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The Invasive Species Challenge in Estuarine and Coastal Environments: Marrying Management and Science

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Abstract Despite the widely acknowledged threat posed by invasive species in coastal estuaries, there are substantial gaps at the intersection of science and policy that are impeding invasive species management. In the face of pressing management needs in coastal and estuarine environments, we advocate that introduced species should receive the kind of management effort dedicated, for example, to reducing pollution. We support our argument with some examples of economic costs of estuarine and coastal introduced species and a summary of recent evidence for the ecological costs. We highlight some of the issues that either thwart or facilitate the successful marriage between science and management of introduced species, including the regulatory framework for management. We use the available information on coastal eradication programs, including case histories of the programs for *Caulerpa taxifolia* and *Spartina alterniflora* (and hybrids) in the western USA, to indicate the feasibility of managing introduced species and to help point out how management and science can improve the outcome. We close with a research agenda that focuses primarily on science that will really assist with invasive species management and reflects our own experience and the opinions of managers directly involved with this issue.

Keywords Marine invasive species · Eradication · Economic costs · Management · *Caulerpa* · *Spartina*

Introduction

In this essay, we advocate that introduced species in coasts and estuaries should be managed with the same resolve dedicated to overexploitation, pollution, and climate change. We define an introduced species as having been introduced outside its native range through human activities; invasive species are a subset that are likely to, or cause economic or ecological harm. Estuaries and coasts are particularly susceptible to introductions of nonnative species partly a consequence of being centers for the activities that represent the major vectors for introductions: shipping and boating (Carlton and Geller 1993; Ruiz et al. 2000a); aquaculture (Naylor et al. 2001); aquarium trade (Padilla and Williams 2004); live seafood and bait (Chapman et al. 2003; Weigle et al. 2005). Research has progressed from identifying new introductions and determining the origin and probable vector to addressing the ecological effects of the introductions (Ruiz et al. 1999; Grosholz 2002). The media has heightened public awareness by trumpeting many cases, including the cholera virus transported in ballast waters (BBC News, 1 Nov. 2000), the ‘Killer Alga’ (*Caulerpa taxifolia*) invasions of the Mediterranean, California, and Australia (Simons 1997; Perlman 2000), and recently, pythons in the Florida Everglades (Revkin 2007). Despite this increased scientific interest and public awareness, research articles on introduced species are relatively few and tend to be published in general

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marine journals compared to ones specializing in estuaries and coasts (Fig. 1). We suggest this finding indicates that introduced species are not a sufficiently high priority for many scientists and managers dedicated to estuarine and coastal environments.

We begin this essay by reviewing progress toward management of invasive species in estuaries and coasts and why progress has not been faster, starting with the regulatory framework for management. We play the devil's advocate by asking whether slow progress even matters in the face of other pressing environmental perturbations to coasts and estuaries, at the risk of inciting our colleagues. We forego reviewing the relevant literature on the numbers of introduced species in estuaries and in coastal waters, which has been done well by others (Eno et al. 1997; Ruiz et al. 2000a; Ruiz and Carlton 2003; Streftaris et al. 2005). Instead, we provide new summaries of economic impacts of introduced species and eradication programs, along with our personal perspectives gained while serving as scientific advisers to two eradication efforts in the USA. Thereafter, we outline a research agenda aimed at providing the science needed by resource managers faced with invasive species. Several recent reviews have emphasized the need for more research on a number of topics of more basic interest to ecologists and evolutionary biologists, with limited application to on-the-ground management (Mack et al. 2000; Sax et al. 2005, 2007). Our goal here is to outline a science agenda that will bring the needed science into the management decision process. Many scientists are increasingly interested in contributing to management projects, beyond publishing in journals that busy managers have scarce time to read. Because the cultures and timelines for meaningful results for the two groups are so different, we hope that this essay will provide a perspective that might be useful as scientists head into the management arena. For example, familiarity with the regulatory framework for management can help scientists communicate better with their manager colleagues. Many calls for action are available (e.g., Carlton 2001; Lodge et al. 2006), so we only reinforce recommendations for the management of high-priority introduced species through prevention, early detection, rapid response, and, if these fail, eradication or control.

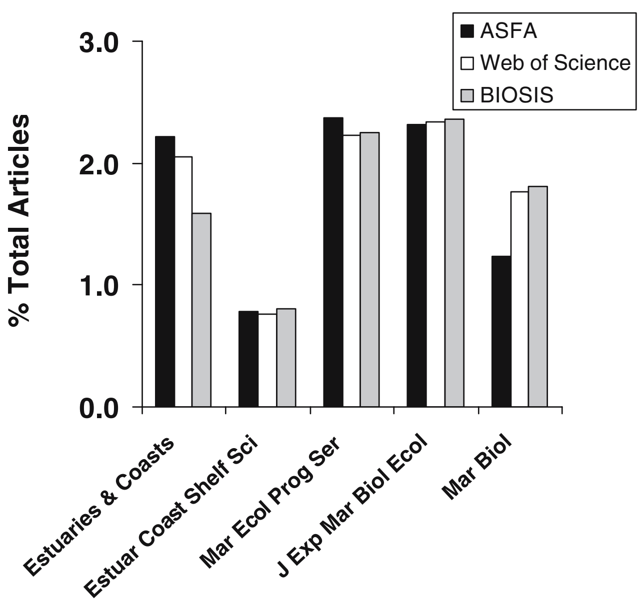

Fig. 1 Scientific publications on introduced species in estuarine and coastal versus general marine journals as percent of total number of articles published from 2000–2006. Results from searches using Aquatic Sciences and Fisheries Abstracts (ASFA), Web of Science, and BIOSIS. The total number of articles published and indexed by the Web of Science were: Estuaries and Coasts (535), Estuarine Coastal Shelf Science (1,189), Marine Ecology Progress Series (2,776), Journal of Experimental Marine Biology and Ecology (1,195), Marine Biology (1,307). Estuaries and Coasts was not indexed by BIOSIS until 2004

Progress Toward Management: The Regulatory Framework

Australia and New Zealand stand out among nations in taking proactive approaches to dealing with the prevention, eradication, and control of invasive marine organisms. These countries have experienced obvious severe impacts to the endemic biotas they take pride in and consequently, their federal and regional governments have made substantial investments in invasive species management. For instance, in the 1990s, Australia created the Center for Research on Invasive Marine Pests (CRIMP) within the Commonwealth Scientific and Industrial Research Organization (CSIRO), which led to the Introduced Marine Pest Coordination Group, which leads the management efforts. Marine scientists and resource managers also attribute a more coordinated federal management approach to a small number of sovereign provinces, unlike in the USA or Europe. The approach to the management of introduced species in these countries is strongly science-based, easily evident in the number of scientific journal articles contributed by agency scientists and the data-rich management plans readily accessible through the internet.

In contrast, in the USA, the federal government has not created a similar centralized agency that has had the necessary resources or the authority for nimble management of introduced species. Intergovernmental structures, such as the Aquatic Nuisance Species Task Force created in 1990 and the National Invasive Species Council created in 1999, have been slow to move forward with their plans, including the national Invasive Species Management Plan of 2001. This situation has left states to act independently in areas such as regulating ballast waters, aquaculture, and the aquarium trade (e.g., Brown et al. 2005). The lack of federal leadership has created overlapping mosaics of federal and state regulations, which are difficult for affected stakeholders to navigate and have led to lawsuits over ballast water regulation.

The European Union seems equally uncoordinated as individual countries forge their own approaches to introduced species in coastal and estuarine communities within the same body of water (Manchester and Bullock 2000; Council of Europe 2004) or lack resources for management (Genovesi 2005). That said, many European nations have signed the Convention on Biodiversity (CBD), which the USA has not, and the Codes of Practice on the Introductions and Transfers of Marine Organisms set by the International Counsel for Exploration of the Seas (2005). These policies provide some of the most comprehensive guidelines for preventing deliberate introductions of invasive species.

For nations intent on preventing injurious effects of introduced species, more than 50 international and regional legal instruments exist that address the intentional introductions of nonnative species, including the CBD (Shine et al. 2000; Hewitt and Campbell 2007). However, few are binding or carry penalties for noncompliance. The only convention where costs of noncompliance are potentially heavy enough to deter introductions is the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS) under the World Trade Organization. When nations such as New Zealand attempt to regulate introductions of potentially invasive species, they must do so without impeding trade (Jenkins 1996) and they carry the cost of the required risk assessment (Hayes 2003). Adjudication of SPS cases has favored the exporting nations (Pauwelyn 1999). In the face of trade restrictions on biosecurity, even Australia and New Zealand are limited in their attempts to achieve better outcomes for their coastal and estuarine resources.

The existing legal instruments concerning invasive species focus heavily on preventing introductions. Preventing introductions of nonnative species and acting quickly when a potentially invasive one slips through the screen is undoubtedly the best way to reduce future costs of management (McNeely et al. 2003). Why then has there been so little prompt action in estuaries and along coasts (Defenders of Wildlife 2007), with the notable exceptions in Australia and New Zealand? We propose several reasons for the lack of prompt action. The stakeholders, e.g., fishermen and recreational users, who would typically advocate for increased protection of coastal resources, are a singularly dispersed group, and the effects of these introductions are rarely evident to them. In contrast, the shipping, aquaculture, aquarium, live seafood, and live bait industries stand to lose from attention that leads to increased regulation. Aquaculturists have small profit margins, which ironically can be reduced to nonviability from species introduced through the business (e.g., *Terebrasabella uncinata* infestation of California abalone farms, Culver and Kuris 2000).

Because the economic impact of introduced estuarine and coastal species are understudied and mostly qualitative (Table 1), in comparison to damage from introduced crop pests, the incentive to manage is proportionally reduced. Externalities, which are the costs to society or native biota above identifiable direct costs associated with the specific economy (aquaculture products, eradication programs), are notoriously difficult to estimate, particularly in the marine environment (Margolis et al. 2005).

Why Allocate Precious Resources to Introduced Species in the Coastal Environment?

Would resources be better spent on reducing other anthropogenic influences on estuaries and coasts, such as overexploitation, pollution, eutrophication, and increased hypoxia, as opposed to introduced species? After all, the effects of pollution can ramify through the food web to reach human consumers, and severe eutrophication can spill downstream to profoundly influence extensive areas of deeper marine environments, as has occurred in the Gulf of Mexico (Mitch et al. 2001). And, sea level rise under global warming looms as a pressing issue to address, with its predicted profound effects on coastal societies and ecological communities around the world (Michener et al. 1997; Nicholls and Lowe 2004; Kerr 2006).

In the face of such critical issues and the largely uncertain economic consequences of introduced species (although the economic impact of the other issues are equally unquantified), it might seem hard to argue that introduced species should be a top priority of concern. The companion ecological argument that introduced species have negative effects on marine and estuarine species, communities, ecosystems, and resources often has relied heavily on anecdotal evidence (Reise et al. 2006; Galil 2007). Now, however, as evidence accumulates, it is clearer that introduced species in coastal and estuarine waters largely have negative effects, although good economic assessments for introduced marine and estuarine species are still lacking. Recent reviews provide evidence that the majority of introduced marine and estuarine species that have been studied rigorously have quantifiable negative effects on native species, including protected ones such as seagrasses (Grosholz 2002; Williams 2007; Williams and Smith 2007). The link between introduced marine and estuarine species and human health risks is increasingly evident as pathogens (Ruiz et al. 2000b) and toxic dinoflagellates (Hallegraeff 1998) are being found in ballast waters or can hitchhike on other invasive species (e.g., Oriental lung fluke, *Paragonimus westermanii*, in native

Table 1 Examples of economic impacts of introduced estuarine and marine species

Introduced Species	Economic Impact	Estimated Cost	Reference
Seaweeds			
Caulerpa taxifolia killer algae	Eradication	>US$6M (6 year)	Authors
Codium fragile v. *tomentosoides* oyster thief, deadman's fingers	Cultured oyster mortality, kelp valuation	C$1,500,000 /yr	Colautti et al. 2006
	Removal from native seaweed farm	Bankruptcy	Neill et al. 2006
Hypnea musciformis	Removal	US$55,000	Van Beukering and Cesar 2004
	Reduced property values		
Undaria pinnatifida Wakame	Eradication	NZ$2,923,500 (total)	Wotton et al. 2004
Invertebrates			
Carcinus maenas European green crab	Reduces bivalve aquaculture	US $22M/yr	Grosholz et al. 2000, Lovell et al. 2007
Eriocheir sinensis Chinese mitten crab	Invasion of fish salvage facility	US$1M (2000)	Aquatic Nuisance Species Task Force 2003
Mnemiopsis leidyi Ctenophore	Correlated loss of anchovy fishery	US$250M/yr	Zaitsev 1992
Mytilopsis sallei black striped mussel	Eradication	A$2.2M	Bax et al. 2002
Phyllorhiza punctata Scyphomedusa	Potential loss in shrimp landings	US$10M (2000)	Graham et al. 2003
Terebrasabella heterouncinata Sabellid polychaete	Reduced cultured abalone product quality	Bankruptcy	Culver and Kuris 2000
	Eradication	Several US$K	Kuris 2003
Teredo navalis Shipworm	Structural damage (ships, docks)	US$200M/yr	Cohen and Carlton 1995

populations of Chinese mitten crabs, *Eriocheir sinensis*). There is also evidence that certain introduced species can accumulate higher levels of contaminants than native species (e.g., the Asian clam, *Corbula amurensis*, in San Francisco Bay, Richman and Lovvorn 2004). New data also indicate that introduced species are among the top factors associated with threatening or endangering marine species (sea birds, sea turtles, fishes) with extinction (Kappel 2005; Venter et al. 2006). Obviously, extinctions are irreversible, unlike pollution and eutrophication. In addition to the specter of extinction, other effects of species introduced to estuaries and coasts can be reversed only with great effort, if at all. The options for effective management are more limited than in terrestrial environments (see section on eradication and control research needs).

In the near universal absence of effective prevention (Simberloff 2005), the management options are reduced to eradication and control. However, the situation is not hopeless. We will present evidence (Table 2) to dispel a common misconception that managing established invasive species in marine systems is not very feasible. Marine invasive species do not inevitably spread rapidly and extensively beyond control (Thresher and Kuris 2004). In fact, there are many examples of introduced species that have not spread far beyond the initial site of introduction and other species that are a significant problem in one estuarine system have not spread beyond that estuary (e.g., *Ilyanassa obsoleta* and *Guekensia demissa* have been restricted to certain areas within California for decades). For the invasive ones, eradication, which is less costly than prolonged control programs, can be feasible in the early stages of invasion when the distribution of the invader is limited. Time lags between introduction and spread allow a window of opportunity, if the species can be detected (Crooks 2005). Feasibility has been demonstrated by several recent programs in coastal marine and estuarine environments (Table 2). Feasibility aside, we emphasize that prevention is the best management policy.

These examples of eradication programs for marine and estuarine introduced species likely represent most of the documented programs; we contacted colleagues and introduced species list-serves and searched the internet extensively. Europe has attempted few eradications in general, let alone in marine environments, which is considered a result of limited awareness, legal frameworks, and resources (Genovesi 2005). If Europe has not mounted concerted efforts, the situation is worse for developing regions of the world. We did not include small geographically restricted

Table 2 Examples of eradication programs for introduced estuarine and coastal marine species, listed in chronological order

Introduced Species	Eradication Site	Date Initiated	Status	Reference
Thais clavigera Japanese oyster drill	British Columbia, Canada	1951	Successful	Carlton 2001
Spartina anglica hybrid cordgrass	Ireland	1960s	Unsuccessful; reverted to control	Hammond and Cooper 2002
Macrocystis pyrifera Giant kelp	Hawaii, USA	1972, 1980s	Successful	Shluker 2003
Sargassum muticum Wireweed	England	1973, 1976	Unsuccessful	Carlton 2001
Avicennia marina black mangrove	California, USA	1980	Completed 2000; reappeared 2006	Kay et al. 2006
Spartina alterniflora, S. anglica, and hybrids cordgrasses	New Zealand	1987	Successful in Southland; ongoing elsewhere	http://www.biodiversity.govt.nz/news/media/current/05nov04.html (accessed 14 December 2007) Krikwoken and Hedge 2000
Spartina alterniflora, S. patens, and hybrids	Oregon,	1990	Completed one site; ongoing	Pfauth et al. 2003
cordgrasses	Washington,	2003		Murphy et al. 2007
	California, U.S	2005		Olofson et al. 2007
Asterias amurensis Northern Pacific seastar	Victoria, Australia	1993 2002	Unsuccessful in Port Phillip Bay; near completion at Inverloch	Dommisse and Hough 2004
Perna canaliculus green lipped mussel	South Australia	1996	Successful	Bax and McEnnulty 2001
Terebrasabella heterouncinata sabellid parasite of abalone	California, USA	1996	Successful	Culver and Kuris 2000
Undaria pinnatifida wakame seaweed	Tasmania, Australia	1997	Ongoing	Hewitt et al. 2005
	Catham Islands, New Zealand	2001	Successful	Wotton et al. 2004
	California, USA	2002	Unsuccessful; reverted to control	Lonhart 2003
Mytilopsis sallei black-striped mussel	Northern Territory, Australia	1999	Successful	Bax et al. 2001
Caulerpa taxifolia 'killer' algae	California, USA	2000	Successful	Authors
Ascophyllum nodosum Atlantic rockweed	California, USA	2002	Successful	Miller et al. 2004
Didemnum vexillum colonial sea squirt	New Zealand	2003	Unsuccessful in some areas; ongoing	Coutts and Forrest 2007
Zostera japonica Japanese eelgrass	California, USA	2003	Ongoing	Eicher 2006
Littorina littorea periwinkle snail	California, USA	2005	Near completion	Chang et al. *personal communication*
Batillaria attramentaria horn snail	California, USA	2006	Ongoing at 2 sites	Weiskel and Zabin *personal communication*
Carcinus maenas European green crab	California, USA	2006	Ongoing	Grosholz et al. *unpublished*

eradications, such as for *Caulerpa taxifolia* in the Mediterranean or Australia, because the invasions overall are so extensive that even control will be difficult (Meinesz et al. 2001; Collings et al. 2004), although these efforts provide critically valuable information for a new restricted infestation. Nor did we include specific feasibility trials such as the mechanical removal of invasive seaweeds with a suction device (supersucker) to control them in Hawaii (Coordinating Group for Alien Pest Species 2006).

The outcome of these eradication programs has been varied but generally predictable. Successes occurred when the introduced populations were small and restricted, human and financial resources were available, and early action was taken, exactly the criteria predicted for success (Myers et al. 2000).

When eradication proved unfeasible, information gained then fed into fall-back control programs (*Asterias, Spartina* in Great Britain, also see Cheshire et al. 2002 for *Caulerpa*). Both 'gold-standard' successes (*Mytilopsis* in Australia; *Caulerpa* in California) were highly coordinated by cooperating government agencies committed to the goal of total eradication and undertaken early when populations were restricted. Another point evident from our compilation is the number of the examples (*Ascophyllum*, *Avicennia*, *Batillaria*, *Littorina*, *Macrocystis*, *Perna*, *Terebrasabella*) conducted by nonagency scientists. In the case of *Perna*, a cluster of mussels was found attached to a single fish, which was removed by a research diver (Bax and McEnnulty 2001).

To assess how managers viewed the role of science in these programs (Table 3), we queried them about what was useful from the scientific community and what would the managers have liked in addition, and supplemented their responses with formal evaluations of programs (Ferguson 2000; Bax et al. 2006). Managers were in consensus that access to experts and basic biological and ecological information was critical to managing the eradications and more was desirable (see Research Agenda). Managers also relied on scientists to provide eradication success/failure benchmarks and reviews of programs to facilitate adaptive management. They recommended that these roles for scientists be formalized early in programs. Risk assessment and cost-benefit analyses were useful even if qualitative; the more extensive the scientific evidence for the risk, the easier it was to take or defend management actions. Clearly, scientists need to undertake more quantitative risk assessment and develop and assess alternative treatment technologies. Interestingly, several managers pointed out a slow or absent response from their agencies in supporting their on-the-ground efforts.

In the next section, we provide an insider's view of case histories of eradication programs for two introduced species. We want to provide a sense of how an eradication program is shaped by the regulatory framework for management and where and how science can contribute to the success of the management process.

Two Case Histories: The Introductions of *Caulerpa* and *Spartina*

Caulerpa taxifolia (Mediterranean aquarium strain) The eradication of the invasive seaweed *Caulerpa taxifolia* in southern California is held up as a gold standard of estuarine and marine invasive species management, along with the earlier eradication of the black striped mussel in Australia. When *Caulerpa taxifolia*, considered one of the world's top 100 invasive species (Lowe et al. 2004), was identified in a native eelgrass bed in southern California in 2000, an ad hoc advisory team immediately began an eradication program (Anderson 2005) and success was declared in 2006. The rapid response proceeded in part because of the attention the species received, first from scientists, since it was found in 1984 in the Mediterranean (Meinesz 1999), where it had spread too far to consider eradication (Meinesz et al. 2001). At the prompting of scientists, *Caulerpa taxifolia* had been placed on the US Noxious Weed list in 1999, which provided the United States Department of Agriculture (USDA) with the authority to prohibit importation and interstate transfer of the Mediterranean clone of *C. taxifolia* and to treat the introduction as an emergency. However, the authority to take action does not insure a response, which the *C. taxifolia* example brought to light. In this case, eradication would not have proceeded without a self-appointed ad hoc management team SCCAT (Southern California *Caulerpa* Action Team) of exceptionally committed local and

Table 3 Perspectives of managers on the contribution of science/scientists to eradication programs

What was useful to eradication management?	What else would be/has been useful from the scientific community?
Access to biological/ecological information on the species	Further research relevant to invaded range (long-term effects, restoration requirements)
Risk assessments (informal, formal), particularly for likelihood of spread and control efficacy	Easier access to information through databases (bibliographic, treatment strategies/alternatives, scientific experts)
Identification of the introduction and taxonomic verification	Coordinated surveys and mapping
Access to information on previous management programs (or for similar species)	Earlier results
Lab and limited field studies on control strategies for local conditions	Early definition of respective roles of scientists and managers early
Scientific benchmarks, review, and recommendations	Improved certainty of data
Monitoring, including ecosystem function	General guidelines for eradication of new infestations
Articulate media communications	Cost-benefit analyses
Vector analysis	More information on threat
	Vector analysis

regional managers, seeded by funding provided by a responsible corporation. In addition to managing and seeking funding for the eradication and the public education program, SCCAT was forced to sort out lines of authority and relevant regulations (e.g., for chemical applications).

Agencies with strikingly different experiences and practices came together in the case of *Caulerpa taxifolia*. The federal and state agricultural agencies advocated rapid deployment of chemicals as practiced successfully on land, but the suite of herbicides effective for controlling freshwater nuisance plants does not work for *C. taxifolia* (Anderson et al. 2005). Copper, which is toxic to *C. taxifolia* (Uchimura et al. 2000), is regulated as a marine pollutant and its application could have serious nontarget effects. When copper treatment was considered, the USA Fish and Wildlife Service (USFWS) objected. The USFWS and other collaborating agencies experienced in marine environments but not in eradication were attuned to the concerns of a marine conservation constituency. An action-delaying impasse was luckily avoided.

Because listing under the federal Noxious Weed Act did not provide adequate protection against repeated invasions, California also passed legislation prohibiting the possession and sale of *C. taxifolia* and other species of *Caulerpa* easily confused with *C. taxifolia* or known or suspected to have invasive potential, to bridge gaps in relevant federal legislation (Withgott 2002). California attempted to ban the entire genus *Caulerpa* because of mounting evidence of ecological risks, widespread availability (Walters et al. 2006), troublesome identification to species (Fig. 2), and the threat of spread beyond tropical regions (Zaleski and Murray 2006). Despite the scientific evidence to ban the genus, the aquarium trade (the known vector for the introduction, Jousson et al. 1998) mounted a successful campaign to amend the bill to a few species, few of which can be identified reliably by enforcement agents, thus creating a loophole for *C. taxifolia* to re-enter California. Although California's efforts at a genus-level ban failed, USDA is considering genus-level bans for the first time because definitive specific identification is also a problem for an invasive aquatic plant (Giant *Salvinia*, *S. molesta*). Ecological data on invasiveness were sufficient to support a genus-level listing for both genera. Yet, the agency still has not responded to the *Caulerpa* petition submitted in 2003 requesting the action, despite the recommendations of agency biologists and the National *Caulerpa* Management Plan. USDA is worried about setting a precedent and also not having sufficient funds to enforce a genus-wide listing. Despite state and federal regulation, the prohibited *Caulerpa* species are still being sold in California (Zaleski and Murray 2006), slip through customs (W. Paznokis and S. Ellis, California Department of Fish and Game, personal communication), and are widely available through internet commerce (Walters et al. 2006). The Pet Industry Joint Advisory Council, which represents the aquarium industry, has been slow to follow through with a commitment to step up public education campaigns. It seems only a matter of time before *C. taxifolia* or another weedy *Caulerpa* species becomes established again.

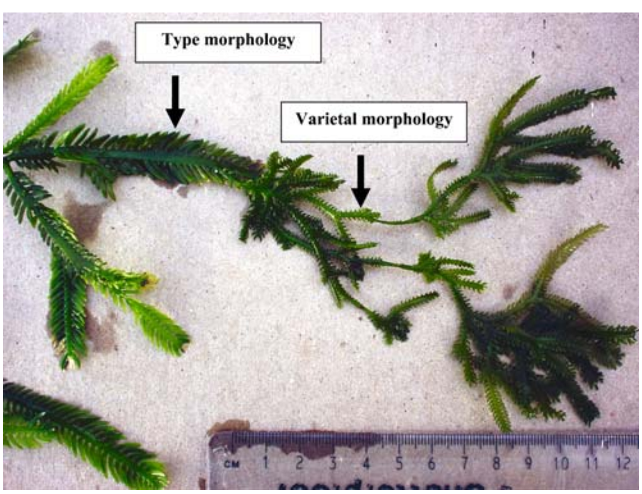

Fig. 2 *Caulerpa taxifolia* from Huntington Harbor, California, showing morphological variation ranging from the type form to forms more closely resembling *C. cupressoides* var. *lycopodium* f. *elegans*. Such morphological variation makes species identification, and thus regulation, difficult; photo by B. Nyden

When that happens, managers will seek information from the California effort. Unfortunately, the opportunity to collect valuable field data in support of the management effort, as recommended by scientists (Dalton 2000, 2001), was largely missed. Scientists did not recommend delaying eradication in order to study *C. taxifolia* (Anderson 2005), but rather that data should be collected as the eradication proceeded. No delay in eradication was necessary because a full year was required to treat all infested areas. There were lost opportunities to measure the relative efficacy of light reduction versus chlorine in the eradication (Williams and Schroeder 2004), which would have provided a basis to potentially reduce hazardous chlorine applications near urban settlements, residual chemical effects on nontarget biota, and cost. Information on the temperature and light regimes and algal growth rates in infested areas also is not available, which would be invaluable to target areas of potential establishment and predict spread rates.

The eradication of *Caulerpa taxifolia* in the US contrasts with the situation in temperate Australia. When discovered in temperate Australia in 2000, it had already spread too widely to attempt eradication. Managers focused on controlling it with coarse sea salt in New South Wales, which was effective in small plots, had no residual effects on native biota 6 months later, but was prohibitively expensive for use in all invaded sites (Glasby et al. 2005). In South Australia, a river system was diverted into an infested artificial lake to lower the salinity (Cheshire et al. 2002; Collings et al. 2004). The massive effort was successful in a small area, but not in adjacent areas. The management priority has become controlling *C. taxifolia* at points of potential dispersal or new introductions, such as boat ramps and fishing sites. Although management could not be effected early enough to eradicate *Caulerpa*, Australian scientists and managers have provided some of the most rigorous data not only in support of management options but also on the ecological effects of introduced *C. taxifolia* (Davis et al. 2005; Gollan and Wright 2006; Gribben and Wright 2006a,b; York et al. 2006).

Spartina alterniflora Among the most extensive ongoing eradication efforts for an estuarine invasive species is the one focused on eastern cordgrasses *Spartina* spp. in western North America. The dramatic impacts of *Spartina alterniflora* and its hybrids on benthic food webs and ecosystem structure and function have been well documented in both San Francisco Bay (SFB), California (Neira et al. 2005, 2006, 2007; Brusati and Grosholz 2006, 2007; Levin et al. 2006) and Willapa Bay (WB), Washington (Zipperer 1996; O'Connell 2002; Tyler et al. 2007; Grosholz et al. in press). *Spartina* is also a significant threat to economies in both bays including loss of grow-out habitat for the commercial oyster production industry in WB and clogging of flood control channels and loss of water-front property values in SFB. As a result, multi-million dollar eradication programs have been undertaken in both estuaries (California Coastal Conservancy 2007; Murphy et al. 2007, Fig. 3).

The history of invasion proceeded very differently in California and Washington. In California, *Spartina alterniflora* was first introduced from its native range in eastern North America into SFB in 1975 by the Army Corps of Engineers for marsh restoration (Ayres et al. 2004). It has

Fig. 3 Mechanized eradication of *Spartina alterniflora* in Willapa Bay, Washington

since hybridized with the native *S. foliosa* (hybrid *Spartina*; Daehler and Strong 1997) producing a highly invasive strain that has now invaded approximately 800 ha of SFB, including extensive areas of open mudflat. In Washington, the invasion of WB began with the accidental introduction of *Spartina alterniflora* around 1890 (Feist and Simenstad 2000; Davis et al. 2004; Civille et al. 2005). Since then, it has rapidly colonized open mudflat and spread to cover more than 2,400 ha. This invasion is entirely the result of the spread of *S. alterniflora*; there are no hybrids.

Eradication efforts in Washington also proceeded differently than in California. In WB, the eradication program began in 1995 amid lack of coordination between various state and federal agencies. Cooperation and more effective eradication was enacted in 2003 such that nearly the entire bay was treated by 2007 (Murphy et al. 2007) and the rest (600 acres) is expected to be treated in 2008. In SFB, eradication of the nearly 300 ha invaded by hybrid *Spartina* has only been underway since 2005. Unlike in Washington, the program has been conducted by a single entity, the Invasive *Spartina* Project of the California Coastal Conservancy. The eradication program is expected to be effective, but accurate estimates of the success of eradication efforts in 2006 are not yet available.

Scientific investigations of the food web and ecosystem impacts of hybrid *Spartina* in SFB and WB (see citations above) were conducted mostly before the broad-scale eradication efforts and proceeded largely unimpeded by management, unlike in the *Caulerpa taxifolia* case where science was an afterthought. Also unlike the *Caulerpa taxifolia* case, there was little discussion or exchange among the scientists and managers, although there were several shared goals that could have been more productively addressed through cooperative action. Once eradication programs were initiated, collaborative research projects were outlined and conducted involving both scientists and managers in both states, largely at the behest of the scientists. In both states, the agencies conducting the eradication efforts agreed to avoid or delay spraying herbicide in focal sites under study during the previous years, to incorporate some of the research goals of the scientists. The results of these very limited collaborations between science and managers were mixed, although they did provide some experimental results. Unfortunately, conducting the agreed eradication procedures were complicated by problems with herbicide application. In addition, the objective of saving some unsprayed areas as controls was negated in part because of their small size relative to the large scale of the surrounding sprayed areas. Nevertheless, the *Spartina* examples demonstrate that the goals of science and management do not need to conflict.

A pressing question for managers attempting *Spartina* eradication under budget restrictions is where to start.

Should eradication efforts focus on the center of the invasion where plants are dense and are presumably seeding future expansions or at the leading edge of the invasion where plant density is lower? Interestingly, the answer differs depending on the resources available to the eradication program (Taylor and Hastings 2004, 2005).

A second example stems from the manager's need to monitor recovery and if necessary, restore the previously invaded habitat (Blossey 1999). But how and at what rate will restoration of the system proceed once the invader has been eradicated? Research on the invasion and recovery of sites following *Spartina* eradication suggests that several factors including tidal elevation and sediment grain size strongly influence the rate of recovery and thus how quickly restoration of the pre-invasion condition will occur (Grosholz et al. in press; Tyler et al. 2007). The knowledge to prioritize which sites are most likely to be restored to the pre-invasion condition is invaluable under inevitable funding limitations.

Marrying Science and Management In hindsight, the *Caulerpa* and *Spartina* cases make it clear that the goals of the scientists and the managers were not far apart. Eradication and control should and can be done as adaptive management experiments (Myers et al. 2000), as demonstrated in the Australian management of the northern Pacific seastar (*Asteria amurensis*) and *Caulerpa taxifolia* (Cheshire et al. 2002, Bax et al. 2006). Most eradication programs require multiple years for completion, allowing for scientific study in small areas temporarily excluded from the overall eradication plan. 'Mopping up' these areas near the end of the eradication program will generally not create any obstacles for the ultimate goal of complete eradication. Effects of eradication and control on nontarget organisms should be part and parcel of every field effort to make choices among alternative eradication and control strategies. Invasive species management plans that explicitly integrate science with rapid response, control, and management in the field offer a more powerful outcome than relegating science to essentially an appendix, as has been done more often that not in the USA.

Highlighting an Agenda for Management-Focused Research

By any measure, the focus on invasive species and their impacts has clearly sharpened within the past decade (Mack et al. 2000; Sax et al. 2005, 2007). There has been a rapid emergence of new tools for managing invasive species (Lodge et al. 2006). However, because of the idiosyncratic nature of specific management needs and funding opportunities, there has been uneven coverage of the broad range of issues that need to be addressed to really strengthen prevention and management of invasions. In the research agenda to follow, we outline specific topics central to realizing the common goals of intelligent management of invasions and broad based learning about the invasion process.

Effects on Communities and Ecosystems The rationale for managing depends strongly on the impacts of an introduced species on the native biota. Over the past 15 to 20 years, ecological impacts have become a major focus of invasion research in coastal areas. However, most studies have focused on interactions between the introduced species and its immediate competitors, predators, and prey, typically species by species (reviewed by Grosholz 2002; Williams 2007; Williams and Smith 2007). Greater impacts accrue to invasions of particular functional groups (e.g., ecosystem engineers, filter feeders, large predators, Table 4, Crooks 2002; Wallentinus and Nyberg 2007), which provide a rough way to prioritize preventing introductions of species with highly undesirable characteristics. A more recent review of impacts across multiple trophic levels demonstrates that two functional groups in particular, ecosystem engineers and filter feeders, are the predominant groups responsible for impacts across trophic levels (Grosholz and Ruiz in press). Ecosystem engineers and filter feeders are also likely to have disproportionately strong impacts on system-wide biodiversity and ecosystem function. Clearly, there is a need to consider a much broader range of interactions and processes.

Ecosystem processes and functions are among the most overlooked effects of introduced species in estuarine and coastal environments. To date, only a handful of studies have measured the effects of invasive species on the cycling and storage rates of carbon and nitrogen in coastal systems (e.g., Larned 2003; Ruesink et al. 2005, 2006; Tyler et al. 2007; Williams and Smith 2007 for introduced seaweeds). Examples from the invasion of *Spartina* (see above) have shown that *Spartina* can significantly affect macroalgal production, increase storage of carbon and nitrogen in plant detritus, and cause a shift from a net autotrophic to a net heterotrophic system (Tyler and Grosholz, in review). Filter feeders in particular can produce profound effects on ecosystem function as demonstrated by the shift in primary production water column to the benthos after the introduced clam *Corbula amurensis* became abundant in San Francisco Bay (Alpine and Cloern 1992; Kimmerer et al. 1994).

Prevention Much research has been devoted to new methodologies to replace species-by-species assessments of the risk of deliberate introductions. A species-by-species risk approach is not very effective, as was made patently

Table 4 Examples from major functional groups of concern for estuarine and coastal introduced species and their effects

Type of Species	Example	Effect	Reference
Clonal or Weedy	*Caulerpa taxifolia* (seaweed)	Overgrows seagrasses	Ceccherelli and Cinelli 1997
	Caulerpa racemosa (seaweed)	Overgrows seagrasses	Ceccherelli and Campo 2002
	Watersipora subtorquata (bryozoan)	Fouls ship hulls and marinas	Floerl et al. 2004
Predator	*Carcinus maenas* (green crab)	Eats bivalves and crabs	Grosholz et al. 2000, 2001
	Rapana venosa (veined whelk)	Eats commercially important bivalves	Savini and Occhipinti-Ambrogi 2005
	Asterias amurensis (seastar)		Ross et al. 2002
Filter feeder	*Corbula amurensis* (Asian clam)	Reduces phytoplankton Correlates with zooplankton declines	Alpine and Cloern 1992; Kimmerer et al. 1994
Ecosystem Engineer	*Spartina alterniflora* (smooth cordgrass)	Converts mudflats; reduces shorebird foraging	Neira et al. 2005, 2006, 2007; Levin et al. 2006; Tyler et al. 2007
	Zostera japonica (Japanese eelgrass)	Converts mudflats	Posey 1988
	Crassostrea gigas (commercial oyster)	Creates reefs	Ruesink et al. 2005
	Musculista senhousia (Asian mussel)	Creates byssal mats in sediments	Crooks & Khim 1999

clear when California and the USA tried to regulate *Caulerpa* species, and the consequence is that very few marine invasive species are regulated. Trait-based approaches are promising because previous invasion history elsewhere in the world is one of the most reliable ways to predict future problems (Hayes and Sliwa 2003; Kolar and Lodge 2002; Marchetti et al. 2004). Taxa with a higher than average propensity for successful establishment in nonnative habitats can be pinpointed (Daehler 1998; Lockwood 1999; Williams and Smith 2007). However, trait-based prevention approaches will require some refinement to be effective for marine species. For example, Wonham et al. (2000) found few biological correlates among 24 fish invasions linked to ballast water.

Another approach to screening undesirable species is based on the assumption that introductions will be most successful in habitats that closely match the characteristics of the donor environment. These matching approaches are variously referred to as 'environmental', 'niche', 'climate', and 'species distribution modeling (SDM)'. They all rely on multivariate analyses of the physiological tolerances and abiotic factors that set the range limits for a species, complemented by Geographic Information Systems (GIS; McKenney et al. 2003; Peterson 2003; Thuiller et al. 2005); they are also used to predict biogeographic ranges under climate change scenarios. These approaches are the backbone to screening plants in Australia (Australian Quarantine and Inspection Service 2003). The approach has not been applied much to marine species and will require an improved understanding of the abiotic factors that promote recruitment and population increase and more detailed marine GIS (Breman 2002) to be successful. Because the algorithms run quickly once the data are available, many species could be tackled in a short time. The approach could be refined by including ecological interactions that limit distributions of species. All approaches have limitations but, as described in studies from Australia and New Zealand cited above, there is no need to stall on preventing introductions while attempting to perfect the approach.

Early Detection Until prevention becomes a matter of policy, one can only hope to detect new introductions early enough to eradicate them. One of the most pressing needs for both research and management is rapid identification of introduced species (Campbell et al. 2007). New methods are being developed to detect stages of introduced species not readily identified by morphology (eggs, larvae, spores, etc.), but much more work is needed in this regard (Pradillon et al. 2007). Several new methods including genetic dipsticks, barcoding (Armstrong and Ball 2005), and shotgun sequencing are now in development for sampling water column stages. There is much discussion of the merits of these approaches with respect to identifying 'species' (Darling 2006; Fitzhugh 2006), and the resolution for some of these methods still needs improvement. One of the biggest limitations is the availability of sequence data in GenBank, which is quite sparse for many taxa. Nonetheless, Australia is using genetic probes to detect invasive marine and estuarine species (Hayes et al. 2005).

Risk Assessment The probability that a species will establish successfully multiplied by the probability that it will cause harm constitute the risk that managers need to know to prioritize and initiate their actions. All of the research needs discussed above fold into formal risk assessments, and the lack of data in many cases explains why there have been so few formal risk analyses for coastal and estuarine species (Bax et al. 2001; Floerl et al. 2005). Canada's Centre of Expertise for Aquatic Risk Assessment is advancing risk assessment by standardizing risk assessments for fisheries and invasive species (Canadian Government 2003). Their draft assessments are based on including extensive biological information, which they intend to acquire, and include genetic and disease impacts along with ecological risks. They also consider the impact of any hitchhiking nonnative species.

Understanding Connectivity to Prioritize Eradication and Control Efforts In absence of effective prevention and rapid detection, managers need a means to prioritize which introduced species to eradicate and control. One critical factor that could diminish the effectiveness of eradication and control programs for marine species is high connectivity among different populations. Introduced species characterized by widespread and open populations, connected by the rapid dispersal of propagules, can recolonize more rapidly than relatively isolated populations with lower connectivity. Species with highly connected populations thus will be more difficult to eradicate or control (Fig. 4). Despite this evident conclusion, scientists and managers lack a fundamental understanding of the connectivity among populations of marine species (Kinlan and Gaines 2003; Levin 2006). Such knowledge will help prioritize which species to manage. It will also support the application of models, which depend on identifying dispersal 'kernels', to predict the spread of invasive species (Neubert and Caswell 2000). Promising technology (elemental fingerprinting) is being developed to quantify connectivity among marine populations of species that secrete hard parts (otoliths, shells, carapaces; DiBacco and Levin 2000; Becker et al. 2007).

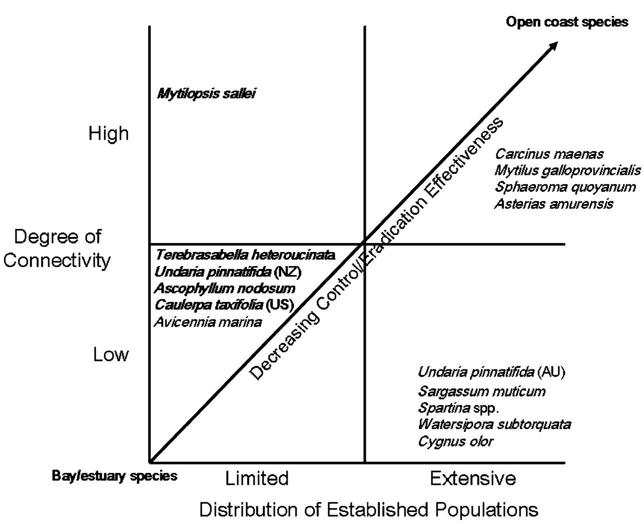

Fig. 4 Conceptual relationship between connectivity (natural dispersal) and expanse of populations of introduced species and the probability of successful management. Species in bold have been successfully eradicated

Eradication and Control Needs Managers need an arsenal of tested techniques for eradication and control. Ideally, the methodology would not harm native species. Biocontrol theoretically could achieve this end, but the few natural enemies of introduced marine and estuarine species investigated to date have not proven sufficiently selective to function as biocontrol agents (Lafferty and Kuris 1996; Trowbridge and Todd 2001; Secord 2003). In Willapa Bay, Washington, however, a trial program was initiated in 2000 to control *Spartina alterniflora* using the planthopper, *Prokelisia marginata*, with promising early results (Grevstad et al. 2003). Transgenic approaches to controlling the reproduction of introduced marine species are also receiving research attention (Bax et al. 2006). The salty equivalent of a pheromone control, which has proven effective for many insect pests of agricultural crops (Arn 1990), awaits discovery. Disruption of molting or development in invasive crustaceans through molting hormones might be promising, but so far all species examined respond to the same hormones (E. Chang, personal communication).

A special challenge for mitigating undesirable effects of estuarine and coastal introduced species is the open and fluid nature of the ocean. Rapid dilution of pesticides in flowing waters reduces exposure to the pest, while increasing exposure to sensitive native species, and adequate containment structures are difficult and expensive to engineer. Nevertheless, the eradications of *Mytilopsis sallei* and *Caulerpa taxifolia* circumvented these challenges (Table 2).

The Need for Decision Support A pressing need expressed by both scientists and managers is a single source, readily accessible, step-wise management decision support system. When confronted with a potential new introduction, scientists and certainly managers cannot be expected to sift through scientific journals or individual websites. They need to identify the species and then proceed along a decision analysis pathway to options for response, identification of authorities and required regulations and permits, access to experts along the way, and an archive to support decision audits. Obviously, the system would be useful only as long as resources are available for its maintenance, but its costs could be shared across many users. Major developments in informatics place this kind of decision support system in reach (Ricciardi et al. 2000; Simpson et al. 2006), although lack of appropriate data is still an obstacle. Prototypes are in use (Wittenberg and Cock 2001), including NIMPIS, which was developed in part to memorialize the lessons learned from the eradication of the black striped mussel in Australia (Hewitt et al. 2002).

Evolutionary Potential An area that remains poorly investigated is the degree to which short-term or rapid evolution influences the success or failure of introduced species. The practical side to this research question is that certain tools used to screen potentially invasive species (see species distribution matching methods above) are based on the assumption that rapid adaptation to the new environment does not occur. Furthermore, managers of long-term invasions have noted changes in the biology of the introduced species (M. Wecker, personal communication). High levels of genetic variation within populations of introduced species (Roman 2006; Roman and Darling 2007; Lavergne and Molofsky 2007) can provide the opportunity for rapid evolution and adaptation to the new environment of the introduced range. Distinct introduction events can result in higher genetic diversity overall. On the other hand, species with low genetic diversity could also acclimate to new conditions by being phenotypically plastic (Dybdahl and Kane 2005). It is important to understand how the population genetic structure influences the likelihood that an introduced species will become a management problem.

Ecological Economics and Introduced Species Cross-disciplinary approaches are also needed to understand the importance of the impacts of introduced species, which bears directly on how managers will respond to a given species. Ecologists and economists have begun to formally address the costs of introduced species (Leung et al. 2005; Finnoff et al. 2007) and to develop better recommendations for invasive species management (Buhle et al. 2005). However, there are few data available for most species with which to either conduct a formal risk analysis or to develop damage functions for use in traditional economic models (Lovell et al. 2007).

The following research needs are ones that have practical implications for management but are not widely recognized in the management community.

Facilitation of Subsequent Introduced Species To understand the impacts of invasive species, it is critical to consider how an introduced species can influence subsequent introductions. Some introduced species can facilitate subsequent invasions and knowing which species are likely to be “facilitators” can provide critical information for management efforts. In cases where facilitation occurs, the need for preemptive management strategies is even greater. Although there have been discussions of potential mechanisms (Simberloff and Von Holle 1999; Rodriguez 2006), there are only a handful of documented examples in marine systems (Levin et al. 2002; Floerl et al. 2004; Grosholz 2005; Wonham et al. 2005). In some cases, new invasive species can facilitate and accelerate the invasion of species introduced many years earlier turning them into new management headaches (Grosholz 2005). It however is unknown whether facilitative interactions such as these occur more commonly among invasive species than among native species, although the same types of approaches are available.

Climate Change and Species Introductions Finally, understanding how climate change interacts with coastal invasions will be critical for understanding and predicting successful invasions as well as managing their impacts. The recent Intergovernmental Panel on Climate Change (IPCC) makes it clear that many factors including increasing sea-surface temperatures, rising sea levels, increasing atmospheric CO_2 and ocean acidification will significantly impact coastal habitats in the coming decades (Bindoff et al. 2007). Temperature increases alone can lead to the increased success of introduced species (Stachowicz et al. 2002). Rising sea-levels pose a significant risk for coastal estuaries, particularly ones with armored boundaries that prevent migrations as tides creep up. Given a eustatic sea level rise of nearly 3 mm/year (Bindoff et al. 2007; Stevenson and Kearney 2007), tidal marshes will become increasingly inundated with largely unknown consequences for species invasions. For example, changes in tidal height of a few centimeters can determine whether mudflats invaded by *Spartina* will transition to either a vegetated high marsh state, the original open mudflat (SFB), or will be colonized by invasive *Zostera japonica* (Grosholz et al. in press). Tidal inundation coupled with the lack of sediment deposition has also been implicated in the stresses faced by tidal marshes in the Gulf of Mexico (Mendelssohn and Kuhn 2003).

Elevated CO_2 levels are also likely to play a role in altering the success of introduced species. Long-term experimental studies have shown that invasive C_3 plants are likely to benefit from increased CO_2 levels in complicated ways (Curtis et al. 1989; Marsh et al. 2005; Rasse et al. 2005). Finally, ocean acidification under increasing CO_2 concentrations could make communities of bivalves and coral reefs less resistant to introduced species that do not calcify (e.g., ascidians). In estuaries, which are less well buffered than the open ocean, the effect of increasing CO_2 partial pressures on the carbonate equilibrium will be site specific. Thus, it will be more difficult to predict the effects on calcification processes.

The overarching challenge will be figuring out how the suite of climate change effects on individual species will scale up to marine communities. Few studies have addressed factors in addition to rising temperatures (e.g., Erickson et al. 2007), let alone effects on introduced species (Braby and Somero 2006; Schneider and Helmuth 2007). The complexity of ecological interactions will necessitate sophisticated ecological forecasting (Helmuth et al. 2006). On the policy side, there is a danger that as species shift their distributions in response to climate change, the distinction between species introduced by humans and the others will blur (Rocha et al. 2007; Perry et al. 2007), to the detriment of preventing and managing new introductions. After the IPCC's compelling 2007 report, some of the attention on invasive species management has been diverted. However, it is important that we not lose sight of the rapid acceleration of observed invasions and the fact that invasions have significant impacts and will interact with other anthropogenic changes. To balance the perspective, the changes in the distributions of species over the past 200–500 years due to human activities have rivaled those during ice ages (di Castri 1989).

Summary

The overall situation in estuaries and on coasts is one of great and interrelated anthropogenic changes. The establishment of nonnative species is likely to increase as the ocean warms (Stachowicz et al. 2002) and as eutrophication-related hypoxia increases (Jewett et al. 2005) and the vectors that distribute them proliferate. The challenge for scientists and managers is to determine how multiple perturbations to these environments interact, and which ones can be managed effectively. Management of introduced species requires the same will and resources that nations have applied to reducing pollution and restoring wetlands and fisheries stocks, with high pay-offs, and investments spent on restoration efforts risk being obliterated by the introduction of just one successful nonnative species.

Thanks to the rapid scientific advances that offer new tools for managers, the time has never been better to halt the increasing number and costs of introduced species in estuaries and on coasts. Australia and New Zealand have demonstrated that research and management can be effectively integrated. Canada is developing risk assessments that require extensive biological information. European nations have grappled with managing introductions from their extensive aquaculture (Gollasch 2007). Introduced species have been on the scientific and management radar globally for a relatively short time, compared to species extinctions, pollution, and habitat destruction. Their effects have come to light faster than those associated with global warming. Unlike the daunting challenge of mitigating global climate change, the solutions to the problem of invasive species are known and well within reach. It is not rocket science: the vectors and high-priority species have been identified, and good institutional models are already working. In particular, the management emphasis in most countries must shift from costly eradication and control programs to proactive prevention, following the leads by Australia and New Zealand.

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