstrom

Dear Professor Hewitt

The Tasmanian Social Sciences HREC Ethics Committee approved the above project on 16 August 2009.

All committees operating under the Human Research Ethics Committee (Tasmania) Network are registered and required to comply with the *National Statement on Ethical Conduct in Human Research* (NHMRC 2007).

Therefore, the Chief Investigator's responsibility is to ensure that:

1) All researchers listed on the application comply with HREC approved application.
2) Modifications to the application do not proceed until approval is obtained in writing from the HREC.
3) The confidentiality and anonymity of all research subjects is maintained at all times, except as required by law.
4) Statement 5.5.3 of the National Statement states:

   Researchers have a significant responsibility in monitoring approved research as they are in the best position to observe any adverse events or unexpected outcomes. They should report such events or outcomes promptly to the relevant institution/s and ethical review body/ies and take prompt steps to deal with any unexpected risks.

A PARTNERSHIP PROGRAM IN CONJUNCTION WITH THE DEPARTMENT OF HEALTH AND HUMAN SERVICES

5) All participants must be provided with the current Information Sheet and Consent form as approved by the Ethics Committee.

6) The Committee is notified if any investigators are added to, or cease involvement with, the project.

7) This study has approval for 4 years contingent upon annual review. A *Progress Report* is to be provided on the anniversary date of your approval. You will be sent a courtesy reminder closer to this due date.

8) A *Final Report* and a copy of the published material, either in full or abstract, must be provided at the end of project.

Yours sincerely

Emily Keenan

for **Ethics Executive Officer**

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Appendix B: Table 3. Participant demographics for US/CA scientists.

Factor		Total(%)
Nationality	U.S.	25(93%)
	Canada	2(7%)
Gender	Male	11(41%)
	Female	16(59%)
Age	18-25	1(4%)
	26-35	13(52%)
	36-45	6 (24%)
	46-55	1(4%)
	56-65	2(8%)
	65+	1(4%)
	Prefer not to answer	1(4%)
Highest level of education	Postgraduate by coursework	2(7%)
	Masters by research	12(44%)
	Doctorate	13(48%)
Area of educational expertise (this question allowed multiple selection, totals will exceed 100%)	Aquaculture	2(7%)
	Aquatic/Marine Biology	13(48%)
	Biology	3(11%)
	Ecology	6(22%)
	Economic	0(0%)
	Environmental Science	1(4%)
	Fisheries Science	1(4%)
	Natural Resources Management	1(4%)
	Oceanography	2(8%)
	Physiology	1(4%)
	Philosophy	1(4%)
	Marine Invasions Biology	1(4%)
Taxonomic specialty (this question allowed multiple selection, totals will exceed 100%)	Amphipod	5(19%)
	Ascidian/tunicate	7(26%)
	Barnacle	4(15%)
	Bryozoan	3(11%)
	Clam	3(11%)
	Copepod	4(15%)
	Crab	9(33%)
	Fish	2(7%)
	Gastropod	8(30%)
	Algae	5(19%)
	Hydroid	2(7%)
	Isopod	4(15%)
	Protozoan	0(0%)
	Worm	3(11%)
	None of the above – ANS generalist	6(22%)
	Fungi, Marine	1(4%)
	Zooplankton	1(4%)
	Echinoderms – urchins	1(4%)

Appendix B: Table 3 cont.

Factor		Total(%)
Years of ANS experience	0 – 2 years	3(11%)
	2– 5 years	5(19%)
	5 – 10 years	10(37%)
	10-15 years	5(19%)
	More than 15 years	4(15%)

Appendix B: Table 4. Participant demographics for AU scientists.

Factor		Total(%)
Nationality	Australia	16(94%)
	Australia and New Zealand	1(6%)
Gender	Male	10(59%)
	Female	7(41%)
Age	18-25	5(29%)
	26-35	8(47%)
	36-45	3 (18%)
	46-55	1(6%)
	56-65	0(0%)
	65+	0(0%)
	Prefer not to answer	0(0%)
Highest level of education	Undergraduate	8(47%)
	Postgraduate by coursework	2(12%)
	Masters by research	0(0%)
	Doctorate	7(41%)
Area of educational expertise (this question allowed multiple selection, totals will exceed 100%)	Aquaculture	0(0%)
	Aquatic/Marine Biology	13(76%)
	Biology	0(0%)
	Ecology	8(47%)
	Economic	0(0%)
	Environmental Science	2(12%)
	Fisheries Science	0(0%)
	Natural Resources Management	0(0%)
	Oceanography	0(0%)
	Microbiology	1(6%)
Taxonomic specialty (high knowledge)	Amphipod	0(0%)
	Ascidian/tunicate	4(24%)
	Barnacle	3(18%)
	Bryozoan	3(18%)
	Clam	2(12%)
	Copepod	0(0%)
	Crab	1(6%)
	Fish	1(6%)
	Gastropod	2(12%)
	Algae	2(12%)
	Hydroid	0(0%)
	Isopod	1(6%)
	Protozoan	0(0%)
	Worm	2(12%)
Years of ANS experience	0 – 2 years	8(47%)
	2– 5 years	3(18%)
	5 – 10 years	3(18%)
	10-15 years	1(6%)
	More than 15 years	0(0%)
	N/A I do not work on ANS issues	2(12%)

Appendix B: Table 5. Participant demographics for US/CA managers.

Factor		Total(%)
Nationality	U.S.	21(78%)
	Canada	5(19%)
	New Zealand	1(4%)*
	Mexico	2(7%)*
Gender	Male	15(56%)
	Female	12(44%)
Age	18-25	0(0%)
	26-35	8(30%)
	36-45	6 (22%)
	46-55	10(37%)
	56-65	3(11%)
	65+	0(0%)
	Prefer not to answer	0(0%)
Highest level of education	Undergraduate	3(11%)
	Postgraduate by coursework	3(11%)
	Masters by research	10(37%)
	Doctorate	11(41%)
Area of educational expertise (this question allowed multiple selection, totals will exceed 100%)	Aquaculture	0(0%)
	Aquatic/Marine Biology	6(22%)
	Biology	6(22%)
	Ecology	8(30%)
	Economic	0(0%)
	Environmental Science	2(7%)
	Fisheries Science	4(17%)
	Natural Resources Management	3(11%)
	Oceanography	1(4%)
	Physiology	1(4%)
	Philosophy	0(0%)
	Marine Invasions Biology	0(0%)
	Entomology	2(7%)
	Biogeography	1(4%)
	Library and Information Science	1(4%)
	Conservation Biology	1(4%)
	Environmental Education	1(4%)
	Electrical Engineering	1(4%)

Appendix B: Table 5 cont.

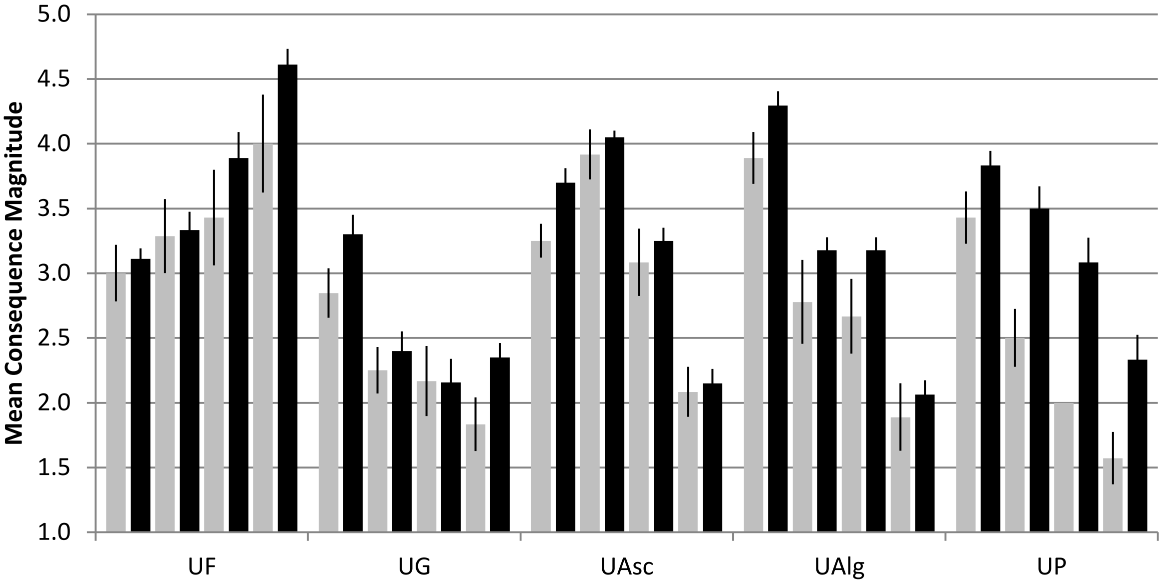
Factor		Total(%)
Taxonomic specialty (high knowledge)	Amphipod	1(4%)
	Ascidian/tunicate	2(7%)
	Barnacle	0(0%)
	Bryozoan	1(4%)
	Clam	2(7%)
	Copepod	2(7%)
	Crab	2(7%)
	Fish	9(33%)
	Gastropod	1(4%)
	Algae	5(19%)
	Hydroid	0(0%)
	Isopod	1(4%)
	Protozoan	2(7%)
	Worm	1(4%)
Years of ANS experience	0 – 2 years	7(26%)
	2– 5 years	9(33%)
	5 – 10 years	8(30%)
	10-15 years	1(4%)
	More than 15 years	2(7%; 17,19yrs)

Appendix B: Table 6. Participant demographics for AU managers.

Factor		Total(%)
Nationality	Australian	13 (100%)
Gender	Male	8(62%)
	Female	5(38%)
Age	18-25	0(0%)
	26-35	6(46%)
	36-45	3(23%)
	46-55	3(23%)
	56-65	1(8%)
	65+	0(0%)
Highest level of education	Undergraduate	2(15%)
	Postgraduate by coursework	7(54%)
	Masters by research	0(0%)
	Doctorate	4(31%)
Area of educational expertise (this question allowed multiple selection, totals will exceed 100%)	Aquaculture	2(15%)
	Aquatic/Marine Biology	1(8%)
	Ecology	3(23%)
	Environmental Science	4(30%)
	Philosophy	1(8%)
	Commerce	1(8%)
	Public Policy/Public Sector Mgmt.	1(8%)
Taxonomic specialty (high knowledge; this question allowed multiple selection, totals will exceed 100%)	Clam	1(8%)
	Copepod	1(8%)
	Crab	15(2%)
	Fish	3(23%)
	Gastropod	1(8%)
	Algae	2(15%)
	Protozoan	1(8%)
Years of ANS experience	0 – 2 years	4(31%)
	2– 5 years	4(31%)
	5 – 10 years	5(38%)
	10-15 years	0(0%)
	More than 15 years	0(0%)

Appendix B5: Figure 1. Consequence estimates for unknown species.

a)



b)

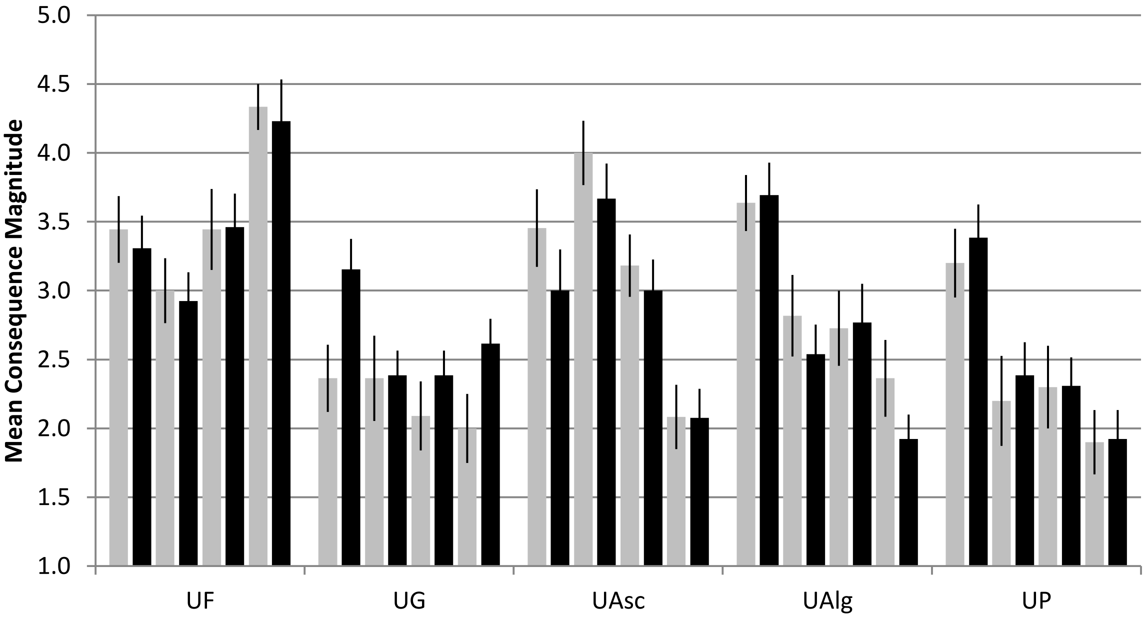
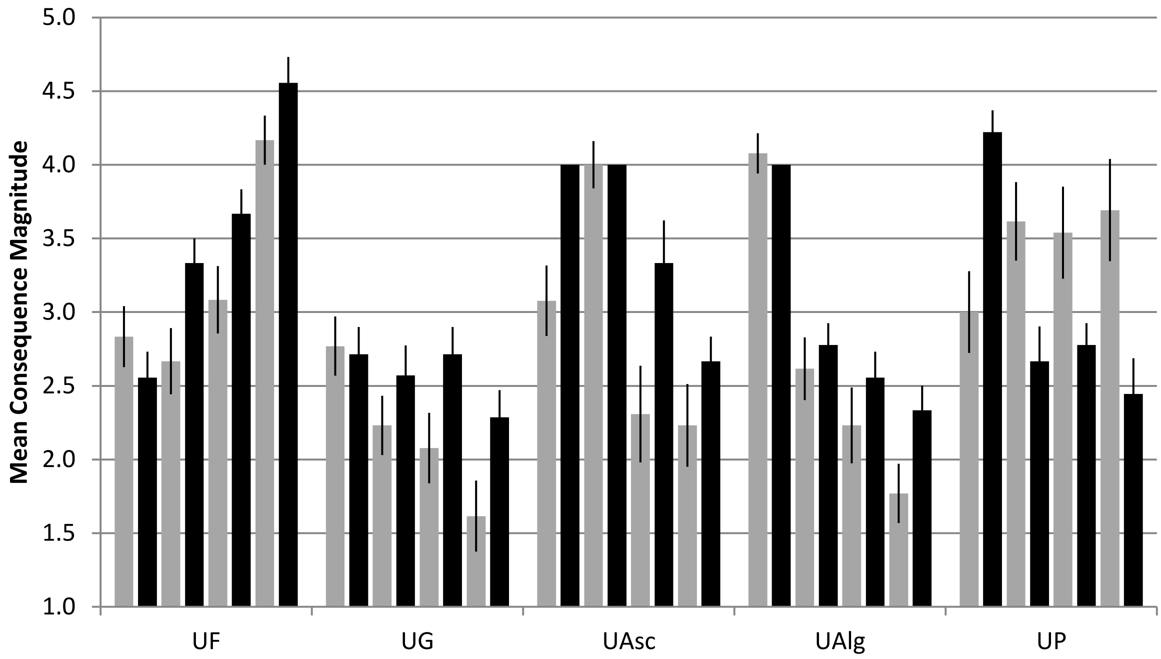


Figure 1. Average consequence for each core value, for 'unknown species' for a) US/CA scientists; b) US/managers; (overleaf) c) AU scientists; and d) AU managers. UF=Unknown Fish; UG=Unknown Gastropod; UAsc=Unidentified Ascidian; UP=Unknown Parasite; UAlg=Unknown Algae. For each species, two bars at left=environmental; two bars second from left=economic; two bars second from right=social/cultural; and two bars at right=human health; grey=second assessment; and black=third assessment.

c)



d)

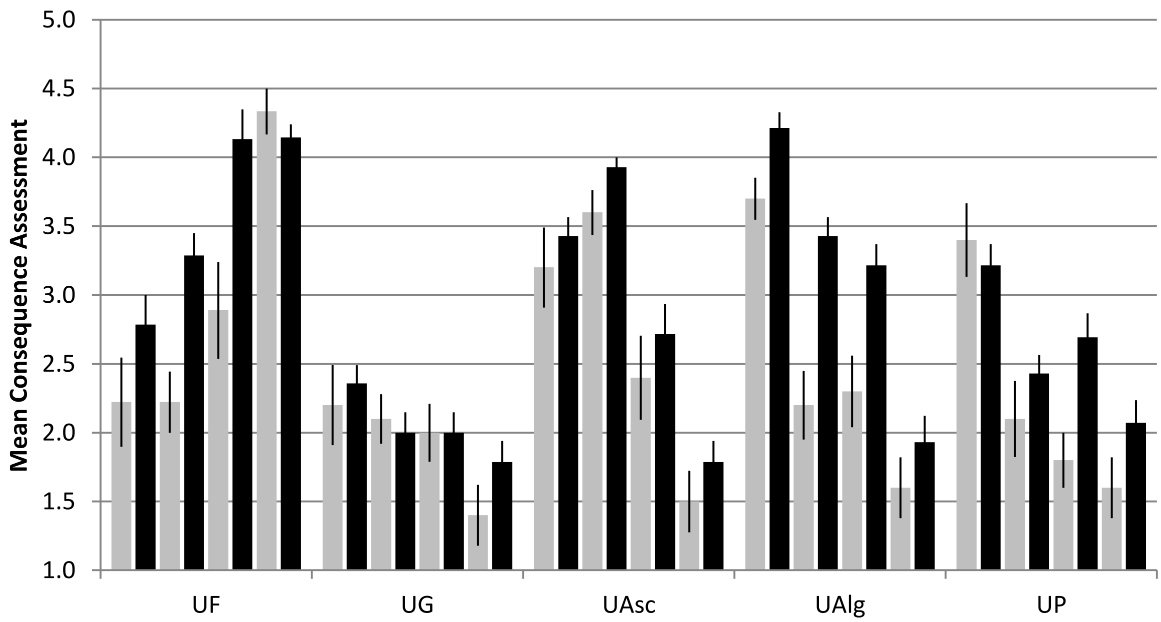
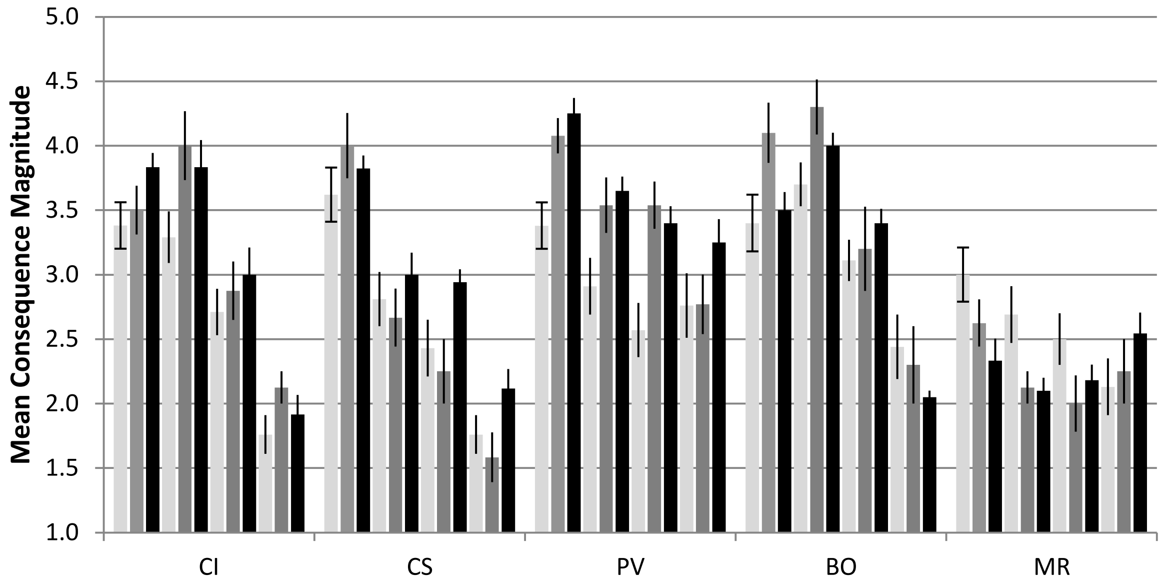


Figure 1 cont. Average consequence for each core value, for 'unknown species' for a) US/CA scientists; b) US/managers; c) AU scientists; and d) AU managers. UF=Unknown Fish; UG=Unknown Gastropod; UAsc=Unidentified Ascidian; UP=Unknown Parasite; UAlg=Unknown Algae. For each species, two bars at left=environmental; two bars second from left=economic; two bars second from right=social/cultural; and two bars at right=human health; grey=second assessment; and black=third assessment.

Appendix B5: Figure 2. Consequence estimates for known species.

a)



b)

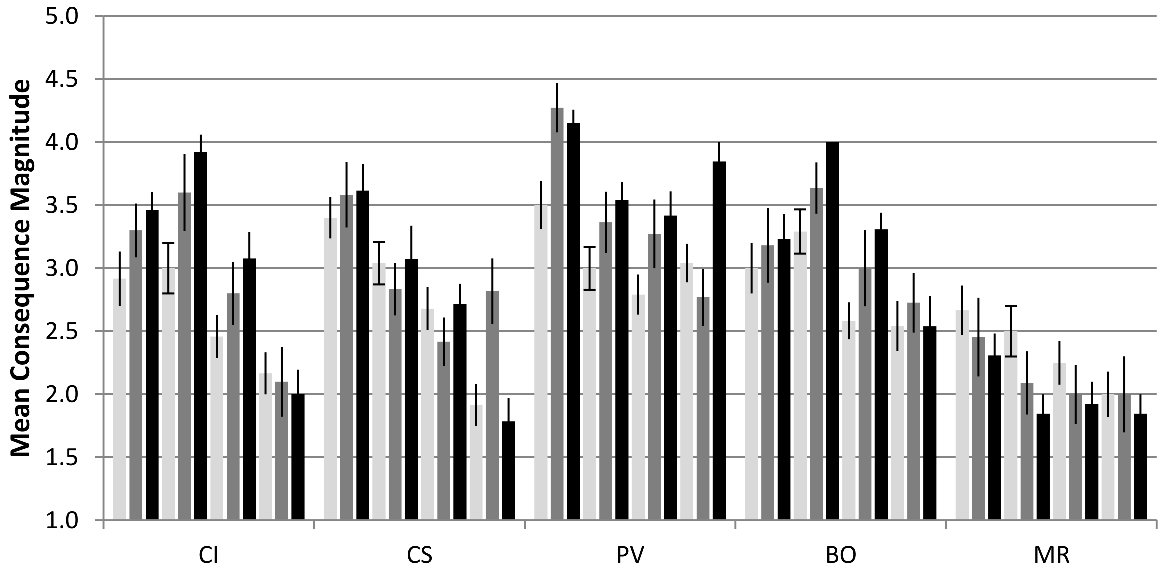
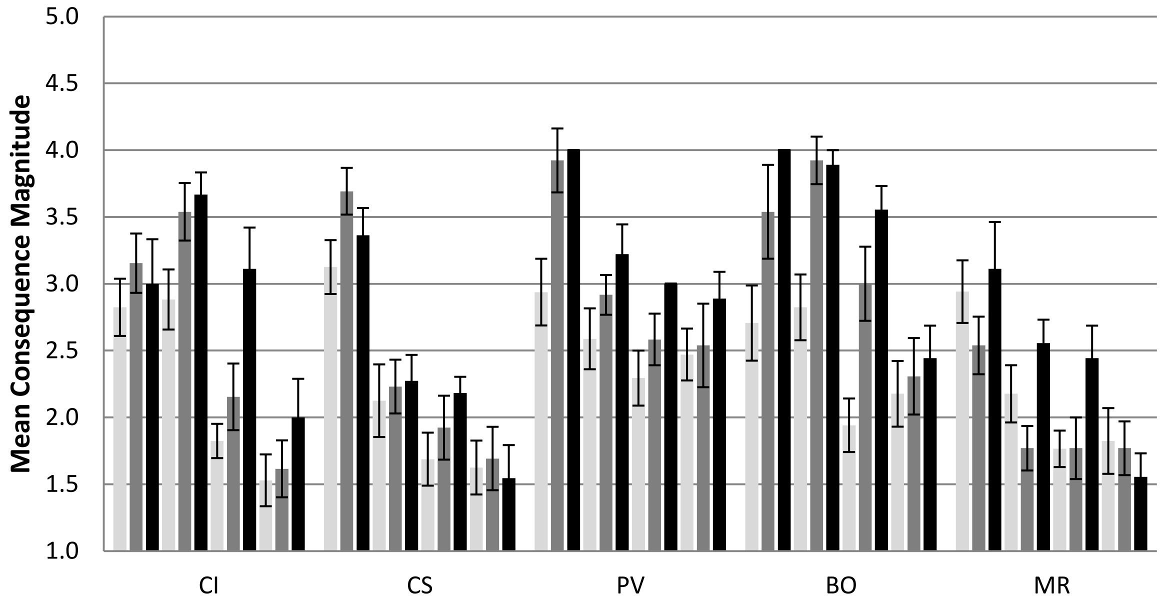


Figure 2. Average consequence for each core value, for 'known species' for a) US/CA scientists; b) US/CA managers; (overleaf) c) AU scientists; and d) AU managers. CI=*Ciona intestinalis*; CS=*Caulerpa scalpelliformis*; PV=*Pterois volitans*; BO=*Bonamia ostreae*; MR=*Maoricolpus roseus*. For each species, three bars at left=environmental; three bars second from left=economic; three bars second from right=social/cultural; and three bars at right=human health. Light grey=first assessment; medium grey=second assessment; and black=third assessment.

c)



d)

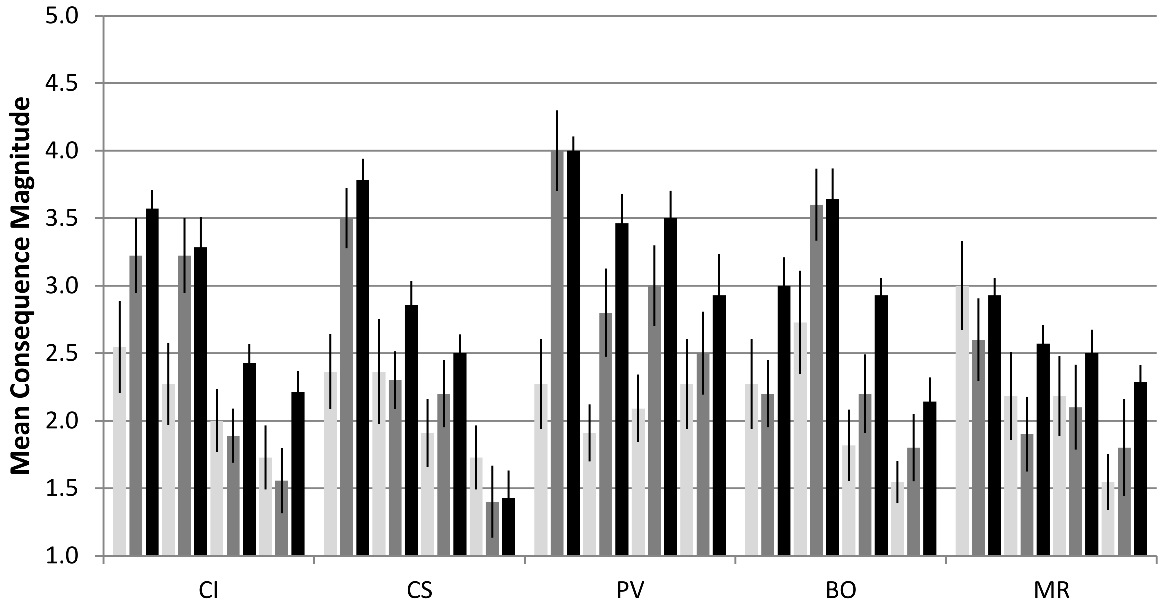


Figure 2 cont. Average consequence for each core value, for 'known species' for a) US/CA scientists; b) US/CA managers; c) AU scientists; and d) AU managers. CI=*Ciona intestinalis*; CS=*Caulerpa scalpelliformis*; PV=*Pterois volitans*; BO=*Bonamia ostreae*; MR=*Maoricolpus roseus*. For each species, three bars at left=environmental; three bars second from left=economic; three bars second from right=social/cultural; and three bars at right=human health. Light grey=first assessment; medium grey=second assessment; and black=third assessment.

Appendix C: Table 1. List of algal species included in review. Those with abbreviations had articles with analyses used in the review.

Species
Codium fragile (CF)
Caulerpa racemosa (CR)
Caulerpa taxifolia (CT)
Sargassum muticum (SM)
Undaria pinnatifida (UP)
Womersleyella setacea (WS)

Appendix C: Table 2. List of crustacean species included in review. Those with abbreviations had articles with analyses used in the review.

Species	**Species cont.**
Ampelisca abdita	*Gammarus tigrinus*
Anadara demiri	*Hemigrapsus penicillatus*
Alpheus inopinatus	*Hemigrapsus sanguineus* (HS)
Alpheus rapacida	*Homarus americanus*
Acartia tonsa	*Laticorophium baconi*
Briarosaccus callosus	*Ligia exotica*
Balanus eburneus (BE)	*Loxothylacus panopaei*
Balanus glandula	*Megabalanus coccopoma*
Balanus improvisus (BI)	*Pachygrapsus fakaravensis*
Callinectes bocourti	*Palaemon elegans*
Crangonyx floridanus	*Pseudodiaptomus inopinus*
Charybdis japonica	*Pseudodiaptomus forbesi*
Caprella mutica	*Paramysis lacustris*
Chthamalus proteus (CP)	*Pseudodiaptomus marinus*
Carcinoscorpius rotundicauda	*Pontogammarus robustoides*
Callinectes sapidus	*Rhithropanopeus harrisi*
Caprella scaura	*Sphaeroma annandalei*
Dikerogammarus haemobaphes	*Sinocalanus doerri*
Dikerogammarus villosus (DV)	*Solidobalanus fallax*
Echinogammarus berilloni	*Sylon hippolytes*
Echinogammarus ischnus	*Sphaeroma terebrans*
Eriocheir sinensis (ES)	*Tortanus dextrilobatus*
Gmelinoides fasciatus	

Appendix C: Table 3. List of algal literature. SM=*Sargassum muticum*, CF=*Codium fragile*, CR=*Caulerpa racemosa*, CT=*Caulerpa taxifolia* and UP=*Undaria pinnatifida*. S= significant analyses; NSP=nonsignificant analyses from which power can be calculated; and NSNP=nonsignificant analyses from which power cannot be calculated.

Citation	Species	S	NSP	NSNP
Airoldi, L. 2000. Effects of disturbance, life histories, and overgrowth on coexistence of algal crusts and turfs. Ecology **81**:798-814.	WS			X
Ambrose, R.F. and B.V. Nelson. 1982. Inhibition of giant kelp recruitment by an introduced brown alga. Botanica Marina **25**:265-268.	SM	X	X	
Britton-Simmons, K.H. 2004. Direct and indirect effects of the introduced alga *Sargassum muticum* on benthic, subtidal communities of Washington State, USA. Marine Ecology Progress Series **277**:61-78.	SM	X	X	
Bulleri, F., L. Airoldi, G. M. Branca, and M. Abbiati. 2006. Positive effects of the introduced green alga, *Codium fragile* ssp. *tomentosoides*, on recruitment and survival of mussels. Marine Biology **148**:1213-1220.	CF	X		
Ceccherelli, G. and D. Campo. 2002. Different effects of *Caulerpa racemosa* on two co-occurring seagrasses in the Mediterranean. Botanica Marina **45**:71-76.	CR	X		X
Ceccherelli, G. and F. Cinelli. 1997. Short-term effects of nutrient enrichment of the sediment and interactions between the seagrass *Cymodocea nodosa* and the introduced green alga *Caulerpa taxifolia* in a Mediterranean Bay. Journal of Experimental Marine Biology and Ecology **217**:165-177.	CT	X		
Ceccherelli, G. and N. Sechi. 2002. Nutrient availability in the sediment and the reciprocal effects between the native seagrass *Cymodocea nodosa* and the introduced rhizophytic alga *Caulerpa taxifolia*. Hydrobiologia **474**:57-66.	CT		X	
Ceccherelli, G., D. Campo, and L. Piazzi. 2001. Some ecological aspects of the introduced alga *Caulerpa racemosa* in the Mediterranean: way of dispersal and impact on native species. Biologia marina mediterranea **8**:94-99.	CR			X
Chavanich, S. and L. Harris. 2004. Impact of the non-native macroalga *Codium fragile* (Sur.) Hariot ssp. *tomentosoides* (van Goor) Silva on the native snail *Lacuna vincta* (Montagu, 1803) in the Gulf of Maine. Veliger **47**:85-90.	CF	X		
De Wreede, R. E. 1983. *Sargassum muticum* (Fucales, Phaeophyta): regrowth and interaction with *Rhodomela larix* (Ceramiales, Rhodophyta). Phycologia **22**:153-160.	SM	X		
Farrell, P. and R. L. Fletcher. 2006. An investigation of dispersal of the introduced brown alga *Undaria pinnatifida* (Harvey) Suringar and its competition with some species on the man-made structures of Torquay Marina (Devon, UK). Journal of Experimental Marine Biology and Ecology **334**:236-243.	UP			X

Appendix C: Table 3 cont.

Citation	Species	S	NSP	NSNP
Levin, P. S., J. A. Coyer, R. Petrik, and T. P. Good. 2002. Community-wide effects of nonindigenous species on temperate rocky reefs. Ecology **83**:3182-3193.			X	
Piazzi, L., D. Balata, G. Ceccherelli, and F. Cinelli. 2005. Interactive effect of sedimentation and *Caulerpa racemosa* var. *cylindracea* invasion on macroalgal assemblages in the Mediterranean Sea. Estuarine, Coastal and Shelf Science **64**:467-474.	CR	X		X
Piazzi, L. and G. Ceccherelli. 2006. Persistence of biological invasion effects: recovery of macroalgal assemblages after removal of *Caulerpa racemosa* var. *cylindracea*. Estuarine, Coastal and Shelf Science **68**:455-461.	CR	X		
Sánchez, Í. and C. Fernández. 2005. Impact of the invasive seaweed *Sargassum muticum* (phaeophyta) on an intertidal macroalgal assemblage. Journal of Phycology **41**:923-930.	SM	X	X	X
Scheibling, R. E. and P. Gagnon. 2006. Competitive interactions between the invasive green alga *Codium fragile* ssp. *tomentosoides* and native canopy-forming seaweeds in Nova Scotia (Canada). Marine Ecology Progress Series **325**:1-14.	CF	X	X	
Schmidt, A. L. and R. E. Scheibling. 2007. Effects of native and invasive macroalgal canopies on composition and abundance of mobile benthic macrofauna and turf-forming algae. Journal of Experimental Marine Biology and Ecology **341**:110-130.	CF	X	X	
Valentine, J. P. and C. R. Johnson. 2005. Persistence of the exotic kelp *Undaria pinnatifida* does not depend on sea urchin grazing. Marine Ecology Progress Series **285**:43-55.	UP	X		X
Viejo, R. M. 1997. The effects of colonization by *Sargassum muticum* on tidepool macroalgal assemblages. Journal of the Marine Biological Association of the United Kingdom **77**:325-340.	SM	X	X	X

Appendix C: Table 4. List of crustacean literature. BI=*Balanus improvisus*, BE=*Balanus eburneus*, HS=*Hemigrapsus sanguineus*, DV= *Dikerogammarus villosus,* ES= *Eriocheir sinensis*, CT= *Chthamalus proteus.* S= significant analyses; NSP=nonsignificant analyses from which power can be calculated; and NSNP=nonsignificant analyses from which power cannot be calculated.

Citation	Species	S	NSP	NSNP
Barnes, B. B., M. W. Luckenbach, and P. R. Kingsley-Smith. 2010. Oyster reef community interactions: the effect of resident fauna on oyster (*Crassostrea* spp.) larval recruitment. Journal of Experimental Marine Biology and Ecology **391**:169-177.	BI	X		
Boudreaux, M., L. Walters, and D. Rittschof. 2009. Interactions between native barnacles, non-native barnacles, and the eastern oyster *Crassostrea virginica*. Bulletin of Marine Science **84**:43-57.	BE	X		
Brousseau, D. J. and R. Goldberg. 2007. Effect of predation by the invasive crab *Hemigrapsus s*anguineus on recruiting barnacles *Semibalanus balanoides* in western Long Island Sound, USA. Marine Ecology Progress Series **339**:221-228.	HS	X	X	
Dürr, S. and M. Wahl. 2004. Isolated and combined impacts of blue mussels (*Mytilus edulis*) and barnacles (*Balanus improvisus*) on structure and diversity of a fouling community. Journal of Experimental Marine Biology and Ecology **306**:181-195.	BI			X
Griffen, B. 2006. Detecting emergent effects of multiple predator species. Oecologia **148**:702-709.	HS			X
Kotta, J. et al. 2006. Ecological consequences of biological invasions: three invertebrate case studies in the north-eastern Baltic Sea. Helgoland Marine Research **60**:106-112.	BI	X		
Lohrer, A. M. and R. B. Whitlatch. 2002. Relative impacts of two exotic brachyuran species on blue mussel populations in Long Island Sound. Marine Ecology Progress Series **227**:135-144.	HS	X		
Platvoet, D., J. T. A. Dick, N. Konijnendijk, and G. van der Velde. 2006. Feeding on micro-algae in the invasive Ponto-Caspian amphipod *Dikerogammarus villosus* (Sowinsky, 1894). Aquatic Ecology **40**:237-245.	DV	X		
Rudnick, D. and V. Resh. 2005. Stable isotopes, mesocosms and gut content analysis demonstrate trophic differences in two invasive decapod crustacea. Freshwater Biology **50**: 1323-1336.	ES	X	X	
Tyrrell, M. C., P. A. Guarino, and L. G. Harris. 2006. Predatory impacts of two introduced crab species: inferences from microcosms. Northeastern Naturalist **13**:375-390.	HS	X	X	
Young, C. M. and J. L. Cameron. 1989. Differential predation by barnacles upon larvae of two bryozoans: spatial effects at small scales. Journal of Experimental Marine Biology and Ecology **128**: 283-294.	BE	X		
Zabin, C. J. 2005. Community ecology of the invasive intertidal barnacle *Chthamalus proteus* in hawai'i. Department of Zoology, University of Hawai'i.	CP	X		

Appendix C: Table 4 cont.

Citation	Species	S	NSP	NSNP
Zabin, C. J. and A. Altieri. 2007. A Hawaiian limpet facilitates recruitment of a competitively dominant invasive barnacle. Marine Ecology Progress Series **337**:175-185.	CP	X		

Appendix C: Table 5. Significant results for nonindigenous algal abundance impact studies. SM=*Sargassum muticum*, CF=*Codium fragile*, CR=*Caulerpa racemosa*, CT=*Caulerpa taxifolia* and UP=*Undaria pinnatifida.* PC=percent cover.

Citation	Species	Location	Experimental methods	Results
Ambrose and Nelson (1982)	*Sargassum muticum*	Santa Catalina, California	Removal of SM to test effects on density for *Macrocystis pyrifera*	Greater density in removal treatments for *M. pyrifera* [plants/m2±SD], June 1979, site1: removal=5±5.91, control=.4±.63; site2a: removal=1.9±1.38, control=.2±.37; September 1979, site1: removal=1.9±2.06, control=.1±.31; site2a: removal=.4±.6, control=0±0; site2b: removal=.1±.31, control=0±0
Britton-Simmons (2004)	*Sargassum muticum*	San Juan Islands, Washington State	Removal of SM to rest effects on PC of native canopy algae, understory algae and urchin *Strongylocentrotus droebachiensis*	Less abundant canopy algae (F=22.86, p=0.000) and understory algae (F=8.81, 0.009) in removal treatments; more abundant *S. droebachiensis* (t=-6.34, p<0.001) in removal treatments.
Bulleri et al (2006)	*Codium fragile*	Italy, Adriatic Sea	Removal of CF to test effects on density of *Mytilus galloprovincialis*	Lesser density in removal treatments than on bare rock (F=6.20)
Ceccherelli and Campo (2002)	*Caulerpa racemosa*	Italy, Mediterranean Sea	Removal of CR to test effects on shoot density of *Zostera noltii*	Lesser (though variable) shoot density of *Z. noltii* in CR removal treatment (F=1881.74)
Ceccherelli and Cinelli (1997)	*Caulerpa taxifolia*	Galenzana Bay, Italy	Removal of CT to test effects on shoot density of *Cymodocea nodosa*	Greater shoot density of *C. nodosa* in CT removal treatment (F=8.506)
Chavanich and Harris (2004)	*Codium fragile*	Maine and New Hampshire	Reciprocal transplant of *Codium* and *Laminaria* to test effects on density of *Lacuna vincta*	Greater density of *L. Vincta* in *Laminaria* treatments (*Laminaria*: 17.21 snails/g algae; *Codium*: 2.7 snails/g algae
De Wreede (1983)	*Sargassum muticum*	British Columbia, Canada	Removal of SM to test for effects on PC of *Rhodomela larix* and articulated corraline algae	Greater PC of *R. larix* in removal treatments; lesser PC of articulate corraline algae in removal treatments

Appendix C: Table 5 cont.

Citation	Species	Location	Experimental methods	Results
Levin et al (2002)	*Codium fragile*	Isles of Shoals, New Hampshire	Removal of CF to test for effects on PC and density of native kelps and mobile animal species	Greater PC of kelp in removal treatments (F= 4.496); greater density of cunner *Tautogolabrus adspersus* in removal treatments (6-fold)
Piazzi and Ceccherelli (2006)	*Caulerpa racemosa*	Italy, Mediterranean Sea	Removal of CR to test effects on PC for encrusting, turf and erect algae	Greater PC in removal treatments for encrusting (F=723.89); turf (F=13.57); and erect (F=14.44) algae
Piazzi et al (2005)	*Caulerpa racemosa*	Italy, Mediterranean Sea	Addition of CR to test effects on PC of turf, erect and prostrate algae, as well as several specific species within these	Greater PC in non-CR treatments of erect and prostrate algae (F=119.5, 101.2) as well as for *Halimeda tuna* (F=26.88)
Scheibling and Gagnon (2006)	*Codium fragile*	Nova Scotia, Canada	Removals of CM in press (monthly) and pulse (annual) treatments to test effects on PC of kelps (*Laminaria longicruris* and *Laminaria digitata*) and algae (*Desmarestia viridis* and *D. aculeata*) and kelp *Saccorhiza dermatodea*.	Greater percent cover of *Laminaria* and *Desmarestia* after first pulse removal (F=14.5, 22.9); after half of press and second pulse removals (4.8, 14.8 - greater than control but no difference between removal treatments); and *Laminaria* at end of experiment (F=58.2, with press greater than pulse - *Desmarestia* not mentioned)
Schmidt and Scheibling (2007)	*Codium fragile*	Nova Scotia, Canada	Repeated measures removal of CF from breakwaters dominated by CF to test effects on PC of coarsely branched algae, jointed calcerous algae, sheet forming algae, filamentous algae and benthic macrofauna	Lesser density of benthic macrofauna in CF removal treatment: *P. gunnellus* [mean±SE (individuals m−2]; Canopy Intact (CI): 0.17±0.13, Canopy Removed (CR): 0.03±0.06]; *Asterias* spp. (CI: 0.75±0.35, CR: 0.2±0.16); *C. irroratus* (CI: 0.59±0.36, CR: 0.34±0.28); and *Pagurus* spp. (CI: 4.55±1.2, CR: 2.38±0.8)
Valentine and Johnson (2005)	*Undaria pinnatifida*	Tasmania, Australia	Removals of UP to test effects on PC of total native algae, red algae, native canopy-forming algae, green algae and brown turf algae	Greater percent cover after removal for green and brown turf algae (F= 4.20, 6.88 respectively) in first sample date only

Appendix C: Table 5 cont.

Citation	Species	Location	Experimental methods	Results
Viejo (1997)	*Sargassum muticum*	Spain, East Atlantic	Removals of SM to test effects on PC of foliose algae, filamentous algae, coarsely branched macrophytes, leathery macrophytes, articulated calcerous and articulate crustose algae.	Greater percent cover of total native and leathery algae greater in non-SM site 3 (F=6.23, 6.29 respectively; no ES)

Appendix C: Table 6. Significant results for nonindigenous crustacean abundance impact studies. BI=*Balanus improvisus*, BE=*Balanus* eburneus, HS=*Hemigrapsus sanguineus*, DV= *Dikerogammarus villosus*, ES= *Eriocheir sinensis*, CT= *Chthamalus proteus*. PC=percent cover.

Citation	Species	Location	Experimental methods	Results
Barnes et al (2010)	*Balanus improvisus*	Chesapeake Bay, Maryland	Varying PC of BI (no, low, medium and high) to test effects on density (settlement) of *Crassostrea virginica* and *Crassostrea ariakensis*.	Difference in density (settlement), with lower density on control (absence of BI) treatments than for low, medium or high treatments for both *C. ariakensis* (F=5.82) and *C. virginica* (F=11.00).
Boudreaux et al (2009)	*Balanus eburneus*	Florida	Varying densities of BE (control/0%, low/25%, medium/25-50% and high/>50%) to test effects on density (settlement) of *Crassostrea virginica*.	Difference in density (settlement) (F=3.545), with greatest density in absence of barnacles, followed by low barnacle levels
Brousseau and Goldberg (2007)	*Hemigrapsus sanguineus*	Long Island Sound, Connecticut	Used presence/absence treatments: no crabs, low density (15 crabs), medium density (45 crabs) and high density (90 crabs) to determine effect on density of *Semibalanus balanoides*	Greater densities of *S. balanoides* in no and low crab treatments (F=2.67) in middle of experiment, though no difference by end of experiment.
Kotta et al (2006)	*Balanus improvisus*	Baltic Sea	Varying PC of BI (0, 10, 20, 40, 70, 80 and 100%) to test effects on density of *Enteromorpha intestinalis*	Greater density of *E. intestinalis* was found with increasing PC of BI (r^2=0.91)
Lohrer and Whitlatch (2002)	*Hemigrapsus sanguineus*	New Hampshire	Used three presence/absence experiments to determine effect of HS on density of *Mytilus edulis*. The second and third were one year later, and the third used greater densities of smaller crabs.	Lower densities of *M. edulis* in presence treatments for both experiments (~25-60% decrease).
Platvoet et al (2006)	*Dikerogammarus villosus*	The Netherlands	Presence/absence treatments to tested effect of 3 groups of DV (adult male, adult female and juvenile) and control (no DV) on density of *Monoraphidium griffithii*.	Greater concentration in control treatment (F=10.3), with no differences between DV-present groups.

Appendix C: Table 6 cont.

Citation	Species	Location	Experimental methods	Results
Rudnick and Resh (2005)	*Eriocheir sinensis*	San Francisco, California	Presence/absence treatments to test effect on oligochaetes, *Trichoptera* (caddisfly *Gumaga nigricula*), *Ephemeroptera* (Trichorythidae and Leptophlebiidae), large and small *Corbicula fluminae*, algae and macrophytes.	Lower density of the caddisfly *Gumaga* (by 90%) and *C. fluminae* (by 50%). Greater abundance of oligochaetes (>150%). Also, greater biomass of algae (F = 19.7) and lower biomass of detritus (F = 40.1 for *Salix*, 33.8 for *Platanus*).
Tyrrell et al (2006)	*Hemigrapsus sanguineus*	New Hampshire	Used varying densities in lab (control and 2 crabs/cage) and short and long field (control and 5 crabs/cage) to test effect on *Semibalanus balanoides*, *Spirorbis* sp and ephemeral, crustose and fucoid algae.	Great densities of *S. balanoides* in control treatments for lab [PC control, PC present] (5.56, -85.25) and field (short: -2.73, -35.45; long: -6.70, -83.84) experiments. Greater densities of *Spirorbis* sp (0, -83.36) but lower crustose (-3.00, 10.74) algae PC in control lab experiments
Young and Cameron (1989)	*Balanus eburneus*	Florida	Presence of live/dead BE to test effects on density (settlement) of bryozoans *Bugula neritina* and *B. stolonifera*	Presence of live barnacles lead to greater settlement than dead barnacles (F=4.81)
Zabin (2005)	*Chthamalus proteus*	Hawaii	Removal treatments to determine effect on PC and on density (settlement) of *Balanus reticulatus*	Greater PC (F=96.79) and density (F=18.72) of *B. reticulatus* in CP removal treatments
Zabin and Altieri (2007)	*Chthamalus proteus*	Hawaii	Removal treatments (press, pulse and control) to test effect on *Siphonaria normalis*	Greater density in CP removal treatments (F=27.59), with greatest density in press removal, followed by pulse removal then no removal.

Appendix C: Table 7. Power calculations for non-significant nonindigenous algae abundance impact studies. [1] indicates power analysis via test (otherwise via ANOVA). SM=*Sargassum muticum*, CF=*Codium fragile*, CR=*Caulerpa racemosa*, CT=*Caulerpa taxifolia* and UP=*Undaria pinnatifida.* PC=percent cover.

Citation	Species	Location	Experimental methods	Results
Ambrose and Nelson (1982)	*Sargassum muticum*	Santa Catalina, California	Removal of SM to test effects on density of *Macrocystis pyrifera*	No effect[1] on density of *M. pyrifera* for site 2b in June 1979 (ES=0.34, power=0.17) or September 1979 (ES=0.46, power-0.28)
Britton-Simmons (2004)	*Sargassum muticum*	San Juan Islands, Washington State	Removal of SM to rest effects on PC of bare rock, crustose corraline algae and turf-forming algae	No effect on PC of bare rock (author-calculated power=0.05), crustose corraline algae (author calculated power=0.2), or turf-forming algae (author-calculated power=0.4).
Ceccherelli and Sechi (2002)	*Caulerpa taxifolia*	Italy (Galenzana Bay)	Removal of CT to test effects on shoot density of *Cymodocea nodosa*	No effect on density of *C. nodosa* (ES=3.62, power=1).
Levin et al (2002)	*Codium fragile*	Gulf of Maine	Removal of CF to test for effects on PC and density of native kelps and mobile animal species	No effect on density of *Cancer irroratus* (ES=0, power=0.05), *Carcinus maenas* (ES=0.043, power=0.050) or *Homarus americanus* (ES=0.052, power-0.053)
Sanchez and Fernandez (2005)	*Sargassum muticum*	Spain, East Atlantic	Removal treatments of SM to test for successional effects on PC of dominant macroalgal species. Both treatments started as bare rock, with removals of SM as one treatment and non-removal as control.	No effect on PC of *Bifurcaria bifurcata* (ES=0.35, power=0.32) or *Gelidium spinosum* (ES=0.24, power=0.18)
Scheibling and Gagnon (2006)	*Codium fragile*	Nova Scotia, Canada	Removals of CM in press (monthly) and pulse (annual) treatments to test effects on PC of kelps (*Laminaria longicruris* and *Laminaria digitata*) and algae (*Desmarestia viridis* and *D. Aculeata*) and kelp *Saccorhiza dermatodea*.	No effect on density of *Saccorhiza dermatodea* (ES=0.42, power=0.23)

Appendix C: Table 7 cont

Citation	Species	Location	Experimental methods	Results
Schmidt and Scheibling (2007)	*Codium fragile*	Nova Scotia, Canada	Repeated measures removals of CF from breakwaters dominated by CF to test effects on PC of coarsely branched algae, jointed calcerous algae, sheet forming algae, filamentous algae and benthic macrofauna	No effect on PC of *Myoxocephalus scorpius* (ES=0.16, power=0.13).
Viejo (1997)	*Sargassum muticum*	Spain, East Atlantic	Removals of SM to test effects on PC of foliose algae, filamentous algae, coarsely branched macrophytes, leathery macrophytes, articulated calcerous and articulate crustose algae.	No effect[1] on any group, specifically crustose algae at site 1 (ES=0.43, power=0.08), 2 (ES=0.37, power=0.08), or 3 (ES=0.10, power=0.05); or *Bifurcaria bifurcata* site 1 (ES=0.47, power=0.09) or 2 (0.50, power=0.09)

Appendix C: Table 8. Power calculations for non-significant nonindigenous crustacean abundance impact studies. BI=*Balanus improvisus*, BE=*Balanus eburneus*, HS=*Hemigrapsus sanguineus*, DV= *Dikerogammarus villosus,* ES= *Eriocheir sinensis*, CT= *Chthamalus proteus.* PC=percent cover.

Citation	Species	Location	Experimental methods	Results
Brousseau and Goldberg (2007)	*Hemigrapsus sanguineus*	Long Island Sound, Connecticut	Used presence/absence treatments in 2 experiments: (1): exclosure, enclosure (15 crabs/0.25m^2), partial open, and open cages in 2003 and 2004; and (2): no crabs, low density (15 crabs/0.25m^2), medium density (45 crabs/0.25m^2) and high density (90 crabs/0.25m^2) cages in 2005 to determine effect on density of *Semibalanus balanoides* and *Ulva* spp. (in experiment 2)	No significant effect of HS on *S. balanoides* in 2003 experiment 1 (ES=0.65, power=0.43) or 2005 experiment 2 (ES=0.89, power=0.72). Despite strong trend of decreasing PC of *Ulva* spp with higher crab densities, no significant effect of HS (ES=0.70, power=0.49).
Rudnick and Resh (2005)	*Eriocheir sinensis*	San Francisco	Presence/absence treatments to test effect on oligochaetes, Trichoptera (caddisfly *Gumaga nigricula*), Ephemeroptera (Trichorythidae and Leptophlebiidae), large and small *Corbicula fluminae*, algae and macrophytes.	No significant effect on change in PC of macrophytes (*Ludwigia*) (ES=0.29, power=0.17
Tyrrell et al (2006)	*Hemigrapsus sanguineus*	New Hampshire	Used varying densities in lab (control and 2 crabs/cage) and short and long field (control and 5 crabs/cage) to test effect on change in percent cover for *Semibalanus balanoides*, *Spirorbis* sp and ephemeral, crustose and fucoid algae, and *Mastocarpus/Chondrus* spp.	No significant effect of HS on fucoid algae (ES=0.30, power=0.37) or *Mastocarpus/Chondrus* (ES=0.13, power=0.10) in lab; on *Spirorbis* sp (ES=0.47, power=0.57), *Mytilus edulis* (ES=0.17, power=0.11), ephemeral (ES=0.17, power=0.12), crustose (ES=0.23, power=0.17) or fucoid (ES=0.17, power=0.11) algae or *Mastocarpus/Chondrus* (ES=0.13, power=0.09) in 2-day field; or on *Spirorbis* (ES=0.73, power=0.67), ephemeral (ES=0.75, power=0.70) or crustose (ES=0.39, power=0.23) algae, or *Mastocarpus/Chondrus* (ES=0.64, power=0.54) in 14-day field experiment.

Appendix C: Table 9. Non-significant results for nonindigenous algal abundance impact studies. SM=*Sargassum muticum*, CF=*Codium fragile*, CR=*Caulerpa racemosa*, CT=*Caulerpa taxifolia* and UP=*Undaria pinnatifida*. PC=percent cover.

Citation	Species	Location	Experimental methods	Results
Airoldi (2000)	*Womersleyella setacea (turf)*	Ligurian Sea, Calafuria, Italy	Removal of WS (initial removal of turf; repeated removal of turf; abrasion of turf; control) to test effects on crust algae	No effect on PC of crust algae (F=2.08, p>0.05).
Ceccherelli and Campo (2002)	*Caulerpa racemosa*	Italy, Mediterranean Sea	Removal of CR to test effects on shoot density of *Cymodocea nodosa*	No effect(F=5.49, p=0.1438)
Ceccherelli et al (2001)	*Caulerpa racemosa*	Mediterranean (Italy)	Removals of CR to test effects on shoot density of *Cymodocea nodosa*	No effect (p=0.1438)
Farrell and Fletcher (2006)	*Undaria pinnatifida*	Devon, UK	Removals of UP to test effects on PC of red and green algae, and density of *Styela clava*	No effect on any group ("NS")
Piazzi et al (2005)	*Caulerpa racemosa*	Italy, Mediterranean Sea	Addition of CR to test effects on PC of turf, erect and prostrate algae, as well as several specific species within these	No effect on PC of turf (F=1.26) or density of *Flabellia petiolata* (10.25), *Laurencia obtusa* (8.04) and *Peyssonnelia rubra* (4.93) (p>0.05).
Sanchez and Fernandez (2005)	*Sargassum muticum*	Spain, East Atlantic	Removal of SM to test for effects on PC of dominant macroalgal species	No effect on PC of *Bifurcaria bifurcata* (λ-1.85, p=.203); *Gelidium spinosum* (λ=2.20, p=0.169); or rest of species (λ=0.51, p=0.488).
Valentine and Johnson	*Undaria pinnatifida*	Tasmania, Australia	Removals of UP at two difference dates to test effects on PC of total native algae, red algae, native canopy-forming algae, green algae and brown turf algae	No effect on PC at either date for total native algae [2000:F,p; 2001:F,p] (1.21, 0.157; 2.5, 0.125), red algae (1.07; 0.31; 3.05, 0.092) or native canopy-forming algae (1.63, 0.213; 0.32, 0.577). No effect on PC in 2001 for green algae [F,p] (0.1, 0.76) or brown turf algae (0, 0.963)

Appendix C: Table 10. Non-significant results for nonindigenous crustacean abundance impact studies. PC=percent cover.

Citation	Species	Location	Experimental methods	Results
Durr and Wahl (2004)	*Balanus improvisus*	Baltic Sea	Removal treatments to determine effect on PC (small specimens) or density (large specimens) of *Zoothamnium* spp, *Laomedea flexuosa*, *Ceramium strictum*, *Folliculina* spp, *Mytilus edulis*, *Membranipora crustulenta*, *Polydora* spp, *Corophuim* spp, and *Clava multicornis*	No effect on any group (F, p not given)
Griffen (2006)	*Hemigrapsus sanguineus*	New Hampshire	Presence/absence treatments to test effect on single and two different densities (low and high) of *Mytilus edulis*	No effect on either single ($F=0.005$, $p=0.946$) or two different densities of *M. edulis* ($F=0.036$, $p=0.850$).

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