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Status, Environmental Threats, and Policy Considerations for Invasive Seaweeds for the Pacific Coast of North America

Report Prepared for the Commission on Environmental Cooperation, Montreal, Canada

By

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Technical Report

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Preface

This report was prepared for the Commission on Environmental Cooperation at the request of Hans Hermann, Head of the CEC's Conservation of Biodiversity Program. The goals of this report were to review the status of knowledge concerning invasive seaweeds for the Pacific coast of North America and to analyze the potential threats to the environment posed by these species; in addition, our aim was to examine selected policies and to suggest possible policy options for improving the ability of Canada, Mexico, and the United States to address these threats.

The science sections of this report (Sections 2 through 8 and the science recommendations) were developed by Steven N. Murray, Professor of Biology at California State University and José A. Zertuche-González, Director of the Marine Science Institute at the Universidad Autónoma de Baja California Norte, Ensenada, Mexico. The economic and policy analyses (Sections 9 through 13 and policy recommendations) were prepared by Linda Fernandez, Associate Professor of Economics at the University of California, Riverside. All authors collaborated in developing the recommendations.

The contents of this report, including its recommendations, solely represent the opinions and findings of the authors, and do not necessarily reflect the views or policies of the Commission on Environmental Cooperation or the governments of Canada, Mexico, and the United States.

Acknowledgements

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1.0 Executive Summary and Recommendations

Introductions of nonindigenous species (NIS) of marine organisms, many of which become invasive and are referred to as Invasive Alien Species (IAS[1]), have accelerated greatly during the last few decades and will continue to increase due to improvements in transportation systems, expanded trade on global and regional scales, and more efficient transportation methods. Global climate change can make ecosystems more susceptible to these introductions. On a global basis IAS represent the second leading cause of species extinctions and are considered to be a significant threat to biodiversity and a major agent of biotic change. One study estimates that 50,000 NIS have been introduced to the U.S., with costs associated with IAS damage and control amounting to approximately US$137 billion per year.

The ecological and economic impacts of terrestrial IAS are better known and have received more attention than IAS introduced into marine waters. In the U.S., less than 1 % of federal spending on IAS in 2000 was directed towards aquatic species; Canadian and Mexican spending on aquatic IAS has paralleled this low priority in funding. Yet, it has become clear that NIS are now common components of many marine ecosystems and that IAS pose serious threats to marine biodiversity.

With few exceptions,NIS of seaweeds are the least well documented and understood of introduced marine macro-organisms. Seaweeds are often difficult to identify, skilled seaweed taxonomists are few in number, and seaweed floras are often poorly known making it difficult to recognize new introductions or to tally the number of historical introductions accurately. The purposes of this report are to:

1. Describe the current state of knowledge of seaweed NIS, with emphasis on IAS, found in Pacific coastal waters of North America, and

2. Consider selected policies that address the threats posed by seaweed IAS to the environments and economic activities on the west coast of Canada, Mexico, and the United States.

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[1] An nonindigenous species (NIS) is defined as "any species or other viable biological material that enters an ecosystem beyond its historic range, including any such organism transferred from one country to another" (USCOP 2004). Not all NIS function as major agents of change in invaded ecosystems. The term IAS has been selected from a variety of terms that have been used to describe problematic nonindigenous species to conform with terminology used in documents available from the Convention on Biological Diversity website (http://www.biodiv.org/programmes/cross-cutting/alien/default.asp). Because not all NIS become invasive, IAS has been used in this report to refer only to those NIS that are considered to be or have become invasive or policies and actions directed at known or putative invaders.

Many seaweeds have characteristics that make them very good candidates for invasion. These include the ability: 1) to grow on the outer and inner surfaces of ships and on the shells of oysters and other shellfish; 2) to survive suboptimal conditions, either as whole individuals or in the form of small, cryptic stages; 3) to spread by small, detached fragments or through the production of large quantities of spores; and 4) to exhibit rapid growth rates in nutrient-rich coastal conditions. Reports of seaweed invasions are most numerous for the Mediterranean Sea and the European Atlantic; fewer seaweed invasions have been documented for the Pacific coast of North America. Only 27 alien seaweeds are listed for the Baja California to Bering Sea corridor (Baja to Bering or B2B). However, it is likely that many more undocumented seaweed introductions have occurred in the region. Moreover, three alien seaweeds (*Caulerpa taxifolia*, *Undaria pinnatifida*, and probably *Caulacanthus ustulatus*) have been introduced in the last five years in southern California alone, suggesting that seaweed introductions may be increasing in frequency.

The major pathways for introducing marine alien species into non-native waters are: 1) shipping transport, either in ballast water or as hull fouling organisms; 2) aquaculture enterprises, either as targeted species or as unintentional hitch-hiker associates; 3) fishing activities, including net fouling and bait use; 4) the aquarium trade; 5) scientific research through intentional outplanting or accidental escapes; and, 6) the opening of new canals or waterways. Besides canals and waterways, the most significant global pathways for seaweed introductions appear to be: 1) aquaculture, often as associates of targeted species such as oysters; 2) shipping, mostly as fouling organisms attached to hulls and other ship parts; and 3) the aquarium trade. More work needs to be done to determine the degree to which non-indigenous species of seaweeds are being introduced as packing material for transporting fish bait, aquaculture organisms, and other marine species. Seaweeds appear to be much less likely than other non-indigenous marine species to be introduced through the discharge of ballast water but are very likely to be moved along the coast as fouling organisms on ship hulls or other marine gear.

Existing policies in the B2B are ineffective in preventing new marine invasions and in dealing with marine IAS once they have been identified. The recently published report by the U.S. Commission on Ocean Policy indicates that in the U.S. “invasive species policies are not keeping pace with the problem primarily because of inadequate funding, a lack of coordination among federal agencies, redundant programs, and outdated technologies.” Similar management issues appear to exist in Canada and Mexico. Clearly, the need exists for more effective national management structures for addressing threats posed by IAS, and increased efforts to improve trinational coordination, a requirement for addressing IAS threats in the B2B.

Management policies for addressing threats posed by marine IAS, including seaweeds, should focus on prevention, eradication and control. Most scientists argue that the management of marine IAS needs to be more proactive and call for greater emphasis on preventing introductions. Besides working on the scientific principle that the rate of invasion is a function of the frequency and density of inoculations, policies that focus on prevention also have the advantage of being applicable to multiple species. Management interests would benefit if invaders with the potential to create significant impacts could be identified prior to or during the very early stages of their introductions. Predicting the impacts of potential IAS before they arrive, however, has been difficult. Some species can be benign in one region but may cause significant ecological impacts in another. More research needs to be done to improve understanding of the ecological characteristics of invasive seaweeds and other marine IAS and the characteristics that make a region susceptible to invasion.

Much recent attention has been given to addressing ballast water as a pathwayfor marine introductions. Higher plants, planktonic organisms, and many marine invertebrates (as adults and as larval forms) are readily transported and introduced in ballast waters. Ballast water, however, appears to be less significant than other pathways for introducing IAS of seaweeds. To reduce the likelihood of seaweed introductions, more attention needs to be given to other pathways, including ship fouling, aquaculture transport, and the aquarium trade.

Once an IAS has arrived, it must be detected before management options can be developed. There must be in place a transparent structure for receiving reports of new introductions if timely decisions on management actions are to be made. Only under rare circumstances have eradication efforts been successful in open marine systems once an IAS has become established. Hence, in marine habitats, eradication efforts should be regarded as experiments and studied accordingly to improve understanding of the requirements for success.

Early detection and rapid management responses are of paramount importance if eradication efforts are to be successful. The combination of early detection and rapid management response was seen in the apparently successful eradication of *Caulerpa taxifolia* in southern California. This effort, which stands as an excellent example of multiple agency cooperation, was advantaged by early detection resulting from the presence of an active, field study program, and the rapid response of managers. Unfortunately, coastal field monitoring programs are generally limited and are difficult to sustain over the periods required to be effective in detecting marine IAS. Moreover, little trinational or even interstate coordination takes place between those monitoring programs that exist. Perhaps the last management option is to attempt to control (or manage) the spread or damage of an invader. For decades, efforts have been made to control unwanted IAS in terrestrial and freshwater ecosystems; control of marine invasions, however, is in its infancy.

Policy considerations should emphasize preventing the introduction of seaweeds and other marine IAS. For marine IAS, emphasis should be placed on four pathways: 1) ballast water, 2) hull fouling, 3) aquaculture activities, including seaweed packing materials for seed stocks and fish bait, and 4) aquarium trade release.

The IAS pathway now receiving the greatest attention in the B2B is ballast water in ships that enter and exit the 200 nautical mile (370 km) Exclusive Economic Zone (EEZ) from western parts of the Pacific Ocean. Although this East-West dimension in shipping traffic requires continued attention, IAS in the ballast water of ships transiting the north-south B2B coastal corridor also needs to be addressed. For example, approximately 80 % of shipping traffic to California takes place within 200 nautical miles (370 km) of the coastal mainland, primarily from vessel traffic from Mexico and Canada.

Currently, variation in ballast water regulations exists among the different countries in the B2B. It is widely recognized that existing programs in the B2B and in other areas of the world, are inadequate for preventing the introduction or spread of IAS through marine shipping activities. Recognizing this problem, member countries of the International Maritime Organization (IMO), recently finalized a global treaty addressing the introduction of IAS through ballast water. However, this treaty is not yet in force and is unlikely to be implemented for several years. Hence, the United States, Mexico, and Canada should consider developing coordinated measures to reduce the risk of IAS introductions to North American waters through East-West shipping activities that transit the EEZs of the three countries as well as through north-south shipping activities confined to the coastal B2B corridor.

The hulls and surfaces of both commercial and recreational vessels in the B2B are potential pathways for introducing and dispersing marine IAS, including seaweeds. The significance of this pathway appears to have been underestimated, particularly for smaller vessels (e.g., fishing vessels, smaller coastal freighters, and recreational craft) that mostly travel in coastal waters of the north-south B2B corridor. Yet, ship fouling clearly appears to be an important method of spreading seaweed IAS. More attention needs to be given to developing proven measures for reducing the transport and introduction of seaweeds and other marine IAS associated with hull fouling.

Aquaculture enterprises take place in coastal waters of the B2B and warrant attention as an IAS pathway. Separate sets of regulations are now in place for managing aquaculture activities in Mexico, the U.S., and Canada. Perhaps, Canada's national code appears to include the strongest protection for preventing international IAS introductions. This code uses a risk assessment approach for the approval of permits, which is consistent across Canada. Introductions of marine IAS, including seaweeds, can occur not just from the accidental release of targeted aquaculture organisms but also by the escape of species associated with the substratum and packing materials for aquaculture species. Existing regulations should be examined to ensure that they also address organisms associated with substrata and packing materials as well as the intended aquaculture species.

The aquarium trade is potentially an important pathway for introducing seaweed IAS and other marine alien organisms. This was highlighted by the *Caulerpa taxifolia* invasion in California in 2000, which generated an emergency task force response and State legislation banning the sale and possession of selected *Caulerpa* species. Enforcement of the existing State ban, however, is lax and applies only to California. Additional aquarium introductions of *C. taxifolia* or other seaweeds are possible in California and elsewhere in the B2B. This industry remains largely unregulated throughout the B2B and requires multinational attention if efforts are to be made to prevent introductions of IAS of seaweeds and other marine organisms.

Coordinated strategies for dealing with new arrivals of IAS from beyond the EEZ and with the spread of already established IAS within the EEZ require preventative and reactive measures carried out at larger than a local scale. Such policies for dealing with marine IAS in the B2B must contend with risk and uncertainty in space and in time. A concise distinction between risk and uncertainty is that risk is defined by a probability distribution for the event to occur. Uncertainty, on the other hand, implies true randomness, and the likelihood of an event taking place has no known probability distribution. Risk management across pathways, in addition to episodic control efforts for individual invasions, should be implemented in the B2B. This approach offers the potential for coordinating scientific data generation, education and outreach, and policy development for addressing threats posed by seaweed IAS and other invasive marine organisms. Joint protection in the form of surveillance and prevention could be considered a public good that needs the right incentives to work. These incentives could be structured to maximize net benefits between countries, while taking into account national differences in the availability of financial and technical resources.

Several policy alternatives exist that incorporate risk and uncertainty and offer potential approaches for addressing threats posed by seaweed and other marine IAS. These include: 1) insurance or environmental bonds, 2) emission regulation with best available technology and performance standards, 3) liability for damages of IAS, 4) deposit-refund and environmental (performance) bond programs, and 5) educational and technical assistance programs.

Costs and benefits of alternative IAS abatement strategies need to be determined and aggregated over the B2B. Costs need to include planning costs as well as costs of enacting abatement policies. Abatement benefits need to be based on appropriate valuation methods. These methods include consideration of: 1) avoided costs, 2) factor income, 3) travel cost, 4) hedonic pricing, 5) contingent valuation, and 6) replacement cost. Benefits involve ecosystem services, which can be broken down into: 1) recreation and cultural, 2) nutrient cycling, 3) ecosystem protection, 4) habitat value, 5) food and raw materials, 6) existence value, and 7) genetic resources. Each ecosystem service can be valued economically using a combination of valuation methodologies.

Clearly, much needs to be done to address the threats posed by seaweed and other marine IAS in the B2B. More scientific research is needed to improve understanding of the biology and ecology of invasive seaweeds and other marine IAS and the characteristics of coastal ecosystems that makes them susceptible to invasion.

More effective management structures, greater levels of multinational cooperation, improved and more effective programs for pathway interdiction, and more effective monitoring and detection programs also are needed to improve management of marine IAS. The following recommendations are offered as a starting point for addressing IAS of seaweeds and other marine organisms in the B2B.

1.1 Science Recommendations

1. Increased attention must be given to developing programs to increase trinational scientific research on IAS of seaweeds in the B2B if we are to improve understanding of their biology, ecology, and the characteristics of the systems that they have invaded. In particular, studies are needed to:

    a. survey for and document the spread of seaweed alien species, (with emphasis on those that have become invasive), investigate their impacts on native ecological communities, and test hypotheses about the ecological correlates of invaded versus native communities;

    b. determine the environmental conditions required for survival, growth, and reproduction of seaweed invaders;

    c. determine the likely pathways and genetic origins of seaweed IAS populations and subpopulations; and

    d. explore, test, and evaluate methods for preventing, controlling, and eradicating invasive seaweed populations.

2. Trinational efforts should be initiated to ensure the perpetuation of long-term, and scientifically robust coastal monitoring programs that can lead to the early detection of invading seaweeds and other marine IAS, follow the progress of identified invasions, and evaluate the effectiveness of eradication and control efforts.

3. Implement programs for assessing and evaluating risks associated with identified pathways for introducing IAS. These studies are needed to identify the importance of the various pathways for introducing seaweed IAS, the species most likely to be introduced, and for making recommendations on how to minimize risks of new IAS introductions.

4. Encourage the scientific study of seaweed floras using both modern molecular approaches as well as traditional herbarium-based methods. Information from these studies will enable early detection and accurate identification of the species and strains of seaweed IAS.

5. Develop a trinational scientific panel of phycological experts to advise managers and assist in the development of response plans for dealing with newly detected seaweed invaders. This panel can be convened to provide scientific advice on the biology of newly detected seaweed aliens, their potential impacts, and on the eradication or control efforts that managers might undertake in response to an introduction or invasion.

1.2 Policy Recommendations

1. Since the current investment in research, monitoring and enforcement of IAS falls far short of their, there is a potential benefit of investigating how each of the policy options proposed in this study can generate funds for these necessary activities.

2. Shipping registration requirements through the International Ship and Port Facility Security (ISPS) Code can highlight and strengthen attention on IAS through improved information on shipping maintenance and documentation of cargo manifests to facilitate the monitoring of IAS shipping pathways (i.e., ballast water and hull fouling).

3. Coordinate requirements for shippers entering ports in the North-South as well as East-West transit pathways to facilitate implementation of prevention technologies for reducing IAS introductions in ballast water and from hull fouling. Align regional goals with IMO conventions while still allowing for member states to enter into regional agreements that meet or exceed upcoming IMO standards. The transaction costs to deal with separate, local requirements make it difficult for both shippers and ports to achieve effective IAS control throughout the B2B. A successful model to follow for cooperation through emergency planning, information sharing, technology adoption, and liability requirements might be that in place for addressing threats posed by oil spills.

4. The various policy alternatives discussed in this report need more economic analysis to evaluate the efficacy of specific IAS interdiction programs in the B2B. For example, to set the right level of an environmental bond, deposit-refund, or liability, effort to derive measures of potential damages from IAS are required. Such liability rules and environmental bonds have been implemented for offshore oil platforms and for terrestrial areas of environmental risk.

5. More economic analyses need to be performed to better quantify and aggregate costs and benefits across the B2B to augment some of the examples provided in this study. The variety of valuation techniques and categories to be valued in the B2B indicate that many studies will be needed to derive viable estimates for developing cost effective trinational programs that address the threats posed by marine IAS, including invasive seaweeds.

6. In order to prevent introductions of seaweed IAS from aquariums, rigorous efforts are needed to implement technical assistance and public education amongst aquarium traders, consumers, and the regulating inspectors. Educational efforts can be tied to the policy alternatives discussed in this report.

7. Explore the feasibility of extending the aquaculture control regulations now being used in Canada to the U.S. and Mexico as a means of preventing harmful transfers of IAS with aquaculture activity in the B2B. These regulations (Code on the Introduction and Transfers of Aquatic Organisms in Canada) were jointly developed by the Canadian government and the aquaculture industry.

8. Promote technology transfers through educational outreach programs to address IAS. An example of such a program is the California Sea Grant program on nontoxic hull coatings. In addition, such programs should be developed to address additional pathways of seaweed IAS such as the aquaculture and aquarium industries.

9. Addressing IAS like an epidemiological threat requires action beyond the preventative measures emphasized above. Besides preventative action, early response institutional structures and ongoing monitoring programs should be enacted throughout the B2B.

2.0 Introduction

The world's terrestrial, freshwater, and marine ecosystems are experiencing an unprecedented breakdown of natural biogeographic barriers through the human-generated movements of species beyond their natural ranges. These movements have accelerated greatly during the last several decades, and promise to continue to increase with improvements in transportation systems, expanded global trade, and the implementation of more efficient and rapid transportation methods. Moreover, global climate change might increase the threat of introduced species by rendering native ecosystems more susceptible to invasion (Dukes and Mooney 1999, Carlton 2000, USCOP 2004). A variety of terms have been used to describe these non-native species, including alien species, exotics, introduced species, immigrants, translocated species, naturalized species, colonists, adventives, neophytes, weeds, invaders, nonindigenous species, invasive alien species, and invasive species (see Ruiz and Carlton 2003a, USCOP 2004). An nonindigenous species (NIS) is defined as "any species or other viable biological material that enters an ecosystem beyond its historic range, including any such organism transferred from one country to another" (USCOP 2004). Not all NIS function as major agents of change in invaded ecosystems. Many have benign and perhaps largely unrecognized effects and some are considered to be beneficial to human activities; however, once introduced some NIS have the capacity to be aggressive invaders and to cause significant changes in invaded ecosystems, sometimes with great ecological and economic consequences. This subset of NIS is referred to as Invasive Alien Species (IAS) in this report and by some governmental agencies, and is the term used in documents available from the Convention on Biological Diversity (http://www.biodiv.org/programmes/cross-cutting/alien/default.asp). On a global basis, invasive species represent the second leading cause of extinctions (Wilcove et al. 1988). Because of their capacity to alter ecosystem structure and functioning, IAS are considered to be a major agent of biotic change (Vitousek, et al. 1996, 1997) and a significant threat, not only to biodiversity but also to human enterprises dependent on natural resources.

Approximately 50,000 NIS are thought to have been introduced to the United States (Pimentel et al. 2000), a number far greater than the 4,500 NIS reported as known introductions by the Office of Technology Assessment (OTA 1993). Of those NIS recorded by OTA, approximately 15 % were estimated to be IAS or nuisance species, which caused significant ecological or economic impacts (OTA 1993). Hence, many of the changes brought about by IAS have had and will have significant ecological and economic consequences on human populations and the environmental resources on which they depend. The economic magnitude of this problem is very large. Pimentel et al. (2000) estimated that land and aquatic IAS cost the U.S. economy US$137 billion per year. In Canada, conservative estimates of annual economic losses and direct costs associated with 12 IAS totaled Can$5.5 billion (Environment Canada 2003). Introductions of IAS into marine waters and the Great Lakes cost the U. S. millions to billions of dollars per year in economic and ecological damage (USCOP 2004). Shared loss because of the impacts of aquatic IAS in the Great Lakes to Canada and the U.S. in recreational and commercial fishing revenues alone is believed to be as high as US$4.5 billion per year (International Joint Commission 2001).

3.0 Purpose of this Report

The purposes of this report are to:

1. Describe the current state of knowledge of seaweed NIS, with emphasis on IAS, found in Pacific coastal waters of North America, and

2. Consider selected policies that address the threats posed by seaweed IAS to the environments and economic activities on the west coast of Canada, Mexico, and the United States.

First, we discuss review marine NIS and IAS to set the stage for this report. We then briefly describe the ocean conditions occurring in the geographic region under consideration (Baja California, Mexico to the Bering Sea, Alaska). Next, we address marine and seaweed NIS with emphasis on invasive seaweeds. Because scientific information on seaweed IAS is sparse for the Pacific coast of North America, we draw heavily on published reports of seaweed IAS from other parts of the world and the global pathways identified as vectors for their introductions. These discussions are followed by biological characterizations of selected seaweed IAS found in the Pacific coastal waters of North America. The final section of our report discusses current management policy shortcomings, including a consideration of risk and uncertainty and examples of methods for quantifying costs and benefits in dealing with seaweed IAS. Lastly, we provide recommendations for trinational cooperative actions needed to address this problem, including the need to develop strategies and funding for more studies of seaweed NIS and economic policy alternatives for addressing marine invasions in the Pacific coastal waters of Canada, Mexico, and the United States.

4.0 Marine NIS and IAS

The ecological and economic impacts of terrestrial and freshwater IAS have received much more attention compared with those established in marine environments (Mooney and Drake 1986, Carlton 1989, OTA 1993). This is evidenced by the fact that in 2000 more than 90 % of the approximately US$600 million spent on NIS in the United States was allocated to the U.S. Department of Agriculture primarily to contend with terrestrial invasions while less than 1 % of this federal spending was directed towards aquatic IAS (USCOP 2004). Canadian and Mexican spending to address aquatic IAS has paralleled the low priorities seen in the U.S. and amounts to only a small percentage of their federal budgets for environmental protection (Environment Canada 2003, SAGARPA 2003). Nevertheless, marine IAS are considered to be one of the greatest threats to coastal environments (NRC 1995, USCOP 2004). It has become increasingly appreciated that NIS are now common components of many marine ecosystems and can be agents of significant biotic change (Cohen and Carlton 1995, Lafferty and Kuris 1996, Ruiz et al. 1997) that pose serious threats to marine biodiversity (Lubchenco et al. 1995) on local, regional, and global scales.

A minimum of 298 invertebrates and algae (316 according to NEMESIS 2002, Fofonoff et al. 2003), 200 vascular plants, and 100 fishes are now established as NIS in marine and estuarine waters of North America (Ruiz et al. 2000). This includes at least 240 NIS of algae, invertebrates, fish, and vascular plants within the San Francisco Bay and Delta alone (Cohen and Carlton 1995, Ruiz et al. 2000, Ruiz and Crooks 2001). Excluding Alaska and Hawai'i, Ruiz et al. (1997) estimate that between 70 and 235 NIS, respectively, can be found in each estuary searched for NIS. Moreover, rates of NIS establishment in North American coastal waters (Fig. 1) have increased greatly in recent years (Ruiz et al. 2000). In San Francisco Bay, where studies of NIS have been on-going for > 30 years (Carlton 1979, Carlton et al. 1990, Cohen and Carlton 1995, 1998), one new introduction is now being detected every 14 weeks (Cohen and Carlton 1998). Besides recognized NIS, additional unrecognized introductions (i.e., cryptogenic species that are neither demonstrably native nor introduced *sensu* Carlton 1996a) also occur in North American coastal waters; hence, the actual number of NIS found in these habitats is even greater than reported. Failure to recognize many of these NIS is attributed to the long, undocumented history of human transportation of marine organisms around the world and the availability of the information needed to determine if a species is actually non-indigenous. Suspected NIS or cryptogenic species are likely to be numerous when thorough inspections of floral and faunal lists are performed. For example, Carlton (1999) estimates that between 900 and 1500 species of coastal marine plants and animals now regarded as naturally cosmopolitan may actually have been introduced prior to 1800. In San Francisco Bay alone, Carlton (1996a) conservatively estimates that approximately 100 species of aquatic plants, animals, and protists are cryptogenic.

Seaweeds are probably the least well documented and understood of introduced marine macro-organisms. This is because seaweeds can be difficult to identify, seaweed floras have been recently compiled or remain poorly known for many parts of the world, and because skilled seaweed taxonomists are few (and becoming fewer) in number. In addition, most benthic marine NIS have been identified from harbors, bays, and estuaries, habitats frequented and studied by few seaweed biologists, and many of the seaweeds most likely to be introduced into these habitats are small, opportunistic species that can be recognized only by specialists or through the use of molecular techniques.

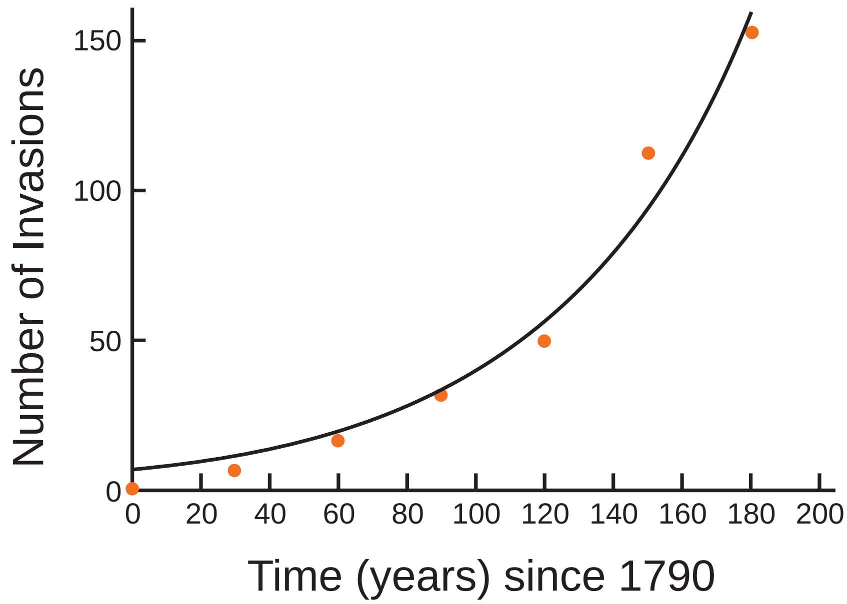

Fig. 1. Rate of introductions of NIS of marine invertebrates and algae since 1790 based on estimates of new introductions for the first year of each 30-year interval. Redrawn from Ruiz et al. (2000).

5.0 Geographic Setting

The geographic region covered in this report ranges from Pacific Baja California, Mexico (approximately 23 °N), to the coastal waters of the Bering Sea in Alaska (approximately 60° N), hereafter referred to as Baja to Bering or the B2B. This range of almost 40° of latitude conservatively traverses four major biogeographic provinces according to Briggs (1974), the Aleutian, Oregon, San Diego, and Mexican (Fig. 2), which differ greatly in key ocean parameters such as sea temperature, upwelling intensity, and nutrient availability. Moreover, there are strong regional differences in ocean conditions, particularly upwelling periodicity and strength, even within provincial boundaries. For example, within the Oregon and San Diego provinces, four major environmental compartments can be characterized based on seasonal differences in sea conditions such as storm frequencies and intensities, current patterns, and upwelling magnitude and periodicity (Longhurst 1998): Oregon to British Columbia (42 to 48 °N), Point Conception to Cape Mendocino (33 to 41 °N), Southern California Bight (32 to 33 °N), and Baja California (22 to 31 °N).

The great differences in ocean conditions across biogeographic provinces, together with regional features such as upwelling periodicity and strength and differences in local ocean current conditions, are extremely important for analyses that address the potential for invasive species to spread over the B2B. For example, most IAS will be incapable of successfully establishing populations or becoming invasive throughout the Pacific coastal waters of North America. Most will be capable of establishing nuisance populations along the outer coast in only one or two of the four biogeographic provinces. Historically, seawater temperature has been given a preeminent role in influencing the distributional limits of seaweeds and other marine organisms (Setchell 1915, Druehl 1981, Lüning 1990, Murray and Bray 1993); hence, if suitable physical habitat is available, seawater temperature might be the best predictor of the geographic regions that potentially could be occupied by a particular IAS once introduced along the Pacific coast of North America. Moreover, increased sea temperatures resulting from changes in ocean climate can alter the distributions and abundances of coastal species (Lubchenco et al. 1993) and may make northern regions more susceptible to invasions by warmer water species with established populations at lower latitudes (Chapman 1988).

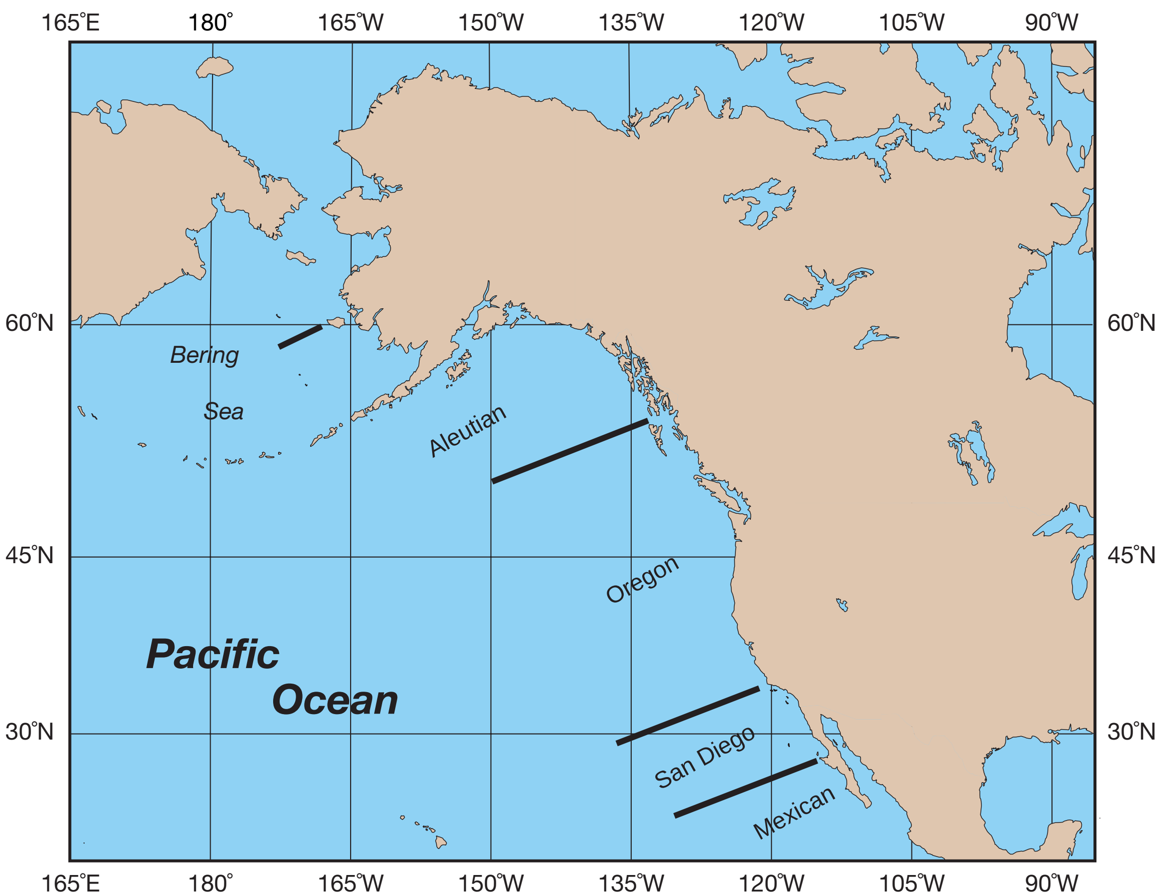

Fig. 2. The Baja California to Bering Sea Corridor (B2B) extends over nearly 40° of latitude and encompasses four biogeographic provinces (Aleutian, Oregon, San Diego, and Mexican) according to Briggs (1974).

The Aleutian Province, whose southern boundaries are sometimes reported by marine biogeographers to extend beyond the Bering Sea to include the Gulf of Alaska (O’Clair and Zimmerman 1986), is characterized by colder, upwelling sea temperatures that range from 0 to 10 °C (Hood 1993). The islands in the Aleutian Archipelago, which separate the Bering Sea from the Gulf of Alaska and traverse more than 30° of longitude, is a complex area of biotic transition between Arctic and cold temperate species and between Asiatic (western) and North American (eastern) Pacific biotas (O'Clair and Zimmerman 1986, Lüning 1990). Similarly, biota of the southern coast of Alaska can be divided into two units: south central Alaska, including the Alaska Peninsula, Kodiak Island, Cook Inlet, and Prince William Sound; and southeastern Alaska (The Alexander Archipelago) (Lüning 1990).

Most of the Pacific coast of North America, including the coastal waters of southeastern Alaska, British Columbia, Washington, Oregon, and central and northern California, is influenced strongly by the cold California Current. Biogeographers typically assign the biota along this entire stretch of coastline to the cold-temperate Oregon province (Briggs 1974). Although local and regional ocean conditions vary, particularly in bays, embayments, and among the fjords, islands, and inland passages of southeast Alaska and British Columbia (Lüning 1990), seawater temperatures are relatively similar over this large latitudinal range. From the Aleutian Islands to Point Conception, California, coastal sea temperatures range between 10 and 17 °C in August and between 5 and 14 °C in February (Lüning 1990). Many species have long geographic ranges and occur throughout this region from Alaska to central California.

Point Conception, California, has long been considered to function as the boundary between the cold-temperate Oregon and the warm-temperate San Diego provinces (Briggs 1974). Much of this San Diego province is occupied by the Southern California Bight (SCB), which includes an area of about 78,000 km^2 extending from Point Conception southward to points just south of the U.S.- Mexican border. The surface waters of the SCB are influenced by the southward flowing, colder waters of the California Current and the northward flowing, warmer waters of the Southern California Countercurrent. Here, temperatures range on the average from 14 to 19 °C (Hood 1993), with slightly warmer temperatures found in shallow coastal waters nearer shore and on the southern islands (Santa Catalina and San Clemente Island), which are more strongly exposed to the warm, northward flowing waters of the Southern California Countercurrent. The western edge of the SCB, including the westernmost Channel Islands (San Miguel, Santa Rosa, and San Nicolas Islands), is more strongly influenced by the colder California Current and supports a colder, more northerly biota (Murray and Bray 1993), while the southern and eastern portions of the SCB, including Anacapa Island in the north and Santa Catalina and San Clemente Islands in the south, tend to have warmer waters and warmer water biota; hence, the SCB is commonly referred to as a transition region between cold (Oregon) and warm (San Diego) temperate biogeographical provinces (Murray and Littler 1981). Farther south, the California Current moves closer to the shore between San Diego, California, and Cabo Colonett, Mexico, resulting in colder nearshore waters. In addition, persistent cold, upwelling areas to the south of peninsulas and headlands such as Cabo Colonett, Cabo San Quintin, Punta Baja, and Punta Eugenia have long been known to occur along the Pacific coast of northwestern Baja California and to support colder water species (Dawson 1951).

Warmer coastal waters become more prevalent south of 26 °N where warmer ocean conditions prevail. In the Mexican province along the southern coast of Pacific Baja California, annual sea temperatures range from 16 to 28 °C. The Southern California Countercurrent, whose influence in southern California reaches about 100 km from shore, is much narrower along the Baja California Peninsula and sometimes can go undetected (Lynn and Simpson 1987). Whereas temperate waters mostly influence the northern part of the peninsula, a greater tropical influence prevails from Punta Eugenia to Cabo San Lucas. Gómez and Vélez (1982) describe the coastline ranging from southern California to the northern part of Baja California (between 30 and 35 ºN) as a transition zone, and the coastal waters of the southern part of the Baja California peninsula from Punta Eugenia to Cabo San Lucas as a zone of equatorial influence. Thus, the Pacific coast of Baja California represents the southern limit of many warm temperate species and the northern limit of many tropical ones.

Besides broad, geographic differences in coastal conditions, the biota of Pacific North America also are influenced by changing ocean climate, including shifts in sea temperature, which occur over periods of a few years to decades. El Niño-Southern Oscillation (ENSO) events, which occur over 2-10 year periods, push warmer surface waters north from lower latitudes and influence coastal processes along Pacific Baja California and throughout the SCB and areas to the north. The most intense ENSO signals occur at lower latitudes but ENSO effects are felt as far north as the Gulf of Alaska and the eastern Bering Sea (Niebauer 1985, Royer 1985). In southern California, for example, sea surface temperatures can increase by as much as 7 to 10 °C during an ENSO event (Hood 1993) with profound effects on marine biota. In addition to intradecadal scale events such as ENSOs, longer lasting, interdecadal ocean regime shifts also have strong effects on the coastal conditions of Pacific North America. For example, a major climate regime shift occurred in the North Pacific Ocean around 1976 (Wu and Hsieh 1999), resulting in gradual increases in sea temperature in southern California (Roemmich and McGowan 1995) and regions to the north. Much recent attention has been given to the biological correlates of this interdecadal scale shift in ocean regimes (e.g., Bakun 1999, McGowan et al. 1999). For example, decreases in macrozooplankton (Roemmich and McGowan 1995) and reduced abundances of pelagic seabirds (Veit et al. 1996) were associated with the warming and stratification of southern California surface waters during the post-1976 warm period. In addition, changes in the abundances of intertidal organisms consistent with ocean warming were reported in central California (Barry et al. 1995, Sagarin et al. 1999), and significant changes in coastal populations linked with ocean climate change have been observed as far north as the Gulf of Alaska (Anderson and Piatt 1999).

6.0 Invasive Seaweeds

Seaweeds have several characteristics that can make them very good invaders. For example, many species are able to establish inconspicuous growths on objects, including the outer and inner surfaces of ships and shells of oysters and other shellfish, which are being moved throughout the world’s oceans. Many can survive suboptimal conditions while being transported great distances, either as whole thalli or in the form of persistent, cryptic stages. In addition, many seaweeds are able to disperse and establish populations from small, detached vegetative fragments or through the germination of sexual or asexual spores, which can be produced in prolific quantities. Many species exhibit rapid growth rates, particularly under nutrient-rich conditions that characterize most urban harbors and coastal environments of Pacific North America and elsewhere. Where outbreaks of IAS of seaweeds have been recognized and intensely studied, for example the invasion of *Caulerpa taxifolia* (also known as the “Killer Alga”) in the Mediterranean Sea (Meinesz 1999), we have learned that seaweed invasions can have significant ecological consequences, impact commercial and recreational activities in coastal waters, and result in substantial economic costs. The recent appearance of the very same Mediterranean strain of *Caulerpa taxifolia* in California waters (Dalton 2000, Kaiser 2000, Jousson et al. 2000) has raised concern about threats posed by invasive seaweeds, not only in California but also throughout Pacific North America. Clearly, based on experiences with *Caulerpa taxifolia* in the Mediterranean Sea, invasive seaweeds represent a significant but often unrecognized threat to the native ecosystems and the natural resources of Pacific Mexico, the United States, and Canada.

Recently, Ribera Siguan (2003) compiled a list of NIS of marine plants for the world, except for Central and South America where published information was considered to be lacking. This compilation listed 189 species (excluding supraspecific taxa and doubtful species), including 100 (53 %) red algae, 42 (22 %) brown algae, 21 (11 %) green algae, 15 (8 %) phytoplankton species, and 11 (6 %) higher plants (Fig. 3). As pointed out by Ribera Siguan (2003), however, these numbers are probably lower than the actual number of marine plant introductions. It should not be surprising that worldwide the best known and best studied seaweed NIS are larger,

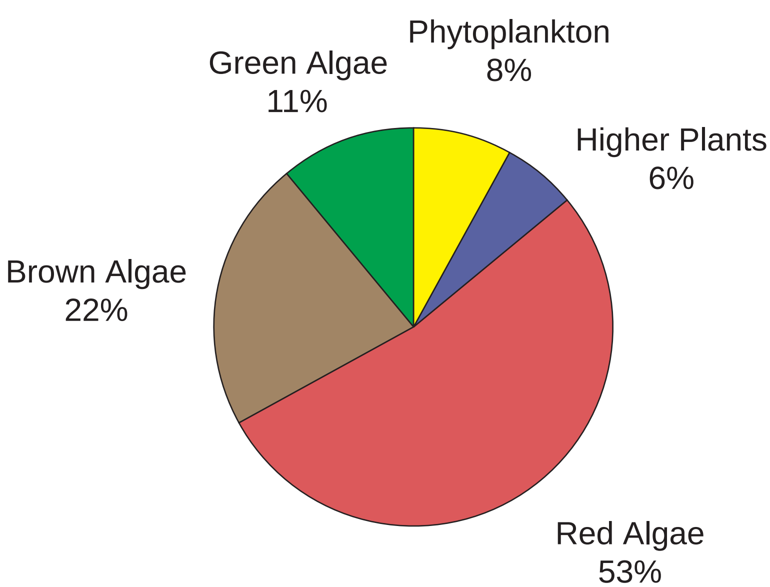

Fig. 3. Percentage of NIS of marine plants by group based on the 189 NIS species listed by Ribera Siguan (2003). The red, green, and brown seaweeds

form by far the largest number of NIS of marine plants. Higher plants represent seagrasses and halophytes. Redrawn from Ribera Siguan (2003).

conspicuous IAS that have developed dense populations in more intensely studied temperate seas. Most of these studies have taken place outside of Pacific North America where invasive seaweeds have received much more scientific attention. Of the geographic regions (Fig. 4) analyzed by Ribera Siguan (2003), the greatest number of marine plant NIS was found in the Mediterranean Sea (83 species), followed by the European Atlantic coast (49), Australian coasts (26), and New Zealand coasts (21). For North America, Ribera Siguan (2003) reported 19 marine plant species (13 seaweeds) for the Pacific coast and 17 marine plant species (13 seaweeds) for the Atlantic coast; only 2 seaweed species were recorded as NIS for both coasts of North America. An additional 15 NIS of seaweeds can be added to this list based on the compilations of Hansen (2000) and Trowbridge (in press), studies and observations on *Polysiphonia harveyi* by McIvor et al. (2001) and *Ascophyllum nodosum* by Miller (2004), and the recent finding of *Sargassum horneri* in Los Angeles Harbor (K. Miller, pers. Comm.). Inclusion of these records brings the number of NIS of seaweeds reported for Pacific North America up to 28 (Table 1).

Table 1. List of the 28 reported NIS of seaweeds for Pacific North America, including presumed general region of their origin. Listing based mostly on records reported by Hansen (2000), Ribera Siguan (2003), and Trowbridge (in press).

NIS of Seaweeds	Presumed Origin (mostly after Trowbridge in press)
Red Seaweeds (Div. Rhodophyta) (14 taxa)	
Aglaothamnion tenuissimum (Bonnem.) Feldm. Maz. (= *Callithamnion byssoides*)	NW Atlantic
Bonnemaisonia hamifera Har.	NW Pacific?
Caulacanthus ustulatus (Turner) Kütz.	NW Pacific
Ceramium sinicola Setch. and Gardn.	??
Chroodactylon ornata (= *C. ramosum*) (C. Agardh) Basson	??
Gelidium vagum Okamura	??
Halymenia actinophysa Howe	??
Hypnea musciformis (Wulfen) Lamour.	??
Lomentaria hakodatensis Yendo	NW Pacific
Pikea yoshizakii Maggs et Ward	NW Pacific (Japan)
Polysiphonia brodiaei (Dillwyn) Spreng.	NE Atlantic
Polysiphonia denudata (Dillwyn) Grev. ex Harv.	NW Atlantic
Polysiphonia harveyi J. Bailey	NW Pacific
Porphyra tenera Kjellm.	NW Pacific
Brown Seaweeds (Cl. Phaeophyceae) (11 taxa)	
Acinetospora sp.	??
Ascophyllum nodosum (L.) Le Jolis	N Atlantic
Fucus cottoni Wynne and Magne	NE Atlantic; Arctic
Ishige isiforme Yendo	??
Macrocystis integrifolia Bory	NE Pacific
Microspongium globosum Reinke	N Atlantic? NW Pacific (Japan)?
Sargassum hornori (Turner) C. Agardh	NW Pacific

Sargassum muticum (Yendo) Fensholt	NW Pacific (Japan)
Scytothamnus sp.	??
Undaria pinnatifida (Harvey) Suringar	NW Pacific (Japan)
Waerniella sp.	??
Green Seaweeds (Div Chlorophyta) (3 taxa)	
Bryopsis sp.	??
Caulerpa taxifolia (Vahl) C. Ag.	Australia??
Codium fragile subsp. *tomentosoides* (van Goor) Silva	NW Pacific

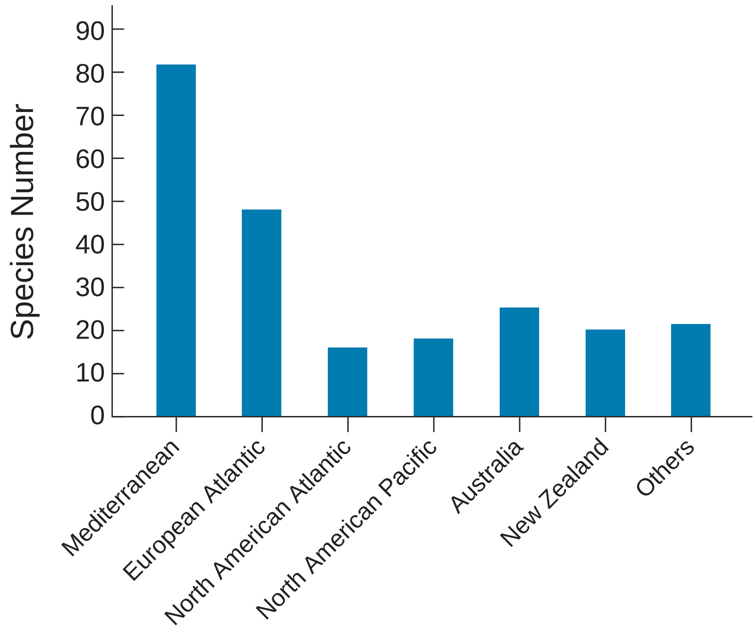

Fig. 4. Numbers of NIS or marine plants reported for the indicated geographic regions. Redrawn from Ribera Siguan (2003).

6.1 Selected Examples of IAS of Seaweeds

Of the 28 NIS of seaweeds identified as occurring in Pacific North American waters, those selected for discussion include the IAS of brown algae *Sargassum muticum* and *Undaria pinnatifida*, the green seaweed IAS *Codium fragile* subsp. *tomentosoides* and *Caulerpa taxifolia*, and the red seaweed *Caulacanthus ustulatus*, a putative introduction.

6.1.1 *Sargassum muticum* (Yendo) Fensholt

Sargassum muticum (also commonly known as wire-weed or strangle weed) is a brown seaweed native to Japan and the coasts of China and Korea (Yendo 1907). This large seaweed is able to establish populations in lower intertidal and subtidal habitats where it can persist by regrowing from perennial, basal fronds and holdfasts. *S. muticum* thalli are diploid and monoecious; they produce eggs and sperm in pitlike structures called conceptacles, which develop on specialized reproductive structures (receptacles) on frond tips. The eggs are not released into the water, but are retained inside the conceptacles where they remain attached following fertilization until the developing embryos produce small, adhesive rhizoids. At this point, the embryos are released and settle onto the substratum in close proximity to parent plants.

Fig. 5. *Sargassum muticum*. *S. muticum* thalli growing in intertidal tidepool habitats at Crystal Cove in southern California. Source: Steve Murray

The rapid spread of *Sargassum muticum* throughout temperate seas during the 1970s and 1980s elevated scientific interest in seaweed introductions, and *S. muticum* is now considered to be a highly invasive species. *S. muticum* occurs as an introduction in the Northeastern Atlantic, the Mediterranean Sea, and along the Pacific coast of North America (Setzer and Link 1971, Critchley et al. 1990). It is thought to have been first introduced to the Pacific coast of North America in British Columbia sometime prior to 1941 with the importation and outplanting of the Japanese oyster *Crassostrea gigas* (Scagel 1956). *S. muticum* remained low in abundance until the early to mid 1940s when it apparently became widespread in the Strait of Georgia (Scagel 1956), and then subsequently spread rapidly along the west coast of North America. *S. muticum* is now a common constituent of intertidal and shallow coastal waters along most of the Pacific coast of North America where it is distributed from British Columbia to San Diego (Abbott and Hollenberg 1976) and south into Baja California, Mexico (Epinoza 1990).

The first non-native population of *Sargassum muticum* to appear in the Atlantic was found in 1971 off the south coast of Britain. The source of its introduction, however, is subject to much controversy, but most likely was from plants associated with the French oyster beds of Normandy, France (Critchley et al. 1983). Once introduced, *S. muticum* spread very rapidly in European waters (Knoepffler-Peguy et al. 1985), and is now present along the Atlantic coasts of Scandinavia (Karlson and Loo 1999, Staehr et al. 2000), the Netherlands and Belgium (Critchley et al. 1983, Critchley and Dijkema 1984), Portugal and Spain (Fernández et al. 1990, Fernández 1999), and Italian coasts in the Mediterranean and Adriatic Seas (Curiel et al. 1998). As occurs with other invasive seaweeds, *S. muticum* can grow to larger sizes outside of its native range. Whereas in its native Japan, *S. muticum* fronds reach lengths of 1-1.5 m, fronds of 5-6 m are reported for invasive populations in California (Nicholson et al. 1981) and plants of up to 10-12 m have been collected from the Atlantic coast of France (Critchley et al. 1990).

The capacity of *Sargassum muticum* to spread and invade new areas is related to its high reproductive potential and its wide tolerance of ocean conditions. Individuals are self-fertile and produce large numbers of eggs. In addition, floating fronds of *S. muticum* can be transported large distances by ocean currents (Paula and Eston 1987). These fronds do not reattach, but are able to survive and even become fertile as they drift, increasing the potential for long-range dispersal and recruitment. The dispersal rate of *S. muticum* is very high, being estimated at 10 km yr^{-1} in the Mediterranean, 60 km yr^{-1} in the NE Pacific, and 90 km yr^{-1} in the NE Atlantic (Shanks et al. 2003). *S. muticum* can grow intertidally and subtidally on a wide variety of substrata, including rock, broken shells, and even mud (Fernández et al. 1990, Fernández 1999). It can grow at temperatures ranging from 10 to 30 °C, and can survive temperatures close to 0 °C. It tolerates salinities of 6-34 ‰ and grows in habitats experiencing a wide range of light conditions and wave exposures. Interestingly, *S. muticum* grows mostly in relatively sheltered areas in its native range (Espinoza 1990) and has a high tolerance for polluted waters (Curiel et al. 1998).

Among other geographic regions in Pacific North America, *S. muticum* is a very common and abundant constituent of communities on rocky substrata in shallow, subtidal waters in the San Juan Islands in Washington. Surveys here have shown that it can occur in densities as high as 126 plants m^{-2} (Britton-Simmons, in press). Experimental manipulations performed by Britton-Simmons (in press) in the San Juan Islands revealed that this IAS can have major impacts on native ecological communities. Fronds of *S. muticum* can overgrow and shade the large, native kelp *Laminaria bongardiana*, reducing its growth rate. Reductions in the abundance of the palatable *L. bongardiana* led to increases in the relative abundance of another kelp, the chemically-defended *Agarum fimbriatum*, with negative, indirect effects on the native herbivorous sea urchin *Strongylocentrotus droebachiensis. S. muticum* also has been found to compete with native species and affect community structure in other rocky intertidal (DeWreede 1983, Viejo 1997, but see Wilson 2001) and subtidal (Staehr et al. 2000) habitats and to inhibit recruitment of native kelps (Ambrose and Nelson 1982).

6.1.2 *Undaria pinnatifida* (Harvey) Suringar

The large kelp, *Undaria pinnatifida*, also commonly known as Asian kelp, apron ribbon vegetable, wakame (Japanese), and miyeuk (Korean), is native to Japan, Korea, and China, where it has been cultivated since the late 1950s on thousands of kilometers of ropes suspended in harbors and along the open coast. Unlike *Sargassum muticum*, *U. pinnatifida* is commercially sold for its food value. Wakame is the Japanese name for *Undaria* and its uses include addition to miso soup for flavor and texture (Silva et al. 2002). In its native Asia, *U. pinnatifida* is harvested from natural and cultured populations and represents a significant commercial enterprise.

Fig. 6. *Undaria pinnatifida*. Left Panel. Young sporophyte obtained from deeper water habitats off leeward Santa Catalina Island. Right Panel. A small, mature sporophyte collected from Monterey Harbor. Both of these sites are locations where this species has established invasive populations. Sources: Left Panel. Kathy Ann Miller, Wrigley Institute for Environmental Studies; Right Panel. Steve Lonhart, Monterey Bay National Marine Sanctuary.

Undaria pinnatifida first appeared outside its native northwestern Pacific in 1971 when it was introduced to the Thau Lagoon in the Mediterranean Sea with the importation of the Japanese oyster (Fletcher and Manfredi 1995). Due to its potential economic value, *U. pinnatifida* was subsequently intentionally introduced along the coast of Brittany, France, for aquaculture purposes, with the naïve thought that this alga would not be able to reproduce in the cold waters of the North Atlantic Ocean (Fletcher and Manfredi 1995). Since then, *U. pinnatifida* has spread rapidly into previously unoccupied temperate waters along the Atlantic and Mediterranean coasts of Europe (e.g., Pérez et al. 1981, 1984, Floch et al. 1991, Fletcher and Manfredi 1995, Verlaque 1996, Curiel et al. 1998, Castric-Fey et al. 1999). Later it appeared in

New Zealand (Hay and Luckens 1987), Tasmania (Hay 1990, Sanderson 1990), southeastern Australia (Campbell et al. 1999), and Argentina (Piriz and Casas 1994, Casas and Piriz 1996). *Undaria* appeared in California in 2000 (Silva et al. 2002) and Mexico (Aguilar-Rosas et al. 2003) in 2002. *U. pinnatifida* was first found growing in Los Angeles Harbor in spring 2000 and is now found in six California Harbors and from Button Shell Cove on leeward Santa Catalina Island where it grows at depths of 20-25 m. It has established abundant growths in Santa Barbara and Monterey, California, harbors and, given the range of environmental conditions under which it can grow and reproduce, it is likely that *U. pinnatifida* will soon spread into waters north of Monterey Bay. Although *U. pinnatifida* was introduced accidentally with oysters and intentionally for cultivation purposes (Floc'h et al. 1991), it also has been dispersed unintentionally by shipping activity (Silva et al. 2002, Valentine and Johnson 2003). The original source of *U. pinnatifida* in Californian waters is unknown, but its occurrence almost exclusively in harbor environments and its ability to grow on fouled ship hulls (Hay 1990) suggest that it was and is being transported by shipping activities.

Like *Sargassum muticum*, *Undaria pinnatifida* is a large, brown seaweed that can reach frond lengths of 1-3 m. Unlike *S. muticum*, however, *U. pinnatifida* is a kelp with a life history consisting of a conspicuous macroscopic stage (the sporophyte) and a cryptic, microscopic stage (the gametophyte). Sporophytes consist of a lanceolate, golden-brown blade, with a central midrib. The stipe develops small pinnae where it joins the blade and, during the reproductive season, these grow into distinctive, convoluted spore-producing structures known as sporophylls. In native Asian waters, *Undaria* shows an annual cycle with the sporophytes appearing in the fall and winter and disappearing in the summer (Floch et al. 1991). In many invasive populations, however, sporophyte cohorts can overlap and be present year round (Hay and Villouta 1993, Castric-Fey et al. 1999).

Sporophylls on the mature sporophyte produce millions of spores with motile periods of up to 5 hours and a propensity for colonizing floating objects. In native habitats, the spores germinate into microscopic (few-celled), male and female gametophytes, which can lay dormant (Arasaki and Arasaki 1983). Then, when conditions become favorable, the gametophytes produce eggs and sperm and the resultant zygotes germinate into a sporophytes. *Undaria* gametophytes can lay dormant for up to three years (Castric-Fey et al. 1999), making these microscopic stages excellent candidates for the cryptic fouling of ship hulls and for dispersing *U. pinnatifida* into non-native habitats.

Undaria pinnatifida is a highly invasive seaweed and is listed (Lowe et al. 2000) as one of the world's 100 worst invasive alien species by the International Union for the Conservation of Nature (IUCN). It possesses five features that make it a highly successful invader (Fletcher and Manfredi 1995): 1) its behavior as an opportunistic weed and its ability to rapidly colonize new or disturbed substrata and artificial floating structures; 2) its occurrence in dense, vigorous stands on benthic shores communities, where it forms thick canopies; 3) its ability to colonize a wide range of shores, which vary in wave exposure and depth; 4) its extensive vertical distribution, from low tide level down to > 15 m in suitably clear waters; and, 5) the extended period of reproductive spore formation and release observed in introduced populations where sporophytes are present year round.

As with other invasive seaweeds (e.g., *Caulerpa taxifolia*), introduced thalli of *Undaria* are of larger size, have longer reproductive periods, and are able to tolerate a wider range of environmental conditions compared with native populations (Fletcher and Manfredi 1995, Curiel et al. 1998, Campbell et al. 1999, Castric-Fey et al. 1999). *U. pinnatifida* can grow from the low intertidal to 25 m depths (Hay and Villouta 1993, Silva et al. 2002) in habitats ranging from the silty waters of harbors and sheltered marinas to the open coast where it can grow over a wide range of wave exposures. *Undaria* can colonize any hard surface, including artificial substrata such as ropes, pylons, buoys, the hulls of vessels, bottles, floating pontoons and plastic (Fletcher and Manfredi 1995, Curiel et al. 1998). On natural hard substrata, it inhabits stable rocky reefs, mobile cobble habitats, and mudstone, whereas in primarily soft sediment habitats, it attaches to hard surfaces such as shell. *Undaria* also can grow on seagrass (as small sporophytes), the shells of abalone, bivalves and other invertebrates, and epiphytically on seaweeds. The sporophytes can maintain populations under salinities of 20-34 ‰ and temperatures ranging from 0 to 27 °C, although its temperature tolerances vary in different geographic locations. Nutrient-enriched waters do not seem to limit the spread of this alga but may even be an advantage, because it can colonize sewage-influenced habitats (Curiel et al. 1998).

6.1.3 *Codium fragile* ssp. *tomentosoides* (van Goor) Silva

Codium fragile ssp. *tomentosoides* (commonly known as dead man's fingers, green sea-fingers, oyster thief, and sea staghorn) is a green seaweed, and one of six subspecies of *Codium fragile*; although other subspecies (ssp. *atlanticum* and ssp. *scandinavicum*) of *C. fragile* can be invasive, ssp. *tomentosoides* as an invasive, has received the most scientific attention (Trowbridge 1998). Distinguishing characteristics of ssp. *tomentosoides* are utricle shape, frond density, type of reproduction, and seasonality in growth (Trowbridge 1998, 2001). Native populations of *C. fragile* ssp. *tomentosoides* are distributed in the NW Pacific, from Japan to the Kamchatka Peninsula. Now, however, *C. fragile* ssp. *tomentosoides* is one of the most widely distributed of all introduced macroalgae, having established invasive populations in the NW and NE Atlantic Oceans, in the Mediterranean Sea, in SE Australia, NE New Zealand, and along the coast of California (Ben-Avraham 1971, Ribera and Boudouresque 1995, Trowbridge 1998, 1999, 2001, Campbell 1999).

Like other subspecies of *Codium fragile*, the thallus of *C. fragile* spp. *tomentosoides* consists of one or several thick, upright branches arising from a spongy basal disk. Branches are formed from aggregated, siphonous tubes with club-shaped tips called utricles that make up the thallus surface. In *C. fragile* ssp. *tomentosoides*, branches are dichotomous and in general 15-20 cm long and 3-10 mm in diameter, but thallus lengths up to 90 cm have been recorded. On NW Atlantic shores, fronds are normally annual, growing for 9 months of the year and then disappearing during winter; regrowth can occur from a prostrate, siphonous base that can persist for 3 years (Trowbridge 1998). On Scottish shores, however, winter dieback does not occur and *C. fragile* ssp. *tomentosoides* can maintain abundant growths throughout the year (Trowbridge 1998).

Fig. 7. *Codium fragile.* Thallus of *Codium fragile* (not *C. fragile* ssp. *tomentosoides)* growing intertidally in southern California. Differences between *C. fragile* subspecies are based mostly on the size and shape of the microscopic utricles (Trowbridge 1998). Source: Steve Murray

Codium fragile can reproduce sexually and asexually; however, in the invasive ssp. *tomentosoides* reproduction occurs by the parthenogenetic development of female gametes and by vegetative fragmentation (Trowbridge 1998, 2001). When *C. fragile* reproduces sexually, biflagellate anisogametes are released into the water where they fuse to form zygotes. Zygotes develop into undifferentiated, juvenile thalli in 4 to 7 days (Trowbridge 1998), which can grow on any hard substrata, including rocks, algae, or the shells of gastropods and bivalves. The undifferentiated juvenile stage is non-septate and can remain undifferentiated and be difficult to detect for months to years (Trowbridge 1998). When reproducing by parthenogenesis, the female gametes germinate directly into undifferentiated juveniles, which can form siphonous mats (Trowbridge 1998). Both the undifferentiated juvenile phase and the differentiated, upright thallus of *C. fragile* ssp. *tomentosoides* can regrow from small, detached, vegetative fragments (Trowbridge 1999).

Codium fragile ssp. *tomentosoides* is among the most invasive seaweeds in the world, with extensive interoceanic spread during this century. In some areas it is considered a pest, due to its propensity to attach to shellfish (Ribera and Boudouresque 1995, Campbell 1999, Trowbridge 1998, 1999). *C. fragile* ssp. *tomentosoides* was first observed in the NE Atlantic Ocean at the beginning of the 1900s in the Netherlands (Silva 1955), and spread to other countries during the following decades, including the British Isles (Trowbridge 1998). The alga appeared in the Mediterranean Sea in 1950 (Ribera and Boudouresque 1995). At first the alga was a cryptic invader in the NE Atlantic and the Mediterranean Sea because of the presence of other native and morphologically similar *Codium fragile* subspecies. *C. fragile* ssp. *tomentosoides* appeared in the NW Atlantic in 1957 when it was encountered in Long Island Sound (Carlton and Scanlon 1985). Subsequently, *C. fragile* ssp. *tomentosoides* spread rapidly from North Carolina to Maine and into Nova Scotia and possibly Iceland. Here, the dispersal rate of vegetative fragments was estimated to be 12 km yr^{-1} (Trowbridge 1999). The expansion of the invasion of *C. fragile* ssp. *tomentosoides* into more northerly and colder New England waters appears to have been enhanced by a cold-water strain of this subspecies, which is capable of growing at lower temperatures than those of the more southerly (south of Cape Cod) population (Carlton and Scanlon 1985). By 1973, *C. fragile* ssp. *tomentosoides* had spread to New Zealand (Dromgoole 1975), where it rapidly dispersed along the coast of the North Island. In 1995, it was reported in Australia, where it is currently encountered growing on SE Australian shores (Campbell 1999). In 1977, *C. fragile* ssp. *tomentosoides* was encountered in San Francisco Bay (Silva 1979), and is now common at several sites in California (Trowbridge 1999).

Like *Sargassum muticum* and *Undaria pinnatifida, C. fragile* ssp. *tomentosoides* is able to tolerate a wide range of environmental conditions. As summarized by Trowbridge (1998, 1999), thalli can survive over a temperature range of -2 to 27.5 °C with a lethal temperature maximum of 34 °C. This invasive subspecies can grow in intertidal and subtidal habitats in estuaries and along the open coast. It tolerates salinity ranges of 17-40 ‰ and can survive at salinities as low as 12.5 ‰ (Moeller 1969). On NW Atlantic shores, *C. fragile* ssp. *tomentosoides* is primarily subtidal, but also can occur in pools and mid and low intertidal habitats on New Zealand and British shores (Trowbridge 1998). The growth rate of *C. fragile* ssp. *tomentosoides* is inhibited by high irradiances at high temperatures (Hanisak 1979a), an effect that is increased under longer photoperiods (Hanisak 1979b). Studies of tissue nitrogen content have revealed that ssp. *tomentosoides* is nitrogen-limited during much of the growing season in the NW Atlantic (Hanisak 1979b), and that the spread this alga appears to be enhanced by eutrophication (Ramus 1971).

6.1.4 *Caulerpa taxifolia* (Vahl) C.Agardh

Although several species of the predominantly subtropical and tropical green seaweed *Caulerpa* are known to be invasive (Verlaque 1994, Frisch and Murray 2002), *Caulerpa taxifolia* and *C. racemosa* have probably received the most attention. Clearly, the best-known seaweed invader is *Caulerpa taxifolia*, which has also come to be known in the popular media as the “killer alga” (Meinesz 1999). This term was first used by the French press to warn of the spread of this IAS in the Mediterranean Sea. This seaweed also is commonly known as aquarium *Caulerpa* and as lukay-lukay in the Philippines.

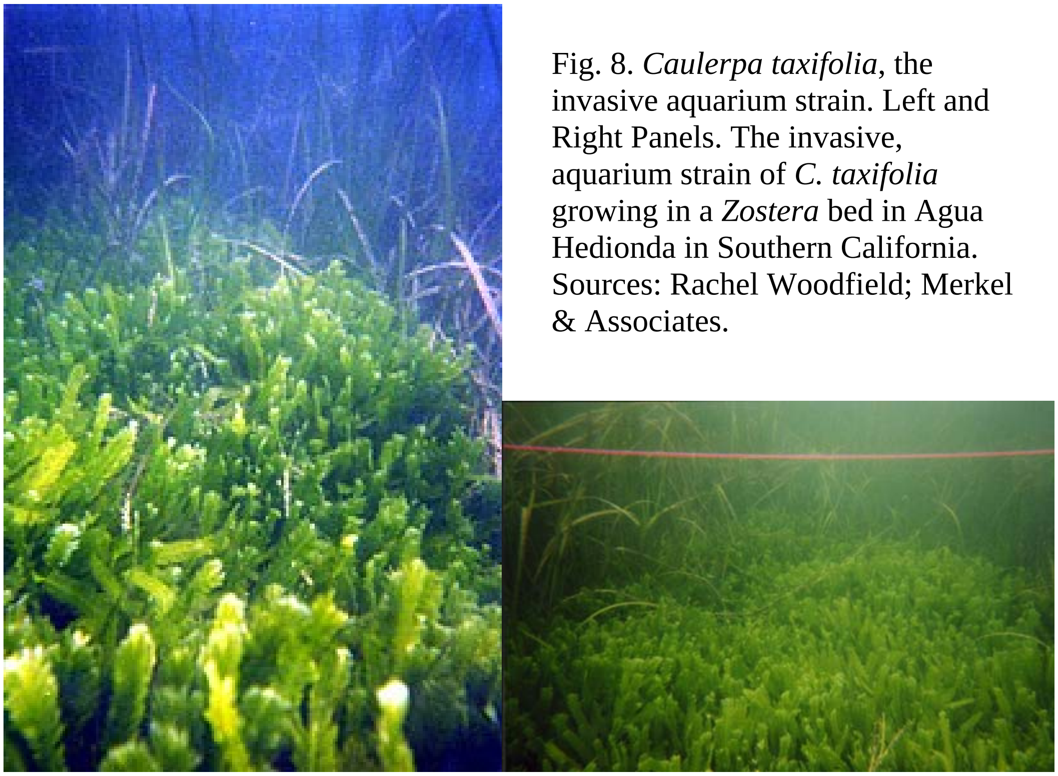

Fig. 8. *Caulerpa taxifolia*, the invasive aquarium strain. Left and Right Panels. The invasive, aquarium strain of *C. taxifolia* growing in a *Zostera* bed in Agua Hedionda in Southern California. Sources: Rachel Woodfield; Merkel & Associates.

Native populations of *Caulerpa taxifolia* are found in the tropical and subtropical waters of the Caribbean Sea, Brazil, and Gulf of Guinea in the Atlantic Ocean, the Red Sea, along the western coast of Africa (from Somalia to Madagascar), India, and throughout the tropical and subtropical Western Pacific from Japan to Australia, Hawaii, and French Polynesia (Meinesz 1999, Frisch 2003, Hewitt et al. 2002). Recent genetic studies have shown that the invasive strain of *C. taxifolia* is an aquarium strain derived from a natural Australian population (Meusnier et al. 2001). The invasive variety has several features, which make it distinct from native populations, and makes it a highly invasive and competitive species. Invasive strains of *C. taxifolia* are larger, grow in higher densities, tolerate a wider range of temperatures, and contain higher concentrations of toxic metabolites (Guerriero et al. 1992, Dumay et al. 2002).

Like other members of the genus *Caulerpa*, *C. taxifolia* is a green, coenocytic (giant-celled) seaweed, with a tubular thallus differentiated into distinct erect, featherlike fronds and prostrate stolons with rhizoids. The fronds are usually 3-15 cm long. The species in its native range has fronds up to 15 cm in length but in the invasive strain fronds of up to 60 cm in length have been recorded (Meinesz et al. 1995, Williams and Grosholz 2002). The maximum stolon length (2.8 m) was found for one thallus of the invasive strain in the Mediterranean; typically stolons reach 1-1.5 m (Ribera and Boudouresque 1995). *C. taxifolia* is a pseudoperennial; although apical growth of the rhizome is indeterminate, no single part of the alga appears to persist for more than one year (Boudouresque 1997). *Caulerpa* spp., including *C. taxifolia*, can reproduce sexually and asexually. Gametes are released in the water where they fuse together to form a zygote and give rise to a new thallus. To date, the invasive aquarium strain of *C. taxifolia* is believed to be exclusively male and is not known to reproduce sexually (Sant et al. 1996, Zuljevic et al. 2001). Reproduction appears to be solely by vegetative regeneration from detached fragments, which can be as small as 1 cm^2. *C. taxifolia* is capable of colonizing a variety of substrata from soft sand and mud to hard rock (Delgado et al. 1996, Boudouresque 1997, Romero 1997). In native habitats, *C. taxifolia* is a subtidal species that grows at depths of 3-50 m but in the Mediterranean Sea, the invasive strain has been found growing at a depth of 100 m (Belsher and Meinesz 1995, Boudouresque 1997).

Invasive populations of *Caulerpa taxifolia* were first recorded in the Mediterranean Sea in 1984 covering about 1 m^2 of shallow ocean floor in front of the Oceanographic Museum of Monaco (Meinesz and Hesse 1991). Since then, this seaweed, which is believed to have been accidentally introduced from aquarium held material (Meinesz 1999), has become widely dispersed in the Mediterranean. By 1990, it was reported to cover 3 ha and by 1996 occurred at 68 sites and occupied 3,000 ha of seafloor (Meinesz 1999). During 2000, the spread of *C. taxifolia* in the Mediterranean had grown to an estimated 8,000 to 10,000 ha and populations were reported to occur in more than one hundred independent localities along the coastal waters of six countries: Monaco, France, Italy, Spain, Croatia and Tunisia (Meinesz et al. 2001, Zuljevic et al. 2001). The dispersal rate of vegetative fragments in the Mediterranean Sea is estimated to be 0.5 km yr^{-1} (Shanks et al. 2003). Following its appearance in the Mediterranean, this aquarium strain of *C. taxifolia* subsequently invaded southern California along the Pacific coast of North America (Dalton 2000, Kaiser 2000, Jousson et al. 2000, Williams and Grosholz 2002) and is believed (Grey 2001, Millar 2001, but see Murphy and Schaffelke 2003) to also have established invasive populations in Australia.

The aquarium strain of *C. taxifolia* is a particularly invasive seaweed that poses a severe threat to invaded ecosystems and was considered by the IUCN to be one of world's 100 worst invasive species in 1999; it also was listed by the United States under the Federal Noxious Weed Act (FNWA) of 1974. *C. taxifolia* can grow vigorously on most substrata over a wide depth range, does not rely on sexual reproduction for dispersal, and is resistant to low temperatures. Invasive populations can grow at least 1 cm d^{-1} (Boudouresque 1997). Several studies (see Meinesz 1999) have reported that invasive populations of *C. taxifolia* functionally and structurally modify invaded coastal ecosystems. Fronds often grow in very high frond densities (its biomass can exceed 10 kg wet weight m^{-2}) creating *Caulerpa* meadows. These dense growths can cause sedimentation of fine mineral and organic particles resulting in hypoxic or anoxic conditions, which can adversely affect seagrass beds and associated meiofauna (Villele and Verlaque 1995). It has been hypothesized (Boudouresque 1997) that these effects may result in additional ecological changes, such as the loss of trophic resources for top predators, interference with sand transport and consequent unbalances in the accretion/erosion budget of beaches, and stimulation of anaerobic processes releasing undesirable compounds such as methane. (Meinesz 1999). It has been reported (Boudouresque et al. 1992, 1995, Romero 1997, Meinesz 1999, Piazzi el al. 2001) that the spread of *C. taxifolia* in the Mediterranean has caused widespread ecological change, particularly through the alteration of native seagrass communities. Other investigators (see Jaubert et al. 1999), however, state that *C. taxifolia* has spread into areas where the native seagrass (*Posidonia oceanica*) was already in decline and that the alga has no effect on seagrass meadows. Similarly, Relini et al. (1998) describe changes in fish diversity near *Caulerpa* beds while Francour et al. (1995) could not find a relationship between *Caulerpa* and fish assemblages.

Because of its notoriety, ability to spread rapidly and grow in dense mats, and its effects on invaded Mediterranean ecosystems, the first appearance of *Caulerpa taxifolia* along the Pacific coast of North America attracted much attention (Kaiser 2000, Dalton 2000, Jousson et al. 2000). *Caulerpa taxifolia* was first reported from southern California waters in summer 2000 in two shallow inland embayments, Agua Hedionda Lagoon in San Diego County and Huntington Harbour in Orange County (Jousson et al. 2000). Inoculation of *C. taxifolia* into these habitats was apparently due to the release of material originally held in saltwater aquariums. Although aquarium introductions into freshwaters have been known to be a serious problem for years, most seaweed introductions are believed to be associated with aquaculture efforts or with shipping activities (Ribera Siguan 2003). The introduction of *C. taxifolia* into California waters appears to be an exception to this pattern and to be associated with the aquarium trade, which also sells several other potentially invasive species of *Caulerpa* besides *C. taxifolia* over the internet and in retail stores (Frisch and Murray 2002, Padilla and Williams 2004).

The invasive strain of *Caulerpa taxifolia* grows between 15 and 31.5 ºC and is able to survive temperatures as low as 6 ºC; the lethal high temperature is reported to be 32.5 °C (Gillespie et al. 1997). It can tolerate salinities of 17-38 ‰, and can grow under very low irradiation (1.23-1.98 mol m^{-2} d^{-1}). This invasive seaweed is able to live in oligotrophic waters (Delgado et al. 1996) but also can establish dense populations in polluted habitats (Boudouresque 1997). *C. taxifolia* is avoided by most grazers such as sea urchins and fishes due to the presence of deterrent chemical compounds (Guerriero et al 1992, Boudouresque 1997, Dumay et al. 2002). Hence, it is avoided by most Mediterranean macro-herbivores (sea urchins, fish and mollusks), especially during the growth period when the production of secondary metabolites is at its peak (Boudouresque 1997, Dumay et al. 2002). As a result, these herbivores move from *Caulerpa* meadows to communities dominated by native macroalgae and seagrasses, which can become overgrazed (Villele and Verlaque 1995). Some species of sea slugs are capable of feeding on *C. taxifolia* and its relatives in the order Caulerpales, and consequently have been proposed as possible biological control agents (Thibault et al. 1998, Thibault and Meinesz 2000). Unexpectedly, experiments with one such Mediterranean sea slug (*Lobiger serradifalci*) showed that its grazing actually disperses the alga, because while feeding it cuts the fronds into tiny living fragments capable of regeneration (Zuljevic et al. 2001). The Caribbean sea slug *Elysia subornata*, which feeds exclusively on members of the Caulerpales, also has been suggested as a potential control agent (Thibaut et al. 1998, 2001) but this species would not be able to survive the low winter temperatures in the Mediterranean Sea.

Although species of *Caulerpa* were commonly encountered in a recent survey of retail saltwater aquarium outlets performed in southern California (Frisch and Murray, 2002), to date only *C. taxifolia* is known to have invaded Pacific North American waters. Another species of *Caulerpa*, *C. racemosa* (now referred to as *C. cylindracea*, Verlaque et al. 2003) also has become invasive in the temperate waters of the Mediterranean Sea. This species has not been found in natural environments in California or anywhere else along the Pacific coast of North America, despite the availability of several "*C. racemosa*" species in aquarium stores. *C. racemosa* is a morphologically variable (Weber van Bosse 1898), pan-tropical to warm-temperate species of *Caulerpa* that was first reported (Hamel 1926, Verlaque et al. 2000) in the Mediterranean Sea in the 1920s. *C. racemosa* was reported sporadically and with little notice throughout much of the eastern Mediterranean until the beginning of the 1990s. Then, *C. racemosa* began to spread rapidly and develop abundant populations (Verlaque et al. 2000). The invasive strain of *C. racemosa* now occurs in the coastal waters of at least 11 countries and all of the large islands in the Mediterranean (Verlaque et al. 2003) where it has been shown (Piazzi et al. 1997, 2001) to significantly alter invaded ecosystems. Recent genetic and morphological studies have determined that three *C. racemosa* taxa occur in the Mediterranean and that the invasive variety, previously known as *C. racemosa* var. *laetevirens* f. *cylindracea* and now referred to as *C. cylindracea*, is endemic to southwest Australia and is a recent introduction (Verlaque et al. 2003).

6.1.5 *Caulacanthus ustulatus* (Turner) Kütz.

This apparently new introduction to the California seaweed flora is a small, mat-forming, red seaweed, which occurs in native habitats in warm temperate waters where it grows intertidally, and in tropical waters where it often grows in association with mangroves (Zuccarello et al. 2002). *Caulacanthus ustulatus* and all other species of the genus are absent from the western Atlantic and from Central and South America. *C. ustulatus* has been reported from the warm temperate and tropical coasts of West Africa (Lawson and John 1982, Wynne 1986), the European Atlantic coast from southern Spain (Seonae-Camba 1965), Portugal (Ardré 1970), northern Spain (Perez-Cirea 1975, Casares 1989) and Biarritz, France (Feldmann and Hamel 1937). It also occurs in the eastern Atlantic on the island of Madeira (Levring 1974), the Azores (Schmidt 1931, South and Tittley 1986), and the Canary Islands (Børgesen 1927, Kristiansen et al. 1993). In the western Pacific, *C. ustulatus* is known from the Philippines and North Queensland (as *C. indicus*) and from Korea (as *C. okamurae*) (West and Calumpong 1990). *C. ustulatus* was first noticed outside of its native geographic range growing intertidally on the north coast (Brittany) of western France in the late 1980s (Rio and Cabioch 1988). Molecular analyses performed by Rueness and Rueness (2000) revealed that Brittany specimens grouped with samples from China and Japan and not with those native to southern Europe. Based on these data, Rueness and Rueness hypothesized that *C. ustulatus* was a non-native species that was possibly introduced from Japan with the oyster *Crassostrea gigas*. *C. ustulatus* is reported to have a geographically disjunctive distribution along the Pacific coast of North America, being collected in British Columbia (Gabrielson and Scagel 1989), Washington (Norris and Wynne 1968), and Pacific Mexico (Dawson 1961), but until the late 1990s was apparently absent from California and Oregon (see Abbott and Hollenberg 1976, Scagel et al. 1989).

Fig. 9. *Caulacanthus ustulatus*. Left Panel. Growing in mid-intertidal habitats among rockweeds at Shaw's Cove, in southern California. Right Panel. Thallus branching pattern and shapes of branch termini. Sources: Steve Murray.

Caulacanthus ustulatus was first encountered in California growing in red algal turfs along the southern California coastline in 1999 and subsequently has become very abundant in upper, mid-intertidal habitats at several sites near harbors and marinas (Murray, personal observations). Genetic analysis (Rueness and Rueness 2000, Zuccarello et al. 2003) aligns members of this southern California population with the same western Pacific specimens introduced to Brittany (Roscoff). Samples of *C. ustulatus* from both sides of the North Pacific (and from Roscoff) exhibit little genetic variation, but the molecular markers utilized have relatively slow mutation rates (Zuccarello and West 2002) so the lack of genetic variation between western and eastern North Pacific specimens cannot be used to conclusively determine if an introduction has occurred. Nevertheless, *C. ustulatus* has exhibited invasive behavior and become very abundant in several southern California intertidal habitats during the last five years, where it is now the dominant species in upper shore algal mats and turfs and can be found growing on rocks, rockweed stipes and fronds, mussel shells, and barnacles (Whiteside and Murray, unpublished data). *C. ustulatus* also occurs in central California in Tomales Bay (Hughey 1995), San Francisco Bay (K. A. Miller, personal communication), and Elkhorn Slough (P. Gabrielson, personal communication), and is distributed in southern California from San Diego to Santa Monica Bay (Whiteside and Murray, unpublished data). Most *C. ustulatus* specimens obtained from Brittany have been sterile, indicating that recruitment is largely by fragmentation and vegetative propagation (Rueness and Rueness 2000). Culture studies (Rueness 1997) on Brittany specimens revealed that *C. ustulatus* was capable of growing at temperatures ranging from 6 °C to 26 °C with best growth at 17 °C. To our knowledge, ecological studies on either native or introduced populations of *C. ustulatus*, other than those in progress in California (Whiteside and Murray, unpublished data), have not been performed.

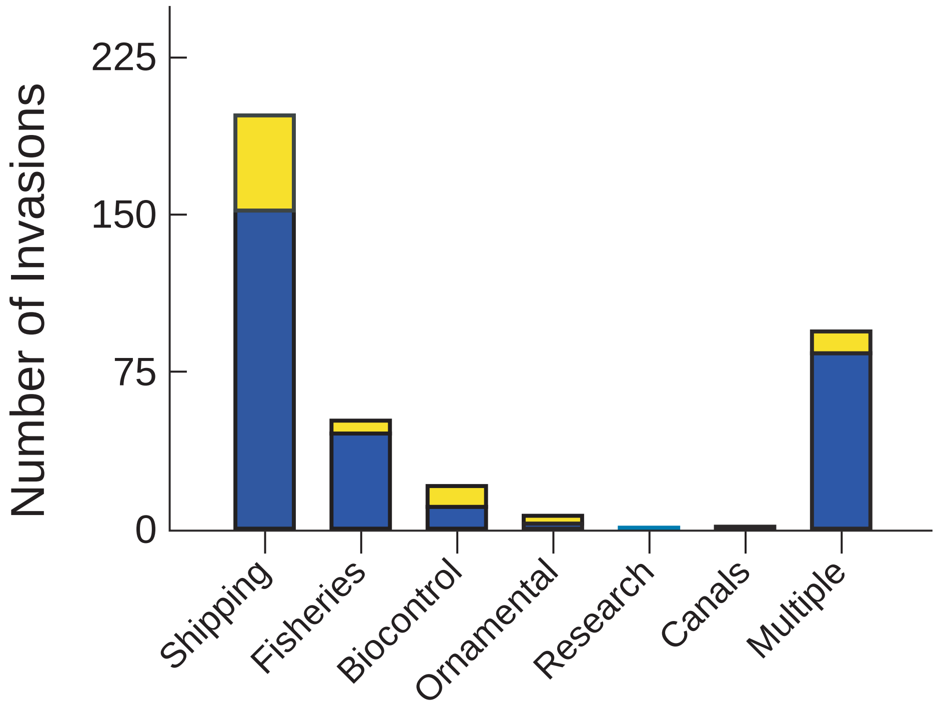

Fig. 10. Numbers of established NIS of invertebrates and algae for marine waters. Filled bars represent number of unique or initial invasions (n = 298); Open bars represent number of repeat invasions among coasts (n = 76). Redrawn from Ruiz et al. (2000).

7.0 Introduction Pathways

In order to develop sound management strategies to address invasive species, it is important to understand the various pathways by which marine NIS have been introduced. Ribera Siguan (2003) identified the following major pathways for spreading NIS of marine plants (and other marine organisms) (Table 2). The first and most significant of these potential pathways for marine introductions is shipping transport. Organisms can be transported in ship's ballast, attached to ship's hulls, or associated with other ship parts, including anchors and anchor chains, propellers, and decks. Another important pathway for introducing marine organisms is through aquaculture activities. Targeted aquaculture species can be moved to non-native waters where they can be grown directly in the sea or escape unintentionally from holding pens; in addition, other species can 'hitch-hike' as epibionts or endobionts associated with targeted species. Fishing activities, scientific research activities, the ornamental or aquarium trade, and the opening of new canals or waterways are additional pathways for introducing marine species.

Recently Ruiz et al. (2000) reviewed the introductions of 298 marine introductions in North America and concluded that shipping and fisheries (including aquaculture related activities) were the dominant pathways for marine NIS. Shipping was found to be the sole vector for 51 % of these initial introductions, with fisheries responsible for another 15 %; multiple pathways were plausible for 29 % of all initial introductions but of these either shipping or fisheries was the only plausible pathway for 78 % of those assigned to the multiple pathway category (Fig. 10). Thus, Ruiz et al. (2000) concluded that shipping and fisheries together accounted for 89 % of the 298 initial introductions. They also concluded that shipping and fisheries were responsible for 74 % of the secondary or repeat introductions, cases where an initially introduced species was transported to another coast.

Introductions of marine NIS due to shipping activities have increased greatly since the early 1800s and most of these introductions have been associated with ballast water transport (Fig. 11) and with hull fouling (Fig. 12) (Fofonoff et al. 2003). Much attention has been given to the role of ballast (dry and water) as a pathway for species introductions since the studies and reviews on this subject by Carlton (1979, 1985). Solid materials (e.g., rubble, gravel, stones, pebbles, cobbles, and boulders) were the predominant forms of ballast until the late nineteenth century (Carlton 1985), and the indiscriminate collecting and dumping of dry ballast materials along the shore was a common practice near ports. Nonindigenous species of terrestrial plants, were recorded from dry ballast dumping grounds near seaports during Victorian times and later (Mack 2003), but the historical significance of dry ballast as a pathway for transporting marine plants is not well understood, difficult to separate from the possibility of inoculation from hull fouling, and usually only can be estimated from records of dates of first colonization. Marine species most likely to be transported with dry ballast are species that live in the intertidal or supralittoral zones and which are able to tolerate prolonged emersion if maintained in damp environments (Fofonoff et al. 2003).

By the 1890s, ballast water was in wide use, and by 1900 most ships were using ballast water instead of dry ballast, although as pointed out by Fofonoff et al. (2003), this transition was not absolute. Ballast water has now become the single largest pathway for introducing marine NIS throughout the world (Carlton 1985, Carlton et al. 1995). Ships intentionally draw in ambient water into floodable ballast tanks and use this water as weight for balance and stability, and to compensate for the lack of cargo. The water is then discharged while the ship is under way or upon arrival in port. Depending on the ship, ballast tanks vary in number, type (empty cargo holds and dedicated tanks), and range in volume from several hundreds of liters to several hundreds of thousands of liters (Carlton 1985). Ballast containers also may have sediments in tanks that can support benthic invertebrates (Carlton 1999).

Table 2. Hypothesized method of introduction for nonindigenous seaweeds found on the Pacific coat of North America (mostly after Hansen 2000, Ribera Siguan 2003, Trowbridge in press). Sources of most seaweed introductions are unknown. Note: Species may be introduced through more than one pathway. For example, *Undaria pinnatifida* (Etang de Thau, France) and *Caulacanthus ustulatus* (Brittany, France) also are believed to be aquaculture associates, having have been introduced to European waters with Japanese oysters.

Aquarium Escape
Caulerpa taxifolia (Vahl) C. Ag.
Aquaculture Associates and Packing Material for Bait
Ascophyllum nodosum (L.) Le Jolis
?*Chroodactylon ornata* (C. Agardh) Basson
Lomentaria hakodatensis Yendo
?*Microspongium globosum Reinke*
Sargassum muticum (Yendo) Fensholt
Aquaculture Targets
Gelidium vagum Okamura
Macrocystis integrifolia Bory
Porphyra tenera Kjellm.
Shipping (Fouling or Ballast)
Bonnemaisonia hamifera Har.
Caulacanthus ustulatus (Turner) Kütz.
Codium fragile ssp. *tomentosoides* (Gook) Silva
?*Fucus cottoni* Wynne and Magne
Ishige isiforme Yendo
Polysiphonia brodiaei (Dillwyn) Spreng.
Undaria pinnatifida (Harvey) Suringar
Pathway Unknown
Acinetospora sp.
Aglaothamnion tenuissimum (Bonnem.) Feldm. Maz.
Bryopsis sp.
Ceramium sinicola Setch. and Gardn.
Halymenia actinophysa Howe
Hypnea musciformis (Wulfen) Lamour.
Pikea yoshizakii Maggs et Ward
Polyiphonia denudata (Dillwyn) Grev. ex Harv.
Polysiphonia harveyi J. Bailey
Sargassum hornori (Turner) C. Agardh
Scytothamnus sp.
Waerniella sp.

Ballast water is known to transport large numbers of species, as exemplified by a Coos Bay, Oregon, study (Carlton and Geller 1993) in which the planktonic components of ballast water from 159 cargo ships originating from 25 Japanese ports were found to contain 367 distinctly identifiable taxa from all major and most minor phyla. The magnitude of ballast water transport during modern times is enormous. For example, Carlton et al. (1995) estimated that > 70 million metric tons of ballast water was carried into U.S. waters by commercial vessels in 1991. It has been estimated that at any given moment, more than 3,000 species may be carried around the world in ballast water (NRC 1995), although Carlton (1999) reports that this number is probably an underestimate, and argues that if more vessel types are considered, more than 10,000 species may actually be in motion in ballast water during any given 24 hour period. Species considered the most likely to be transported in ballast water are species with postlarval stages or long lived (> 5 days) larvae that occur in the water column or that are small surface-dwelling organisms that can be resuspended and entrained during ship operations (Fofonoff et al. 2003). Although less likely to occur in ballast water, taxa with a strictly benthic life style and with brooded or crawl-away young, or benthic algae can also be taken in and transported with ballast water (Carlton and Geller 1993).

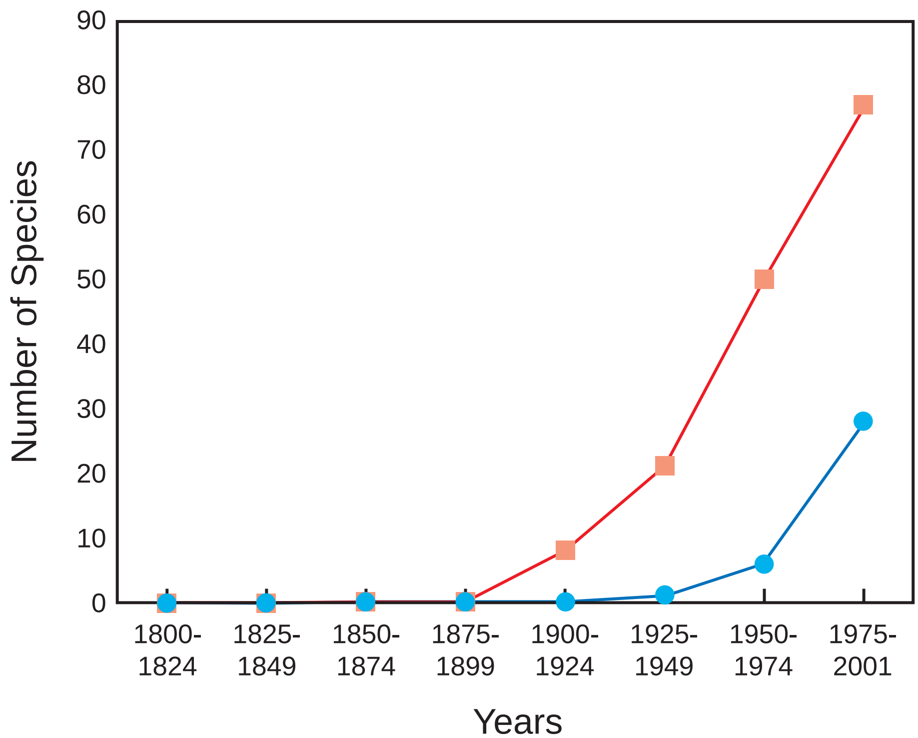

Fig. 11. Rate of introduction of NIS of marine invertebrates, algae, and fishes in coastal waters of continental North America associated with ballast water. Plotted are number of newly detected species in the indicated time intervals for: those NIS where ballast water was the sole pathway (blue line) and where ballast water was the sole or one of several possible pathways (red line). Redrawn from Fofonoff et al. (2003).

In addition to dry or wet ballast, growths of organisms on hulls and other submerged ship surfaces (ship fouling) represent a significant pathway for introducing marine NIS. Species transported as part of the fouling community on ships hulls are likely to be sessile or sedentary forms or those that attach eggs to hard substrata. The hulls of ships likely played a large but incompletely known role in the global transportation of NIS marine organisms, including those introduced to the Pacific coast (Carlton 1979, 1996b) during early periods when ships first sailed the world's oceans. Most early ships were made of wood and provided favorable habitat for a variety of fouling and boring organisms, including seaweeds, sponges, mussels, barnacles, and wood-boring clams and crustaceans (Ruiz and Crooks 2001). These wooden 'floating marine biological islands' *sensu* Carlton (1999) could easily transport a large number of benthic species. Carlton (1999) estimates that an older, well-fouled and well-bored vessel with muddy or colonized anchor systems, and with mixed sand and rock ballast could easily have transported more than 150 species in a single voyage. Moreover, he hypothesized that if between 1500 and 1800, a minimum of 3 to 5 species per year were successfully introduced to non-native waters via shipping, between 900 and 1,500 marine plant and animal species now considered to

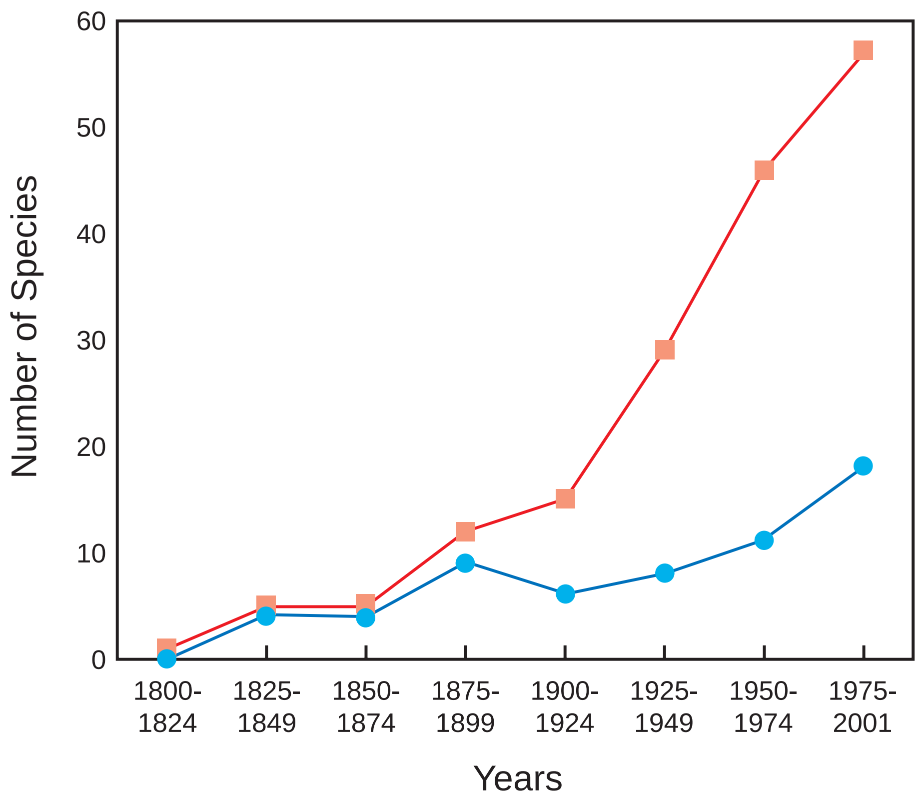

Fig. 12. Rate of introduction of NIS of marine invertebrates, algae, and fishes in coastal waters of continental North America associated with ships' hulls. Plotted are number of newly detected species in the indicated time intervals for: those NIS where ships' hulls were the sole pathway (blue line) and where ships' hulls were the sole or one of several possible pathways (red line). Redrawn from Fofonoff et al. (2003).

have broad geographic distributions might actually be overlooked introductions. Today, ship fouling remains a significant pathway for introducing marine NIS (Carlton et al. 1995, Gollasch 2002). It has been estimated (Ruiz et al. 2001) that 50,000 commercial vessels with a total of > 300 million m^2 of submerged hull surface arrive in U.S. ports each year from origins outside the country. In addition, many commercial ships move from port to port between states, and perhaps an even larger number of non-commercial vessels routinely make shorter trips and dock for lengthy periods in coastal marinas and harbors. Hull fouling appears to be the most likely or only pathway for certain IAS, which continue to become established in new coastal habitats despite the faster speed of modern ships, and the widespread use of anti-fouling paints and compounds (Fofonoff et al. 2003).

The movement of oysters from one part of the world to another has been in practice for 500 to 600 years and has been the vector for the introduction of numerous marine NIS (Carlton 1999). The Japanese oyster *Crassostrea gigas*, which has been moved to most parts of the world, and the American Atlantic oyster *Crassostrea virginica* were brought to Pacific North America beginning in the early to mid 1900s and the late 1800s respectively, and with them a rich association of NIS in silt and mud and on oyster shells (Carlton 1999, Ruiz and Crooks 2001). The movement of NIS with intentional introductions of more valued, non-native oyster species was considered by Ruiz and Crooks (2001) to represent the second in three phases of introductions along western North America, with the first phase being the arrival of fouling organisms on ship hulls and the third and current phase being mediated through ballast water.

7.1 Seaweed Introduction Pathways

It is difficult and often not possible to identify with certainty the introduction pathway for most marine NIS, and multiple pathways may be involved in the movements of many taxa (Ribera Siguan 2003). According to a recent global review of the pathways of marine plant introduction, Ribera Siguan (2003) reported that accidental transport with intentionally introduced target species (e.g., oysters) accounted for more global introductions (30 % of 189 assigned species) than any other single pathway. This was followed by fouling the hulls or other submerged parts of ship surfaces (24 %), transportation in ships' ballast water (16 %), dispersal through man-made canals and waterways (15 %), and outplants or accidental escapes from seaweed aquaculture enterprises (9 %); fishing (packing for bait and organism transport and by attachment to nets), escapes from research experiments (accidental and outplantings), and the release of aquarium-traded plants together accounted for the remaining 6 % of assigned cases (Fig. 13). This is a different pattern from that gathered for most marine animals whose juvenile (larval) and adult life forms and living requirements (e.g., lack of dependence on light) make long-distance transport in ballast tanks much more likely and introductions from ballast discharge more probable compared with seaweeds (Fofonoff et al. 2003).

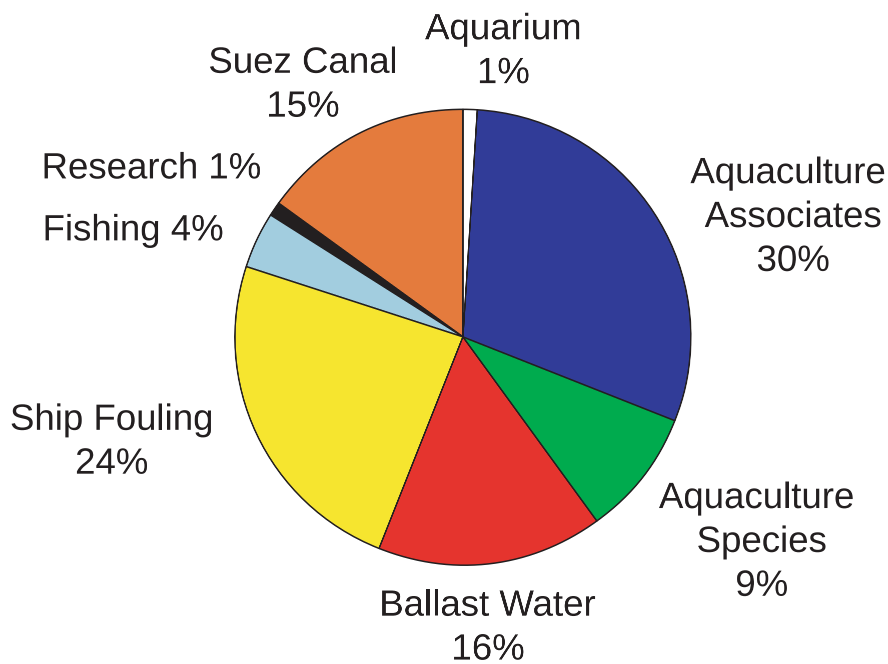

Fig. 13. Percentage of NIS of marine plants (algae, phytoplankton, seagrasses and halophytes) introduced by the indicated pathways. Redrawn from Ribera Siguan (2003).

7.1.1 Associates of Species Targeted for Aquaculture

The accidental movements of marine plants accompanying the intentional transport of target species, particularly oysters, stands as the most important global pathway for introducing NIS of seaweeds (Ribera Siguan 2003). Red algae (29 species) represent the greatest number of seaweeds believed to be introduced by this mechanism, followed by brown algae (14 species). Most of these introductions are thought to have originated from plants transported with target species as hitch-hiking associates and epibionts or as packing material. Hence, aquaculture sites, and particularly sites used for growing oysters, are well known for their high numbers of marine NIS. For example, studies of such sites in the Thau Lagoon in the Mediterranean Sea (Verlaque 2001) and the Venice Lagoon in the Adriatic (Verlaque 1994, Occhipinti Ambrogi 2001) have found large numbers of NIS. Yet, of the 11 recognized species of seaweeds introduced to the Pacific coast of North America where the pathway for introduction is known or strongly suspected (Table 2), only three (*Gelidium vagum*, *Sargassum muticum* and *Lomentaria hakodatensis*) are believed to have been introduced as associates of transported aquaculture species, and in each case the aquaculture species involved was oysters.

7.1.2 Shipping

On a worldwide basis, shipping (e.g., hull fouling, ballast water, anchor fouling) accounts for the greatest number of marine introductions, and this is also the case for marine plants when all shipping pathways are combined. Of the seaweed NIS known to occur in Pacific North America, seven are believed to have been introduced directly by shipping (Table 2). Hull fouling appears to be the most common shipping method of introducing marine macroalgae, while ballast transport seems to be more important for introducing marine phytoplankton and higher plants. Hull fouling was found to account for 24 % (39 of 184 species) of marine plant introductions worldwide; interestingly, none of these were flowering plants (Ribera Siguan 2003). Most algal introductions associated with hull fouling (31 of 39 species) were red seaweeds. Although most algal species believed to be transported in ship fouling communities are fast-growing smaller species, even sporophytes of the large kelp *Undaria pinnatifida* can be transported considerable distances on ship hulls (Hay 1990).

Although ballast water transport is widely regarded as the most important method for the global transportation of marine NIS (Carlton 1985, Carlton et al. 1995), this pathway does not seem to be as important for marine macroalgae as it is for marine invertebrates. This is likely because to be successfully transported long distances in ballast water, marine macroalgae need to survive lengthy periods without light, changes in temperature and oxygen concentration, and possibly heavy grazing pressure (Carlton 1985, Galil and Hülsmann 1997, Fofonoff et al. 2003). As summarized by Ribera Siguan (2003), ballast water is the most likely method for transporting phytoplankton and other microscopic organisms that live in the water column, dinoflagellates and other algal species that form cysts capable of persisting for lengthy periods in ballast sediments, macroalgae capable of reproducing vegetatively by fragmentation, and higher plants with fruits or seeds capable of surviving long periods in low light while submerged or damp. Ribera Siguan (2003) attributed ballast water as the introduction pathway for only four macroalgal and five higher plant NIS; the other 16 species of marine “plants” assigned to this introduction pathway were phytoplankton. As pointed out by Ribera Siguan (2003), these numbers are probably underestimates, particularly for microscopic phytoplankton where the baseline information against which to compare newly discovered species is poorly developed (Ruiz et al. 2000) and the number of organisms found in ballast water can be very high (Carlton and Geller 1993). Indeed, more work needs to be done to uncover the degree to which the observed global increase in the frequency of harmful algal blooms (HABs) can be attributed to ballast water introductions of phytoplankton NIS.

7.1.3 Targeted Aquaculture Species

Several species of marine algae represent valuable raw materials for the food and chemical industries and have long been harvested from wild populations and cultured for these purposes. These are mostly red and brown algal species; green algae account for a much smaller portion of the seaweed industry. Brown algae are widely sought for among other chemicals, their alginates (e.g., *Macrocystis*, *Laminaria*, *Ascophyllum*). In addition, brown algae such as *Laminaria japonica* (kombu) and *Undaria pinnatifida* (wakame) are extensively used for food in Asia and other parts of the world. Red seaweeds such as *Porphyra* (nori) also are harvested for food, while others serve as the raw material for agar (e.g. *Gelidium*, *Gracilaria*) or carrageenan (e.g. *Kappaphycus*, *Hypnea*). Almost 94 % of edible seaweeds come from aquaculture enterprises instead of being harvested from wild stocks (Dawes 1998), with prices ranging several years ago from US$7,500 to $10,000 per dry metric ton (Ohno and Critchley 1993). In contrast, most algae sought for their chemicals are harvested from wild populations, although aquaculture successes with *Gracilaria* have made notable impacts on this market. A few years ago, approximately 900,000 metric ton wet wt (50,000 metric ton dry wt) of seaweed were harvested for their colloidal chemicals (alginates, agars, and carrageenans) (Lüning 1990). Alginates are in increasing demand and the annual value of the alginate harvest in the United States alone exceeds US$100 million (Dawes 1998). Globally, the value of agars and carrageenans each exceed US$200 million (Dawes 1998). Hence, given the worldwide and expanded demand for macroalgal products, it should not be surprising that increasingly attempts are being made to cultivate macroalgae successfully to create predictable and abundant stocks suitable for harvesting. A byproduct of these ventures has been and will continue to be the accidental or purposeful introduction of IAS of macroalgae into the sea.

Ribera Siguan (2003) estimates that 15 NIS of marine plants (11 red and 4 brown algae) have either been released into the sea purposefully or have escaped from aquaculture farms. Most of these introductions have occurred outside of North America. Only perhaps 4 of the 14 species assigned to specific pathways have been introduced into Pacific North American waters (Table 2). A species of the giant kelp *Macrocystis*, a seaweed that created controversy when attempts were made to culture it in the Northwestern Atlantic in the 1970s (Boalch 1981), has been transported from southeast Alaska to Prince William Sound, Alaska, where its fronds are placed in the sea and used as a substratum for herring eggs (Hansen 2000). Presumably because of physiological constraints, *Macrocystis integrifolia* has not yet been able to establish introduced populations in Prince William Sound despite the presence of drifting blades and holdfasts (Hansen 2000).

7.1.4 Aquarium Release

The aquarium industry has long been known to be an important pathway for the introduction of exotic freshwater species (Courtenay and Stauffer 1990, Ruiz et al. 1997). Much less attention has been given to saltwater introductions of aquarium held organisms. Currently, more than 150 identified NIS have been introduced through the aquarium and aquatic ornamental culture trade (Padilla and Williams 2004). Moreover, this industry now services more than 11 million aquarium hobbyists in the U.S. alone and on a worldwide basis is growing by 14 % annually (Padilla and Williams 2004). The aquarium trade has been a particularly important pathway for introducing NIS of fish. For example, as of 1984 there were 40 established reproducing populations of exotic fishes in fresh and coastal waters in the United States (Taylor et al. 1984), and that number rose to 46 by 1990 with 65 % having been introduced by the aquarium fish trade (Courtenay and Stauffer 1990). On reefs in southeast Florida, Semmons et al. (2004) recently found 16 species of non-native fishes, and report that all resulted from aquarium releases. In contrast, only one NIS of marine plant was classified as being introduced by this pathway (Ribera Siguan 2003). However, this species was the IAS *Caulerpa taxifolia*, which in the Mediterranean produced one of the most widespread and notorious invasions of any coastal sea. In recent years, there has been an increase in the shipping of ornamental species for personal use by hobbyists (Tlusty 2002), and *Caulerpa taxifolia* and other potentially invasive *Caulerpa* species were found (Frisch and Murray 2002) to be widely available in retail aquarium outlets throughout southern California. *C. taxifolia*, along with virtually all seaweed species now listed as a federal or state noxious weed (Kay and Hoyle 2001), also can be readily purchased over the internet.

8.0 Management of Marine IAS and Invasive Seaweeds

IAS have been identified by scientists and managers as a major threat to marine biodiversity and have resulted in hundreds of millions of U.S. dollars in direct costs and losses of ecosystem services during the last century (Bax et al. 2001). Moreover, escalating trade among nations, on global and regional scales, is now the primary driver of biological invasions (Ruiz and Carlton 2003b).

Bax et al. (2001) argue that an effective IAS policy should "prevent new introductions and control established populations in an environmentally sound and safe manner". As ably stated by Ricciardi and Rasmussen (1998), "the science and management of exotic species need to become more proactive to prevent or mitigate invasion threats". Current national and international policies in the B2B, however, have not been effective in preventing new marine invasions and also in dealing with identified introductions once they have occurred. For example, the U.S. framework for dealing with IAS has long been viewed as uncoordinated and fragmented (OTA 1993). In its recent report, the U. S. Commission on Ocean Policy (USCOP 2004) reaffirmed this position by stating that: "invasive species policies are not keeping pace with the problem primarily because of inadequate funding, a lack of coordination among federal agencies, redundant programs, and outdated technologies". Further, the report states that "numerous federal agencies are involved in efforts to prevent the introduction of such species and many laws and regulations have been developed to combat the problem, but more needs to be done to reduce this threat" (USCOP 2004). We were unable to find similar reviews of existing national management frameworks for Canada and Mexico, but surely similar problems exist. Hence, new thinking and new policies need to be developed and, to be effective in the B2B, these should include not only on-going efforts to revise and strengthen the existing U.S. national management frameworks but also the development of similar efforts in Canada and Mexico, all of which must include considerations of trinational cooperation. U.S. Senate Bill 363 Section M underscores the need for international cooperation with emphasis on cooperation between Canada, the U.S., and Mexico to address invasive species threats in a meaningful way.

It is widely recognized (e.g. Ruiz and Crooks 2001) that the first and foremost line of defense for combating the potentially damaging effects of marine IAS is to prevent introductions. This position was recently supported by the U. S. Commission on Ocean Policy (USCOP 2004): "recognizing the economic and biological harm caused by invasive species, and acknowledging the difficulty of eradicating a species once it is established, aggressive steps should be taken to prevent such introductions". Preventing introductions requires effective management of the various transportation pathways. As pointed out by Ruiz and Carlton (2003b), preventing IAS introductions is a recognized priority in policy development and preventive measures are being taken in various ways throughout the United States and the world. Actions focusing on preventing IAS introductions through pathway management have the advantages of focusing on the mechanism of introduction and being applicable to multiple species (Ruiz and Crooks 2001). Moreover, this approach is based on scientific principles: the rate of invasion is a function of the frequency and density of inoculations (Carlton 1996c, Lonsdale 1999, Kolar and Lodge 2001).

With regard to marine invasions, most attention has been given to ballast water as a pathway for introducing IAS. Ruiz and Carlton (2003b) point out that in the United States alone, two federal laws, six separate state laws, and requirements governing U. S. Navy vessels have been implemented since 1990 with the goal of preventing introductions from ships' ballast water. In recent years, ships have been asked to limit the possibilities of transporting IAS by high seas exchange or the exchange of ballast water in the open ocean (Locke et al. 1991). Open ocean exchange is designed to reduce the abundances of coastal organisms, which have the greatest probability of being able to survive in the non-native waters of distant ports, by replacing them with open ocean species (Ruiz and Crooks 2001). Alternatively, efforts are being made to prevent IAS introductions by treating ballast water using various physical procedures or chemical agents (Ruiz et al. 2001, Taylor et al. 2002, Fofonoff et al. 2003). Unlike for marine invertebrates, higher plants, and planktonic organisms (including phytoplankton), ballast water transport does not appear to be as important of a pathway for IAS of seaweeds (Fig. 13). For example, ballast water was implicated in the introductions of only four macroalgal NIS in a global survey reported by Ribera Siguan (2003). To reduce the likelihood of macroalgal introductions, more attention needs to be given to other pathways, including ship fouling (hulls, anchor chains, and ship surfaces), aquaculture transport (targeted species and hitch-hiking associates), and the aquarium trade. Clearly, additional research needs to be undertaken to analyze the strength and temporal behavior of these and other pathways for seaweed introductions.

Management interests would benefit if invaders with the potential to create significant impacts could be identified either prior to or during the very early stages of their appearance in non-native ecosystems. Attempts at predicting the success and impacts of specific IAS in terrestrial and aquatic ecosystems, however, have been beset with difficulty (Gilpin 1990, Rjemánek 1996, Kolar and Lodge 2001, Peterson 2003). Some IAS can be relatively benign in one region but cause significant ecological impact in another. Hence, the a-priori identification of those potential invaders that present the greatest ecological risk is limited to specific biological and environmental circumstances and is problematic for any particular region (Ruiz and Crooks 2001, Ruiz and Carlton 2003b). This has led some to advocate a statistical or probability based approach for characterizing the outcomes of an invasion. Williamson and Fritter (1996), working with British animals and plants, developed such an approach known as the tens rule, which states that 1 of 10 introduced species appearing in transportation pathways will appear in the wild, 1 in 10 of those appearing in the wild will become established, and 1 in 10 of those established will become a pest. Thus, reducing the number of NIS inoculations results in fewer predictable nuisance invasions. A major challenge for resource managers working in terrestrial and aquatic systems is to develop the needed tools to identify potential IAS, particularly those with the greatest probability of causing significant changes in invaded ecosystems, so attention can be focused on preventing their introductions. Research is needed to develop improved understanding of the ecological characteristics of invasive seaweeds (and other marine organisms), which might lead to improved understanding of potential invasiveness. Additional questions requiring research attention include the identification of those characteristics that make a region susceptible to invasion. As discussed by Ruiz and Crooks (2001), one such topic deserving attention is determining if a relationship exists between environmental degradation and the susceptibility of an ecosystem to invasion.

Once an IAS has arrived, it first must be detected before management decisions can be made. Early detection is of paramount importance if attempts are to be made to eradicate newly-introduced IAS (Bax et al. 2001), particularly in open marine ecosystems where eradication attempts are rarely successful (Bax 1999, Culver and Kuris 1999, Kuris and Culver 1999). Early detection is dependent on coastal field monitoring and survey programs where newly introduced species can be noticed before they have established large populations or dispersed widely. Managers working to eradicate the invasive, aquarium strain of *Caulerpa taxifolia* in southern California were advantaged by early detection, an event associated with an on-going field program.

Besides eradication, another management option is to focus on controlling the spread or damage caused by an invader. For decades, efforts have been undertaken to control unwanted IAS in terrestrial and freshwater ecosystems; control of marine invasions, however, is in its infancy (Bax et al. 2001). As a consequence, there are few examples of either successful eradication or control efforts in marine systems (Lafferty and Kuris 1996). Recently, a multinational workshop was held to discuss options for controlling marine invaders using four IAS as examples, including the seaweed *Caulerpa taxifolia* and the marine flowering plant *Spartina alternifolia* (Bax et al. 2001). An outcome of this workshop was the development of a flowchart (Fig. 14) depicting information needs, consultations, decision points, and risk-minimization steps needed to identify management options. Highlighted in this flowchart are information needs enabling the definition of the problem, the setting of clear objectives, and determination of risks and benefits of actions. In addition, the outlined process recognizes the important role to be played by stakeholders and society in making the value judgement of whether or not to proceed with a control program.

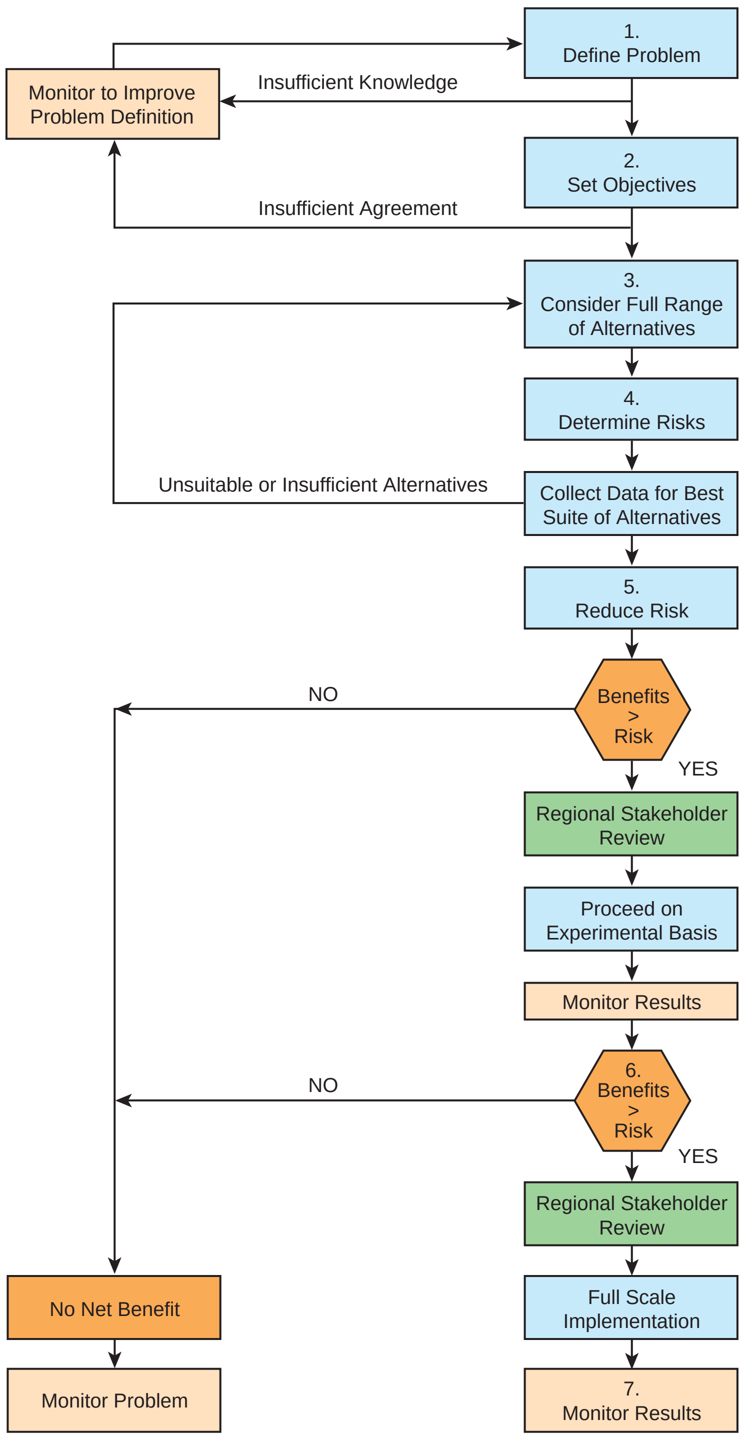

Fig. 14. Flow chart showing steps needed to identify management options for addressing threats posed by marine IAS. Redrawn from Bax et al. (2001).

A common theme in recommendations concerning effective IAS management action is the development of effective field monitoring programs. Field programs are needed for early detection, to track the rate of spread of invaders, and to determine their ecological impacts. Effective monitoring programs also can provide data for evaluating the efficacy of pathway interdiction or other control programs (Ruiz and Crooks 2001, Ruiz and Carlton 2003b). For seaweeds, such programs need to track species distributions and abundances in shallow subtidal, intertidal, and estuarine/marina habitats. Unfortunately, effective monitoring programs are rarely carried out over large spatial areas and sufficient time spans to provide for early detection or for tracking control efforts or dispersal of IAS. As emphasized by Ruiz and Carlton (2003b), well-defined, highly coordinated, field monitoring and tracking programs are badly needed but conspicuously lacking. The need for improved monitoring also was recently recognized in the USCOP (2004) report, which stated "enhanced monitoring to detect invasive species should be part of the national monitoring network". Hence, an effective, trinational field monitoring program to address introductions of IAS of seaweeds and other marine organisms should be implemented. Such a program should be highly coordinated, implemented across a network of sites, and include robust, standardized measures of species composition, distributions, and abundances over time.

9.0 Selected Economic and Policy Considerations for Seaweed IAS

The four main pathways for seaweed IAS identified in this report are ships' ballast water, fouling of ships' hulls, aquaculture, and aquarium trade release. This section discusses current management and selected policy shortcomings for addressing the threats posed by seaweed and other marine IAS. The themes to be addressed are: 1) the North-South spatial dimension in shipping and pathways besides ballast water that need attention to combat seaweed IAS in the B2B, 2) possible policies to address risk and uncertainty in developing management responses to seaweed and other marine IAS, and 3) examples of methods for quantifying costs and benefits of seaweed IAS abatement.

The commercial shipping traffic for international trade between ports is substantial for the B2B. For example, the Port of Los Angeles/Long Beach is the third largest port in the world (Montaigne 2004). Approximately 95.8 % of traffic to Prince William Sound is from U.S. Pacific ports (USDOT 2001). This commercial shipping traffic includes cruise ships, cargo ships, and tankers. The geographic route of commercial shipping that has received attention for IAS is the East-West spatial dimension in terms of entering and exiting the 200 nautical miles (370 km) from the North American continent for the U.S., Mexico, and Canadian Exclusive Economic Zones (EEZs) if ships travel between the main Mexican port of Ensenada up through ports in the U.S. and to the main port in Canada, Vancouver. Ships arriving from outside the EEZ in the East-West spatial dimension are now asked to conduct ballast water exchange in water greater than 200 nautical miles (370 km) from land and greater than 2,000 meters in depth according to International Maritime Organization guidelines (IMO 2002).

10.0 Pathways for Seaweed IAS

10.1 Ballast Water: The North-South Spatial Dimension

The IAS pathway now receiving greatest attention is ballast water in ships that enter and exit the 200 nautical mile (370 km) Exclusive Economic Zones (EEZ). Clearly, the East-West spatial dimension in and out of EEZs of North America will continue to need attention through all of the policy options and economic valuation strategies discussed in subsequent sections. However, the East-West dimension is not the only one in the B2B that matters. The North-South spatial dimension also needs attention. Approximately 80 % of shipping traffic in California takes place *within* 200 nautical miles (370 km) of the coastal mainland, primarily from vessel traffic from Mexico and Canada, the two largest trading partners for the U.S. (USDOT 2001). These vessels are not subject to any ballast water exchange and reporting requirements that are in place through the West Coast Ballast Water Exchange Program and California State Lands Commission for ships entering California from outside the EEZ. Time and fuel considerations by shippers on the north-south route and lack of regulations governing that route, however, are factors to consider. The coast traders are limited because full ballast water exchange takes 24-36 hours and the deviation en-route to reach 200 nautical miles (370 km) offshore and 2,000 meters in ocean depth would take longer than the actual voyage (Taylor et al. 2002). Data show ships traveling north from California and Mexico can transport large numbers of IAS into British Columbia, Canada (Levings et al. 2004). The Vancouver Port Authority Harbormasters allow ships with ballast water from north of Cape Mendocino, California, to bypass ballast water exchange before discharging in Vancouver even though a ballast water exchange rule for 50 nautical miles (92.6 km) from the port is in place. In 2002, about 11 % of the ships arriving in Vancouver was from this exclusion zone and released unexchanged ballast water (VPA 2003). Likewise, 95.8 % of the shipping volume to Prince William Sound from western domestic ports are not subject to the ballast water requirements of the 1996 Public Law 104-58 for ballast water exchange applicable to exporting oil tankers.

Variation abounds related to mechanisms of controlling the ballast water transfer in the North-South path of the B2B. Different states within the U.S. as well as different countries differ in their regulations, and existing programs have limited ability to prevent further introductions or to curb IAS that already have arrived (Union of Concerned Scientists 2003). The U.S. National Invasive Species Act of 1996 and the U.S. Aquatic Invasive Species Act of 2003 call for state plans. As a result, there is now focus on the state scale of action rather than on actions involving coordination between and among states. For example, the state of Washington requires that coastal shipping traffic from California conduct ballast water exchange 50 nautical miles (92.6 km) offshore before entering Washington. In contrast, Oregon does not require ballast exchange for ships entering Oregon waters if traveling north of Cape Mendocino, California. However, Oregon and Washington share waters with similar ocean conditions, increasing the likelihood for IAS survival when moved from one region to the other. A proliferation of local approaches will be difficult for shipping interests to accommodate. In addition, such a piecemeal approach is counterproductive when dealing with a transboundary and global industry such as shipping as a pathway for introducing seaweeds and other marine IAS.

The trend towards unilateral approaches along the B2B for addressing the ballast water problem reinforces the general conclusion of the General Accounting Office (USGAO 2002) that the primary reason for the IAS problem is incomplete unilateral action. Similarly, the report by the U.S. Commission on Ocean Policy (USCOP 2004) calls for increased financing and increased coordination of institutional response to address ocean protection. Clearly, piecemeal requirements increase transactions cost for everyone (policymakers and shippers) with less likelihood of truly tackling the transboundary problem given the limited financial resources devoted to curtailing IAS introductions by the public and private sectors. All of the recommendations by the U.S. Commission on Ocean Policy for prevention, early response, and public education, emphasize coordination among regulating entities in order to address the various IAS pathways.

The April 2004 meeting in Oakland, California, convened by the California State Lands Commission, is a recent attempt to develop consistent guidelines for ballast water exchange along the B2B following new guidelines from the IMO (2004) for coastal traffic (50 nautical miles (92.6 km) offshore). The efforts for consistency would be enhanced if participation included representatives from Mexico, Canada, and Alaska along with those from California, Oregon, and Washington. There are places where nearshore waters drop to depths greater than 1,000 meters within 200 meters from shore. In these cases, ballast exchange could take place closer to shore (15-25 nautical miles, 27.8-46.3 km) and California may allow for exceptions to the 50 nautical mile (92.6 km) rule (M. Faulkner.personal communication). However, large vessels would not be able to complete such an exchange because the trip time is too short. For example, exchange might take 36 hours to complete, a time greater than the duration of the entire coastal trip.

The success of oceanic exchange of ballast water has not been verified, but it is known that new introductions have occurred since this strategy was implemented, and there are known limitations to this approach (USCOP 2004). Therefore, recommendation 17-1 by the U.S. Commission on Ocean Policy (USCOP 2004) relates to including new ballast water technologies into a national framework.

10.2 Ship Hull Fouling

Commercial and recreational marine vessels in the B2B are pathways for biofouling transfers of IAS of seaweeds and other marine organisms. Policymakers have not properly accounted for the transportation of invasive species as fouling organisms on boat hulls (GAO 2002, Fofonoff et al, 2003). For example, biofouling as a pathway for IAS is given little attention in the report by the U.S. Commission on Ocean Policy (USCOP 2004). For the B2B and beyond, movement towards phasing out the antibiofouling hull coatings that contain toxic tributyltin (TBT) has been the extent to which biofouling has been addressed. While the IMO has initiated the phase out of TBT based coatings, more environmentally friendly options that reduce hull fouling on commercial and recreational ships are needed. Localized effort has begun to identify options in places such as San Diego, California, that take the form of technical assistance and public education for recreational boaters to encourage the adoption of nontoxic, antibiofouling alternatives to TBT for their vessels.

New Zealand and Australia, through their national plans for prevention and management of marine invasive species, represent examples of countries that have moved beyond ballast water to address pre-border and post-border control systems for a variety of pathways. These include monitoring activities to distinguish between new incursions or the spread of existing IAS, IAS emergency response including interagency coordination, and cost-sharing arrangements (Bax et al. 2003). Hence, it is useful to note actions taken by these two countries in discussing the potential for the B2B region to address biofouling. Hayes and Sliwa (2003) list criteria that can be used to focus management efforts by identifying the next IAS that might arrive through ballast water and hull fouling. It appears that Canada's proposal for a "National Action Plan to Address the Threat of Aquatic Invasive Species" is aimed at following New Zealand's comprehensive approach (Aquatic Invasive Species Task Group 2004). The Proposal was approved in September 2004. The implementation schedule will be developed by September 2005. Action and funding to follow through with implementation may start in 2006.

Preventative action related to shipping and IAS also could take place within the existing framework of ship registration. The IMO has regulations related to operation, maintenance, and pollution prevention for flag states and their ships that involve inspection and certification. This framework could highlight prevention of marine IAS. Enforcement of existing laws would go a long way towards improving the situation, knowing that the costs of enforcement are significant. Policies that generate finances from those who do not comply may be a way to pay for the enforcement. Such policies will be discussed in Section 11. The ability to keep up with maintenance records of ships might reduce transaction lags and costs for ships, ports, and consumers of shipped products (Llacer 2004). The International Ship and Port Facility Security (ISPS) Code from the IMO was adopted in December 2002, and requires all ships to be security-certified by July 1, 2004, or risk being barred from many ports of call, which could lead to trade losses of US$100,000 per vessel per day (Botelho 2004). This may serve as a fruitful channel of information regarding possibilities for addressing marine IAS, for example through hull maintenance and ballast water programs.

10.3 Aquaculture

Aquaculture takes place in coastal and offshore areas of the B2B and warrants attention as an IAS pathway. Even though the U.S. Commission on Ocean Policy report (USCOP 2004) does not mention the active offshore aquaculture sites in the B2B (such as offshore oil platforms in California), recommendation 22-1 by the Commission applies in the B2B by calling for a refinement of the National Aquaculture Act to achieve better regulation of aquaculture activities. While The U.S. EPA recognizes the possible spread of invasive species as a problem in aquaculture activities, noted in Chapter 9.3 of a report describing the agencies' focus on aquaculture, there are no guidelines addressing invasive species related to effluent or other components of what the EPA might regulate in aquaculture systems (http://www.epa.gov/guide/aquaculture/ea/ch9.pdf). NOAA asserts that harvest of aquaculture species falls under the Magnuson-Stevens Fishery Conservation and Management Act. Therefore, the Regional Fishery Management Councils (RFMCs) develop management measures for aquaculture in coastal and offshore waters. Besides the harvest of aquaculture species, more attention may need to be given to monitoring possible introductions of IAS. Currently, for California's commercial aquaculture operations on offshore oil platforms, the Minerals Management Service (MMS) has oversight on the lease for oil extraction on platforms within federal waters with a requirement of maintenance to prevent top heavy weight on the platform thereby reducing the likelihood of a platform toppling (Fernandez and Hitz 2001). This maintenance involves removal of fouling and aquaculture organisms through regular harvests of shellfish that results in revenue generation for the oil platform owners or the divers contracted to remove the biological growth. For example, an average shellfish yield per oil platform can be 22,680-45,359 kg of mussels, 500-5,000 bushels of oysters, and 454-4,536 kg of scallops, according to a sample of 10 offshore platforms in California (Love et al. 2001).

There is no regulatory attention directed towards the materials that are seeded as substrata in the pens suspended from offshore platforms for growing oysters and clams in terms of their possible role in introducing IAS of seaweeds or other organisms. Therefore, recommendation 22-2 by the U.S. Commission on Ocean Policy for establishing a new office in NOAA for environmentally sound permitting of such operations would help if this office were to be coordinated with the general practices of leases of offshore platforms through MMS.

Coastal aquaculture operations are separately regulated by Mexico, the U.S., and Canada. For example, Mexico has statutes such as NOM-010-PESC-1993 that addresses sanitary requirements and NOM-011-PESC-1993 that addresses the introduction of live aquatic organisms for aquaculture (Alvarez 2001). The agency responsible for fisheries management, monitoring, and enforcement is the National Commission of Aquaculture and Fisheries (Comision Nacional de Acuacultura y Pesca or CONAPESCA). The aquaculture industry (Cámara Nacional de las Industrias Pesquera y Acuícola = CANAINPESCA) has a central line of communication through a website that could conceivably be utilized for information related to seaweed IAS.

Canada’s National Code on Introduction and Transfers of Aquatic Organisms (Department of Fisheries and Oceans 2002a) appears stronger than the rest of coastal regulations for coastal aquaculture in the B2B in terms of effective enforcement. The Canadian Code acts to prevent uncontrolled transport where vendors, wardens, policymakers, and the public are adequately warned through education using multimedia (written, oral, visual). This Code uses a risk assessment approach for the approval of permits for the transfer and introduction of aquatic organisms, which is consistent across Canada between different jurisdictions (Black 2001). The Code also includes consultation with non-Canadian jurisdictions (for example, states that neighbor provinces that might be transporting and/or setting up aquaculture activities involving IAS). The Canadian Aquaculture Industry Alliance has helped develop this code along with government resource managers. Since introductions of seaweed IAS in aquaculture may be associated with the substratum or packaging material for the cultivated aquaculture species, these regulations could be modified to include these materials in addition to those directed at the intended aquaculture organisms.

Transfers and introductions of aquaculture across the B2B and beyond could be formally addressed with specific attention on substratum and packaging materials containing seaweeds or other NIS through a trilateral arrangement to coordinate the separate regulations of each country and the states within each country. Recommendation 22-4 by the U.S. Commission on Ocean Policy (USCOP 2004) to work with the United Nations Food and Agriculture Organization to encourage and facilitate worldwide adherence to the aquaculture provisions of the Code of Conduct for Responsible Fisheries would be useful to follow throughout the B2B. This would guarantee appropriate assessments and monitoring to minimize adverse impacts as well as consultation with neighboring countries prior to the introduction of NIS in order to reduce impacts.

10.4 Aquarium Release

While throughout Canada it is illegal to release any aquatic organisms into the wild without a permit (see Fisheries Act), lack of enforcement means releases from aquarium trade do happen (Aquatic Invasive Species Task Group 2004). The aquarium industry remains largely unregulated throughout the B2B. The Fish Rescue Program is a joint educational effort of the Ontario government, museums, the Canadian Association of Aquarium Clubs, the Federation of Anglers and Hunters, and the federal Department of Fisheries and Oceans to make aquarium owners (commercial and recreational) aware of the dangers of releasing pets or plants into the wild; these groups also facilitate finding homes for unwanted aquarium pets (Aquatic Invasive Species Task Group 2004). Given that releases by private citizens cannot be fully stopped, it is possible to reduce the number of releases by giving incentives at pet stores to accept returns and dispose of them properly.

For the aquarium trade as well as aquaculture, the Animal and Plant Health Inspection Services (APHIS) of the U.S. Department of Agriculture (USDA) needs to act on its responsibility for surveillance related to interstate movement of federal noxious weeds to include coordinating states' individual policies so that the jurisdictions within the B2B match. Bans on possession, transport, or sales of species such as *Caulerpa taxifolia* in the U.S. have been piecemeal and episodic. What is needed is a formal emergency response framework to guide enforcement or the development of uniform guidelines for carrying out existing bans on larger than a local scale (Padilla and Williams 2004). It is difficult to enforce regulations on species such as *Caulerpa taxifolia* when genetic analyses are needed to definitively identify species and strains. Methods for rapid and economical means of identifying such species that lack clearly recognizable and reliable morphological characteristics are needed.

The potential for seaweed IAS introductions from the aquarium trade in the B2B was highlighted by the *Caulerpa taxifolia* outbreak in California in 2000, which generated an emergency task force response and legislation resulting in a State ban on the sale and possession of selected *Caulerpa* species to prevent another introduction. However, *Caulerpa taxifolia* continues to be distributed in aquarium stores from Los Angeles and San Francisco (Padilla and Williams 2004). Internet trade is thought to be a significant source of aquarium trade and requires new efforts to monitor and enforce restrictions on potential IAS. An internet surveillance program is now being used by USDA-APHIS (Padilla and Williams, 2004).

In response to the potential for aquarium IAS to be released into the environment, the U.S. Fish and Wildlife Service, NOAA, Sea Grant and Pet and Joint Advisory Council started the Habitattitude education program in November 2004. Efforts to load information onto a website related to acquisition, collection, possession, purchase, sale, release and transfer of aquarium species are underway and may be accessible this year. In this regard, as an educational tool The U.S. National Invasive Species Council website (http://www.invasivespecies.gov) provides fact sheets supplying taxonomic information for identified invasive species.

11.0 Risk and Uncertainty of IAS and Policy

The strategies to deal with the four major pathways for the introduction of seaweed IAS along the B2B not only depend on the significance of these pathways in the North-South and East-West corridors, but also the existing infrastructures (e.g., governments, property rights, and trade rules) that address these pathways. Coordinated strategies for dealing with new arrivals from beyond the EEZ as well as dealing with the spread of already arrived IAS within the EEZ require preventative and reactive measures carried out at a larger than local scale. In general, stronger political will and more effective institutions to deal with these problems should be matched with additional financial and technical resources focused on the B2B scale of coordinated effort. The U.S. Commission on Ocean Policy's report echoes this position (USCOP 2004). International, national, and state policies that discuss marine IAS, not specifically seaweed IAS, are described in references such as Ruiz and Carlton (2003b). In this report, we focus on ways of enhancing existing policies with strategies that truly address seaweed IAS in the shared ocean of the B2B.

Two features complicate matters for the ballast water and hull fouling pathways for IAS. First, not every vessel will actually release a species, yet ex ante each vessel is a potential releaser, and there are expected benefits from all vessels undertaking biosecurity actions to reduce the risk probability of an invasion. Second, biological releases from ships are difficult to observe uniformly across locations that might be primary places for enacting inspection and monitoring programs (like ports of entry). These two characteristics will limit any policy attempts for strict release-based standards and will require the policymaker to grapple with both risk and uncertainty in developing management measures.

A concise distinction between risk and uncertainty is that risk can be defined by a probability distribution for the potential for an event to occur. For example, the tens rule of Williamson and Fritter (1996), which states that 1 of 10 introduced species appearing in transportation pathways will appear in the wild, 1 in 10 of those appearing in the wild will become established, and 1 in 10 of those established will become a pest represents a description of risk. Although variation exists from case to case, the 10 x 10 x 10 rule offers a starting point for evaluating risks associated with IAS introductions. Learning all of these probability distributions is part of what risk assessment entails. Uncertainty implies true randomness, without a known probability distribution. It may accompany a risk assessor's description of risk in order to allow for variability. While Naylor (2000) emphasizes uncertainty over time in relation to IAS, it is also important to contend with uncertainty over space, as emphasized in this report by spatial concerns over North, South, East, and West directions for introduction pathways for seaweed IAS.

From the sections describing marine macroalgal IAS and their pathways for introduction, uncertainty abounds at each stage (arrival, establishment, spread, and harm) due to the two characteristics defined above related to shipping and incomplete monitoring. Likewise, the uncertainty involved in aquaculture pertains to the lack of monitoring programs and consistent management practices across the B2B. Information from monitoring and other scientific programs is needed to gain understanding of the risk and uncertainty associated with IAS and to become better informed about which IAS might invade and impact non-native environments. Established programs for risk assessment of IAS, such as those in Australia, do not directly account for uncertainty (Hayes 2003). The public administered program is through the Australian Quarantine and Inspection Service. In this program, there is an automated quantitative risk assessment based on environmental similarity and species specific risks that include infection status of donor ports, infestation of vessels, journey survival, and survival of the species in the recipient port (Hayes 2003).

Management and policy options might as well accommodate uncertainty rather than ignore it. Not acknowledging uncertainty delays policy formulation until a risk probability distribution is defined with certainty. Preventative rather than reactive policy measures are necessary to control the spread of unintentionally introduced IAS due to the extremely difficult nature of locating and eradicating these species and the uncertainty of their impacts on native ecosystems (Ruiz and Carlton 2003b). Ruiz and Carlton (2003b) advocate prevention through management measures that focus on controlling pathways of arriving IAS due to lack of comprehensive monitoring programs and resources for early detection and rapid response on a species-by-species basis. The U.S. Oil Pollution Act of 1990 is a useful example of tackling stochastic pollution events in a preventative manner along with including emergency response in a coordinated manner. An extension of the Act is the MEXUS Plan of 2000 that enables binational oil spill response drills between Mexico and the U.S., such as the one conducted in May 2004 for government and industry participation to address transboundary logistical issues.

Without repeating chapters by Orr (2003) and Hayes (2003) in the edited volume by Ruiz and Carlton (2003b), we apply a basic, non-numerical classification of high risk to the specific pathways and the impacts of seaweed IAS described in previous sections as a supplement to the subsequent discussion of policy options and examples of economic valuation of benefits and costs of seaweed IAS abatement. Vessels traveling in the North-South coastal dimension of the B2B are virtually unregulated for ballast water and hull fouling and there is uncertainty in the actual number of individuals of an IAS needed for an invasion. Thus, pathways for IAS such as *Undaria pinnatifida* are high risk, even for the portion of ships that arrive from outside the EEZ and then become coastal traffic. Earlier sections of this report address the environmental conditions that could lead to successful establishment of an IAS. Therefore, if these conditions are met in areas of the B2B, it is plausible for an invasion to occur. The aquaculture pathway for IAS such as *Undaria pinnatifida* poses a high risk stemming from accidental introduction as substratum or as a hitch-hiker associated with targeted shellfish species and from its purposeful cultivation for human consumption. The aquarium pathway for *Caulerpa taxifolia* appears to have a lower risk for introduction because of the few known cases of aquarium inoculation, but high impact risk because environmental damage could be large. As Orr (2003) indicates, emphasis should be placed on preventing the introduction of IAS with high risk of invasion and high risk of impact, echoing Ruiz and Carlton (2003b). In Section 13 of this report, some values will be highlighted to correspond with the high risk impacts of seaweed IAS.

Analyses that have incorporated risk and uncertainty into other biological management issues are relevant. Using empirical data from a California coastal wetlands, Fernandez and Karp (1998) took into account the uncertain aspects of wetlands growth over time and space for decisions regarding if and how much to invest in wetlands restoration with uncertain outcomes. One of the key findings in their report was that as uncertainty increases in the possible regrowth or restoration potential of a wetlands, it pays to invest more up front to accomplish restoration and end up with lower overall costs compared to delaying investment until later periods and paying more for less overall restoration. Such a result supports the preventative rather than reactive approach to ecosystem protection.

Preventative measures for IAS exist but there has yet to be an economic analysis of their cost effectiveness. It is likely that efforts to estimate the real costs from damages due to IAS will be instrumental in convincing decisionmakers that prevention is less expensive than addressing IAS impacts after they have taken place. Land-based reactive measures such as eradication for a few species (e.g., Tamarisk; Zavelata 1999) have recently been assessed. Transportation separate from the traded goods as a mode of unintentional species invasion, however, has not been addressed in the economics and cost-effectiveness literature.

11.1 Policy Alternatives with Risk and Uncertainty

The following paragraphs provide brief descriptions of policy alternatives that offer potential approaches for addressing seaweed and marine IAS through the identified pathways given the risk and uncertainty associated with invasions. These descriptions rely on evidence from other contexts where the policies have proven effective. There is some attempt to identify where in the B2B the policy may be implemented. Clearly, it would be useful to conduct a comprehensive analysis of the feasibility to implement any one of these policies. It is imperative to emphasize that each of these policies requires monitoring as a component in order to implement and maintain the policy, and the monitoring in turn must be considered as part of the overall investment of financial and technical resources for addressing the seaweed IAS problem.

11.1.1 Insurance

Shippers, aquarium traders, aquaculturists, and those receiving shipped goods might take out insurance against IAS risks or post environmental bonds. In New Zealand, all costs associated with inspection, cleaning, and abatement are the responsibility of the importer (New Zealand Government 1993). In this manner, the true costs of transporting goods are paid first by those importing the goods, and then the importers pass on the costs to the ultimate consumers of these imports. In this context, insurance for environmental protection should indicate the amount people are willing to pay to reduce the degree of uncertainty through abatement efforts including monitoring. Thus, there is a value of updated information and adaptive management through insurance and abatement.

11.1.2 Emission Regulation with Best Available Technology and Performance Standards

Policy has been directed towards mandatory equipment to abate emissions in countries like the U.S. and Canada for addressing uncertainties associated with air and water pollution. Such policy gives the regulating policymaker leverage but reduces its ability to hold firms accountable as long as they follow the technical prescriptions such as installing a scrubber in a smokestack. Firms have no incentive to innovate to try other technology that may lower overall costs. The burden to research and develop new technology rests with the regulating policymaker. With full information about abatement and damage costs, this burden would be easier to bear. However, there is less than full information over time and space and it is a daunting responsibility for the public regulator to generate all of the technological options. The result relevant for IAS of seaweeds and other marine organisms is that, other than the prescribed technology of ballast water exchange, alternative technologies for abating ballast water introductions as well as technology for addressing other IAS pathways (e.g., hull fouling) are not widely implemented.

Within the realm of aquarium trade, the Marine Aquarium Council is poised to develop an international certification system and best practice guidelines. Suggestions have been made to improve this system by expanding it to include guarantees that wholesalers and retailers market "invasives-free" products as well as require aquatic ornamental cultivators and large-scale aquariums to sterilize their outflows and take active steps to reduce the risk of IAS introductions (USGS 2003).

The national entity in the U.S. with principal responsibility for enforcement and monitoring of ships is the U.S. Coast Guard (USCG). The USCG has established the Experimental Ballast Water Treatment Systems STEP program that consists of financial resources (subsidies in the form of grants) and technical assistance to help transfer alternative technologies to the shipping sector to address the ballast water transport pathway for IAS (USCG 2004). Foreign and domestic vessel owners and operators can coordinate with the USCG to install and operate experimental ballast water treatment technologies. The assistance from the USCG helps overcome some of the hurdles of initial investment in new technology. At the international level, the G-8 nations, including Canada and the U.S., have taken up a focused effort with the European Union to expand technical cooperation programs in order to meet IMO standards. A Model Audit Scheme to be implemented in the near future by the IMO will help member states by providing feedback on how well their enforcement efforts are working.

Uncertainty and asymmetry in the pathways and their actual IAS emissions, spatially and dynamically, mean that treating everything uniformly across locations and over time may not efficiently address IAS transport and introduction. Performance standards as an alternative to required technological regulations involve setting limits on such introductions but give the shippers flexibility in the choice of how to meet these emissions limits. The IMO adopted the International Convention for the Control and Management of Ships' Ballast Water and Sediments in 2004 setting a limit of 10 organisms per cubic meter of ballast water as a performance standard along with a couple of other limits corresponding with organisms of different sizes (IMO 2004). It is plausible to pursue strategies that would utilize existing management frameworks, for example, established protocols at public ports for inspection and biosecurity. The method of financial payment to support, for example, the ballast water reporting and collection program may be expanded. An extreme level for a performance standard could be zero where an outright ban is in place, such as the ban on the introduction of *Caulerpa taxifolia* through the aquarium trade (California Fish and Game Code Section 2300). However, to date this ban has been ineffective and may not prevent future introductions (Padilla and Williams, 2004).

There has been recent interest by some environmental groups to seek a total maximum daily load (TMDL) regulatory standard for IAS (Coyne 2004). It would be useful to explore the ramifications of such a measure and what economic instruments could accompany it. The March 2004 guideline by the IMO of 10 organisms per cubic meter of ballast water will be the starting point to explore the feasibility of TMDL measures for ports and shippers. There has yet to be action on the 1998 listing of invasive species from ballast water as a source of preventing San Francisco Bay from attaining water quality standards under Section 303 of the U.S. Clean Water Act due to depleted oxygen levels and structural changes from IAS. The TMDL of zero for San Francisco Bay requires rigorous attention towards all ballast water in the bay and coastal ballast water sources as well.

11.1.3 Liability

Under strict liability, the shipper, aquaculturalist, aquarium trader, or others involved in the potential transportation of seaweed IAS would bear responsibility for damages, irrespective of the care exercised. The Invasive Species Specialist Group of the IUCN has called for the development of liability and criminal penalties for the consequences of unchecked, purposeful introductions of IAS with responsibility for all costs associated with control, enforcement, and damages (Invasive Species Specialist Group 2000). A strict liability system is established in the U.S. Outer Continental shelf for oil tract leasing in addition to the land-based programs related to mining and hazardous waste. Liability creates incentives for taking efficient levels of precaution and striving to innovate to reduce potential impacts where the shipper bears the burden of proof related to the pollution incident. Legal action could extend long after impacts of IAS occur. The regulations built into ship flagging and registration include liability in terms of a program of inspection and certification to determine if a ship's operation and pollution prevention efforts under the International Ship and Port Facility Security code are adequate (Llacer, 2004). The International Ship and Port Facility Security code is the IMO's new security regime that entered into force worldwide in July 2004. One example of the incentives provided by this liability framework is the U.S. Coast Guard's QUALSHIP 21 program, which involves rewards for foreign flag vessels that have attained high levels of compliance with international safety and environmental requirements as evidenced by reductions in Coast Guard inspections. The records for registration make this possible and ships in compliance expedite port calls and reduce costs of shipping delays (USCOP 2004). The EQUASIS database on ships is one source of information to disseminate to port managers worldwide regarding shipping behavior. Interestingly, U.S. Senate Bill 770 Section 1.C mentions liability as a plausible policy to assign civil penalty for not addressing invasive species introductions. This language then reinforces the discussion of a plausible policy mediated through existing shipping registration that assigns liability to shippers who may carry invasive species.

11.1.4 Deposit-Refund and Environmental Bond

Economic instruments, such as deposit-refund systems and environmental (performance) bond programs, involve a pool of deposits provided upfront, which would be sufficient to cover possible future damages from introduced seaweeds or other marine NIS. To the extent that damages do not occur, the deposit and any accumulated interest would be refunded. The amount of the deposit should adequately represent the cost of treatment and disposal for the particular IAS pathway. Deposit-refund and environmental bond shift the financial risk of damage to the entity involved in shipping, aquaculture, and aquarium trade release. With an upfront financial cost, there is incentive to take precaution and preventive action. This approach could improve interdictive measures for IAS that have not yet arrived. There also is incentive for entities to monitor the consequences of their actions to receive refunds by demonstrating they are not causing environmental damage through the introduction of IAS. They bear the burden of proof that they acted in an environmentally sound way. While these policies are similar in theory to liability law for internalizing damage costs, the upfront financial requirement makes the deposit-refund and environmental bond policies different. Setting the right level of deposit and refund is key. It is not necessary that the deposit equal the refund (Mrozek 2000).

The structure of an environmental bond or deposit-refund program is such that pooling across all users (shippers, aquarium traders, and aquaculturalists) means that the potential problem is avoided where it is jointly paid as a cost instead of a leftover externality impacting the global ocean commons. A fee in this context is not so far fetched because there are existing access fees for ports related to entry and loading. Port costs represent only a minor fraction of total transportation costs to deliver goods, for example from Asian to Californian ports (Rust 2004). The value of the bond is based on the estimate of damages from the worst outcome of invasive species. Therefore, the monetary cost of commercial and recreational values associated with habitat and species is the value of the bond. Examples of such values will be presented in Section 13. Payments on the bond or deposits could be placed in a fund to be refunded to shippers that avoid invasive species problems, or used for abatement for shippers who do not. It will be useful to compare the difference between incentives tailored to individual vessel's marginal environmental impacts versus more general incentives that are designed to reduce the risk of invasion. Environmental bonds are currently used for fossil fuel extraction and administered by the U.S. MMS for offshore oil platforms among other extraction operations involving uncertain environmental accidents.

The final report of the U.S. Commission on Ocean Policy (USCOP 2004) suggests collecting resource rent to be used for protecting public ocean resources. Such rent collection is in place for potential carriers of marine IAS in the B2B. One example is from California Assembly Bill 433, that assigns a US$500 fee per vessel (e.g., like a vessel tax) for the Marine Invasive Species Control Fund Act to cover partial administrative costs of the ballast water reporting program for ships entering California from outside the EEZ. A second example is related to the proximity of aquaculture activities to oil and gas extraction platforms. This means that revenue generation by the U.S. MMS from oil and gas leases could be supplemented with a share in the revenues from the platform owners' aquaculture activity in order to channel such revenues into ensuring the management of such operations does not introduce or spread NIS. Since the platforms are leased under the auspices of an environmental bond program addressing the potential environmental impacts from accidental oil spills, it is plausible to include IAS for consideration along with oil and gas to accommodate the environmental bond briefly mentioned in the U.S. Commission on Ocean Policy report (USCOP 2004).

11.1.5 Education and Technical Assistance

Education and technical assistance are vital to address pathways for seaweed and other marine IAS. The voluntary nature of response on the part of those receiving the educational material (oral, written, visual) means that this form of policy cannot be the only policy choice. Educational programs should be considered as necessary along with monitoring, in leading towards the development of an effective, comprehensive program for managing NIS. As an example, the "Stop Ballast Water Invasions" educational campaign from the West Coast Ballast Water Reporting Program has widely disseminated posters and notices in port management and shipping arenas. Another example, is "Reducing the Introduction and Distribution of Aquatic Non-native Invasive Species (RIDNIS)", a local project in the San Francisco Bay area involving public and private entities, which addresses several IAS pathways in an effort to stop new entry by import, sale, and distribution of live plants and animals. The program has resulted in educational efforts funded by CALFED Bay-Delta. In addition, California Sea Grant has implemented a nontoxic hull paint program to abandon toxic (copper and TBT based) antifouling options that have led to leaching problems affecting sea life (Johnson and Miller 2002, 2003). This program involves educational outreach and one-year demonstration of performance and maintenance of boats coated with nontoxic paints. The transition to nontoxic coatings needs to be structured around incentives that boat owners (recreational and commercial) respond to—namely cost, i.e., the coating will eliminate the weight from biofouling that results in drag and extra fuel costs.

Supplemental educational materials, such as fact sheets, could be posted in commercial and recreational domains of aquaculture and aquarium activities. Canada's "National Code on Introduction and Transfers of Aquatic Organisms" (Department of Fisheries and Oceans Canada 2002a) appears strong in terms of effective enforcement. Vendors, wardens, policymakers and the public are adequately warned about the transport of IAS through education in multimedia (written, oral, visual). For example, the "National Code on Introduction and Transfers of Aquatic Organisms" provides all of Canada with a consistent risk assessment approach to the approval of permits for the transfer and introduction of aquatic organisms (Black 2001). The Canadian Aquaculture Industry Alliance has helped developed this code along with government resource managers. Therefore, the same rules can be translated to address invasive species associated with purposeful introductions of marine organisms. Aquariums for public visitation serve as an appropriate venue to provide educational material on the various vectors and abatement strategies to address NIS. Because visitors to a commercial or research aquarium are potential consumers of aquaculture, aquarium trade, or shipped goods, they can learn what steps to take to prevent transfers of IAS.

12.0 Costs and Benefits of IAS Abatement: Costs

Examples of the costs and benefits of IAS abatement relevant for the transport mechanisms impacting the B2B help justify viable policy strategies for action. Different methodologies and baselines have been used in separate examples, and do not enable a simple aggregation of values for the entire region. Although a point estimate of the total value of benefits of IAS control (avoided damages) in the B2B is unavailable, these benefits are substantial, running into billions of U.S. dollars for direct values such as recreation and consumption of ocean products. Since the entire B2B has not been the scale of analysis for a valuation, the following examples become a starting point from which to conduct a more comprehensive scale of valuation for the entire region. Based on the previous section, these examples should be viewed as a gauge for what might happen when risk and uncertainty are taken into account.

12.1 Examples of IAS Abatement Costs

12.1.1 Planning Costs

Planning and establishing abatement agendas constitute part of abatement costs. Such costs to Alaska were estimated to be US$373,000 in 2003, US$690,000 in 2004, and US$760,000 in 2005 for addressing aquatic IAS (Alaska Department of Fish and Game 2002). Half of the Alaska Department of Fish and Game emergency response fund of US$200,000 was included in the annual totals listed above.

12.1.2 Antifouling of Ship Hulls

Costs of abatement of seaweed IAS in shipping pathways are based on the flow of traffic in terms of wetted surface area of hull and volume of ballast water for the hull fouling and ballast water transport mechanisms. Lloyd's Marine Information Service offers information related to the frequency, magnitude, and dimensions of vessels between different ports. Each vessel's costs for abatement depend on its tonnage, length, draft, and size, and these parameters vary greatly among ships frequenting ports in the B2B. Drawing from this information, we estimate the hull surface area of aggregate commercial boat traffic in the B2B at 378 million m^2 per year. This value can then be entered into an estimate of cost per square meter of treatment (e.g., coating, manual removal), which will be discussed in the following paragraph. Collection and containment of fouling organisms is treated not only by applying antifouling coatings but also by hosing, water blasting, scrubbing and scrapping biomass from wetted ship hulls and surfaces (Johnson and Miller 2002, 2003).

Nontoxic antifouling alternatives to TBT based coatings for recreational hulls vary between those with enzymes or phytochemicals (silicon, epoxy, polymer bases) according to California Sea Grant (Johnson and Miller 2002, 2003). The frequency of maintenance would differ between the options due to longevity of the coating and need for cleaning. While the nontoxic coatings last for 5 to 10 years, mechanical cleaning every two weeks is a necessary complement to nontoxic coatings. The survey of boat repair yard owners and hull cleaners in San Diego and Orange counties in California helped to derive total lifetime costs along with a value for each year of waiting to reapply a coat. The cost of US$700 per boat per year for the nontoxic coating and maintenance cleaning is based on an average surface area of a 12.2 meter hull and an average cost of the range of costs of coatings (Johnson and Miller 2003). Applying the range of costs for coatings to the aggregate figure of hull surface area for the B2B (378 million m^2) yields US$198 million to US$2.208 billion per year based on the seven different coating alternatives.

A fouled boat bottom increases drag resistance to movement through water by 7 % to 10 % (Lamb 1981). A rough hull can increase fuel consumption and related pollution by 0.3 % to 1 % or more, depending on the amount of fouling (Milne 1990). Since biofouling causes drag and additional fuel and time costs for boat owners, they are likely to adopt any economical and effective biofouling remedy, thereby helping reduce IAS fouling and introductions. Thus, the benefits of coatings and cleaning include the value of fuel savings and time saved in transit. Proper calculation of all costs of cleaning, including considerations of the time and location where cleaning takes place, would help to assess whether fuel savings truly offset costs of cleaning hulls.

12.1.3 Ballast Water Treatment

Factors influencing abatement costs and risk reduction are: vessel ballast tank volume, estimated number of organisms per metric ton, and vessel frequency and treatment methods. Taylor et al. (2002) provide estimates of costs for the ballast water exchange treatment according to varied ship speed, and ballast pumping capacity. The aggregate 16 billion m^3 of ballast water discharged in the B2B during 2003 is estimated from various ports with the limitation that the ballast water reporting is only required of ships entering and exiting the EEZ and the authors attempted to estimate the coastwise traffic ballast water quantity from less than complete data. A rule of thumb is 30 % of boating capacity (weight) is devoted to ballast water (Langevin 2003).

Alternative options to ballast water exchange include techniques that mechanically, physically, chemically or biologically kill or remove the unwanted invasive species (Taylor et al. 2002, Tamburri et. al 2002). Alternatives include: 1) heat in-transit practices, 2) ultra violet treatment, 3) filtration, 4) ozonation, and 5) deoxygenation. These alternatives to ballast water exchange may overcome the spatial limitations and incomplete effectiveness of exchange in cases involving coastal traffic in the B2B. The volumes of ballast and rate of treatment are being examined through the STEP program of the USCG (2004) and other efforts in order to help gauge a measure of the cost-effectiveness (cost per unit volume of ballast water treated) of each treatment alternative.

12.1.4 Early Response Abatement Costs: *Caulerpa taxifolia* in California

California's effective reaction to the discovery of the marine alga *Caulerpa taxifolia* is an excellent example of effective rapid response. Within a few weeks of the June 2000 discovery of the *C. taxifolia* infestation in Agua Hedionda Lagoon near San Diego, a coalition of federal, state, and local agencies and the private sector formed the Southern California *Caulerpa* Action Team (SCCAT). Containment and chemical treatments with tarp and chlorine injections started within 17 days of discovery. Chlorine applied below tarps worked there and also at a second invasion site in Huntington Harbour. In September 2001, a ban on the sale and possession of *Caulerpa* and eight other species was passed by state legislation. According to L. Anderson (USDA, personal communication), the steps that made the rapid response effective were: 1) quick confirmation of species identity; 2) immediate communication to agencies; 3) immediate access to data on impacts and the past history of *C. taxifolia* impacts elsewhere; 4) access to expertise on the biology of *Caulerpa* and eradication of aquatic plants; 5) early consensus to attempt to eradicate (not to manage) the invasion; 6) knowledge of regulatory issues and solutions; 7) the availability of a field crew; 8) access to funds and other resources sufficient to act quickly; and 9) evaluation of efficacy. The cost of the initial eradication, management, and surveillance programs totaled US$4.1 million from July 2000 through July 2002 (Padilla and Williams, 2004). The current strategy is to continue to monitor sites for five years in order to deem the eradication successful. Since *Caulerpa taxifolia* spreads by vegetative growth and fragmentation, chemicals and tarping were chosen instead of mechanical control efforts to prevent dispersal during treatments. This mode of dispersal also enhances the likelihood of inadvertent spreading of this alga by small fragments associated with boats and anchors (Secord 2003).

12.1.5 *Undaria pinnatifida* Eradication in California

Estimates from current efforts to eradicate *Undaria pinnatifida* conducted over more than 1 year in Monterey Bay can be obtained from marine biologist, S. Lonhart who is managing manual cutting and scraping programs and using SCUBA on boat hulls and 400 boat slips (Lonhart, personal communication). The manual removal of *U. pinnatifida* fronds involves labor and cutting equipment. In Monterey Bay, average percent cover of *U. pinnatifida* before removal was 47.2 % and the average man-hours for removal were 3.75 hours per 0.25 m^2 quadrat. The mean biomass removed was 5,385.6 grams m^{-2}. Regrowth data showed that *U. pinnatifida* thalli returned in 64.9 % of the plots after four months. In order to derive the costs of this eradication effort, a wage rate per hour can be multiplied by the labor quantity in hours. Eradication efforts also are underway on Todos Santos Island in Baja California, Mexico, where *U. pinnatifida* has been found growing near an abalone farm (Zertuche-González, personal communication).

The potential for abatement cost-offsets need to be examined because *Undaria* has a value as a food for human consumption as well as for growing abalone in aquaculture (Lonhart, personal communication). Abatement costs, therefore, could turn into financial earnings by selling removed *U. pinnatifida* thalli, not only in Monterey Bay but also in Baja California, Mexico, and elsewhere when invasive populations of *U. pinnatifida* are discovered.

12.1.6 Restoration Costs

The cost of restoring tidal marshland is US$7,500 per acre (US$18,533 per hectare) in terms of construction costs only (Zentner et al. 2003). Clearly, any land acquisition costs and costs of labor derived voluntarily from nonprofit organizations involved in restoration would need to be added in order to provide full cost estimates.

13.0 Costs and Benefits of IAS Abatement: Benefits

13.1. Valuation Methods

Table 3 is an organizational chart to introduce established methods that have been used to derive values of benefits from abatement programs that could be applied to seaweed and other marine IAS. This section is a summary of a lengthy presentation on this topic by Fernandez (2002). Table 3 highlights six major ecosystem service valuation techniques (in the columns) when there are no adequate market valuations:

- Defensive Measures or Avoided Costs (AC): this method quantifies avoided costs that would have been incurred in the absence of the natural habitat impacted by the IAS; for example, IAS control avoids habitat damage that provides absorption and filtration of nutrients (Fernandez 2002).

- Factor Income (FI): this method quantifies the enhancement of incomes through use of the services as an input to produce a good sold in the market; for example, an acre of San Francisco Bay wetlands is a factor input used to create or enhance jobs to produce and sell crabs for local income.

- Travel Cost (TC): this method quantifies the value of complements to the environment that are affected by IAS such as recreation in the environment as at least equal to the cost incurred in traveling to the recreational and tourist site in terms of monetary expenditures and time; an example is hunting or recreation areas attract distant visitors whose value placed on that area must be at least what they were willing to pay to travel to it (Boardman et al. 1996).

- Hedonic Pricing (HP): this method infers the value of the environment by analyzing the value of a commercial and marketed good, such as real estate, whose value is influenced by the nonmarket environmental good; an example is that housing prices at coastal locations exceed prices of inland homes in the same area.

- Contingent Valuation (CV): values are generated through surveying a sample population; an example is asking people what they would be willing to pay for increased fish catch or conserving an endangered species.

- Replacement Cost (RC): estimates what it would cost to replace ecosystem services with man-made systems; an example is natural waste treatment can be replaced with costly treatment systems.

Table 3. Methods for the Economic Valuation of Benefits from Abating IAS of Seaweeds and Other Marine Organisms (Adapted from de Groot 1992).

	Valuation Technique					
Ecosystem Service	Replacement Cost	Avoided Cost	Factor Income	Travel Cost	Hedonic Pricing	Contingent Valuation
Recreation and Cultural				X		X
Nutrient	X		X			

Cycling						
Ecosystem Protection	X	X	X	X		X
Habitat Value	X		X	X	X	X
Food and Raw Materials	X	X	X			
Existence Value	X					X
Genetic Resources	X	X	X	X	X	X

Each ecosystem service listed in the rows of Table 3 can be valued economically using those valuation techniques marked with an X. Some services may require that several techniques be used jointly. For example, Whitehead et al. (2003) have grouped together several categories of costs given the multiple environmental impacts of blooms of the dinoflagellate *Pfiesteria* on the east coast. Whitehead et al. (2003) provide values for loss in recreation, lost tourism revenues, seafood values, and possible medical costs for treatment using travel costs, avoidance cost, and contingent valuation.

The following paragraphs provide a description of each ecosystem service listed in Table 3 and the suggested valuation methods as described above.

- Recreation and Cultural Value: The value of recreation for an ecosystem will include not only the value that recreationists place on the site (TC) for activities such as viewing and hunting of wildlife, hiking, swimming, and photography, but also the increased incomes associated with use of the ecosystem as a factor input to produce fish which are sold in the market (FI). It is important that use of alternative methods does not lead to double counting. For example, one could estimate the value of an upstream wetland by either calculating the cost savings inherent in not needing to build levees (AC) or by comparing the prices of otherwise similar lands that either are or are not protected from flooding by the wetland (HP). Since techniques measure the same service, flood protection, only the most accurate estimate should be employed to avoid double counting value. Culture is used to represent a broad array of services supportive of the cultural character of human communities. Aesthetic value through recreation can be considered a cultural value. There is need to measure the value people place on saving the environment for future generations (bequest value) and the environment for its own sake (existence value). By surveying people through CV, there is a means of eliciting value for both. There are underwater and coastal historical and archeological use values too that may be threatened by NIS. These values can be estimated by HP, by measuring the incremental price someone is willing to pay to live near an historical site, or by TC, by determining the price someone pays to travel to visit the site. Research and educational use is also relevant to cultural value. The TC and CV methods are useful to derive such value.

- Nutrient Cycling: The flow of nutrients such as nitrogen and phosphorus, are critical to maintaining ecosystem productivity and biodiversity. Alterations in the nutrient cycling services of ecosystems then alter the viability and productivity of their biotic constituents. If nutrient cycles are disrupted, lost nutrients must be replaced through applications of manufactured nutrients that could be accounted for through the RC valuation method. Similar logic can be applied to the removal of excess nutrients by treatment processes. Nutrient cycle disruptions may affect incomes by reducing commercial yields of fisheries that can be valued through the FI method.

- Ecosystem Protection: The ability of an ecosystem to moderate potentially disturbing natural events such as floods with a healthy wetlands could be valued with AC and RC if there is an attempt to find an alternative to replace natural protection. The vegetative cover may moderate hurricane and flood effects and increase the level or stability of fisheries income to commercial and recreational fishers that the FI and TC valuation methods can quantify. For example, Farber (1987) uses AC to value wetlands for protecting coasts against hurricanes.

- Habitat Value: Indigenous flora and fauna are supported by the marine and coastal ecosystems where they thrive and these could be impacted by IAS and need to be valued. FI can be used to value commercially valuable flora and fauna thriving in the ecosystem and TC and CV can be used to value recreationally valued indigenous species. Habitat and refugia may be restored at a cost (RC) and people can pay higher property prices to be near an ecosystem with abundant indigenous flora and fauna that can be valued with HP.

- Food and Raw Materials: The value of marine food and raw materials for human consumption and use can be quantified directly through the commercial value (price) from a formal market transaction (where these goods are bought and sold). Also, the value can be derived from the income generated from commercial production of food and raw materials through the FI method. Availability of these goods means avoiding nutrition-related health costs and other maladies that can be valued through the AC method.

- Existence Value: Marine ecosystems can be valued for the survival of the ecosystem itself. The existence values would apply to a variety of genetic, species, and ecosystem biodiversity impacts that are listed in Table 3 of a recent Commission for Environmental Cooperation report (CEC 2003). Existence value could include the value of steps taken to increase the survival probabilities of threatened and endangered wildlife. CV is the method used to quantify this value by surveying how much people value preserving an ecosystem that they will never use.

- Genetic Resources: The stock of genetic information present in an ecosystem can be used for a variety of purposes, such as medicine, pest control, development of ornamental and other cultivable material. Nature-based medicines can help avoid health costs that can be valued with AC. They may be cheaper than man-made alternatives that would be valued with RC. The extraction and development of the genetic resources creates incomes, which can be quantified with the FI method. The variety of genetic resources in the marine and coastal environment (biodiversity) can attract recreationists to view them, and these can be valued through the TC method. Also, others may live adjacent to such sites and the access can be valued through the HP method. The stock of genetic resources has within it potential, yet currently unrevealed, values that could be called discovery values as well as option values for future revenues that could be derived from future developments from the genetic resources. These future values may be generated through the CV method or projections of a futures market price accounting for fluctuation.

13.2 Examples of Quantifying Benefits

The following are some estimates of benefit quantification that apply to seaweed IAS in the B2B area.

13.2.1 Native Species Values

Caulerpa t*axifolia* and *Undaria pinnatifida* compete for light and space with native species and thereby can exclude and displace them. These native species have commercial, recreational, and existence value. For commercially marketed ocean flora and fauna, commercial values would be derived from a direct market price, while recreational fishing values would be derived from travel cost or contingent valuation. For example, commercial market value of several native benthic species potentially harmed by seaweed IAS is provided in Table 4 for Baja California, Mexico.

Table 4. 2002 production records, in terms of quantity (in tons) and value (in pesos and in U.S. dollars), are provided for abalone, native seaweeds (primarily *Gelidium*, which is used for agar), clams, snails, sea urchins, oysters, *Macrocystis* (kelp), and others that may include lobsters, sea cucumbers, and sea stars. Source: Estado de Baja (2003).

Organisms	Quantity (tons)	Value (pesos /ton)	Value ($US/ton)
Abalone	158	400,000	4,400.00
Macrocystis	17,416	220	2.42
Other Algae	415	5,000	55.00

Clams	310	462,245	5,084.70
Snails	90	10,122	111.34
Sea Urchin	1,692	26,126	287.39
Oyster	321	14,981	164.79
Others	5,416	17,138	188.52

The value of aquaculture in British Columbia for shellfish is different from wild shellfish in the following way. The wholesale value in 2001 for 8.9 million metric tons of farmed shellfish is Can$26 million and for 20.1 million metric tons of wild shellfish is Can$186 million (Department of Fisheries and Oceans Canada 2002b). The value for British Columbia is an aggregate one for all shellfish because of lack of availability of information on specific species affected by potential seaweed NIS. Likewise, species potentially affected would need to be identified in order to access such values in the U.S. portion of the B2B from the Pacific States Marine Fisheries Commission database on commercial and recreational fisheries values for the rest of North America’s Pacific coast (California, Oregon, Washington, Alaska, and British Columbia, Canada).

As discussed in Section 7.1.3, the values for IAS seaweeds for direct consumption (e.g., *Undaria pinnatifida* for wakame) and for chemicals (e.g., alginates, agars, and carageenans) would be accounted for as plausible revenue generation from ongoing harvesting of these seaweeds. Estimates such as those from Dawes (1998) of US$100 million for alginate harvest in the U.S., would have to be disaggregated to calculate this value for the B2B.

13.2.2. Restoration Benefits

If the restoration of tidal wetlands and associated abatement efforts stimulate economic activity, then these efforts could be thought of as a benefit. For example, in Humboldt County California, 300 jobs and US$14.5 million in 2002 were directly tied to restoration of coastal marshes. This was about twice the value of commercial fishing in the area during that same year (Little 2004). Between 1995 and 2002, restoration activities generated more than US$65 million in Humboldt County (Little 2004).

13.2.3 Recreational Benefits

The following examples from specific locations within the B2B pertain to valuing recreational activities of fishing, boating, and coast and beach access. None of the references cited make a direct connection of the recreational activities and impacts of IAS of seaweeds or other marine organisms, but there are some obvious connections in terms of the role played by boat hulls in seaweed IAS introductions within the B2B, and the spatial access to engage in recreational activities could be impacted from programs attempting to address NIS. *Caulerpa taxifolia* invasions potentially reduce enjoyment gained from recreational diving, ecosystem aesthetics, and biodiversity, and hinder boating and fishing by fouling nets, lines, hooks, and buoys (Meinesz 1999).

Two valuation studies (Hanemann and Strand 1993, Criddle et al. 2003) of recreational benefits for the Alaska area address issues relevant to the B2B domain. Criddle et al. (2003) found that a 10 % reduction in halibut catch would lead to a decrease in participation in sportfishing and lost recreation in Cook Inlet. The monetary value of decreased participation for resident and non-resident fishermen was found to be US$3.7 million. The regional impacts (in terms of tourism revenues) were valued at US$2 million. This amount included the value of recreational sportfishing for halibut, based on the letting of 172,000 permits per year.

Canada's recreational fishing value is presented in numbers of participants and the value of the fish caught. For example, greater than 600,000 anglers per year participate with 5,990 person years of time spent recreating. This number is far larger than the 2,300 person years of time spent in commercial fishing for the same year (Department of Fisheries and Oceans Canada 2002b). The average revenue per salmon caught by sport fisherman is Can$500 versus Can$7 per salmon caught by commercial fisherman (Department of Fisheries and Oceans Canada 2002b).

A study by King and Symes (2004) estimates the recreational value lost if all California beaches were not protected from environmental problems. This study shows for 2,370 household groups that at nine beach locations, US$12-$18 million per year could be lost (King and Symes, 2004). Four to six percent of this amount is classified as direct federal tax loss. In the extreme case of all California beaches being lost and not accessible for recreation, California would lose US$5.5 billion in gross state product (GSP) while the U.S. would lose US$2.4 billion GNP. The tax revenue lost at the state level would be US$509 million and tax revenue lost at the federal level would be US$299 million (King and Symes 2004).

Mexico's values for recreational fishing, estimated without a formal travel cost study having been conducted, could be identified in terms of license sales, which total US$300,00 per year for Baja California and US$4 million per year in San Diego for access to Southern Baja California (Thomas 2004). There are approximately 7,500 domestic registered vessels for recreational fishing in Baja California (INP 2002). Besides fishing vessels, recreational boating revenues in Baja California also should be considered. From an EDAW Inc. (2003) report, in 2002, there were 2,600 boat slips in Baja California, Mexico. There were 1,000 slips in Arizona, 62,000 slips in California, 8,000 in Oregon and 16,000 in Washington. The number of boats registered for all four U.S. states was 77,000 in 2001, with a projected increase to 97,000 boats by 2015. During 1993-2001, boat traffic increased in Baja California by 7 % per year for a total of 1,450 in 2001. EDAW Inc (2003) projects that by 2015 this boat traffic will increase to 5,500. Overall composition of the boat traffic was 80 % from California, with 60% from San Diego, so any attempts to conduct travel cost valuation would involve calculating costs people bear to engage in water recreation in Baja California from neighboring San Diego and other parts of California. The slip fees in Baja California range from US$8 to US$21 per boat per year, and the revenue generated from boating is then 1,450 boats multiplied by US$8 to US$21 or US$11,600 to US$30,450 per year.

13.2.4 Coastal Property

A study that related coastal property to seaweed impacts is by Cesar et al. (2002). Cesar et al. (2002) estimates show that algal blooms on the Kihei coast of Maui, distributed over a 16.1 km length of study area, resulted in US$21 million in potential revenue loss annually. This total can be disaggregated in terms of US$9.4 million from reduced property values, US$10.8 million from reduced occupancy rates at hotels, and US$1.8 million from tax loss. Note, these figures are listed in the study under the category of coastal property for abatement benefits because the revenues would not be lost if abatement succeeds in stopping the impacts of the algal blooms.

13.2.5 Port Commerce

The loss of activity at the ports due to any constraints induced by management of seaweed IAS would be very costly. For example, the 2002 labor dispute that led to the shutdown of ports along the west coast cost the U.S. economy US$10 billion per day (Montaigne 2004). Due to this very high value, most shippers and manufacturers voice willingness to comply with tougher security measures according to Christopher Koch, CEO of the World Shipping Council (cited in Montaigne, 2004). The value of ports in the B2B can be derived through input-output analysis of annual economic activity with income and jobs (Rust 2004). Of course, this will require compiling data from all ports in the B2B. From available data in California, the most recent survey of all ports shows that US$57 billion (and 1.16 million jobs) were added to U.S. Gross Domestic Product (GDP) for 2000 (Rust 2004). Six percent of the US$57 billion was attributed to the recreational boating use of ports (Rust 2004).

13.2.6 Benefits Transfer

Examples of benefits transfer would be to reference values from another economic valuation study to apply to seaweed NIS. For example, the monetary values of damages from the Exxon Valdez oil spill could be referenced. The aggregated amount of US$900 million as a civil settlement (for public resources managed by government) in court during 1991 with a US$100 million re-opener clause for damages that could not reasonably have been known or anticipated may be asserted through 2006 (Rosen 2004). The definition of the oil fate and transport was 41.6 million liters of crude with 610 metric tons remaining in 1995, four years after the start of cleanup (Grigalunas et al. 1998). Sea otters digging into oil are still unleashing toxins and experience swollen and pale livers (Rosen 2004). Another class action settlement resulted in fishermen, Alaska natives, property and business owners, and municipalities being awarded US$4.5 billion plus interest (Rosen 2004).

14.0 Conclusions and Recommendations

Clearly, action is required to address threats posed by IAS of seaweeds and other marine organisms in the B2B. More scientific research is needed to improve understanding of the biology and ecology of invasive seaweeds and other marine IAS and the characteristics of coastal ecosystems that makes them susceptible to invasion. More effective management structures, greater levels of trinational cooperation, improved and more effective programs for pathway interdiction, and more effective monitoring and detection programs also are needed to improve management of marine IAS. The following recommendations are offered as a starting point for addressing IAS of seaweeds and other marine organisms in the B2B.

14.1 Science Recommendations

1. Increased attention must be given to developing programs to increase trinational scientific research on IAS of seaweeds in the B2B if we are to improve understanding of their biology, ecology, and the characteristics of the systems that they have invaded. In particular, studies are needed to:

    a. survey for and document the spread of seaweed alien species, (with emphasis on those that have become invasive), investigate their impacts on native ecological communities, and test hypotheses about the ecological correlates of invaded versus native communities;

    b. determine the environmental conditions required for survival, growth, and reproduction of seaweed invaders;

    c. determine the likely pathways and genetic origins of seaweed IAS populations and subpopulations; and

    d. explore, test, and evaluate methods for preventing, controlling, and eradicating invasive seaweed populations.

2. Trinational efforts should be initiated to ensure the perpetuation of long-term, and scientifically robust coastal monitoring programs that can lead to the early detection of invading seaweeds and other marine IAS, follow the progress of identified invasions, and evaluate the effectiveness of eradication and control efforts.

3. Implement programs for assessing and evaluating risks associated with identified pathways for introducing IAS. These studies are needed to identify the importance of the various pathways for introducing seaweed IAS, the species most likely to be introduced, and for making recommendations on how to minimize risks of new IAS introductions.

4. Encourage the scientific study of seaweed floras using both modern molecular approaches as well as traditional herbarium-based methods. Information from these studies will enable early detection and accurate identification of the species and strains of seaweed IAS.

5. Develop a trinational scientific panel of phycological experts to advise managers and assist in the development of response plans for dealing with newly detected seaweed invaders. This panel can be convened to provide scientific advice on the biology of newly detected seaweed aliens, their potential impacts, and on the eradication or control efforts that managers might undertake in response to an introduction or invasion.

14.2 Policy Recommendations

2. 1. Since the current investment in research, monitoring and enforcement of IAS falls far short of their, there is a potential benefit of investigating how each of the policy options proposed in this study can generate funds for these necessary activities.

2. Shipping registration requirements through the International Ship and Port Facility Security (ISPS) Code can highlight and strengthen attention on IAS through improved information on shipping maintenance and documentation of cargo manifests to facilitate the monitoring of IAS shipping pathways (i.e., ballast water and hull fouling).

3. Coordinate requirements for shippers entering ports in the North-South as well as East-West transit pathways to facilitate implementation of prevention technologies for reducing IAS introductions in ballast water and from hull fouling. Align regional goals with IMO conventions while still allowing for member states to enter into regional agreements that meet or exceed upcoming IMO standards. The transaction costs to deal with separate, local requirements make it difficult for both shippers and ports to achieve effective IAS control throughout the B2B. A successful model to follow for cooperation through emergency planning, information sharing, technology adoption, and liability requirements might be that in place for addressing threats posed by oil spills.

4. The various policy alternatives discussed in this report need more economic analysis to evaluate the efficacy of specific IAS interdiction programs in the B2B. For example, to set the right level of an environmental bond, deposit-refund, or liability, effort to derive measures of potential damages from IAS are required. Such liability rules and environmental bonds have been implemented for offshore oil platforms and for terrestrial areas of environmental risk.

5. More economic analyses need to be performed to better quantify and aggregate costs and benefits across the B2B to augment some of the examples

provided in this study. The variety of valuation techniques and categories to be valued in the B2B indicate that many studies will be needed to derive viable estimates for developing cost effective trinational programs that address the threats posed by marine IAS, including invasive seaweeds.

6. In order to prevent introductions of seaweed IAS from aquariums, rigorous efforts are needed to implement technical assistance and public education amongst aquarium traders, consumers, and the regulating inspectors. Educational efforts can be tied to the policy alternatives discussed in this report.

7. Explore the feasibility of extending the aquaculture control regulations now being used in Canada to the U.S. and Mexico as a means of preventing harmful transfers of IAS with aquaculture activity in the B2B. These regulations (Code on the Introduction and Transfers of Aquatic Organisms in Canada) were jointly developed by the Canadian government and the aquaculture industry.

8. Promote technology transfers through educational outreach programs to address IAS. An example of such a program is the California Sea Grant program on nontoxic hull coatings. In addition, such programs should be developed to address additional pathways of seaweed IAS such as the aquaculture and aquarium industries.

9. Addressing IAS like an epidemiological threat requires action beyond the preventative measures emphasized above. Besides preventative action, early response institutional structures and ongoing monitoring programs should be enacted throughout the B2B.

15.0 Literature Cited

Abbott, I. A., and G. J. Hollenberg. 1976. Marine algae of California. Stanford University Press, Stanford, California, USA.

Aguilar-Rosas, R., L. E. Aguilar-Rosas, and G. Avila-Serrano. 2003. First report of *Undaria pinnatifida* (Harvey) Suringar (Laminariales, Phaeophyta) in the Pacific coast of Mexico. (Unpublished abstract). Western Society of Naturalists, 84th Annual Meeting, November 7-10, 2003, Long Beach, California, USA.

Alaska Department of Fish and Game, Division of Commercial Fisheries. 2002. Overview, available at www. Cf.adfg.state.ak.us/geninfo/budget/02overvw.pdf

Alaska Department of Fish and Game. 2002. Alaskan Aquatic Nuisance Species Management Plan, Juneau, Alaska, USA.

Alvarez, P. 2001. Mexico's perspective on aquatic invasive species. Workshop proceedings of preventing the introduction and spread of aquatic invasive species in North America. Commission for Environmental Cooperation, Montreal, Canada.

Ambrose, R. T., and B. V. Nelson. 1982. Inhibition of giant kelp recruitment by an introduced brown alga. Bot. Mar. **25**: 265-267.

Anderson, P. J., and J. F. Piatt. 1999. Community reorganizationin the Gulf of Alaska following ocean climate regime shift. Mar. Ecol. Progr. Ser. **189**:117-123.

Aquatic Invasive Species Task Group. 2004. Proposal for a national action plan to address the threat of aquatic invasive species, April 14,2004 Draft. Canadian Council of Fisheries and Aquaculture, Ottawa, Canada.

Arasaki, S., and T. Arasaki. 1983. Vegetables from the sea. Japan Publ. Inc., Tokyo, Japan.

Ardré, F. 1970. Contribution a l'étude des algues marines du Portugal. Port. Acta Biol. Ser. B. **10**(1-4):1-423.

Bakun, A. 1999. A dynamic scenario for simultaneous regime-scale marine population shifts in widely separated large marine ecosystems of the Pacific, Pages 2-26 *in* K. Sherman and Q. Tang, editors. Large marine ecosystems of the Pacific Rim. Assessment, sustainability, and management. Blackwell Science, Malden, Massachusetts, USA.

Barry, J. P., C. H. Baxter, R. D. Sagarin, and S. E. Gilman. 1995. Climate-related long-term faunal changes in a Californian rocky intertidal community. Science **267**:672-675.

Bax, N. 1999. Eradicating a dreissenid from Australia. Dreissena **10**:1-5.

Bax, N., J. T. Carlton, A. Mathews-Amos, R. L. Haedrich, F. G. Howarth, J. E. Purcell, A. Rieser, and A. Gray. 2001. The control of biological invasions in the world's oceans. Conserv. Biol. **15**:1234-1246.

Bax, N., A. Williamson, M. Aquero, E. Gonzalez, W. Geeves. 2003. Marine invasive alien species: a threat to global biodiversity. Mar. Policy **27**:313-323.

Belsher, T., and A. Meinesz. 1995. Deep water dispersal of the tropical alga *Caulerpa taxifolia* introduced into the Mediterranean. Aquat. Bot. **51**:163-169.

Ben-Avraham, Z. 1971. Accumulation of stones on beaches by *Codium fragile*. Limnol. Oceanogr. **16**:553-554.

Black, E. 2001. Engaging the aquaculture industry. Workshop proceedings of preventing the introduction and spread of aquatic invasive species in North America. Commission for Environmental Cooperation, Montreal, Canada.

Boalch, G. T. 1981. Do we really need to grow *Macrocystis* in Europe? Proc. Int. Seaweed Symp. **10**:657-667.

Boardman, A., D. Greenberg, A. Vining, D. Weimer, 1996. Cost-benefit analysis: concepts and practice. Prentice Hall, Upper Saddle River, New Jersey, USA.

Børgesen, F. 1927. Marine algae from the Canary Islands especially from Teneriffe and Gran Canaria. III. Rhodophyceae. Part . 1. Bangiales and Nemalionales. K. Dan. Vidensk. Selsk. Biol. Medd. **6**:1-97.

Botelho, R., 2003. Maritime Security: Implications and Solutions, Sea Technol. **45**:15-18.

Boudouresque, C. F. 1997. Dynamique des populations de *Caulerpa taxifolia* en Mediterranee, y compris les mecanismes de la competition interspecifique. Pages 145-162 *in* Academie des Sciences. Dynamique d'especes marine invasives: application a l'expansion de *Caulerpa taxifolia* en Mediterranee. TecDoc, Paris, France.

Boudouresque, C. F., A. Meinesz, M. A. Ribera, and E. Ballesteros. 1995. Spread of the green alga *Caulerpa taxifolia* (Caulerpales, Chlorophyta) in the Mediterranean: possible consequences of a major ecological event. Scientia Marina **59**(Suppl. 1):21-29.

Boudouresque, C. F., A. Meinesz, M. Verlaque, and M. Knoepffler-Peguy. 1992. The expansion of the tropical alga *Caulerpa taxifolia* (Chlorophyta) in the Mediterranean. Cryptogamie: Algol. **13**:144-145.

Briggs, J. C. 1974. Marine zoogeography. McGraw-Hill, New York, USA.

Britton-Simmons, K. H. (in press). Direct and indirect effects of the introduced alga, *Sargassum muticum*, in benthic, subtidal communities of Washington State, USA. Mar. Ecol. Progr. Ser. **277**:61-78.

Campbell, S. J. 1999. Occurrence of *Codium fragile* subsp. *tomentosoides* (Chlorophyta: Bryopsidales) in marine embayments of southeastern Australia. J. Phycol. **35**:938-940.

Campbell, S. J., J. S. Bite, and T. R. Burridge. 1999. Seasonal patterns in the photosynthetic capacity, tissue pigment, and nutrient content of different developmental stages of *Undaria pinnatifida* (Phaeophyta: *Laminaria*les) in Port Phillip Bay, South-Eastern Australia. Bot. Mar. **42**:231-215.

Carlton, J. T. 1979. History, biogeography, and ecology of the introduced marine and estuarine invertebrates of the Pacific coast of North America. Ph.D. dissertation, University of California, Davis, California, USA.

Carlton, J. T. 1985. Transoceanic and interoceanic dispersal of coastal marine organisms: the biology of ballast water. Oceaogr. Mar. Biol., Annu. Rev. **23**:313-371.

Carlton, J. T. 1989. Man's role in changing the face of the oceans: biological invasions and implications for conservation of near-shore marine environments. Conser. Biol. **3**:265-273.

Carlton J. T. 1996a. Biological invasions and cryptogenic species. Ecology **77**:1653-1655.

Carlton, J. T. 1996b. Marine bioinvasions. The alteration of marine ecosystems by nonindigenous species. Oceanography **9**:36-43.

Carlton, J. T. 1996c. Pattern, process, and prediction in marine invasion ecology. Biol. Conser. **78**:97-106.

Carlton, J. T. 1999. The scale and ecological consequences of biological invasions in the World's oceans. Pages 195-212 *in* O. T. Sandlund, P. J. Schei, and Å. Viken, editors. Invasive species and biodiversity management. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Carlton, J. T. 2000. Global change and biological invasions in the oceans. Pages. 31-53 *in* H. A. Mooney and R. J. Hobbs, editors. Invasive species in a changing world. Island Press, Washington, D. C., USA.

Carlton, J. T., and J. B. Geller. 1993. Ecological roulette: the global transport of

nonindigenous marine organisms. Science **261**:78-82.
Carlton, J. T., D. M. Reid, and H, van Leeuwen. 1995. The role of shipping in the introduction of nonindigenous aquatic organisms to the coastal waters of the United States (other than the Great Lakes) and an analysis of control options. U.S. Coast Guard, Washington, D. C., USA.
Carlton, J. T., and J. A. Scanlon. 1985. Progression and dispersal of an introduced alga: *Codium fragile* ssp. *tomentosoides* (Chlorophyta) on the Atlantic coast of North America. Bot. Mar. **28**:155-165.
Carlton, J. T., J. K. Thompson, L. E. Schemel, and F. H. Nichols. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the asian clam *Potamocorbula amurensis*. I. Introduction and dispersal. Mar. Ecol. Progr. Ser. **66**:81-94.
Casares, C. P. 1989. Catalogo de la flora bentonica marina de la costa de Guipuzcoa. Bulletin du Centre d'Etudes et de Recherches Scientifiques de Biarritz **15**:83-118.
Casas, G. N., and M. L. Piriz. 1996. Surveys of *Undaria pinnatifida* (Laminariales, Phaeophyta) in Golgo Nuevo, Argentina. Hydrobiologia **326/327**:213-215.
Castric-Fey, A., C. Beaupoil, J. Bouchain, E. Pradier, and M. T. L'Hardy-Halos. 1999. The introduced alga *Undaria pinnatifida* (Laminariales, Alariaceae) in the rocky shore ecosystem of the St. Malo area: growth rate and longevity of the sporophyte. Bot. Mar. **42**:83-96.
Cesar, H., P. Vanbeukerling, and S. Prince. 2002. An economic valuation of Hawaii's coral reefs. Hawaii Coral Reef Initiative Research Program, Final Report, Honolulu, Hawai'i, USA (in press).
Chapman, J. W. 1988. Invasions of the northeast Pacific by Asian and Atlantic gammaridean amphipod crustaceans, including a new species of *Corophium*. J. Crust. Biol **8**:364-382.
Cohen, A. N., and J. T. Carlton. 1995. Nonindigenous aquatic species in a United States estuary: a case study of the biological invasions of the San Francisco Bay and Delta. Report for the United States Fish and Wildlife Service, Washington, D. C. and the National Sea Grant College Program, Connecticut Sea Grant NTIS Report Number PB96-166525, Connecticut, USA.
Cohen, A. N., and J. T. Carlton. 1998. Accelerating invasion rate in a highly invaded estuary. Science **279**:555-568.
Commission for Environmental Cooperation (CEC). 2003. Closing the pathways of aquatic invasive species across North America: Overview and resource guide. Montreal, Canada.
Courtenay, W. R. jr., and J. R. Stauffer jr. 1990. The introduced fish problem and the aquarium fish industry. J. World Aquacult. Soc. **21**:145-159.
Coyne, M. 2004. Enviros want TMDLs to include exotics as pollution source. Greenwire (Internet News), April 9, 2004.
Criddle, K., M. Herrmann, S. Lee, and C. Hamel. 2003. Participation for recreation decisions, angler welfare, and the regional economic impact of sportfishing. Mar. Resource Econ. **18**:291-312.
Critchley, A. T., and R. Dijkema. 1984. On the presence of the introduced alga *Sargassum muticum* attached to commercially imported *Ostrea edulis* in the

S.W. Netherlands. Bot. Mar. **27**:211-216.

Critchley, A. T., W. F. Farnham, and S. L. Morrell. 1983. A chronology of a new European site of attachment for the invasive brown alga, *Sargasssum muticum*, 1973-1981. J. Mar. Biol. Ass., U.K. **63**:799-811.

Critchley, A. T., W. F. Farnham, T. Yoshida, and T. A. Norton. 1990. A bibliography of the invasive alga *Sargassum muticum* (Yendo) Fensholt (Fucales; Sargassaceae). Bot. Mar. **33**:551-562.

Culver, C. S., and A. M. Kuris. 1999. The sabellid pest of abalone: the first eradication of an established introduced marine bioinvader? (Abstr.). First International Conference on Marine Bioinvasiions. Cambridge, Massachusetts. USA.

Curiel D., G. Bellemo, M. Marzocchi, M. Scattolin, and G. Parisi. 1998. Distribution of introduced Japanese macroalgae *Undaria pinnatifida*, *Sargassum muticum* (Phaeophyta) and *Antithamnion pectinatum* (Rhodophyta) in the Lagoon of Venice. Hydrobiologia **385**:17-22.

Dawes, C. J. 1998. Marine botany. Second edition. John Wiley and Sons, New York, New York, USA.

Dawson, E. Y. 1951. A further study of upwelling and associated vegetation along Pacific Baja California, Mexico. J. Mar. Res. **10**:39-58.

Dawson, E. Y. 1961. The marine red algae of Pacific Mexico, Part 4. Gigartinales. Pacific Naturalist **2**:191-343.

Dalton, R. 2000. Researchers criticize response to killer algae. Nature (London) **406**:447.

de Groot R. 1992. Functions of nature: evaluation of nature in environmental planning, management and decision making, Wolters-Noordhoff, Groningen, The Netherlands.

Delgado, O., C. Rodriguez-Prieto, E. Gacia, and E. Ballesteros. 1996. Lack of severe nutrient limitation in *Caulerpa taxifolia* (Vahl) C. Agardh, an introduced seaweed spreading over the oligotrophic Northwestern Mediterranean. Bot. Mar. **39**:61-67.

Department of Fisheries and Oceans Canada. 2002a. National code on introduction and transfers of aquatic organisms, Ottawa, Canada. www.dfo-mpo.gcd.ca/science/aquaculture/code/prelim_e.htm.

Department of Fisheries and Oceans Canada. 2002b. Summary of Canadian Commercial Catches, Fisheries Statistics, Fisheries and Oceans Canada, Ottawa, Canada.

DeWreede R.E. 1983. *Sargassum muticum* (Fucales, Phaeophyta): regrowth and interaction with *Rhodomela larix* (Ceramiales, Rhodophyta). Phycologia **22**:153-160.

Dromgoole, F. I. 1975. Occurrence of *Codium fragile* subspecies *tomentosoides* in New Zealand waters. N. Z. J. Mar. Freshwater Res. **9**:257-264.

Druehl, L. D. 1981. Geographical distribution. Pages 306-325. *in* C. S. Lobban and M. J. Wynne, editors. The biology of seaweeds. University of California Press, Berkeley and Los Angeles, USA.

Dukes, J. S., and H. A. Mooney. 1999. Does global change increase the success of biological invaders? Trends Ecol. Evol. **14**:135-139.

Dumay, O., G. Pergent, C. Pergent-Martini, and P. Amade. 2002. Variations in caulerpenyne contents in *Caulerpa taxifolia* and *Caulerpa racemosa*. J. Chem. Ecol. **28**:343-352.

EDAW, Inc. 2003. North west Mexico marine market analysis. Report for the Packard Foundation, Menlo Park, California, USA.

Environment Canada. 2003. Toward a national plan on invasive alien species: A discussion document, Ottawa. Canada.

Espinoza, J. 1990. The southern limit of *Sargassum muticum* (Yendo) Fensholt (Phaeophyta, Fucales) in the Mexican Pacific. Bot. Mar. **33**:193-196.

Estado de Baja. 2003. Serie historica de la produccion pesquera. Available at: http://www.sfa.gov.mx/estadistica/pesca/97-02.pdf.

Farber, S., The value of coastal wetlands for protection of property against hurricane wind damage, J. Environ. Econ. Manage. **14**:143-151.

Feldmann, J., and G. Hamel. 1937. Floridées de France. VII. Gélidiales. Rev. Algol. **9**:85-140.

Fernández, C. 1999. Ecology of *Sargassum muticum* (Phaeophyta) on the north coast of Spain: IV. Sequence of colonization on a shore. Bot. Mar. **42**:553-562.

Fernández, C., L. M. Gutierrez, and J. M. Rico. 1990. Ecology of *Sargassum muticum* on the north coast of Spain. Preliminary observations. Bot. Mar. **33**:423-428.

Fernandez, L. 2002. Economics of biodiversity. Pages 69-94 *in* R. Ambasht and N. Ambasht, editors. Modern trends in applied terrestrial ecology. Kluwer Academic Publishers, New York, USA.

Fernandez, L., and S. Hitz. 2001. Costs and benefits of options for California OCS oil and gas platforms, Section Three. Pages 27-57 *in* M. McGinnis, L. Fernandez, and C. Pomeroy, editors. The politics, economics, and ecology of decommissioning offshore oil and gas structures. MMS OCS Study 2001-006. Coastal Research Center, Marine Science Institute, University of California, Santa Barbara, California, USA.

Fernandez, L., and L. Karp. 1998. Restoring wetlands through wetlands mitigation Banks. Envir. Res. Economics **12**:323-344.

Fletcher, R. L., and C. Manfredi. 1995. The occurrence of *Undaria pinnatifida* (Phaeophyceae, *Laminaria*les) on the south coast of England. Bot. Mar. **38**:355-358.

Floc'h, J. Y., R. Pajot, and I. Wallentinus. 1991. The Japanese brown alga *Undaria pinnatifida* on the coast of France and its possible establishment in European waters. J. Cons. Int. Explor. Mer **47**:379-390.

Fofonoff, P. W., G. M. Ruiz, B. Steves, and J. T. Carlton. 2003. In ships or on ships? Mechanisms of transfer and invasion for nonnative species to the coasts of North America. Pages 152-182 *in* G. M. Ruiz and J. T. Carlton, editors. Invasive species. Vectors and management strategies. Island Press, Washington, D. C., USA.

Francour, P., M. Harmelin-Vivien, J. G. Harmelin, and J. Duclerc. 1995. Impact of *Caulerpa taxifolia* colonization on the littoral ichthyofauna of North Western Mediterranean Sea: preliminary results. Hydrobiologia **300/301**:345-353.

Frisch, S. M. 2003. Taxonomic Diversity, geographic distribution, and commercial availability of aquarium-traded species of *Caulerpa* (Chlorophyta,

Caulerpaceae) in southern California. M.S. Thesis, California State University, Fullerton, Fullerton, California, USA.
Frisch, S. M., and S. N. Murray. 2002. The availability of species of *Caulerpa* and "live rock" in retail aquarium outlets in southern California. Pages 1-16 *in* E. Williams and E. Grosholz, editors. International *Caulerpa taxifolia* conference proceedings, California Sea Grant College Program, University of California, La Jolla, California, USA.
Gabrielson, P. G., and R. F. Scagel. 1989. The marine red algae of British Columbia, northern Washington, and southeast Alaska: division Rhodophyta (red algae), class Rhodophyceae, order Gigartinales, families Caulacanthaceae and Plocamiaceae. Can. J. Bot. **67**:1221-1234.
Galil, B. S., and N. Hülsmann. 1997. Protist transport via ballast waters – Biological classification of ballast tanks by food web interactions. Eur. J. Protistology **33**:244-253.
Gillespie, R.D., A. Meinesz, and A. T. Critchley.1997. Growth responses of *Caulerpa taxifolia* (Ulvophyceae, Chlorophyta) from the South African aquarist trade. A potential invasive of South African coastal waters. S. Afr. J. Bot. **63**:480-483.
Gilpin, M. 1990. Ecological prediction. Science **248**:88-89.
Gollasch, S. 2002. The importance of ship hull fouling as a vector of species introduction into the North Sea. Biofouling **18**:105-121.
Gómez, J., and H. Vélez. 1982. Variaciones estacionales de la temperatura y salinidad en la region costera de la Corriente de California. Ciencias Marinas **8**:167-176.
Grey, D. 2001. *Caulerpa taxifolia*: invasive weed prompt response actions. Fisheries NSW, Sydney **4**:4-5.
Grigalunas, T., J. Opaluch, J. Diamantides, and M. Mazzotta. 1998. Liability for oil spill damages: Issues, methods, and examples. Coast. Manage. **26**: 61-77.
Guerriero, A., A. Meinesz, M. D'Ambrosio, and F. Pietra. 1992. Isolation of toxic and potentially toxic sesqui- and monoterpenes from the tropical green seaweed *Caulerpa taxifolia* which has invaded the region of Cape Martin and Monaco. Helvet. Chim. Acta **75**:689-695.
Hamel, G. 1926. Quelques algues rares ou nouvelles pour la flore méditerranéenne. Bull. Mus. Nation. Sci. Nat., Paris **32**:420
Hanemann, W., and I. Strand. 1993. Natural resource damage assessment: Economic implications for fisheries management. Amer. J. Agricult. Econ. **75**:1188-1193.
Hanisak, M. D. 1979a. Growth patterns of *Codium fragile* subsp. *tomentosoides* in response to temperature, irradiance, salinity, and nitrogen sources. Mar. Biol. **50**:319-332.
Hanisak, M. D. 1979b. Nitrogen limitation of *Codium fragile* subsp. *tomentosoides* as determined by tissue nitrogen analysis. Mar. Biol. **50**:333-337.
Hansen, G. I. 2000. Focal taxonomic collections: marine plants in Prince William Sound. Pages 9C1-28 *in* A. H. Hines and G. M. Ruiz, editors. Biological invasions of cold water ecosystems: ballast mediated introductions in Port Valdez/Prince William Sound, Alaska. Report to the Regional Citizen's Advisory Council of Prince William Sound, Valdez, Alaska, and others.

Hay, C. H. 1990. The dispersal of sporophytes of *Undaria pinnatifida* by coastal shipping in New Zealand, and implications for further dispersal of *Undaria* in France. Br. Phycol. J. **25**:301-313.

Hay, C. H., and P. A. Luckens. 1987. The Asian kelp *Undaria pinnatifida* (Phaeophyta: *Laminaria*les) found in a New Zealand Harbour. N. Z. J. Bot. **25**:329-332.

Hay, C. H., and E. Villouta. 1993. Seasonality of the adventive asian kelp *Undaria pinnatifida* in New Zealand. Bot. Mar. **36**:461-476.

Hayes, K. 2003. Biosecurity and the role of risk assessment. Pages 382-414 *in* G. M. Ruiz, G. M. and J. T. Carlton, editors. Invasive species. Vectors and management strategies. Island Press, Washington, D. C., USA.

Hayes, K., and C. Sliwa. 2003. Identifying potential marine pests-a deductive approach applied to Australia. Mar. Poll. Bull. **46**:91-98.

Hewitt C. L., R. B. Martin, C. Sliwa, F. R. McEnnulty, N. E. Murphy, T. Jones, and S. Cooper. 2002. Editors. National Introduced Marine Pest Information System. Web publication Available at: http://crimp.marine.csiro.au/nimpis, Date of access: 28-Aug-2004.

Hood, D. W. 1993. Ecosystem interrelationships. Pages 782-835 *in* M. D. Dailey, D. J. Reish, and J. W. Anderson. 1993. Ecology of the Southern California Bight. University of California Press, Berkeley, California, USA.

Hughey, J. R. 1995. Noteworthy collections: California. Madroño **42**: 409.

International Joint Commission. 2001. Alien invasive species and biological pollution of the Great Lakes System. Report, Ottawa, Canada.

International Maritime Organization (IMO). 2002. International ship and port facility security code (ISPS). Conference of Contracting Governments to the International Convention for the Safety of Life at Sea, London, UK.

International Maritime Organization (IMO). 2004. Regulation D-2 Performance Standard, Ballast Water News, Issue 16, page 4, January-March 2004, London, UK.

Invasive Species Specialist Group. 2000. IUCN guidelines for the prevention of biodiversity loss caused by alien invasive species. IUCN Report, Gland, Switzerland. Accessible at www.issg.org

Jaubert, J. M., J. R. M. Chisholm, D. Ducrot, H. T. Ripley, L. Roy, and G. Passeron-Seitre. 1999. No deleterious alterations in *Posidonia* beds in the bay of Menton (France) eight years after *Caulerpa taxifolia* colonization. J. Phycol. **35**:1113-1119.

Johnson, L., and J. Miller. 2002. What you need to know about nontoxic antifouling strategies for boats. California Sea Grant College Program Report No. T-049. University of California, San Diego, California, USA.

Johnson, L., and J. Miller. 2003. Making dollars and sense of nontoxic antifouling strategies for boats. California Sea Grant College Program Report No. T-052, University of California, San Diego, California, USA.

Jousson, O., J. Pawlowski, L. Zaninetti, F. W. Zechman, F. Dini, G. Di Guiseppe, R. Woodfield, A. Millar, and A. Meinesz. 2000. Invasive alga reaches California. Nature **408**:157-158.

Kaiser, J. 2000. California algae may be feared European species. Science **289**:222-

223.
Karlson, J., and L. O. Loo. 1999. On the distribution and the continuous expansion of the Japanese seaweed *Sargassum muticum* in Sweden. Bot. Mar. **42**:285-294.
Kay, S., and S. Hoyle. 2001. Mail order, the internet, and invasive aquatic weeds. J. Aquat. Plant Manage. **39**:88-91.
King, P., and R. Symes. 2004. Potential loss in GNP and GSP from a failure to maintain California's beaches. Shore and Beach **72**:3-8.
Knoepffler-Peguy, M., T. Belsher, C. F. Boudouresque, and M. Lauret. 1985. *Sargassum muticum* begins to invade the Mediterranean. Aquatic Bot. **23**:291-295.
Kolar, C. S., and D. M. Lodge. 2001. Progress in invasion biology: predicting invaders. Trends Ecol. Evol. **16**:199-204.
Kristansen, A., R. Nielsen, and P. M. Pedersen. 1993. An annotated list of marine algae collected on Lanzarote, Canary Islands, January 1986. Courier Forschungsinstitut Senckenberg **159**:93-102.
Kuris, A. M., and C. S. Culver. 1999. An introduced sabellid polychaete pest infesting cultured abalones and its potential spread to other California gastropods. Invertebrate Biol. **118**:391-403.
Lafferty, K. D., and A. M. Kuris. 1996. Biological control of marine pests. Ecology **77**:1989-2000.
Lamb, T. 1981. Measuring fishing vessel energy performance and ways to improve it. SNAME/NOAA Fishing Industry Energy Conservation Conference, Seattle, Washington, USA.
Langevin, A. 2003. Ballast water exchange. Shipping Federation of Canada, Vancouver, Canada.
Lawson, G. W., and D. M. John. 1982. The marine algae and coastal environment of tropical west Africa. Nova Hedwigia **70**:1-455.
Levings, C., J. Cordell, S. Ong, and G. Piercey. 2004. The origin and identification of invertebrate organisms being transported to Canada's Pacific coast by ballast water. Can. J. Fish. Aquat. Sci. **61**:1-11.
Levring, T. 1974. The marine algae of the archipelago of Madeira. Bol. Mus. Munc. Funchal **28**:5-111.
Little, J. 2004. Ecology restoration boosts region's economy, study finds. Sacramento Bee, March 17, 2004, Sacramento, California, USA.
Llacer, F. 2004. Open registers: past, present, and future. Mar. Policy **27:**513-523.
Locke, A., D. M. Reid, H. C. van Leeuwen, W. G. Sprules, and J. T. Carlton. 1991. Ballast water exchange as a means of controlling dispersal in freshwater organisms by ships. Can. J. Fish. Aquat. Sci. **50**:2086-2093.
Lonsdale, W. M. 1999. Global patterns of plant invasions and the concept of invasibility. Ecology **80**:1522-1536.
Longhurst, A. 1998. Ecological geography of the sea. Academic Press, San Diego, California, USA.
Love, M., M. Nishimoto, and D. Schroeder, 2001. The ecological role of natural reefs and oil and gas production platforms on rocky reef fishes in southern California 1998-1999 Survey Report. U.S. Dept. of the Interior, U.S. Geological Survey, Biological Resources Division. Minerals Management

Service, Pacific OCS Region. OCS Study MMS 2001-028, Camarillo, California, USA.

Lowe, S., M. Browne, and S. Boudjelas. 100 of the world's worst invasive alien species. IUCN/SSC Invasive Species Specialist Group, Auckland, New Zealand.

Lubchenco, J., G. W. Allison, S. A. Navarrete, B. A. Menge, J. C. Castilla, O. Defeo, C. Folke, O. Kussakin, T. Norton, and A. M. Wood. 1995. Biodiversity and ecosystem functioning: coastal ecosystems. Pages 370-381 *in* United Nations Environmental Programme, editors. Global biodiversity assessment. Cambridge University Press, Cambridge, U.K.

Lubchenco, J., S. A. Navarrete, B. N. Tissot, and J. C. Castillo. 1993. Possible ecological responses to global climate change: nearshore benthic biota of Northeastern Pacific coastal ecosystems. Pages 147-166 *in* H. A. Mooney, E. R. Feints, and B. I. Kronberg, editors. Earth system responses to global change. Contrasts between North and South America. Academic Press, Inc. San Diego, California, USA.

Lüning, K. 1990. Seaweeds. Their environment, biogeography, and ecophysiology. John Wiley and Sons, Inc. New York, New York, USA.

Lynn, R. J., and J. J. Simpson. 1987. The California Current System: the seasonal variability of its physical characteristics. J. Geophys. Res. **92**:12947-12966.

Mack, R. N. 2003. Global plant dispersal, naturalization, and invasion: pathways, modes, and circumstances. Pages 3-30 *in* G. M. Ruiz, and J. T. Carlton, editors. Invasive species. Vectors and management strategies. Island Press, Washington, D. C., USA.

McGowan, J. A., D. B. Chelton, and A. Conversi. 1999. Plankton patterns, climate, and change in the California Current. Pages 63-105 *in* K. Sherman and Q. Tang, eds. Large marine ecosystems of the Pacific Rim. Assessment, sustainability, and management. Blackwell Science, Malden, Massachusetts, USA.

McIvor, L., C. A. Maggs, J. Provan, and M. J. Stanhope. 2001. *rbc*L sequences reveal multiple cryptic introductions of the Japanese red alga *Polysiphonia harveyi*. Mol. Ecol. **10**:911-919.

Meinesz, A. 1999. Killer algae. University of Chicago Press, Chicago, Illinois, USA.

Meinesz, A., and B. Hesse. 1991. Introduction and invasion de l;algue tropicale *Caulerpa taxifolia* en Méditerranée nord-occidentale. Oceanol. Acta **14**:415-426.

Meinesz, A., L. Benichou, J. Blachier, T. Komatsu, R. Lemee, H. Molenaar, and X. Hari. 1995. Variations in the structure, morphology and biomass of *Caulerpa taxifolia* in the Mediterranean Sea. Bot. Mar. **38**:499-508.

Meinesz, A., T. Belsher, T. Thibault, B. Antolic, K. B. Mustapha, C. F. Boudouresque, D. Chiaverini, F. Cinelli, J. M. Cottalorda, A. Djellouli, A. El Abed, C. Orestano, A. M. Grau, L. Ivesa, A. Jaklin, H. Langar, E. Massuti-Pascual, A. Peirano, L. Tunesi, J. de Vaugelas, N. Zavodnik, and A. Zuljevic. 2001. The introduced green alga *Caulerpa taxifolia* continues to spread in the Mediterranean. Biol. Invasions **3**:201-210.

Meusnier, I., J. L. Olsen, W. T. Stam, C. Destombe, and M. Balero. 2001.

Phylogenetic analyses of *Caulerpa taxifolia* (Chlorophyta) and of its associated bacterial microflora provide clues to the origin of the Mediterranean introduction. Mol. Ecol. **10**:931-946.
Millar, A. J. K. 2001. The invasion of *Caulerpa taxifolia* in eastern Australia. Abstracts. XVIIth International Seaweed Symposium, Cape Town, South Africa, p. 92.
Miller, K. A. 2004. California’s non-native seaweeds. Fremontia **32**: 10-15.
Milne, A., 1990. Roughness and drag from the marine chemist’s viewpoint. Proceedings of the International Workshop on Marine Roughness and Drag. Royal Institution of Naval Architects, London, UK.
Moeller, H. W. 1969. Ecology
Montaigne, F. 2004. Policing America’s ports, Smithsonian Magazine January 2004 Volume **30**:90-98.
Mooney, H. A., and J. A. Drake, editors. 1986. Ecology of biological invasions of North American and Hawaii. Springer-Verlag, New York, New York, USA.
Mrosek, J. 2000. Revenue neutral deposit/refund systems. Environ. Res. Economics **17**:183-193.
Murphy, N. E., and B. Schaffelke. 2003. Use of amplified fragment length polymorphism (AFLP) as a new tool to explore the invasive green alga *Caulerpa taxifolia* in Australia. Mar. Ecol. Progr. Ser. **246**:307-310.
Murray, S. N., and R. N. Bray. 1993. Benthic macrophytes. Pages 304-368 *in* M. D. Dailey, D. J. Reish, and J. W. Anderson, editors. Ecology of the Southern California Bight. University of California Press, Berkeley, California, USA.
Murray, S. N., and M. M. Littler. 1981. Biogeographical analysis of intertidal macrophyte floras of southern California. J. Biogeogr. **8**:339-351.
National Research Council (NRC). 1995. Understanding marine biodiversity: A research agenda for the nation. National Academy Press, Washington D. C., USA.
Naylor, R. 2000. The Economics of alien invasions. Pages 241-259 in H. A. Mooney and R. J. Hobbs, editors. Invasive species in a changing world. Island Press, Washington, D. C., USA.
NEMESIS (National Exotic Marine and Estuarine Species Information System). 2002. Unpublished database, partly accessible at Smithsonian Environmental Research Center’s Web site. Available at: http://invasions.si.edu.
New Zealand Government. 1993. Biosecurity act 1993: An act to restate and reform the law relating to the exclusion, eradication, and effective management of pests and unwanted organisms, Auckland, New Zealand.
Nicholson, N.L., H. M. Hosmer, K. Bird, L. Hart, W. Sandlin, C. Shoemaker, and C. Sloan. 1981. The biology of *Sargassum muticum* (wireweed) at Santa Catalina (California, U.S.A.). Proc. Int. Seaweed Symp. **8**:416-424.
Niebauer, H. J. 1985. Southern Oscillation/El Niño effects in the eastern Bering Sea. Pages 116-118 *in* W. S. Wooster and D. L. Fluharty, editors. El Niño North. Niño effects in the eastern Subarctic Pacific Ocean. Washington Sea Grant Program, Seattle, Washington, USA.
Norris, R. and M. J. Wynne. 1968. Notes on marine algae of Washington and southern British Columbia. III. Syesis **1**:133-146.

Occhipinti, Ambrogi A. 2001. Transfer of marine organisms: a challenge to the conservation of coastal biocoenoses. Aquatic Conserv: Mar. Freshw. Ecosyt. **11**:243-251.

O'Clair, C. E., and S. T. Zimmerman. 1986. Biogeography and ecology of the intertidal and shallow subtidal communities. Pages 305-344 *in* D. W. Hood, and S. T. Zimmerman, editors. The Gulf of Alaska. Physical environment and biological resources. Minerals Management Service Publication No. 86-0095, Washington, D. C., USA.

Office of Technology Assessment (OTA). 1993. Harmful non-indigenous species in the United States. OTA Publication OTA-F-565, U.S. Government Printing Office, Washington, D. C., USA.

Ohno, M., and Critchley, A. T., editors. 1993. Seaweed cultivation and marine ranching. Japan International Cooperative Agency, Nagai, Yokosuka, Japan.

Orr, R. 2003. Generic nonindigenous aquatic organisms risk analysis review process. Pages 415-434 *in* G. M. Ruiz, and J. T. Carlton, editors. Invasive species. Vectors and management strategies. Island Press, Washington, D. C., USA.

Padilla, D. K., and S. L. Williams. 2004. Beyond ballast water: aquarium and ornamental trades as sources of invasive species in aquatic ecosystems. Front. Ecol. Environ. **2**:131-138.

Paula, E. J., and V. R. Eston. 1987. Are there other *Sargassum* species potentially as invasive as *S. muticum*? Bot. Mar. **30**:405-410.

Pérez, R., J. Y. Lee, and C. Juge. 1981. Observations sur la biologie de l'algue japonaise *Undaria pinnatifida* (Harvey) Suringar introduite accidentellement dans l"Etang de Thau. Sci. Pêche **343**:1-12.

Pérez, R., R. Kaas, and O. Barbaroux. 1984. Culture expérimentale de l'algue *Undaria pinnatifida* (Harvey) Suringer introduite accidentellement dans l"Étang de Thau. Sci. Pêche **315**:1-12.

Pérez-Cirera, J. L. 1975. Catalogo floristico de las algas bentonicas de la Ria de Corme y Lage, NO de Espana. Anales del Instituto Botánico Antonio José Cavanilles **32**:5-87.

Peterson, A. T. 2003. Predicting the geography of species' invasions via ecological niche modeling. Q. Rev. Biol. **78**:419-433.

Piazzi, L., E. Balestri, M. Magri, and F. Cinelli. 1997. Expansion de l'algue tropicale *Caulerpa racemosa* (Forsskåll) J. Agardh (Bryopsidophyceae, Chlorophyta) le long de la côte toscane (Italie). Cryptogamie Algol. **18**:343-350.

Piazzi, L., G. Ceccherelli, and F. Cinelli. 2001. Threat to macroalgal diversity: effects of the introduced green alga *Caulerpa racemosa* in the Mediterranean. Mar. Ecol. Progr. Ser. **210**:149-159.

Pimentel, D., L. Lach, R. Zuniga, and D. Morrison. 2000. Environmental and economic costs of nonindigenous species in the United States. Bioscience **50**:53-65.

Piriz, M. L., and G. Casas. 1994. Occurrence of *Undaria pinnatifida* in Golfo Nuevo, Argentina. Appl. Phycol. Forum **10**:4.

Ramus, J. 1971. *Codium*, the invader. Discovery **6**:59-68.

Relini, G., M. Relini, and G. Torchia. 1998). Fish biodiversity in a *Caulerpa taxifolia* meadow in the Ligurian Sea. Italian J. Zool. **65**(Suppl.):465-470.

Ribera, M. A., and C. F. Boudouresque. 1995. Introduced marine plants, with special reference to macroalgae: mechanisms and impact. Pages 187-268 *in* F. E. Round and D. J. Chapman, editors. Progress in Phycological Research Volume 11, Biopress Ltd, Bristol, U.K.
Ribera Siguan, M. A. 2003. Pathways of biological invasions of marine plants. Pages 183-226 *in* G. M. Ruiz and J. T. Carlton, editors. Invasive species. Vectors and management strategies. Island Press, Washington, D. C., USA.
Ricciardi, A., and J. Rasmussen. 1998. Predicting the identity and impact of future biological invaders: a priority for aquatic resource management. Can J. Fish. Aquat. Sci. **55**:1759-1765.
Rio, A., and J. Cabioch. 1988. Apparition du *Caulacanthus ustulatus* (Rhodophyta, Gigartinales) dans la Manche Occidentale. Cryptogamie Algol. **9**:231-234.
Rjemánek, M. 1996. A theory of seed plant invasiveness: the first sketch. Biol. Conserv. **78**:171-181.
Roemmich, D., and J. A. McGowan. 1995. Climatic warming and the decline of zooplankton in the California Current. Science **267**:1324-1326.
Romero, J. 1997. Consequences de l,expansion de *Caulerpa taxifolia* en Mediterranee. Pages 241-255 *in* Academie des Sciences. Dynamique d'especes marine invasives: application a l'expansion de *Caulerpa taxifolia* en Mediterranee. TecDoc, Paris, France.
Rosen, Y. 2004. Exxon penalties could rise as Valdez oil lingers. Reuters Planet Ark, March 24, 2004. Internet news service. Available at: http://www.planetark.com/dailynewsstory.efm/newsid/story.htm.
Royer, T. C. 1985. Southern Oscillation/El Niño effects in the eastern Bering Sea. Pages 107-115 *in* W. S. Wooster and D. L. Fluharty editors. El Niño North. Niño effects in the eastern Subarctic Pacific Ocean. Washington Sea Grant Program, Seattle,Washington, USA.
Rueness, J. 1997. A culture study of *Caulacanthus ustulatus* (Caulacanthaceae, Gigartinales, Rhodophyta) from Europe and Asia. Cryptogamie Algol. **18**:175-185.
Rueness, J., and E. Rueness. 2000. *Caulcanthus ustulatus* (Gigartinales, Rhodophyta) from Brittany (France) is an introduction from the Pacific Ocean. Cryptogamie Algol. **21**: 355-363.
Ruiz, G. M., and J. T. Carlton. 2003a. Preface, pp. ix-xiii, *in* G. M. Ruiz and J. T. Carlton, editors. Invasive species. Vectors and management strategies. Island Press, Washington, D. C., USA.
Ruiz, G. M., and J. T. Carlton. 2003b. Invasion vectors: a conceptual framework for management. Pages 459-504 *in* G. M. Ruiz and J. T. Carlton, editors. Invasive species. Vectors and management strategies. Island Press, Washington, D. C., USA.
Ruiz, G. M., J. T. Carlton, E. D. Grosholz, and A. H. Hines. 1997. Global invasions of marine and estuarine habitats by non-indigenous species: mechanisms, extent, and consequences. Amer. Zool. **37**:621-632.
Ruiz, G. M., and J. A. Crooks. 2001. Biological invasions of marine ecosystems: patterns, effects, and management. Pages 3-17 *in* L. Bendell-Young and P. Gallaugher editors. Waters in peril. Kluwer Academic Publishers, Dordrecht,

The Netherlands.
Ruiz, G. M., P. W. Fofonoff, J. T. Carlton, M. J. Wonhman, and A. H. Hines. 2000. Invasion of coastal marine communities in North America: apparent patterns, processes, and biases. Ann. Rev. Ecol. Syst. **31**:481-531.
Ruiz, G. M., A. W. Miller, K. Kion, B. Steves, A. Arnwine, E. Collinetti, and E. Wells. 2001. Status and trends of ballast water management in the United States. First biennial report of the National Ballast Information Clearinghouse. Submitted to the U.S. Coast Guard. 48 pp.
Rust, E. 2004. The economic benefits of ports and harbors in the U.S. Sea Tech. **45**:20-25.
Sagarin, R. D., J. P. Barry, S. E. Gilman, and C. E. Baxter. 1999. Climate-related change in an intertidal community over short and long time scales. Ecol. Monogr. **69**:465-490.
Sakai, A. K., F.W. Allendorf, J. S. Holt, D. M. Lodge, J. Molofsky, K. A. With, S. Baughman, R. J. Cabin, J. E. Cohen, N. C. Ellstrand, D. E. McCauley, P. O'Neil, I. M. Parker, J. N. Thompson, and S. G. Weller. 2001. The population biology of invasive species. Ann. Rev. Ecol. System. **32**:305-332.
Sanderson, J. C. 1990. A preliminary survey of the introduced macroalga, *Undaria pinnatifida* (Harvey) Suringar (Laminariales, Phaeophyta) on the east coast of Tasmania. Bot. Mar. **33**:153-157.
Sant, N., O. Delgado, C. Rodriguez-Prieto, and E. Ballesteros. 1996. The spreading of the introduced seaweed *Caulerpa taxifolia* (Vahl) C. Agardh in the Mediterranean Sea: testing the boat transportation hypothesis. Bot. Mar. **39**:27-430.
Scagel, R. F. 1956. Introduction of a Japanese alga, *Sargasssum muticum* into the northeast Pacific. Fish. Res. Pap., Washington Dept. of Fisheries **1**:49-58.
Scagel, R. F., P. W. Gabrielson, D. J. Garbary, L. Golden, M. W. Hawkes, S. C. Lindstrom, J. C. Oliveira, and T. B. Widdowson. 1989. A synopsis of the benthic marine algae of British Columbia, Southeast Alaska, Washington, and Oregon. Phycological Contribution No. 3, The University of British Columbia, Vancouver, British Columbia, Canada.
Schmidt, O. C. 1931. Die marine Vegetation der Azoren in ihren Grundzügen dargestellt. Bibl. Bot. **102**:1-116.
Secord, D. 2003. Biological control of marine invasive species: cautionary tales and land-based lessons. Biol. Invasions **5**:110-131.
Semmens, B. X., E.R. Buhle, A. K. Salomon, and C. V. Patengill-Semmens. 2004. A hotspot of non-native marine fishes: evidence for the aquarium trade as an invasion pathway. Mar. Ecol. Prog. Ser. **266**:239-244.
Seoane-Camba, J. 1965. Estudios sobre las algas bentónicas en la costa sur de la Península Ibérica (litoral de Cádiz). Invest. Pesq. **29**:1-216.
Setchell, W. A. 1915. The law of temperature connected with the distribution of the marine algae. Ann. Mo. Bot. Gard. **2**:287-305.
Setzer, R. and Link, C. 1971. The wanderings of *Sargassum muticum* and other relations. Stomatopod **2**:5-6.
Shanks, A.L., B. A. Grantham, and M. H. Carr. 2003. Propagule dispersal distance and the size and spacing of marine reserves. Ecol. Appl. **13**(Suppl.):159-169.

Silva, P. C. 1955. The dichotomous species of *Codium* in Britain. J. Mar. Biol. Ass., U. K. **2**:7-9.

Silva, P. C. 1979. The benthic algal flora of central San Francisco Bay. Pages 287-311 in T. J. Conomos, editor. San Francisco Bay: The urbanized estuary. American Association of the Advancement of Science, Pacific Division.

Silva, P. C., R. A. Woodfield, A. N. Cohen, L. H. Harris, and J. H. R. Goddard. 2002. First report of the Asian kelp *Undaria pinnatifida* in the northeastern Pacific Ocean. Biol. Invasions **4**:333-338.

South, G. R., and I. Tittley. 1986. A checklist and distributional index of the benthic marine algae of the North Atlantic Ocean. Huntsman Marine Laboratory and British Museum (Natural History), St. Andrews, New Brunswick, Canada and London, U. K.

Staehr, P. A., M. F. Pedersen, M. S. Thomsen, T. Wernberg, and D. Krause-Jensen. 2000. Invasion of *Sargassum muticum* in Limfjorden (Denmark) and its possible impact on the indigenous macroalgal community. Mar. Ecol. Progr. Ser. **207**:79-88

Tamburri, M., K. Wasson, and M Matsuda. 2002. Ballast water deoxygenation can prevent aquatic introductions while reducing ship corrosion. Biol. Conser. **103**:331-341.

Taylor, J. N., W. R. Courtenay, jr., and J. A. McCann. 1984. Known impacts of exotic fishes in the continental United States Pages 322-373 *in* W. R. Courtenay, Jr. and J. R. Stauffer, Jr., editors. Distribution, biology, and management of exotic fishes. The Johns Hopkins University Press, Baltimore, Maryland, USA.

Taylor, A., G. Rigby, S. Gollasch, M. Voigt, G. Hallegraeff, T. McCollin, and A. Jelmert. 2002. Preventive treatment and control techniques for ballast water. Pages 484-507 *in* E. Leppäkoski, S. Gollasch, and S. Olenin, editors. Invasive aquatic species of Europe: distributions, impacts, and management. Kluwer Academic Publishers, Dordrecht, The Netherlands

Thomas, P. 2004. Buy a license, save a fish, Los Angeles Times, February 10, 2004, Los Angeles, California, USA.

Thibaut, T., and A. Meinesz. 2000. Are the Mediterranean ascoglossan molluscs *Oxynoe olivacea* and *Lobiger serradifalci* suitable agents for a biological control against the invading tropical alga *Caulerpa taxifolia*?.C. R. Acad. Sci. Paris. Sciences de la vie/Life Sciences **323**:477-488.

Thibaut, T., A. Meinesz, L. Burtaire, S. Charrier, L. Mangialajo, D. Ireardi, and V. Vidal. 1998. Biological control of *Caulerpa taxifolia* in the Mediterranean Sea: use of tropical and Mediterranean ascoglossans. Pages 105-111 *in* C. F. Boudouresque, C. F., V. Gravez, A. Meinesz, and F. Palluy, editors. Third international workshop on *Caulerpa taxifolia*. GIS Posidonie Publication, Marseille, France.

Thibaut, T., A. Meinesz, P. Amade S. Charrier, K. De Angelis, D. Ierardi, L. Mangialajo, J. Melnick, and V. Vidal. 2001. *Elysia subornata* (Mollusca) a potential control agent of the alga *Caulerpa taxifolia* (Chlorophyta) in the Mediterranean Sea. J. Mar. Biol. Ass., U.K. **81**:497-504.

Tlusty, M. 2002. The benefits and risks of aquacultural production for the aquarium trade. Aquacult. **205**:203-219.

Trowbridge, C. D. 1998. Ecology of the green macroalga *Codium fragile* (Suringar) Hariot 1889: Invasive and non-invasive subspecies. Oceanogr. Mar. Biol., Ann. Rev. **36**:1-64.

Trowbridge, C. D. 1999. An assessment of the potential spread and options for control of the introduced green macroalga *Codium fragile* ssp. *tomentosoides* on Australian shores. Hobart: CSIRO Marine Research (ISBN 0 643 06202 5). Tasmania, Australia. 43 pp.

Trowbridge, C. D. 2001. Coexistence of introduced and native congeneric algae: *Codium fragile* and *C. tomentosum* on Irish rocky intertidal shores. J. Mar. Biol. Ass., U.K. **81**:931-937.

Trowbridge, C. D. (in press). Xenodiversity: non-native macroalgae on marine and brackish shores. *in* A. T. Critchley and M. Ohno, editors. Non-native macroalgae. Seaweed resources of the world. ETI Information Services Ltd., UNESCO, Natuur&Techniek and Kosmos-Z&K.

Union of Concerned Scientists. 2003. "Scientists warn that U.S. is under assault by invasive species," Press Release, December 2003.Available at: http://www.ucsusa.org/global_environment/invasive_species/page.cfm?pageID=1275.

United States Coast Guard (USCG). 2004. Shipboard technology evaluation program (STEP): Experimental ballast water treatment systems. Coast Guard Navigation and Vessel Inspection Circular 1/04. Available at: http://www.uscg.mil/hq/g-m/pscweb/.

United States Commission on Ocean Policy (USCOP). 2004. An ocean blueprint for the 21st century. Final report of the U.S. Commission on Ocean Policy, Wash. D.C..

United States Department of Transportation (USDOT). 2001, Report to congress on the voluntary national guidelines for ballast water management. Washington, D. C., USA.

United States General Accounting Office (USGAO). 2002. Invasive species: Clearer focus and greater commitment needed to effectively manage the problem. Report GAO-03-1. Washington D. C., USA.

United States Geological Survey (USGS). 2003. Problems with the release of exotic Fish. Available at:http://nas.er.usgs.gov/fishes/dont_rel.html.

Valentine, J. P., and C. R. Johnson. 2003. Establishment of the introduced kelp *Undaria pinnatifida* in Tasmania depends on disturbance to native algal assemblages. J. Exp. Mar. Biol. Ecol. **295**:63-90.

Vancouver Port Authority (VPA). 2002 Harbor operating manual. Available at: http://www.portvancouver.com/the_port/docs/harbor_manual.pdf.

Vancouver Port Authority (VPA). 2003. Port Vancouver ballast water management program. Distributed at the meeting of the ICES Study Group on Ballast and Other Ship Vectors, March 23, 2003. Available at: http://www.portvancouver.com/the_port/docs/.

Verlaque, M. 1994. Inventaire des plantes introduites en Méditerranée: origins et repercussions sur l'environnement et les activités humaines. Oceanol. Acta

17:1-23.
Verlaque, M. 1996. L'etang de Thau (France), un site majeur d'introduction d'especes en Méditerranéen – relations avec l'ostreiculture. Pages 423-430 *in* M. A. Ribera, E. Ballesteros, C. F. Boudouresque, A. Gome, and V. Gravez. editors. Second International Workshop on *Caulerpa taxifolia*, Publications Universitat Barcelona, Spain. 15-17 December 1994. University of Barcelona, Barcelona, Spain.
Verlaque, M. 2001. Checklist of the macroalgae of Thau Lagoon (Herault, France), a hot spot of marine species introduction in Europe. Oceanol. Acta **24**:29-49.
Verlaque, M., C. F. Boudouresque, A. Meinesz, and V. Gravez. 2000. The *Caulerpa racemosa* complex (Caulerpales, Ulvophyceae) in the Mediterranean Sea. Bot. Mar. **43**:49-68.
Verlaque, M., C. Durand, J. M. Huisman, C. F. Boudouresque, and V. L. Parco. 2003. On the identity and origin of the Mediterranean invasive *Caulerpa racemosa* (Caulerpales, Chlorophyta). Eur. J. Phycol. **38**:325-339.
Viejo R. M. 1997. The effects of colonization by *Sargassum muticum* on tidepool macroalgal assemblages. J. Mar. Biol. Ass., U. K. **77**:325-340.
Viet, R. R., P. Pyle, and J. A. McGowan. 1996. Ocean warming and long-term change in the pelagic bird abundance within the California Current system. Mar. Ecol. Progr. Ser. **139**:11-18.
Villele, X. D., and M. Verlaque. 1995. Changes and degradation in a *Posidonia oceanica* bed invaded by the introduced tropical alga *Caulerpa taxifolia* in the North Western Mediterranean. Bot. Mar. **38**:79-87.
Vitousek, P. M., C. M. D'Antonio, L. L. Loope, and R. Westbrooks. 1996. Biological invasions as global environmental change. Am. Sci. **84**:218-228.
Vitousek, P. M., C. M. D'Antonio, L. L. Loope, M. Rejmánek, and R. Westbrooks. 1997. Introduced species: a significant component of human-caused global change. N. Z. J. Ecol. **21**:1-16.
Weber van Bosse, A. 1898. Monographie des Caulerpes. Ann. Jard. Bot. Buitenz. **15**:243-401.
West, J. A., and H. P. Calumpong. 1990. New records of marine algae from the Philippines. Micronesica **23**:181-190.
Whitehead, J., T. Haab, and G. Parsons. 2003. Economic effects of *Pfiesteria*. Ocean Coast. Manage. **46**: 845-858.
Wilcove, D. S., D. Rothstein, J. Dubow, J., and others. 1998. Quantifying threats to imperiled species in the United States. BioScience **48**:607-615.
Williams, S. L., and E. D. Grosholz. 2002. Preliminary reports from the *Caulerpa taxifolia* invasion in southern California. Mar. Ecol. Prog. Ser. **233**:307-310.
Williamson, M. H., and A. Fritter. 1996. The varying sucees of invaders. Ecology **77**:1661-1666.
Wilson M. 2001. Is *Sargassum muticum* a benign invader of tidepools on the Pacific coast of North America? M.S. Thesis, Moss Landing Marine Laboratories, Moss Landing, California, USA.
Wu, J. Q., and W. W. Hsieh. 1999. A modelling study of the 1976 climate regime shift in the North Pacific Ocean. Can. J. Aquat. Sci. **56**:2450-2462.

Wynne, M. J. 1986. Report on a collection of benthic marine algae from the Namibian coast (southwestern Africa). Nova Hedwigia **43**:311-355.

Yendo K. 1907 The Fucaceae of Japan. J. Coll. Sci. Imp. Univ., Tokyo **21**:1-174.

Zavaleta, E. 1999. Valuing ecosystem services lost to Tamarix invasion in the U. S. Pages 261-300 *in* H. A. Mooney and R. J. Hobbs, editors. Invasive Species in a Changing World, Island Press, Washington D. C., USA.

Zentner, J., J. Glaspy, and D. Schenk. 2003. Wetland and riparian woodland restoration costs. Ecol. Restoration **21**:166-173.

Zuljevic, A., T. Thibaut, H. Ellonkal, and A. Meinesz. 2001. Sea slug disperses the invasive *Caulerpa Taxifolia*. J. Mar. Biol. Ass., U. K. **81**:343-344.

Zuccarello, G. C., and J. A. West. 2002. Phylogeography of the *Bostrychia calliptera/B. pinnata* complex (Rhodomelaceae, Rhodophyta) and divergence rates based on nuclear, mitochondrial and plastid DNA markers. Phycologia **41**:49-60.

Zuccarello, G. C., J. West, and J. Rueness. 2002. Phylogeography of the cosmopolitan red alga *Caulacanthus ustulatus* (Caulacanthaceae, Gigartinales). Phycol. Res. **50**:163-172.