Essay

The Control of Biological Invasions in the World's Oceans

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Abstract: *The introduction of alien, or nonindigenous, animals and plants has been identified by scientists and policy makers as a major threat to biodiversity in marine ecosystems. Although government agencies have struggled to control alien species on land and freshwater for decades with mixed success, the control of alien marine species is in its infancy. Prevention of introduction and establishment must be the first priority, but many populations of alien marine species are already well established worldwide. National and international policies leave loopholes for additional invasions to occur and provide only general guidance on how to control alien species once they are established. To address this issue, a multinational group of 25 scientists and attorneys convened in 1998 to examine options for controlling established populations of alien marine species. The discussions resulted in a framework for control of alien marine species to provide decision-making guidance to policymakers, managers, scientists, and other stakeholders. The framework consists of seven basic steps: (1) establish the nature and magnitude of the problem, (2) set objectives, (3) consider the full range of alternatives, (4) determine risk, (5) reduce risk, (6) assess benefits versus risks, and (7) monitor the situation. This framework can provide guidance for control efforts under the existing patchwork of national laws and can help provide a foundation for international cooperation.*

El Control de Invasiones Biológicas en los Océanos del Mundo

Resumen: *La introducción de animales y plantas invasoras, o no indígenas ha sido identificado por los científicos y legisladores como una de las mayores amenazas a la biodiversidad de los ecosistemas marinos. A pesar de las agencias gubernamentales han luchado por décadas por controlar a las especies invasoras en tierra y en agua dulce con resultados mezclados, el control de las especies invasoras marinas se encuentra aún en su infancia. La prevención de la introducción y el establecimiento debe ser prioritaria; sin embargo, muchas poblaciones de especies invasoras marinas ya se han establecido muy bien a nivel mundial. Las políticas nacionales e internacionales dejan espacios para que ocurran invasiones adicionales y proveen una guía solo a nivel general sobre como controlar especies invasoras una vez que ya se hayan establecido. Para enfrentar este tema, un grupo multinacional de 25 científicos y abogados se reunieron en 1998 para examinar opciones para controlar poblaciones de especies marinas invasoras establecidas. Las discusiones dieron como resultado un marco de trabajo para el control de especies marinas invasoras que provee guías para la toma de decisiones para los legisladores, manejadores, científicos y otros interesados. Este marco de trabajo con-*

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siste en siete pasos básicos: (1) el establecimiento de la naturaleza y la magnitud del problema, (2) la delimitación de los objetivos, (3) consideración de todas las alternativas posibles, (4) determinación del riesgo, (5) reducción del riesgo, (6) evaluar los beneficios contra los riesgos y (7) monitorear la situación. Este marco de trabajo puede proveer guías para los esfuerzos de control bajo el marco de trabajo existente de las leyes nacionales y ayuda a proveer los cimientos de una cooperación internacional.

Introduction

The introduction of alien, or nonindigenous, animals and plants into land and freshwater habitats has been recognized as a major problem since the last century. Alien species act as vectors for new diseases, alter ecosystem processes, reduce biodiversity, and cause major economic losses (Vitousek et al. 1996; Mack et al. 2000). Alien species have been identified by scientists and policymakers as a major threat to marine ecosystems as well, with dramatic effects on biological diversity and productivity, habitat structure, and fisheries (Carlton 1999). Alien species inhabiting new environments are often free of the predators, competitors, parasites, and diseases that limit their populations in their native regions (Elton 1958; Debach 1974; Mack et al. 2000). Successful invaders are also often able to exploit resources in novel ways. These invaders can direct more resources to growth and reproduction and thereby reduce or eliminate populations of native species through predation, competition, or other means; disrupt natural ecosystems; and cause economic and social catastrophes (Lafferty & Kuris 1996; Vitousek et al. 1997). Policies and approaches for addressing marine invasions have not kept pace with new introductions.

The history, diversity, distribution, and effects of marine invasions are poorly known for most coasts of the world, and invasions that occurred prior to about 1850 have remained largely ignored (Carlton 1999). Even in those regions that have been relatively well studied, invasions among smaller-bodied and poorly known taxa—no matter how abundant—can remain undetected and ignored as invasion candidates because of taxonomic and historical challenges. The result is that the number of invasions in a given region is always underestimated, underscoring the fact that the ecological effects of nonindigenous species are always greater than we believe.

Scientists have begun to realize the magnitude of the problem (Carlton 1999; Ruiz et al. 1999). Within the lower 48 states of the United States, between 70 and 235 alien species have been detected for each estuary that has been explicitly surveyed for invasions (Ruiz et al. 1997). In San Francisco Bay alone, 235 alien marine and brackish-water (estuarine) organisms are currently recorded, but because of insufficient data the actual number of invasions may in fact be twice as large (Cohen & Carlton 1998). Since 1961, over 135 alien species have invaded the bay, which translates to an average of one new invasion every 14 weeks (Cohen & Carlton 1998). These invasions constitute an ecological roulette, with each successive invasion having unpredictable negative consequences on the environment, economy, and society. Altogether in the United States, marine invasions have caused hundreds of millions of dollars in direct costs and in the loss of ecosystem services in the twentieth century alone (e.g. Cohen & Carlton 1995; Lafferty & Kuris 1996). Studies in Australia indicate that marine pests are even more prolific in that country (Hewitt et al. 1999) and have already led to restrictions on domestic and international vessel traffic. It took 270 people 1 month and over $2 million (Australian dollars) to eliminate a recent invasion of a close (estuarine) relative of the zebra mussel (*Dreissena polymorpha*) in Darwin (Bax 1999).

There has been a vast increase during the 1980s and 1990s in the worldwide spread of nonindigenous marine organisms. It is estimated that 10,000 or more species of marine organisms may be transported around the world in ships' ballast water each week (Carlton 1999). Other major vectors responsible for the global movement of marine organisms include the aquarium industry, aquaculture, the bait industry, and fouling of ships' hulls and seachests (Carlton & Geller 1993; Cohen et al. 1995; Cohen & Carlton 1997; Ruiz et al. 1997). Fouling is not confined to large ocean-going vessels but also occurs on small fishing, recreational, and refugee vessels. Without adequate steps to prevent or reduce the introduction, establishment, and spread of alien marine species, the increasing mobility of human populations and material goods will result in wave upon wave of new invasions, burdening nations with even greater costs in the future.

Government agencies and others have been working to control alien species on land and freshwater for decades, with mixed success, but control of alien marine species is in its infancy. A number of workers have elaborated perceived differences between marine and terrestrial ecosystems (Steele 1985; Steele et al. 1989; Strathmann 1990; Norse 1993; Cohen 1994) that if true have potential implications for management of invasive species. Comparative marine terrestrial attributes identified in the National Research Council's *Understanding Marine Biodiversity* (1995) include higher reproductive output among large marine predators than terrestrial predators, greater trophic interaction among oceanic species than terrestrial species, and the fact that marine primary producers are often represented by numerous highly mobile species in many different phyla. But such differences remain speculative and little understood.

To examine options for controlling established populations of alien marine species, a multinational group of 25 scientists and attorneys participated in a workshop that examined four invasive species in depth. The participants included those with expertise in four alien invaders of concern today: North American salt marsh cordgrass (*Spartina alterniflora*), an invader of the North American Pacific coast; the European green crab (*Carcinus maenas*), an invader in many parts of the world; the western Atlantic comb jelly (*Mnemiopsis leidyi*), an invader in the Azov, Black, Mediterranean, and Caspian seas; and the seaweed *Caulerpa taxifolia*, which is spreading in the Mediterranean Sea. Participants also included those with expertise in organisms associated with these species, in research on the biocontrol of marine species, in control of terrestrial and aquatic invasive species, and marine environmental law. The discussions resulted in a framework for control of alien marine species that provides decision-making guidance to policymakers, managers, and scientists. This framework can improve control efforts under the existing patchwork of national laws and can help provide a foundation for international cooperation.

Additional Guidance on Control

A successful alien species policy should (1) prevent new introductions and (2) control established populations in an environmentally sound and safe manner. Yet current national and international policies leave loopholes for additional invasions to occur and often do not provide the necessary guidance on how to control alien marine species once they are established, particularly when it comes to the complex issues surrounding biocontrol. Such policies ensure that additional invasions will occur and indicate the need for clearer guidance on control. We focus on providing additional guidance of the control of those species that do become established.

In the United States, the spread and control of harmful alien organisms have been addressed by multiple statutes dating from the turn of the twentieth century, including the Plant Quarantine Act of 1912, the Federal Plant Pest Act of 1957, the Noxious Weed Act of 1974, and the Lacey Act, first enacted in 1900. Most of these focus heavily on control of agricultural pests on land and contain large loopholes to allow harmful invasive species to continue entering the country (Miller & Aplet 1993; Strong & Pemberton 2000). Under the Noxious Weed Act and Lacey Act, for example, organisms are controlled only if they are officially added to the lists of prohibited species, often a lengthy and difficult process. All others, even those known to have adverse effects, are not limited by these statutes (Miller & Aplet 1993; Office of Technology Assessment 1993). None of these laws fully addresses the issues surrounding prevention and control of alien species. The congressional Office of Technology Assessment (OTA) noted in 1993 that the federal framework is a largely uncoordinated patchwork of laws, regulations, policies, and programs, and that ". . . present Federal efforts only partially match the problem at hand" (Office of Technology Assessment 1993).

More recent laws address marine invaders. Motivated by the rapid spread and high economic costs of the zebra mussel invasion in the Great Lakes, Congress enacted the U.S. Non-indigenous Aquatic Nuisance Prevention and Control Act of 1990 (NANPCA; as in U.S. Code 2000), as amended by the National Invasive Species Act of 1996, to address alien marine and freshwater species. This law established a combination of mandatory and voluntary programs to limit the introduction of alien species into U.S. waters from ships' ballast exchange by requiring or encouraging ships to exchange their foreign ballast water far from port or in waters where the exchange does not pose a threat. Some other countries, including Australia, Canada, Chile, Israel, and New Zealand, have similar requirements for some or all of their ports (Anonymous 1998). Despite this progress, many nations have little or no regulation of ballast-water exchange. Moreover, these laws address only one route of entry and do not control other routes, ensuring that marine invasions will continue. The discovery in June of 2000 of *Caulerpa taxifolia* in coastal San Diego County in California highlights the weaknesses of current prevention policies. After more than 100 scientists petitioned the U.S. government in October 1998 to add *Caulerpa* to the list of species banned from importation, possession, and sale in the United States under the Noxious Weed Act, *Caulerpa* was added to the list in 1999 (A. Cohen, personal communication). This listing clearly failed to prevent introduction.

Although new national policies and international agreements have begun to recognize the importance of environmentally sound control programs for alien species, the practical aspects have often remained poorly defined, particularly in addressing the complex issues surrounding biocontrol. The theory in biological control is that an introduced predator, competitor, parasite, or disease from the pest species' native habitat can effectively control a pest population, as demonstrated by some spectacular successes in agricultural systems on land (Van Driesche & Bellows 1996; Center et al. 1998; Gurr & Wratten 2000). Nevertheless, damage to nontarget species has often been high, especially before 1950 when the modern, scientific period of biological control began (Center et al. 1998). Effects can go beyond simply predation on nontarget species and include direct competition with native species for resources or disrupting ecosystems through indirect interactions with other species (Howarth 1991; Simberloff & Stiling 1996; Strong & Pemberton 2000). To effectively control an alien species, it is likely that introduced agents must attain high population densities and therefore, if successful, may have ecosystem-level effects. This fact has not been well appreciated in terrestrial biocontrol programs in the past.

Most researchers believe that the safety of nontarget species is paramount and that control agents should be host-specific—that is, only the target alien species should be affected (Center et al. 1998). But in practice, the selection and screening of terrestrial biocontrol agents have rarely been adequate (Strong & Pemberton 2000). In the United States, the Department of Agriculture's Animal and Plant Health Inspection Services (APHIS) regulates the introduction and dissemination of most biological control agents, primarily focusing on weed control. The OTA reported in 1995 that past oversight of introduction of biological control agents by the APHIS has been unbalanced, incomplete, and poorly documented (Office of Technology Assessment 1995). No federal statute in the United States explicitly requires that biocontrols be reviewed before they are introduced (Strong & Pemberton 2000). Moreover, the frequent omission of post-release monitoring has meant that overall costs and benefits—both environmental and economic—of many biocontrol programs have rarely been adequately assessed (Howarth 1991; Simberloff & Stiling 1996; Van Driesche & Bellows 1996; Follett & Duan 1999; Lockwood et al. 2001).

Legal control of alien marine species in the United States appears to be more comprehensive than that of alien land species, but implementation has been slow and spotty. The primary law, NANPCA, created the Aquatic Nuisance Species Task Force to develop a program to prevent, monitor, and control alien nuisance species. The task force is authorized, but not required, to develop control programs for established populations; it includes important language that control efforts are to be based on the best available scientific information and conducted in an environmentally sound manner. Although the act does not specifically address biocontrol, it does require that control methods authorized under the act minimize adverse effects on ecosystems and nontarget organisms, and emphasize integrated techniques and nonchemical measures (16 U.S.C. 1401 et seq.). Since enactment in 1990, no more than 10 proposals for alien species control plans have been presented to the task force, and only 2 of these have resulted in control plans (S. Gross, personal communication). This slow pace reflects in part the inherent difficulty in developing safe and effective control programs and suggests that additional guidance on controlling alien aquatic species can help facilitate this process and increase its effectiveness.

On 3 February 1999, President Clinton signed an executive order (1999) that attempts to improve alien-species management by coordinating federal activities and requiring agencies to develop guidance to prevent, monitor, and control alien invaders in a cost-effective and environmentally sound manner. It establishes a cabinet-level interagency Invasive Species Council to prepare a national invasive species management plan and develop guidelines for agencies on the prevention and control of invasive species. The order indirectly addresses biocontrol by ordering agencies to not carry out actions likely to promote the introduction or spread of invasive species in the United States or elsewhere unless, pursuant to guidelines it has described, the agency determines that the benefits clearly outweigh the potential harm and that measures will be taken to minimize risk (Executive Order 13112, 1999). Federal agencies completed a draft plan in July 2000.

Australia's Biological Control Act of 1984 is the first of only a few biological control laws adopted by a national government. It provides a procedural framework for the discussion and approval of proposed controls, but it contains no substantive standards (Delfosse 1988; Miller & Aplet 1993). In 1996, New Zealand enacted the Hazardous Substances and New Organisms Act, which sets up the independent Environmental Risk Management Authority (ERMA) as the primary authority to determine which new organisms can be introduced into New Zealand. A methodology set up under the act requires the ERMA to evaluate the risks, costs, and benefits of any proposed introduction and to consider scientific and technical uncertainty (New Zealand Hazardous Substances and New Organisms Act of 1996).

Several international conventions and voluntary codes of practice address the need to prevent and control alien species, but, like many national laws, they provide little or no guidance on how to do so. For example, the 1992 United Nations Convention on Biodiversity and the Convention on the Law of the Sea both include goals to prevent the introduction of alien species that threaten the environment, and both require states to control or eradicate established alien species, but neither say anything on how to accomplish these goals. A systematic framework for approaching this problem can help governments more effectively achieve their goals of controlling established populations of alien species.

Framework for Control

We present a framework that provides specific guidance to those in developing programs to control established populations of alien marine species. The framework consists of a series of steps to guide decision making, with particular attention to factors to consider for use of biocontrol. Although we were considering marine alien species when we developed the framework, we believe it can also apply to terrestrial or freshwater species.

The flowchart in Fig. 1 illustrates how the framework steps are part of an iterative rather than linear process, with some steps repeated if additional information is necessary or if agreement is not reached. The flowchart also incorporates the role of regional stakeholders throughout the process. Decisions made at various steps require value judgements to be made based on the best available science, such as determining the objectives to be achieved and deciding whether to proceed based on knowledge of risks and likely benefits.

The goal of the framework is to solve the identified problem with the lowest risk possible. The solution may, or may not, include controlling the alien species. A key principle in achieving this goal is adopting a precautionary approach, particularly with potentially irreversible options like biocontrol. Releasing new alien organisms intentionally to control invasive species without first determining secondary effects is a high-risk strategy: the control may cause greater problems than the original alien invader itself. Therefore, a precautionary approach that minimizes the risk of irreversible secondary effects must be followed.

Step 1: Establish the Nature and Magnitude of the Problem

There are several key questions to be addressed in the first step. First, it is essential to confirm that the species is indeed an alien rather than a locally rare or occasional species responding to an altered environment, and whether the alien species is a primary cause of or major contributor to the problems identified. Second, it is necessary to determine the vector(s) that transported the alien species to its new environment and determine the risk that further invasions could occur. Third, the local and regional distribution of the species, and therefore the areas requiring control, need to be identified. Lastly, preliminary estimates of the actual and potential effects of the species are needed to determine how to proceed.

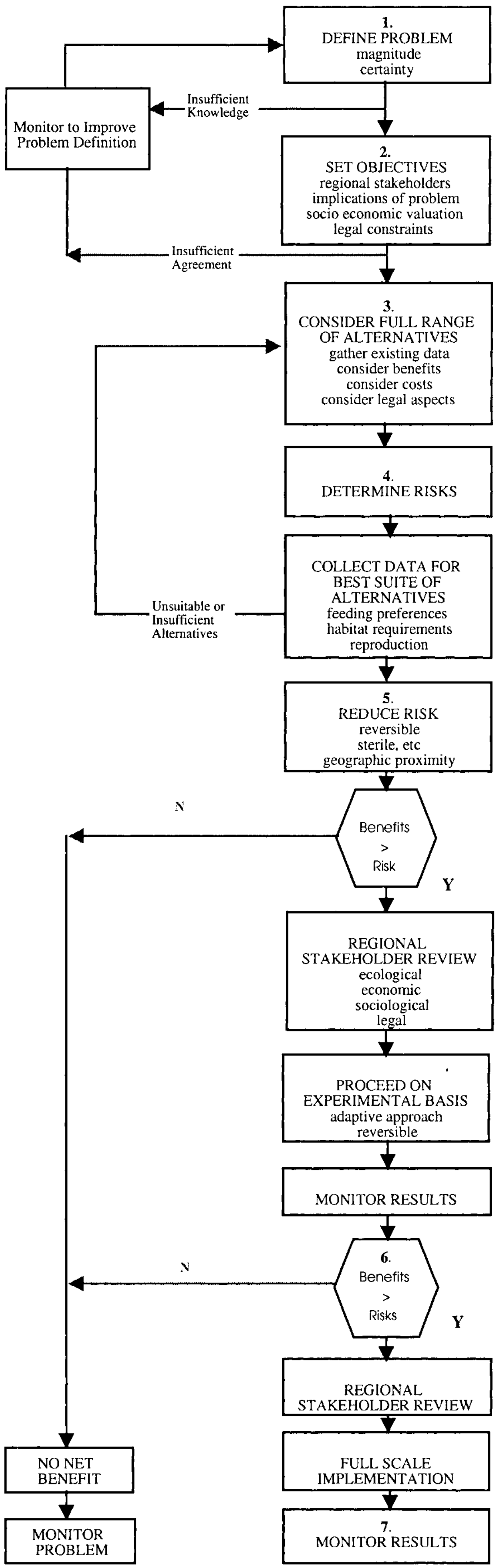
Many factors other than alien species—such as pollution, habitat destruction, and overexploitation of resources—can cause or contribute to environmental degradation. For example, the comb jelly *Mnemiopsis* is known to be a major consumer of zooplankton (Kremer 1979) and might also be detrimental to the forage-fish populations that feed on zooplankton by consuming fish eggs and larvae (Purcell et al. 1994). Although the comb jelly was first recorded in the Black Sea in 1982, it remains unclear whether it is the primary cause or just one of the factors contributing to fishery declines since it blossomed in 1989 (Shiganova 1998; Purcell et al. 2001). If the establishment of the alien species and their adverse effects are enhanced or exacerbated by other environmental factors, then a combination of control and noncontrol management options may be desirable.

If a relationship between the problems observed and the alien species can be established, the dimension of the problem needs to be assessed so it can be weighed against the level of risk involved in control. The basic questions are how bad the situation is and how far we are willing to go to fix it. Assessment could include measurements of direct economic losses from, for example, decreased fisheries or tourism, and measurements of effects on biodiversity, endangered species, ecosystem functioning, and other ecological (and thus indirect economic) costs. The simplest measure would be the direct economic loss caused by the alien. For example, one study suggests that on the U.S. West Coast the European green crab threatens economic activity worth $44 million per year (Lafferty & Kuris 1996). Although the ecological and indirect effects are usually more difficult to quantify, they may be at least as high as direct economic losses and should be made explicit, even if only qualitatively. For example, proliferation of the North Atlantic salt marsh cordgrass (*Spartina alterniflora*) on the U.S. Pacific coast has converted open mud flats, which supported invertebrate, fish, and migratory shorebird populations, to dense stands of vegetation that cannot be used by these species (Patten 1997). Regardless of how effects are determined, the importance placed on these effects is ultimately a value judgement.

Real-world limitations on the assessment of the effect of any given introduced species include temporal and financial restraints. There is often pressure from political, public, and press arenas—and even funding agencies—for instantaneous assessment of the real or potential effects of an invader. But such assessment often requires long-term studies taking years or decades before even a general understanding can be achieved of how a species has inserted itself into an ecosystem. At the heart of such assessments are experimental studies, which rarely have been carried out for marine invasions. All such studies—whether observational or experimental—require extensive funding to support personnel and laboratory and field supplies, and such funding rarely has been forthcoming, especially to sustain long-term research.

It can take many years to progress to step 2 in the control of alien species, especially in the marine environment, where alien species may be hidden from view or overlooked as a local species until effects become severe. For example, the seastar *Asterias amurensis* was misidentified as a local species in Tasmanian waters for almost a decade (Goggin 1998); it is now considered Australia's most damaging marine pest.

The time required for adequate information gathering must be balanced against the fact that control or eradication of an alien invasive species will be easiest, or sometimes only possible, at the earliest stages of an invasion. Crooks and Soulé (1999) suggest that when a species is locally contained and there is an opportunity to eradicate it with acceptable environmental consequences, ex-



tirpation should be early and vigorous. Processes that hasten response to an invasive alien increase the chances of a successful response. Underwater surveys and increased community education and awareness increase the chance that an invasive alien species will be detected early. A preexisting management structure designed to lead the response to a detected (or suspected) alien invasive will hasten progress to step 2.

Step 2: Set and Clarify Objectives

Once the problem has been defined with sufficient certainty, regional stakeholders and decision makers need to determine what they want to accomplish. Do they want to restore economic benefits lost? Do they want to restore or protect native biodiversity and ecosystem functioning? Do they want to address all of these problems? Is total eradication of the alien species desired, or is control to a certain level of abundance acceptable? What legal responsibilities must be addressed? And what are the performance criteria against which the success of any control program will be measured?

Step 3: Consider Full Range of Alternatives

To address the problem and achieve the objectives, the full range of management options should be considered, including noncontrol options. Noncontrol options such as habitat improvement, pollution abatement, or improved fisheries management might be successful in restoring native biodiversity, ecosystem functioning, or economically valuable species. Such options typically have lower risk than control options and have secondary environmental benefits as well. Specific actions may of course take years to implement.

Doing nothing is also a possible option. Populations of some terrestrial invaders have collapsed after their initial buildup. Other alien species have become damaging only after decades of surviving at low population levels (Crooks & Soulé 1999; Mack et al. 2000). Understanding the causes of these population collapses and explosions could help in predicting the outcomes of future invasions and in developing appropriate control procedures.

The level of control and the time period and area over which it is desired are important aspects of the evaluation of various options. For example, if a primary objective is ecological restoration, a risk-averse control program that reduces the ecological effect of the alien

Figure 1. A flowchart of some of the information needs, consultations, decision points, and risk-minimization steps needed to identify risk-averse options for controlling established populations of alien marine species.

species to a state in which it no longer dominates ecosystem functioning over the long term might be suitable. Alternatively, if restoring economic benefits is considered an overriding objective, a more rapid and effective but higher-risk control program might be preferred. Also, many economic objectives might be limited in space because control may be necessary only in the areas under commercial development (e.g., a mariculture farm). Any quick action, however, must be balanced against the need for adequate information to determine the nature of the problem, consider all options, and assess risk.

A successful control program typically contains a suite of control activities, including mechanical options, chemical treatments, biocontrol, and protection from reinvasion. Such integrated pest management potentially allows managers to tie different control options to different areas, times, and life-history stages in an effort to minimize risks and costs while maximizing prospects for control.

Step 4: Determine Risks

Risk is a function of the likelihood of harm occurring and the severity of the harm that results. The goal of successful alien species control is to effectively address the problems generated by the alien species while minimizing the risk of undesired outcomes. Therefore, the risks associated with each control option and the methods by which risks might be minimized should be determined.

The risks associated with biocontrol are high if side effects are not fully evaluated: introducing an additional nonnative predator, parasite, competitor, or other organism to control an alien invader can harm nontarget species if the introduced species is not host-specific, and it may alter ecosystem functioning. Moreover, these effects need not be localized and often are irreversible. Because the biocontrol agent may be able to disperse far beyond the target system and multiply and adapt to different conditions—including increasing environmental tolerance, geographic range, or range of hosts—long-term effects may be difficult to identify. Such effects can appear years after a biocontrol agent is introduced (Simberloff & Stiling 1996; Strong & Pemberton 2000). Risks associated with other options can be high as well, such as chemical treatment that poisons nontarget species. Eradicating an estuarine relative of the zebra mussel from Australia required killing all organisms within three enclosed marinas (Bax 1999).

To determine the harm that might be caused by a potential biocontrol agent, each situation must be studied individually. For example, the biology and taxonomy of proposed biocontrol agents, the target pest, and associated organisms in the potential new range of the agent should be known. Data should be collected on the diet, growth and reproduction, environmental tolerances, habitat preferences, dispersal ability, potential to adapt to new hosts or conditions, and any other key life-history characteristics of the biocontrol agent which might reveal potential direct or indirect effects on native species and ecosystem functioning. This information will help determine the host and habitat specificity of the proposed biocontrol agent and whether nontarget organisms could be affected by it. In practice, host and habitat specificity are difficult to predict. As specific control options are developed, continuing data collection and experiments will be necessary to improve knowledge of the likely effects and constraints of the controls.

Step 5: Reduce Risk

The first rule for reducing the risk associated with control programs is to choose methods specific to the effect to be controlled. Specificity can be increased by limiting control to the identified pest or to a particular area or habitat, especially if that area is not unique and does not support endangered species or other species of particular concern.

In biocontrol it is essential to use agents that will affect only the targeted alien invader. For example, some scientists have been concerned about suggestions that the west Atlantic butterfish (*Peprilus triacanthus*) could be a useful control agent of the comb jelly *Mnemiopsis* in the Azov and Black Seas (Group of Experts on the Scientific Aspects of Marine Environmental Protection, United Nations 1997). The butterfish includes in its diet gelatinous zooplankton such as *Mnemiopsis*, but it does not prey exclusively on ctenophores (Horn 1970), so nontarget native species could also be affected. In contrast, some scientists are considering host-specific insects such as the Atlantic planthopper (*Prokelisia marginata*) for control of salt marsh cordgrass in the Pacific Northwest. This insect feeds only on *Spartina* and is already established in San Francisco Bay (Daehler & Strong 1994, 1995). Introduction of the planthopper in the Pacific Northwest should have no effect on native *Spartina*, which do not extend north of Bodega Harbor in Sonoma County on the central California coast. But a potentially vulnerable inland species of *Spartina* is found in salt marshes in the northern Great Basin, and the potential for these populations to be affected by *Prokelisia* must be considered.

Damage to nontarget organisms during biocontrol operations can be further reduced by using control agents that are indigenous or in geographic proximity to the control site. For example, enhancing the indigenous Azov and Black Sea horse mackerel (*Trachurus*) to control *Mnemiopsis* has less attendant risk than introducing a non-native fish such as the butterfish that, if established, could spread to the Mediterranean and northwest African coast and compete with native fish. If introduction of a non-native fish is warranted, then fish from adjacent geographical areas should be considered. Introduction of *Stromateus fiatola*, a close relative of the butterfish that is native to the Mediterranean and northwest African coasts, would limit any potential adverse results to the Black, Azov, and Caspian seas instead of affecting the entire region. Similarly, the comb jelly *Beroe ovata*, native to the Mediterranean Sea, arrived in the Black Sea and bloomed in 1999. *Beroe* preys specifically on other comb jellies and is believed to have severely reduced the *Mnemiopsis* population. Zooplankton and icthyoplankton populations appear to have rebounded (Purcell et al. 2001). Although not intentionally introduced in this case, the presence of a species from an adjacent area to control *Mnemiopsis* reduces the risks associated with a control agent spreading into adjacent areas.

Reducing risk includes proceeding with preferred alternatives on an experimental basis before full-scale implementation, and monitoring results to determine the effects of the approach. A primary means of reducing risk and proceeding experimentally is to make a biocontrol action, in effect, reversible. In some instances, we can take advantage of the control agent's life history to accomplish this. For example, the European barnacle (*Sacculina carcini*) is a parasitic castrator of the European green crab. Only the female barnacle can parasitize and develop internally in the crab, producing an external reproductive organ after a year or more. Unless a male barnacle is present at this time, no fertilization can take place and the population dies (Høeg & Lützen 1995). A male barnacle would be present only if the decision were made to make a second release of the parasite in synchrony with the development of female organs. If there were no second release, there would be no second generation of the parasite, and any adverse effects should be limited to one generation. For species with less accommodating life histories, single-sex releases or artificial sterilization can allow for similar reversible releases.

To control populations of *Caulerpa taxifolia* in the Mediterranean, A. Meinesz at the University of Nice is examining the use of tropical herbivorous slugs that may allow reversible releases. A proposed species, the sea slug (*Elysia subornata*), is believed to be capable of controlling local populations, but its requirements for year-round high temperatures to survive suggest that it should die back with each northern Mediterranean winter (Meinesz 1997; Thibaut et al. 1998). Whether *Elysia* could adapt to such winters or could spread to regions where it would survive in warmer winter conditions elsewhere in the Mediterranean remains to be determined. In addition, while *Elysia* eats *Caulerpa taxifolia*, it would also eat native Mediterranean *Caulerpa* species.

At the start of an invasion, when pest species are usually restricted to a small area, risks can be reduced by acting promptly and accepting damage to this small area so that a larger area can be protected. In the recent eradication of the black striped mussel (*Mytilpsis sallei*) in Darwin, for example, general biocides (chlorine and copper sulphate) were used to eradicate the mussel while it was still contained in marinas separated from open waters with double-lock gates (Bax 1999). The loss of a wide range of taxa in these marinas was accepted because the marinas were small, artificial or highly modified environments of low environmental value. In addition, because local tides have a 7-m range, any chemicals escaping the confines of the marinas would dilute rapidly.

In all instances, experimental application of control methods in controlled situations can be used to determine risk when control of the wider problem is attempted. Biocontrol releases in isolated water bodies can help identify effects before a widespread release. Chemical controls used in eradicating *Mytilopsis* were first tested in the laboratory and then in only one smaller, recently excavated marina before being applied to all three marinas.

Step 6: Assess Benefit or Risk of Full-Scale Implementation

The goal of a control program is to effectively control the species or otherwise address the problem while minimizing risk. But evaluating alternative approaches, even after proceeding with steps 1 through 5, is not clear-cut. A useful tool for deciding whether to proceed with a program is to express the many inputs involved as an equation. A simple formula was first suggested at the workshop by A. Cohen of the San Francisco Estuary Institute is

$$\text{support for control} \propto \frac{\text{magnitude of problem} * \text{likelihood of successful control}}{\text{magnitude of adverse result} * \text{likelihood of adverse result} + \text{cost of control}}$$

This formula is essentially the cost-benefit ratio for a proposed control. The support for control will be high if the magnitude of the problem and the likelihood of successful control are high and/or the magnitude and likelihood of an adverse result, plus costs, are low. If so, then the program is a candidate to proceed. If the support is low—the magnitude and likelihood of an adverse result plus costs are high and/or the problem and likelihood of successful control are low—then the control program should not be undertaken. The formula is straightforward to apply when the magnitude of the problem and magnitude of an adverse result can be expressed in terms of monetary value. The formula is not straightforward to apply when environmental values that cannot be readily expressed in monetary terms are included. The tradeoff between monetary and environmental values is made explicit in a reorganized formula presented in Appendix 1. A hypothetical application of the formula is developed in Appendix 2.

A key parameter in the reorganized equation is B, a constant representing society's weighting of ecological and economic values. One reviewer questioned the subjectivity of this parameter. It is clear that there is as yet no correct value for this parameter, although conceivably by application of the formula to existing environmental decisions, some idea of society's weighting of relative economic and environmental costs and benefits could be obtained. In a new area, such as the control of marine pests, it would be more appropriate to use the formula to explore the implications of alternative control options as an aid to understanding the full ramifications of particular choices.

Step 7: Monitor the Program

The commitment to and funding of a rigorous monitoring program should be a key component of any control program. Sufficient monitoring often has been lacking in terrestrial biocontrol programs and in marine environmental management in general. The control of alien marine invasions is in its infancy, and it is essential that control programs be monitored to permit learning from early successes and failures. Monitoring will need to be specific, targeted closely to the potential problem, and reported openly in the literature. By incorporating effective monitoring programs into control programs, marine scientists and managers can learn from their initial results.

Stakeholder Involvement

Whether or not to proceed with a control program is ultimately a value judgement, ideally made jointly by decision-makers, stakeholders, and society based on the best available scientific information. Because of the potential social, economic, and ecological effects of alien species invasion and control, key steps in the framework require choices that should involve regional stakeholders, including people from all areas likely to be affected by both the invasion and the control options. This includes involvement in setting objectives, reviewing alternatives, and weighing the benefits of control options against their risks and the risks of no action. Ideally, the review should consider the ecological, economic, sociological, and legal ramifications of the proposed control options.

In addition, marine alien invasions and their control usually have international ramifications. For example, butterfish introduced to control *Mnemiopsis* in the Black and Azov Seas could spread and affect North African fisheries. It is therefore important that an international advisory body open to all nations be created to advise and monitor marine-pest management so that one nation's cure is not another nation's curse.

Recommendations

Effective programs to control alien marine species must be developed, because invasions threaten the long-term sustainability of native ecosystems with attendant economic, ecological, recreational, and other costs. To address this growing problem we make the following recommendations.

Because prevention is key to reducing the introduction and spread of invasive species, a first priority is that the strongest possible measures be taken to reduce invasions through all identified vector routes.

Because the best opportunity to control a new and limited invasion will be as soon as possible after establishment, national public awareness programs should be set up to monitor for invasive species, and options for rapid response to new and limited invasions should be developed.

Because of the complexity of managing invasive species in the open marine environment, all proposed control actions should be assessed through a formal risk-assessment process similar to the framework we have detailed.

Because alien marine invasions are an international phenomenon, a working group should be established under an appropriate international agency to review intrusions of alien species in marine waters, to notify appropriate regional bodies when a new invasive species has become established in the area, and to assess appropriate actions for control of established alien species, where necessary.

Invasive species are one of the most difficult marine environmental issues we face, with the potential to impose greater mortality on fish stocks than any fishery, and as great (or greater) changes on habitat as any physical impact. They are pervasive and can undo other conservation initiatives. Without more effective prevention and control, the number of invasions and their subsequent effects will only increase.

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Appendix 1

Decision Index for Implementing Control of Invasive Alien Species

A useful means for sorting out and considering the many inputs involved in making the decision about whether to proceed with a control option is to express each as an equation. First, however, it is necessary to define the full set of terms.

a_1, primary ecological benefit = $B_e \times P(B_e)$ or the product of the magnitude of the ecological benefits (B_e) (magnitude of pest problem to be controlled) and the probability (P) of realizing that gain

a_2, secondary ecological benefit = $B_{2e} \times P(B_{2e})$ or the product of the magnitude of the secondary ecological benefits (B_{2e}) (environmental benefits in addition to those gained from controlling the pest) and the probability (P) of realizing that gain

C_1, ecological cost = $C_e \times P(C_e)$, or the product of the magnitude of ecological costs (C_e) (side effects of the control) and the probability (P) of realizing that loss

b_1, primary economic benefit = $B_\$ \times P(B_\$)$ or the product of the economic benefits ($B_\$$) (magnitude of pest problem to be controlled) and the probability (P) of realizing that gain

b_2, secondary economic benefit = $B_{2e} \times P(B_{2\$})$ or the product of the magnitude of secondary economic benefits (B_2) (economic benefits in addition to those gained from controlling the pest) and the probability (P) of realizing that gain

C_2, economic cost = $C_\$ \times P(C_\$)$ or the product of the economic costs ($C_\$$) (side effects of the control) and the probability (P) of realizing that loss

C_3, economic cost of direct costs of control and monitoring

β, a constant representing society's weighting of ecological and economic values; a high beta means that economic values are greater

These terms are combined in a proportionality to develop a decision index or cost-benefit ratio. Economic costs and benefits are separated from ecological costs and benefits, so that the proportionalities are not constrained by having to express economic and ecological factors in the same units. If the index (I) is high, proceeding with the control is favored; If it is low, the control is probably ill-advised. Thus,

$$I = \left(\frac{a_1 + a_2}{C_1}\right)^{\beta} \times \left(\frac{b_1 + b_2}{C_2 + C_3}\right).$$

According to the formula, proceeding with control is favored (high I) if the problem is large and the probability of successful control (a_1 and b_1) are high. Not proceeding (low I) is suggested if the severity of damage from control and its probability (C_1 and C_2) are high. If society places a high value on economic as opposed to ecological value (high β), the desirability of proceeding with a proposed control would be reduced if treatment and monitoring costs (C_3) were high. On the other hand, desirability is increased if there are substantial secondary ecological or economic benefits (a_2 and b_2) are high. Secondary benefits will often be 0, but they could be significant in situations where the control action may have ecological value, such as habitat improvement, or economic value, such as if a control fish became the subject of a commercial or sport fishery. A worked example is provided in Appendix 2.

Appendix 2

Application of the Decision Index to an Invasive Marine Mussel

We applied the decision index developed in Appendix 1 to a hypothetical example based loosely on the eradication of the black striped mussel in Darwin in 1999. Although some of the values relate to that eradication, others are entirely hypothetical.

We used the decision index to explore the costs and benefits of three possible scenarios for the invasion of an exotic marine mussel. The mussel is assumed to have severe environmental and economic consequences for the marine environment and infrastructure in tropical Australia, including reducing income of a $250 million/year pearl oyster fishery by 10% and engineering and cleaning costs of $50 million per year. Economic values are net present values assuming a discount rate of 10%. Environmental values are qualitative values between 0 and 1 based on the magnitude and extent of an impact or benefit.

The three scenarios are as follows: (1) the mussel is locally contained in an enclosed marina with minimal environmental value, and chemical treatment is possible with some disruption to local businesses; (2) the mussel has escaped local containment but is still restricted to a larger open port, and chemical treatment is still a possibility; or (3) the mussel is locally contained in a degraded environment, and habitat restoration is being considered as a mechanism to reduce local effects of the mussel.

A value of β ranging from 3 to 0.3 was used to compare the decision index between scenarios. There is no correct value for β, although an accepted range of β for different situations could potentially be developed through consistent application of this formula. In this hypothetical instance, it can be seen that scenario 1 has a high cost-benefit ratio regardless of the value of β, because both the economic and environmental cost-benefit ratios are positive. Scenarios 2 and 3 are more interesting, because only one of the two cost-benefit ratios is positive. Economic benefits are reduced in scenario 2 because of the greatly reduced probability of attaining those benefits. At the same time, treatment and monitoring costs are increased. The environmental cost-benefit ratio is <1 because of increased environmental costs of a widespread chemical treatment, and because of a decreased probability of attaining the environmental benefits. The decision index indicates that only when economic benefits are seen to have much greater relative value to society than the environmental benefits could scenario 2 be considered. In contrast, under scenario 3, where the probability of realizing the economic benefits and primary environmental benefits through eradication of the mussel is minimal, only the secondary environmental benefits lead to a positive decision index, and then only when the index is weighted to favor relative environmental benefits.

(Appendix 2 continued)

Appendix 2 (continued)

Environmental and economic costs and benefits associated with using chemical treatment (scenarios 1 and 2) or habitat restoration (scenario 3) to control a hypothetical alien marine mussel population restricted to an enclosed marina (scenario 1), an open port (scenario 2), or a localized degraded environment.*

		Scenario		
Factor	*Variable*	*1*	*2*	*3*
Primary ecological benefit	B_e	0.80	0.80	0.10
Probability of realizing benefit	$P(B_e)$	0.80	0.20	0.50
Secondary ecological benefit	B_{2e}			0.20
Probability of realizing benefit	$P(B_{2e})$			0.80
Environmental cost	C_1	0.20	0.50	0.20
Probability of ecological damage	$P(C_1)$	1.00	0.80	0.20
Primary economic benefit	$B_\$$	731.23	731.23	731.23
Probability of realizing benefit	$P(B_\$)$	0.80	0.20	0.01
Secondary economic benefit	$B_{2\$}$			
Probability of realizing benefit	$P(B_{2\$})$			
Economic cost	C_2	2.00	20.00	68.62
Probability of economic damage	$P(C_2)$	0.80	0.80	0.80
Control and monitoring costs	C_3	2.00	50.00	5.00
Computed economic cost-benefit ratio		162.49	2.22	0.12
Computed ecological cost-benefit ratio		3.20	0.40	5.25
Decision index				
	beta			
↑ Economic value	0.3	239.5	1.6	0.2
	0.5	290.7	1.4	0.3
	1.0	520.0	0.9	0.6
	2.0	1663.9	0.4	3.4
Environmental value ↓	3.0	5324.6	0.1	17.7

**A summary-weighted cost-benefit (decision index) is provided for alternative weightings of economic (low β) or environmental (high β) values. See text and Appendix 1 for full details.*