NATIONAL ESTUARINE RESEARCH RESERVE SYSTEM

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NON-NATIVE SPECIES IN OUR NATION'S ESTUARIES:

A FRAMEWORK FOR AN INVASION MONITORING PROGRAM

K. Wasson, D. Lohrer, M. Crawford, S. Rumrill

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ABOUT THIS DOCUMENT
This document summarizes the results of a workshop held January 14-18, 2002 at Asilomar Conference Grounds in Pacific Grove, California. Elkhorn Slough National Estuarine Research Reserve, The Elkhorn Slough Foundation, and South Slough National Estuarine Research Reserve hosted the workshop; it was funded by the Aquatic Nuisance Species Task Force and the Estuarine Reserves Division of NOAA.

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CONTACT INFORMATION FOR THE AUTHORS
Dr. Kerstin Wasson, Elkhorn Slough National Estuarine Research Reserve, 1700 Elkhorn Road, Watsonville, CA 95076; research@elkhornslough.org
Dr. Drew Lohrer, (formerly of North Inlet-Winyah Bay National Estuarine Research Reserve) National Institute for Water and the Atmospheric Research, PO Box 11-115, Hillcrest, Hamilton, New Zealand; d.lohrer@niwa.cri.nz
Dr. Maurice Crawford, Estuarine Reserves Division, NOAA, N/ORM5, 1305 East West Highway, Silver Spring, MD 20910; Maurice.Crawford@noaa.gov
Dr. Steve Rumrill, South Slough National Estuarine Research Reserve, PO Box 5417, Charleston, OR 97420; srumrill@harborside.com

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ABOUT THE NERRS TECHNICAL REPORT SERIES
The National Estuarine Research Reserves System (NERRS) is a network of protected areas promoting stewardship of the Nation's coasts through science and education. The reserve system's Technical Report Series is a means for disseminating data sets, curricula, research findings or other information that would be useful to coastal managers, educators, and researchers, yet are unlikely to be published in the primary literature. High quality of technical reports is ensured by a thorough peer-review and editorial process.

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EXECUTIVE SUMMARY

Invasions of non-native species are now recognized as being second only to anthropogenic habitat destruction as a cause of global extinctions. The distribution of the world's biota is being altered to an unprecedented degree, largely through human transport. Estuaries are among the most vulnerable ecosystems in the world to anthropogenically-facilitated invasions, in part because entire coastal planktonic assemblages are moved between distant estuarine ports in ballast water of international vessels. Hundreds of non-native aquatic species have become established in U.S. estuaries, and some of them have been shown to have dramatic negative impacts on native biological communities, habitat structure, and ecosystem processes.

Very few attempts have been made to monitor estuarine invasions at a broad spatial scale. Yet standardized, repeated, quantitative measures across multiple sites are the best way of determining the correlates of invasion success, and would shed light both on attributes of species that make them likely to invade and have negative impacts, and on characteristics of the recipient environments that make them resistant or vulnerable to invasion. Monitoring would also facilitate early detection of new invasions, within the window of opportunity where eradication efforts may be successful. By simultaneously carrying out monitoring across estuaries for invaders and native species, along with physical and chemical characterization, scientists could also determine how ecological impacts vary geographically, and attempt to identify the mechanisms behind observed differences. A nationally coordinated invasion monitoring program in estuarine habitats would thus allow coastal managers and resource agencies to better devise and implement effective strategies for preserving regionally distinct native biodiversity.

The National Estuarine Research Reserve System (NERRS) is a network of protected areas established to study and improve the health of U.S. estuaries and coastal habitats. With 25 reserves on all three coasts of the continental U.S., in addition to those in Alaska, Puerto Rico, and the Great Lakes, the reserve system has outstanding spatial coverage to detect and track range expansions of exotic species. Furthermore, every reserve participates in system-wide monitoring, consistently collecting meteorological data and carrying out baseline water quality measurements that would complement any biological monitoring program. The reserves also have strong management, education, and restoration programs excellently suited to an integrated approach to estuarine invasions.

A recent survey of the NERRS revealed that most reserves have been significantly affected by biological invasions, and that non-native species are a medium to high priority for future research funding. Over 85 problematic non-native species were identified by the reserve system, with concerns associated primarily with negative impacts on native species, communities, or habitat structure. More than half the reserves are already monitoring the spread of a non-native aquatic plant of concern, and many are tracking crab invasions.

In January 2002, the NERRS sponsored a workshop to devise a framework for a national estuarine invasion monitoring program, with funding from the Aquatic Nuisance Species Task Force and NOAA. The workshop brought together over 40 participants -- invasion biologists, reserve system representatives, and partner organizations -- to envision elements of an ideal monitoring program for estuarine invasions.

Eleven invasion biologists made recommendations on strategies and protocols for developing a national invasion monitoring program. Some general themes raised by many included:

1) the importance of carrying out biological monitoring across estuaries, targeting native and non-native species,
2) the power of linking biological data with physical variables to explain observed patterns,
3) the value of a central database for monitoring data,
4) the necessity for taxonomic expertise, and
5) the challenges and rewards of question-driven monitoring.

Workshop participants identified and prioritized questions to drive a national invasion monitoring program. The top two questions concerned patterns of species richness and abundance, which comprise basic biological monitoring. Three additional high-ranking questions focused more specifically on invasions, and involved environmental correlates of invasion success, early detection of new invaders, and impacts of non-native species. Examples of monitoring programs for each of the top four questions were developed, including appropriate taxa, methods, and likely scientific and management benefits to answering them.

Participants identified estuarine habitat types and taxa to consider as the focus of invasion monitoring. Marshes, submerged aquatic vegetation, and shellfish beds received the highest ranking overall, because they are ecologically relevant across a broad geographic range, because they are tractable for monitoring, and because they are critical for sustaining key estuarine resources, yet potentially fragile in the face of anthropogenic threats. The top taxa that emerged were plants, macroalgae, mammals and fish. These rose to the top because of their tractability as study organisms, their potential to influence the ecology of estuaries they invade, and the likelihood that they could be eradicated if necessary. Most other taxa were considered difficult to identify for non-experts, and difficult to control. Participants found it difficult to prioritize habitats and taxa without a specific context (scientific question, funding source, user group).

A national invasion monitoring program would best be built of partnerships. Links between various agencies and organizations would increase the geographic coverage and bring greater resources that would allow an increased scope of any program. Academic involvement in agency monitoring programs would be fruitful for the academics, and would enhance the scientific value of the monitoring. Partnerships with local communities would help to raise the profile of estuarine invasions, and could complement any national invasion monitoring program.

The workshop has resulted in a broad blueprint for national invasion monitoring, which can be used to guide future reserve system efforts or those by other agencies. Critical questions about invasions have been identified, and potential approaches illustrated. More generally, the workshop has highlighted the scientific value and management benefits of carrying out biological monitoring consistently at a broad geographic scale. The NERRS, perhaps in collaboration with partners, is poised to institute such a national program.

BACKGROUND: ESTUARINE INVASIONS

Invasions by non-native species are recognized as a leading cause of global biodiversity loss (e.g., Pimm 1987; Gophen et al. 1995; Vitousek et al. 1997) and the distribution of Earth's biota is being altered dramatically as a result of human activities (Elton 1958; Drake et al. 1989; Williamson 1996; Corn et al. 1999). Bays and estuaries are particularly vulnerable to invasion because of the abundance and variety of non-native propagules supplied to them by humans (reviewed by Carlton 2001). For example, entire planktonic assemblages can be moved between estuaries, across oceans, in the ballast water of international vessels (Carlton 1987; Carlton and Geller 1993). Sessile forms can be transported when attached to vessel hulls, and many adult invaders have been stocked and/or accidentally released by people in the aquaculture and seafood trade industries. Hundreds of non-native aquatic species have become established in U.S. estuaries and the rate of non-indigneous species accumulation is apparently increasing (Cohen and Carlton 1998; Ruiz et al. 2000). Non-native species alter estuarine species composition and potentially affect the behavior, distribution, and trophic interactions of native species. Some non-native species alter the physical characteristics of estuarine habitats as well, and constitute a significant force of change affecting population, community, and ecosystem processes in estuaries (Ruiz et al. 1997; Grosholz 2002). While the destructive effects of non-native species are now widely known (Corn et al. 1999; Carlton 2001), experts concede that the patterns of invasion in U.S. estuaries remain confounded and identify a vital need to initiate "standardized ecological surveys of non-native species across major regions of the U.S." (Ruiz et al. 2000).

NERRS SCIENCE PROGRAMS

A key to conserving coastal waters and restoring estuarine habitats is information on how human activities and natural events can change ecosystems. The National Estuarine Research Reserve System (NERRS) has begun a large-scale effort that combines long-term monitoring with applied research to understand changes in coastal ecosystems.

Currently, the NERRS is composed of 25 reserves in 21 states and territories, protecting over 1 million acres of estuarine waters, wetlands and uplands. Reserves are located along Pacific, Atlantic, Great Lakes, Gulf of Mexico, and Caribbean Sea shorelines and represent a diversity of estuarine conditions and 15 biogeographic regions. One mission of the reserve system is to provide information to coastal decision-makers to promote informed resource management. Thus, the reserve system has developed education and outreach programs to translate and distribute research results. An example is the Coastal Decision-Maker Workshop series, which has been implemented at most reserves for the past four years. The workshops have proven effective at bringing scientists and coastal decision-makers together to address specific coastal issues. This is a highly suitable means to educate the public and stimulate information flow between scientists and policy makers. This is critical to the success of any non-native species research program.

The reserve system's Graduate Research Fellowship Program offers qualified graduate students the opportunity to address scientific questions of local, regional and national significance. The result is high-quality research focused on improving coastal management issues. All projects must be conducted in the reserve system and enhance the scientific understanding of the reserve's ecosystem. One of the priority research areas for the fellowships has been the effects of non-native species on estuarine ecosystems.

In the 1990s, the NERRS initiated a System-Wide Monitoring Program (SWMP) to track short-term variability and long-term changes in coastal ecosystems. The initial phase has focused on monitoring a suite of water quality and atmospheric parameters. To provide an accurate characterization of the short-term fluctuations in water quality variables, observations are made every 30 minutes at four sites in each reserve via automated water quality monitoring instruments. Data are collected consistently across the reserves, and are submitted to a Centralized Data Management Office, which compiles and posts data on the Internet (http://cdmo.baruch.sc.edu), free for use by the public. Such an entity would be essential for the management and dissemination of invasion monitoring data.

The System-wide Monitoring Program provides valuable information about the short-term dynamics and long-term trends of water quality in shallow estuarine systems (Wenner and Geist 2001). These data have been used in the analysis of water quality conditions related to oyster diseases, to measure recovery of estuarine areas after hurricanes and to evaluate estuarine restoration projects. Water quality data from SWMP also provides background data from which specific questions can be explored to understand changes in estuarine ecosystems (e.g., non-native species). SWMP is currently in an expansion phase, set to build upon existing physical and chemical data infrastructure. Biological monitoring—standardized, repeated, quantitative measures at multiple sites, perhaps across taxa and habitats—is being considered. This is the only bias-free approach for interpreting the patterns and processes of invasion (Ruiz et al. 2000) and it would serve invasion biologists, conservationists, ecologists, and coastal resource managers extremely well.

NON-NATIVE SPECIES AT THE NERRS

The NERRs have been significantly affected by biological invasions, and non-native species are of concern to many of them. In summer 2000, a survey was conducted regarding non-native species in the reserve system. All 25 reserves responded, so the results accurately represent trends and concerns across the system. The results are summarized here:

Prioritization of invasion monitoring: Non-native species are a medium to high priority at most reserves. If additional funds became available for research and monitoring, allocation to non-native species projects vs. other types of monitoring would be high/highest at 10 reserves, medium/medium-high at 13 reserves, and low/low-medium at 2 reserves.

Problematic non-native species: Over 85 species of important non-native species were identified by the reserve system, including 50 plants, 30 invertebrates, and 13 vertebrates. This number is not an estimate of total non-native species in the reserve system (surely an order of magnitude higher), but rather gives a sense of how many different species are creating problems for the reserves. Eight species (*Phragmites*, purple loosestrife, Chinese tallow, Eurasian water milfoil, European green crab, Japanese crab, zebra mussel, feral hog) were identified as priorities at three or more reserves.

Ecological concerns associated with non-native species: The biggest ecological concerns associated with the spread of non-native species were negative impacts on native species or communities (threats to rare or economically important species, loss of native biodiversity, etc.) and on physical habitats (change in their structure or distribution).

Affected habitat types: Many different habitats on the reserves appear to be significantly impacted by non-native species. Impacts of non-native species on estuarine habitats (including marine, brackish, freshwater, and marsh habitats) are of greatest concern to the reserve system, although upland habitats are also severely impacted.

Existing monitoring for non-natives: More than half of the reserves are already carefully mapping the distribution and spread of at least one non-native plant species, and over a third are keeping a watch on one crab species of concern. Most reserves are also gathering some sort of incidental data on non-natives as a part of other studies or in the course of eradication efforts. Virtually no reserves are carrying out broad-scale, multispecies, long-term monitoring of non-natives for any habitat.

BENEFITS OF MONITORING ESTUARINE INVASIONS

In addition to rigorous research programs funded by federal programs and state partnerships, the reserve system has a well-developed resource management, restoration and education infrastructure. Thus, the reserve system is well-suited to implementing an integrated approach to invasions by non-native species. A nationally coordinated invasion monitoring program in estuarine habitats would allow coastal managers and resource agencies to better devise and implement effective strategies for preserving regionally distinct native biodiversity. The benefits of monitoring estuarine invasions at the NERRs include:

Improved characterization of the biodiversity of estuaries: While terrestrial invaders are relatively well characterized at many of the NERR sites, marine and freshwater invaders are poorly known. For instance, a recent study at Elkhorn Slough NERR (California) revealed one new invasive invertebrate species for every two hours of search effort, and another study documented over 50 non-native marine species within the South Slough NERR (Oregon).

Early detection of new invasions: Eradication of a non-native species is usually only feasible if it is detected early on. However, there is currently insufficient monitoring to detect invasions soon after they occur. Typically non-native species are overlooked until they become widespread and problematic; by that time, it is too late for successful eradication.

Understanding impacts of biological invasions: Most reserves carry out some level of monitoring of biological communities and physical habitat characteristics. Linkages between such existing programs and non-native species monitoring can shed light on the impact of invasions on native communities and habitats. Furthermore, the NERR Graduate Research Fellowship Program, which recognizes invasions as a priority concern, is a useful mechanism for encouraging and funding research on impacts of invasions. Management efforts can then be focused on those species with significant negative impacts.

Identification of aspects of estuaries that make them resistant or vulnerable to invasion: Data from all NERR sites can be integrated into a unique database (with parameters such as landscape setting, habitat types, water quality, disturbance levels, and native biodiversity) that could be used to search for correlates of invasion success. Results can be applied to developing better management strategies for preventing future invasions and controlling existing aliens.

A NATIONAL INVASION MONITORING WORKSHOP

The Aquatic Nuisance Species Task Force developed the concept of holding a workshop to determine how the NERRS could best be used as a platform for national invasion monitoring. They provided funding for the workshop, which was supplemented by the Estuarine Reserve Division of NOAA. The workshop was organized and planned by co-chairs K. Wasson and S. Rumrill, with invaluable advice and assistance (see below). Originally scheduled for mid-September 2001, it was re-scheduled for January 14-18, 2002 following the events of 9/11. The workshop was held at Asilomar Conference Grounds, Pacific Grove, CA, hosted by Elkhorn Slough NERR, the Elkhorn Slough Foundation, and South Slough NERR.

The purpose of the workshop was to bring together invasions biologists, reserve system representatives, and partner organizations to envision an ideal monitoring program for estuarine invasions. While the funding and original conception of the workshop focused on monitoring by the reserve system, the scope was broadened to be applicable to other estuarine ecosystems. The reserve system has not yet committed to invasion monitoring; as biological monitoring is phased in over the next decade, some elements of invasion monitoring may be incorporated. Regardless of the role the reserve system takes in invasion monitoring, the results of the NERR-sponsored workshop will serve as a blueprint for national invasion monitoring useful to any organization considering such efforts. Because estuaries are the most highly invaded marine habitats, the NERRS -- with their existing system-wide monitoring program and centralized data management -- may serve as ideal sites to host invasion monitoring programs, even if other organizations take the lead.

The primary goals of the workshop were:

1) identification and prioritization of national invasion monitoring questions,

2) ranking of priority native habitats and non-native taxa to be the focus of monitoring,

3) design of illustrative monitoring programs incorporating the above priorities, and

4) consideration of joint or complementary efforts by various organizations to create an integrated national invasion monitoring program

There are many other important aspects of non-indigenous species that were <u>not</u> addressed, such as reviews of invasive diversity and impacts, consideration of small-scale, short-term scientific studies to carry out, control strategies for nuisance species, and prevention of ballast water transport. These topics are being discussed in other forums. In contrast, little attention has been paid to designing long-term monitoring programs with consistent sampling at a broad geographic scale. This is what our workshop focused on exclusively. Working together, we envisioned an ideal national monitoring program for estuarine invasions, and brainstormed about how it might be implemented.

WORKSHOP PARTICIPANTS

Invasion biologists

Jeb Byers	*University of New Hampshire*
Jim Carlton	*Williams College*
Ted Grosholz	*University of California, Davis*
Lisa Levin	*Scripps Institution of Oceanography*
Claudia Mills	*Friday Harbor Laboratories, University of Washington*
Ingrid Parker	*University of California, Santa Cruz*
Greg Ruiz	*Smithsonian Environmental Research Center*
Susan Williams	*Bodega Marine Laboratory, University of California*
Bob Whitlatch	*University of Connecticut*

Partner Agency Representatives

Liz Chornesky	*The Nature Conservancy*
Giselle Firme	*Office of the Chief Scientist*
Sharon Gross	*Aquatic Nuisance Species Task Force, USFWS*
Thomas Johengen	*NOAA- University of Michigan Cooperative Institute*
Henry Lee II	*US Environmental Protection Agency*
Judith Pederson	*Massachusetts (MIT) Sea Grant College Program*
Mario Tamburri	*Monterey Bay National Marine Sanctuary*
Donna Turgeon	*NOAA- National Centers for Coastal Ocean Science*
Charlie Wahle	*NOAA-Institute for Marine Protected Areas Science*
Dean Wilkinson	*National Invasive Species Council*

NERR Representatives

NOAA Estuarine Reserve Division		Maurice Crawford
Alabama	Weeks Bay NERR	Scott Phipps
Alaska	Kachemak Bay NERR	Carl Schoch
California	Elkhorn Slough NERR	Becky Christensen, Beth Inman, Kim Hayes, Kenton Parker, Kerstin Wasson
	San Francisco Bay NERR	Todd Hopkins
Florida	Apalachicola NERR	Lee Edmiston
	Rookery Bay NERR	Mike Shirley
Georgia	Sapelo Island NERR	Dorset Hurley
Maine	Wells NERR	Michele Dionne
Mississippi	Grand Bay NERR	Peter Hoar
New Hampshire	Great Bay NERR	Brian Smith
New York	Hudson River NERR	Chuck Nieder
Ohio	Old Woman Creek NERR	Dave Klarer
Oregon	South Slough NERR	Steve Rumrill
Rhode Island	Narragansett NERR	Chris Deacutis
South Carolina	North Inlet-Winyah Bay NERR	Drew Lohrer
Washington	Padilla Bay NERR	Sharon Riggs

Workshop assistance
Jennifer Brown, Stephenie Gutridge-Snode, Cynthia Hays, Sherry Palacios

Workshop coordinator
Jeanne Cureton, South Slough NERR

Workshop co-chairs
Kerstin Wasson, Elkhorn Slough NERR and Steve Rumrill, South Slough NERR

Advisory assistance to the co-chairs
Becky Christensen, Maurice Crawford, Nina Garfield, Peter Hoar, Drew Lohrer, Sharon Riggs

Figure 1. Participants in the January 2002 invasion monitoring workshop at Asilomar.

RECOMMENDATIONS FROM INVASION BIOLOGISTS

Eleven invasion biologists were asked to prepare written recommendations outlining an ideal national monitoring program for estuarine invasions. These are included in their entirety in Appendix 1. Perspectives from the national Sea Grant program are provided in Appendix 2. Oral presentations given at the workshop summarized these recommendations. A few themes and issues emerged from these recommendations and informed subsequent discussions:

<u>Baseline biological monitoring</u>: a recurrent theme was the need for consistent monitoring across multiple estuaries to detect long-term shifts in estuarine communities driven by various stresses (non-native species, shoreline development, sea level rise, etc.); data generated from such a monitoring program would be valuable for coastal management and policy as well as estuarine science.

<u>Native and non-native species</u>: most speakers concurred that any monitoring program should include both native and non-native species; even if the primary focus is invasions, much can be learned about their impacts by assessing natives at the same time.

Physical variables: repeated reference was made to the value of sampling physical variables in conjunction with biological parameters; this allows statistical analyses to be carried out to examine correlates of diversity and abundance patterns.

NERRS as platform: many highlighted the value of using the reserve system as a platform for a biological monitoring program that could be carried out across unprecedented spatial and temporal scales at estuaries; various speakers also suggested including estuaries outside the NERRS to obtain a more comprehensive characterization of North American estuarine ecosystems.

Central database: many emphasized the importance of making monitoring data easily accessible to scientists in a consistent format (e.g., for non-native species information, submitting data to existing databases developed by other organizations).

Estuarine reference collection: various speakers suggested that the reserve system could provide a valuable service by archiving vouchers of all species identified in a biological monitoring program, preserved both for subsequent morphological and genetic investigations.

Taxonomic expertise: to carry out comprehensive characterizations of species diversity, or even to identify new invaders in most taxa (except for well-characterized large animals and plants), highly skilled taxonomists are required, and these are becoming scarce.

Question-driven monitoring: many speakers emphasized the importance of designing a question-driven monitoring program with the goal not only of describing patterns, but also of unraveling the processes behind them; others argued that it is difficult to identify questions in advance, and that carrying out a broad assessment of changes over time will enable novel questions to be formulated and answered in the future.

INVASION MONITORING QUESTIONS

Identification of critical questions

The first step in designing a focused monitoring program is to identify the key questions that it should answer. In this case, we were interested in questions that need to be answered at a broad geographic scale and over long time periods, rather than ones that could be answered by short-term studies at small spatial scales. Our particular interest was in identifying questions suited to a monitoring program at the estuarine reserves, but we kept discussion at a big picture, broad conceptual level that is applicable to other habitats and organizational structures.

Workshop participants generated key invasion monitoring questions in break-out sessions, and described the sort of approach required to answer them and the benefits of obtaining the answers to 1) the science of invasion biology or 2) coastal management. A comprehensive list of all questions identified by this process is provided in Appendix 3. Because there was considerable overlap between questions, they were grouped and combined during the breakout groups. Next, in a plenary session, these questions were shared. This process led to an overall consensus on the top invasion monitoring questions.

Seven high priority questions emerged (Table 1). As a result of the consensus process these questions were stated in very general terms; any monitoring program would need to narrow them to more specific questions. Five of the questions focused directly on non-native species: early detection of new invasions, impacts of invaders, and factors that mediate invasion success, including propagule pressure, intrinsic traits of the invader, and characteristics of the recipient environment. Two of the questions more broadly considered biological communities (both native and non-native species), focusing on species richness and abundance, respectively.

Ranking of questions

The workshop participants scored the seven priority questions according to five criteria. The results were then summarized into a table showing the ranks of each question according to each criterion (Table 1). The advantage of this process is that the criteria are explicit, and each can be considered separately, or the joint result can be examined.

Overall, the top questions were those about species richness and abundance, environmental correlates of invasion success, and early detection. The top rankings received by richness and abundance questions reflect the importance the participants attributed to having good baseline information and to carrying out consistent biological monitoring of both native and non-native species across estuaries. Many participants indicated that basic biological monitoring should be the starting point, from which more focused questions about invasions (or other ecological threats) could be developed. Indeed, various people suggested that knowledge about richness and abundance of estuarine species are a prerequisite to early detection of new invasions or examination of their impacts. Others disagreed, pointing out that monitoring need not be comprehensive across all taxa, and that focused studies of new invasions or impacts of a few species across all estuaries could be carried out without baseline information about the rest of the community.

Examination of the rankings of questions across different criteria reveals contrasting values. For instance, species richness received a low rank for management benefit and scientific value, but garnered the top rank for suitability for a national program, affordability, and feasibility. On the other hand, understanding impacts of non-native species received high scores for management and science, but low scores for the other three criteria: apparently this is an important question, but not one considered very suitable for a national monitoring program. Early detection was considered a high priority for management, but received the lowest ranking for scientific value. Questions about correlates of invasion success received medium to low rankings.

Illustrative monitoring programs for the priority questions

For the four questions that garnered the top total rankings (those about early detection, abundance, richness, and environmental correlates), workshop participants developed illustrative monitoring programs. Participants were divided into four breakout groups, each of which tackled one question. The overall goal was to develop general recommendations useful to any organization considering monitoring programs in these areas, and to provide specific examples to illustrate such monitoring. Because each priority question was phrased very broadly, the first step was to narrow it by taxon or habitat. Next, methods were considered, including issues such as whether sampling must be quantitative (vs. qualitative), whether remote sensing could be used, whether taxonomic experts are required, etc. Finally, the benefits of monitoring for each question were discussed, including contributions to invasion science and wise coastal management. The four illustrative monitoring programs are summarized in Appendix 4.

TABLE 1. Prioritization of invasion monitoring questions. Seven main questions were identified. Each question is ranked (1=highest, 7=lowest) based on scores assigned by 38 participants in the January 2002 workshop. Ranks are shown separately for each criterion, and for the total score.

QUESTIONS	**CRITERIA**					
	suitability for a national program	afford-ability	feasib-ility	manage-ment benefit	scientific value	**TOTAL**
EARLY DETECTION What and where are the incipient invasions?	4	2	4	2	7	**4**
RICHNESS How many and which native and non-native species occur within specific estuarine habitats, and how does this change over time?	1	1	1	5	5	**1**
ABUNDANCE What are the relative abundances of native and non-native species within estuarine habitats, and how do these change over time?	2	4	2	6	1	**2**
IMPACTS What are the impacts of non-native species on estuarine functions and values?	5	7	6	1	2	**5**
INVASION SUCCESS How is propagule pressure and vector type related to invasion success?	6	5	7	3	6	**6**
How do the intrinsic characteristics (incl. life-history, genetics, etc.) of a species affect its invasive abilities?	7	6	5	7	4	**7**
What are the abiotic and biotic characteristics of the recipient environment that affect invasion success?	3	3	3	4	3	**3**

HIGH PRIORITY ESTUARINE HABITATS FOR INVASION MONITORING

To determine which estuarine habitats should be the focus of invasion monitoring, participants individually scored different habitat types with regard to three criteria (Table 2). Overall, based on the combination of all three criteria, the top ranked estuarine habitat types were marshes, submerged aquatic vegetation, and shellfish beds. These habitat types likely emerged as the highest priority because they are common and ecologically important at many estuaries across a broad geographic range, reasonably accessible and tractable for monitoring, and fragile yet critical for sustaining key estuarine resources. Based on this workshop, any of these top three habitat types would be an excellent choice for a national invasion monitoring program.

Examination of rankings for individual criteria is also informative. Participants deemed submerged aquatic vegetation to be the top priority in terms of suitability for a national program. However in terms of feasibility and affordability, docks, pilings, and other artificial substrates garnered top ranking. Most previous rapid assessments of non-native species at estuaries have indeed focused on these habitats, and Table 2 highlights that this is likely the result of practical advantages, not due to particular scientific or management interest in these habitats. In terms of management concern, shellfish beds (including oysters) were ranked the highest, presumably due to the economic value of these resources, as well as worries about declines in recent decades.

For two habitat types, mudflats/sandflats and rocks/cobble, participants separately scored intertidal vs. subtidal areas (scores have been combined in Table 2 because this distinction did not change overall ranking). Overall, intertidal areas ranked higher than subtidal ones for both soft and hard bottom habitats (Figure 2). Examination of individual criteria revealed that intertidal and subtidal areas are of equal management concern, but intertidal areas are considered both more suitable for a national program and more feasible/affordable to monitor.

During discussions at the workshop, some participants expressed reservations about the prioritization process. In part, the comments simply reflected the difficulty of the task – it is challenging to choose just a few habitats when all merit attention. Yet such difficult choices must often be made, given limited funding and resources. Nevertheless, the point made by some – that it is preferable to survey across habitats, rather than limit a program to one or a few – is an important one that should be considered by those designing well-funded and ambitious future programs. For the reserve system, participants suggested it might be useful to determine which estuarine habitat types are most common in terms of spatial coverage across all sites, and to use this as a criterion for prioritization. Finally, many participants felt prioritization at this early stage in a planning process was somewhat premature. They suggested that prioritization of habitats should occur within a more specific context later in the process: after specific questions have been identified, after the primary user group (scientists vs. managers) has been determined, and after the boundaries of the monitoring endeavor (NERR sites only vs. all estuaries) have been set. Certainly any organization concretely designing an invasion monitoring program should follow this suggestion. However, the prioritization process carried out here, as a part of this broad blueprint for national invasion monitoring, is in itself a useful contribution to guide general planning for future monitoring programs.

TABLE 2. Prioritizing estuarine habitats for invasion monitoring. Each of the eight habitat types is ranked (1=highest, 8=lowest) based on average score assigned by 37 participants in the January 2002 invasion monitoring workshop.				
ESTUARINE HABITAT	**CRITERIA**			
	suitability for a national program	feasibility/ affordability	management concern	**TOTAL**
open water	2	6	5	**4**
mudflats & sandflats	4	3	6	**6**
rocks/cobble	8	8	7	**8**
oyster/shellfish beds	5	5	1	**3**
docks, pilings, other artificial substrates	6	1	8	**5**
marshes	3	2	3	**1**
submerged aquatic vegetation	1	7	2	**2**
riparian	7	4	4	**7**

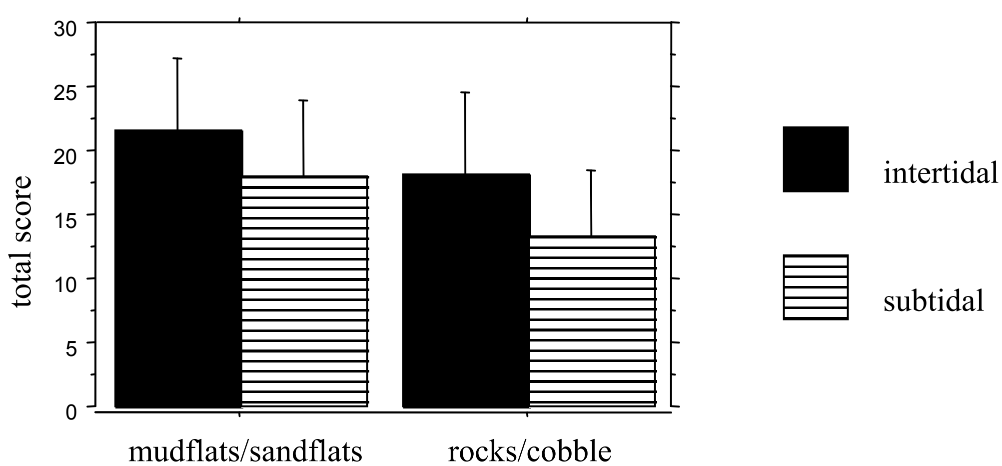

Figure 2. Comparison of the scores received by intertidal vs. subtidal mudflats/sandflats and rocks/cobble. Intertidal habitats scored significantly higher than subtidal ones (P < 0.001), and soft bottoms scored significantly higher than hard substrates (P < 0.001) in a two-way ANOVA analysis. Error bars represent standard deviations.

TAXA TO TARGET FOR INVASION MONITORING

To resolve which groups of organisms should be the target of an invasion monitoring program, participants scored eleven taxa according to five criteria (Table 3). Overall, the top taxa that emerged were plants, mammals, fish, and macroalgae. These probably rose to the top because of the combination of their tractability as study organisms, their potential to influence the ecology of estuaries they invade, and the likelihood that they could be eradicated if necessary. Members of all four groups are relatively easy to identify even by non-experts. Some non-native plants and macroalgae have been shown to dramatically alter the physical structure of habitats they invade, while some non-native mammals and fish have altered communities due to their high trophic position. Eradication or control efforts have been attempted, at least somewhat successfully, for all four taxa.

Each criterion revealed different patterns. Participants were asked to score each taxon for each criterion; the average of these scores was used to determine the final ranking shown in Table 3. In terms of ease of collection, most taxa had relatively high average scores, with plants ranking first. For ease of identification, average scores were quite low, with mammals making the top of the list. Bacteria, fungi, viruses, and protoctists all scored below 4 (1=hardest, 10=easiest): they were considered very difficult taxonomically. Ability to be controlled also had very low average scores across the board. Mammals again garnered the top rank, with plants, birds, and macroalgae following. The remaining seven taxa all had an average score below 4, indicating that participants considered them very difficult to control. In terms of management concern, plants ranked the highest. Most of the other taxa received quite high average scores, suggesting that non-native species of concern span broad phylogenetic categories. Only fungi and protoctists received quite low scores, perhaps indicating more than anything a lack of familiarity with these taxa and the potential problems they create.

The invertebrates had originally been broken down into various taxa for prioritization, but many participants did not feel qualified to evaluate them, so a single invertebrate category was used. In discussions, however, recommendations were made that particular groups of invertebrates would be most fruitful for an invasion monitoring program, because they are readily collected and identified by non-experts, and because they are known to include frequently introduced species. Examples of such invertebrate taxa are decapod crustaceans (particularly crabs), bivalve mollusks, and ascidians (sea squirts).

As with the habitats, participants found this prioritization process challenging, and emphasized that it would be more useful in a specific context, with questions, boundaries, and user-groups identified. Furthermore, coming up with a single score for each taxon was difficult, because for each group there are examples of very aggressive invasive species, and yet also many innocuous members; there are species that are easy to identify, and others that are difficult, etc. Despite these caveats, most participants completely filled out chart with educated guesses. The resulting rankings (Table 3) – from a group of almost 40 invasion biologists, government scientists and estuarine reserve representatives – should therefore be reliable as a broad prioritization of estuarine taxa to be monitored.

Throughout the discussion of prioritization of taxa for monitoring, there was a strong consensus among the participants that both native and non-native members of the groups should be monitored. In this way, changes in native species abundance, distribution, or richness can be assessed in response to new invasions, but also with regard to other anthropogenic disturbances or to assess success of management or restoration strategies.

TABLE 3. Targeting taxa for invasion monitoring. Each of the eleven taxa (which in a typical estuary include many native and some non-native members) is ranked (1=highest, 11=lowest) based on average score assigned by 35 participants in the January 2002 invasion monitoring workshop.

TAXA	**CRITERIA**				
	ease of collection	ease of identification	ability to be controlled	management concern	**TOTAL**
viruses	10	11	11	8	**10**
bacteria	9	9	8	7	**8**
fungi	11	10	7	10	**11**
phytoplankton	3	7	9	5	**7**
other protoctists	8	8	10	11	**9**
macroalgae	2	5	4	3	**4**
plants	1	4	2	1	**1**
fish	4	3	5	2	**3**
mammals	7	1	1	4	**2**
birds	6	2	3	9	**5**
invertebrates	5	6	6	6	**6**

BIOLOGICAL MONITORING AT THE NERRS

A recurrent theme in all sessions of the workshop was the importance and feasibility of carrying out biological monitoring at the NERRS. In terms of invasion monitoring, there was consensus that both native and non-native species should be included in most programs, which in effect would result in biological monitoring. The top questions identified concerned abundance and species richness, key elements of any biological monitoring program. The experts and agency representatives from outside the reserve system were surprised that there is not yet any system-wide, NOAA-funded biological monitoring being conducted at the reserves: the system as a whole cannot answer questions about estuarine biological resources and the factors that may be influencing them. These outside participants were excited about the prospect of biological monitoring, especially since the data about populations could be linked closely to the existing water quality and weather data, providing an unprecedented monitoring program of estuarine ecosystems.

Until now, system-wide biological monitoring has been considered but not implemented at the NERRS, due to lack of adequate funding, and because of the difficulty of reaching consensus about best approaches. Indeed, it will be very challenging to design protocols that are ecologically relevant and feasible across the diverse habitats and biogeography of the 25 reserves. However, perhaps stimulated in part by the interest and enthusiasm expressed at the invasion workshop, the reserve system is now developing and evaluating a number of potential biological monitoring protocols that could be implemented in the near future.

As a first step, ten reserves are voluntarily participating in a pilot program to monitor native and non-native populations of crabs. This project (funded by NOAA, but external to the NERRS) includes 1) preparation of “least wanted” species cards highlighting undesirable invasive crabs, 2) dissemination of these cards and information about biological invasions to the local communities through coastal decision-maker workshops, and 3) standardized biological monitoring for native and non-native crabs and data management by each of the ten sites.

OPPORTUNITIES FOR PARTNERSHIP

One of the most rewarding aspects of the invasion monitoring workshop was the interaction between different groups: academics with expertise in invasion biology, reserve system staff who work on the ground at estuarine reserves, and senior representatives of many different resource management agencies. There was general agreement that the interactions and discussions – both during formal sessions and informally after hours – were extremely fruitful. In this sense, the invasion workshop may serve as a model for future endeavors, where multiple perspectives and joint brainstorming can be beneficial.

Throughout the workshop, and particularly in a dedicated session on the last day, there was discussion of potential partnerships in national monitoring programs. The highlights of these discussions are summarized below.

Alliances between the NERRS and other national agencies or organizations

A number of agencies have an interest either in invasions or monitoring or both. The Aquatic Nuisance Species Task Force and National Invasive Species Council are both comprised of many different agency representatives, and are good starting points to look for links between agencies working on non-native species issues. Natural partners for reserve system biological monitoring efforts include:

- EPA-EMAP program, which carries out quantitative sampling of environmental and biological parameters across estuaries

- EPA-National Estuaries Program, which helps non-NERR estuaries build management and conservation programs, including monitoring

- National Association of Marine Laboratories, which have a developing interest in monitoring of non-native species

- National Science Foundation – Long Term Ecological Research program, which funds intensive site-based investigations, including some estuarine projects

- NOAA-National Centers for Coastal Ocean Science, which include a program of quantitative infaunal surveys, and a new early warning system for coastal marine invasive species

- The Nature Conservancy, which undergoes comprehensive eco-regional planning, has a growing marine conservation program, and is pursuing an ambitious invasions initiative

Partnerships with such groups would have the benefit of extending the geographic coverage of monitoring. Agencies or organizations working together would also have a stronger voice with which to apply for funding, or shape national invasions policy. They could share expertise, and thus reduce the cost per site of carrying out monitoring. A critical prerequisite to a partnered program is an explicit understanding of the roles of each organization, with agreement as to the costs and benefits to each.

Academic involvement in agency monitoring programs

Workshop participants stressed the benefits of collaboration between agencies carrying out national monitoring programs and academic experts. For instance, taxonomy is the backbone of any broad monitoring program, so engaging taxonomists in collaborations would be critical. The taxonomists could be wooed by the potential for access to extensive material from a broad geographic range. In return, the monitoring program should include explicit provisions for enhancing the field of taxonomy, including encouraging more training for new taxonomists and creation of permanent positions for them.

Collaboration with ecologists would be equally essential. These scientists could be attracted by the prospect of geographically and temporally extensive data sets that could be mined for intriguing patterns, and could be used to test hypotheses. The mechanistic understanding of monitoring results that ecologists could provide, particularly if they carry out manipulative experiments to augment the monitoring would enhance the monitoring program.

Funding opportunities

A variety of funding sources are available for broadscale monitoring programs. For any NERR biological monitoring, NOAA funds are obvious sources, and have been successfully garnered in the past for system-wide monitoring. For invasion work in particular, Sea Grant is a superb source for prevention, control, and planning of monitoring programs (but unfortunately not for implementing monitoring). Invasions are extremely relevant to the CZMA, so funds could perhaps be sought through this source.

Workshop participants noted that the issue of estuarine invasions has a low profile currently, at NOAA and at other agencies. Greater publicity for the threat posed by non-native estuarine species – such as in the form of a brochure highlighting colorful, notorious examples for each region, and the negative impacts they have had on native communities – would enhance the ability of the NERRS to secure funding for invasion monitoring. Once the threats are better recognized, a compelling case could be made for the important role the reserve system could play as an early warning system for non-native species, with the reserves as sentinels of new invasions.

Outreach to the public, legislators, and local organizations

To generate more funding, improve the effectiveness of policy, and gain volunteer assistance with monitoring, outreach is critical. The NERR Coastal Training Program, directed at informing coastal decision-makers, would be admirably suited to address this need. Workshops for local officials, for relevant industries (fisheries, recreation), and environmental non-profits could help to raise the profile of non-native species at estuaries. Partnerships with these elements of the local communities would strengthen and complement any national invasion monitoring program.

NEXT STEPS

The invasion monitoring workshop has laid the groundwork for the reserve system or any other interested organization to proceed with the development of a national invasion monitoring program. Critical next steps identified and discussed above include 1) development of partnerships between interested agencies, 2) collaboration with academic scientists and taxonomic experts, 3) further refinement of questions, taxa, and habitats most relevant to the participating partners, 4) development of protocols to be used consistently across time and space, and 5) establishment of a database for national invasion monitoring data. After these steps have been completed, implementation of an invasion monitoring program across estuaries can begin. We hope this process will come to fruition in the near future. Invasions of our nation's estuaries are continuing unabated, and monitoring is one powerful tool to aid in their prevention, early detection, and control.

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APPENDIX 1. Recommendations from invasion biologists.

Recommendations were solicited from the eleven invasion biologists invited to the NERRS workshop. They were asked to:

1) Briefly describe an ideal national monitoring program to be carried out at the reserve system for answering a prominent (unanswered) question in the field of invasion biology;
2) Give an example of how the data resulting from such a monitoring program would be or would have been helpful to you in the course of one of your own scientific investigations of invasions;
3) Would the type of monitoring program you propose also be useful to coastal managers (e.g., for designing prevention or control strategies) or would it be of more basic scientific interest?
4) If applicable, illustrate (with a hypothetical or retrospective example) how data from your ideal monitoring program would be or would have been useful to coastal managers.

The invasion biologists presented their recommendations in oral presentations at the workshop. They also were asked to provide casual written notes to capture the key elements of their recommendations. These informal written recommendations are presented alphabetically below.

MARK BERTNESS, Brown University

Understanding the mechanisms and consequences of biological invasions is an important issue that has received considerable recent attention due to the accelerated rate of anthropogenic introductions over the past few centuries. Of particular concern in estuarine habitats are invasions of numerically dominant habitat modifying organisms like marsh grasses and gregarious filter feeders and top consumers. Invasive habitat modifiers such as cordgrass, mussels, clams and canopy-forming algae like *Codium* are all capable of dramatically impacting estuarine habitats. Invasive top consumers like green crabs are similarly capable of dramatically impacting estuarine communities directly by their control of food webs or indirectly by controlling the abundance of habitat modifying organisms.

Invasive species, however, are not the only or even the most critical anthropogenic problem confronting North American estuaries. Sea-level rise associated with climate change, over harvesting, eutrophication, shoreline development and large-scale manipulations of the freshwater that feeds estuaries are all massive problems. Each of these problems is serious enough, but can also potentially interact with biological invasions to accelerate the homogenization of estuarine biota. The bottom line - North American estuarine habitats are currently undergoing massive change due to human population pressure. Invasive species are only one of the problems. This needs to be kept in perspective in designing any long-term estuarine monitoring program.

The NERRS is a relatively new partnership between NOAA and state or local private organizations. NERRS represents a valuable network of research reserves set aside for research and education. Increasing development pressure on coastal habitats has made the reserves critical refuges for researchers to study coastal systems. The reserve system also has great untapped potential to monitor coastal systems. In spite of wide recognition that estuarine habitats are undergoing or are on the verge of rapid human-induced changes, however, no monitoring program of habitats in the reserve system is in place. This is shameful. NERRS managers cannot really answer such simple critical questions as "How are the biological communities in your reserve changing?" or "What kind of shape are the biological communities in your reserve in?" In 1999 in collaboration with the Ecological Society of America NERRS sponsored a meeting to discuss establishing a system wide monitoring program. The outcome was extremely disappointing. NERRS sites currently only monitor weather conditions and water quality. No monitoring of biological communities is going on or even planned that could detect long-term shifts in estuarine communities driven by the variety of stresses being applied to these habitats by expanding human populations and shoreline development.

Describe an ideal monitoring program to answer invasion biology questions. Any system-wide monitoring program should be designed to detect long-term changes and assess community status as the major objective. Designing a monitoring program to explicitly answer invasion biology questions rather than to best detect change and habitat status, in my opinion, would be irresponsible. It is getting the bandwagon way in front of the horse. Using the current interest in invasive species to get a monitoring program in place, however, is great. An ideal monitoring program would provide annual data on the abundance and distribution of key species along with data on the primary production of the major primary producers. The exact data that would be important to collect would differ among reserves dictated by the types of habitats within each reserve. Using GPS and digital photography could simplify and standardize data collection. On the east coast of North America where most NERRS sites are dominated by salt marshes, monitoring permanent plots on zonal borders, fish and crustacean utilization of marsh creeks, the primary productivity of cordgrass and the abundance and distribution of shallow water benthic assemblages, including seagrass beds, would generate a data set that would detect short and long term changes in these system including the spread of invasive species.

How would the results of this sort of monitoring program be of value in investigations of invasions? A broadly designed monitoring program for NERRS biological communities would provide an unprecedented data set that would give reserve managers hard data on the status of their reserves biological resources. This would include the impact and spread of invasive species, but not be constrained by focusing only on invasive species.

Would the type of monitoring program you propose be useful to managers or would it be of more scientific interest? The general type of monitoring program I envision would be immensely valuable to both reserve managers and estuarine scientists. Monitoring efforts targeted on quantifying the abundance of specific taxa are shortsighted because they can typically only address anticipated questions. A long-term monitoring program focused on assessing the status and detecting change in reserve communities would give resource managers the quantitative data they need to convince funding agencies and the public that changes are occurring in North American estuaries. This would include documenting invasions, but would also detect changes due to sea-level rise, eutrophication and other anthropogenic forces impacting estuaries.

How would the data from this monitoring program have been useful to coastal managers? Currently Narragansett Bay, where I do much of my work, is being heavily impacted by shoreline development, eutrophication and population expansions of nuisance species, some of which may be non-native. In many shallow water benthic habitats shoreline development is precipitating eutrophication, which is leading to anoxia and dense blooms of weedy, ephemeral seaweeds that are suffocating the benthic community. In adjacent salt marshes, increased nitrogen loading is upsetting the traditional competitive relationships of the marsh building halophytes leading to marshes being displaced by monocultures of cordgrass and *Phragmites*. Unfortunately, it is very difficult to unambiguously document even these massive changes since virtually no baseline data exist. If a basic biological community monitoring program had been established 20 years ago, these changes would be well documented and easy to communicate to the general public, regulatory agencies and the scientific community.

JEB BYERS, University of New Hampshire

1. Ideal program to answer unanswered invasion questions

My questions of interest:

- Why are invaders absent from seemingly suitable habitat?
- What causes lag times in invading species' population growth and spatial spread?

To answer these and almost any other question of interest we need: long time scale, large spatial scale data.

Given the infrastructure/networking of NERRS and resources, they provide a great opportunity to gather data on invasions at a large, macro-scale. The monitoring of invaders I feel would function best is NOT to try and serve as a mechanism for impact detection on native species, which is often the focus of many biological monitoring programs (far too much must be known; lag times are too great). The great strength of this program would be in providing baseline data on population trends in invaders for those interested in researching further into mechanisms of success, impact, etc. Providing such a "springboard" can give scientists entering the system a real leg up and time savings on understanding dynamics of the invader and its interactions with natives. Furthermore it gathers data for addressing interesting issues of invasions like lag times in population expansion and spread, which require quality, long term data sets. For this program it would be important to sample effectively and keep a running list of invaders in other regional areas that are NOT present AND the degree to which these species were sampled or looked for (to enable ad hoc power assessment). The other real advantage of this NERR network is that it provides an opportunity for consistent sampling methods and efforts (similar to West Coast PISCO project). Finally, the wide geographic spread of NERRS is nice because can help define edges of range which in many cases may be moving.

Summary/highlights of program:

- Focus NOT on detection of impacts of invaders, but on measuring population numbers of species (both exotic and native)
- Measure densities and create GIS maps of distributions through time
- Measure as many physical variables as possible (this usual cheap and easy automated); already being done to some extent at NERRS
- Consistent techniques and protocol. One NERR person to direct/oversee all to ensure results will be comparable from site to site (similar to PISCO layout)
- Include as many sites outside of reserves as possible—NERRs are far spaced.
- Include many sites where species are absent AND degree to which these species were sampled or looked for (to enable ad hoc power assessment). Sites of absence are equally important as sites of presence in multivariate analyses; determining why a species is absent in a place may be just as insightful as why it is present somewhere else. Sites of absence may also direct/enable vigilance at uninvaded areas because it is far easier to exclude then extirpate an

invader. Furthermore, data on sites where a specific invader initially is not present (but arrives after monitoring has begun) provides a complete data set on species colonization, population growth, founder effects, etc.—all the juicy bits that we usually miss in invasions because they are not noticed until several (or unknown) number of years after invasion.

2. **Example of how such data would have been useful to me**

Nuttallia obscurata

I conducted large-scale sampling and revealed an interesting consistent pattern in this invasive clam's distribution. I then went in and tested mechanisms that may have been driving the invasive clam's distribution on beaches which turned out to be very deterministically set. (Deterministic mechanisms are always a plus from a management perspective because intervention is made much more straightforward). With large-scale data, such a pattern may have been visible from the start, i.e. before I went out and sampled 35 sites from scratch. Such existing data would have been guaranteed to draw a researcher like me into this system, and would have given me a leg up in data collection and in the extent/spatial scale I could reference.

Cerithidea--Batillaria

I delved into this system pretty deeply for my dissertation. There were a number of interesting biological questions and directions I could have gone if I had had access to long-term data from a broad spatial scale. Since I didn't want to spend an eternity in graduate school, I did experiments at only one site and used my own necessarily limited data set. I also had to resort to some molecular techniques to get around my lack of large spatial scale data. A larger data set would have provided geographic replication and broadened my results. For instance, with *Batillaria* population data from Elkhorn, I could have better addressed some of the issues of population lag.

In general, there are scientists investing lots of time into such systems and questions about invisibility. The more of a head-start you can give them, and more temptation you provide with free data sets, the more research you will attract to the issue of invasions and to the NERRS in general!

3. and 4. Useful to managers, or scientific interest? Example

Monitoring data is useful to both – there is definitely a feedback loop between science and management. Some of my work has shown that simply knowing which invaders are increasing in abundance and anticipating the effects they might have on native biota can be a good starting point for prioritizing species for management intervention. But this gathering of data on invader populations also serves basic scientists since you will be generating the long-term data sets which are useful for reasons detailed above. And the more long-term data is available, the more you will have scientists salivating, eager to research aspects of your reserve!

TED GROSHOLZ, University of California, Davis

(The letters A-E reference different monitoring suggestions described under the first question; these same monitoring regimes are discussed under the subsequent questions).

1) *Briefly describe an ideal national monitoring program to be carried out at the NERRs for answering a prominent (unanswered) question in the field of invasion biology.*

A. A one-time census (not monitoring) of invasive species in NERR sites and in paired, unmanaged estuarine sites. Questions: Do Estuarine Protected Areas (EPAs) such as NERRs have fewer invasive species than similar unmanaged areas? Is there a positive or a negative association between the number of native species and the number of invasive species? Is there a relationship between the number of invaders and the proximity of that NERR to a major port, aquaculture facility, or other invasion source?
B. Annual site-wide monitoring of invasive species in each NERR. Questions: What are the rates of new invasions for individual NERR? What is the aggregate rate of new invasions across the US? What is the rate of spread of invaders among NERR sites?
C. Annual monitoring of invasive species with parallel monitoring of water quality. Questions: What is the relationship between nutrient loading and the number of invaders across all NERRs? What is the relationship between nutrient loading and the abundance of targeted invaders within a NERR?
D. One time collection (distinct from census), with annual follow-up for new records, of all invasive species for genetic analysis and museum archives.
E. Annual monitoring of stable isotope signatures for key taxa (primary producers, primary and secondary consumers, top predators) to identify changing trophic position within food webs.

2) *Give an example of how the data resulting from such a monitoring program would be or would have been helpful to you in the course of one of your own scientific investigations of invasions.*
   A. This would have allowed me the opportunity of incorporating data from EPAs and control sites with MPAs and control sites to ask whether this broad category of managed areas (MPAs and EPAs) have fewer exotic species.
   B. I would like to know how invaded Elkhorn Slough is relative to other NERRs. I would also like to know to what degree invaders are moving between NERRs. This would also help to quantify the risk of new invasions for a particular NERR such as Elkhorn Slough.
   C. I am interested to know what human impacts contribute to invasions. I would also like to know to what degree fluctuations in estuarine food webs might are driven by nutrient availability.
   D. This would help with certainty of species identity, which is a constant problem for invasive species research.
   E. This would provide information regarding the changing trophic positions and nutrient sources for invading species

3) *Would the type of monitoring program you propose also be useful to coastal managers (e.g., for designing prevention or control strategies) or would it be of more basic scientific interest?*
   A.-E. Each of these monitoring regimes would be useful to coastal managers as well as being of basic scientific interest.

4) *If applicable, illustrate (with a hypothetical or retrospective example) how data from your ideal monitoring program would be or would have been useful to coastal managers.*
   A. It would be very useful to help coastal managers prioritize NERR sites in need of additional resources for invasive species management. It would also help with prioritizing areas adjacent to the NERR sites for future inclusion within an existing NERR.
   B. This program would allow the prioritization of NERR sites with respect to their risk of future invasion and help with distributing resources and initiating programs aimed at preventing new invasions.
   C. This would permit assessing a pervasive human impact that is known to alter the abundance of exotic species, and that can be reduced under certain management practices.
   D. This would help distinguish new invasions from older invasions, help to identify the source of some invaders, and provide references for management activities.
   E. This would permit allow managers to determine whether prey choices have been altered (potentially leading to declining fish and shorebird populations) after a new predator invaders a NERR.

LISA LEVIN, Scripps Institution of Oceanography

Why Monitor Non-Native Species Invasions?
<u>Invaders can damage the reserve systems by:</u>

*altering habitat structure (ecosystem engineers) & causing habitat loss
*altering food web structure/energy flow
*changing species composition through competition or predation
*hybridization and alteration of genetic structure
*introduction of parasites, differential susceptibility to disease

Early detection promotes successful eradication (sometimes)

Key Scientific Questions

- What factors determine ecosystem invasibility and does this vary for different types of invaders? What promotes ecosystem resistance to invasion? Tolerance following invasion? Does invader genetics play a role?

- What determines the 'threat' caused by invaders? (structural, functional, genetic mixing). Can restored systems provide a key?

- What role does temporal variation play in the invasion process? (El Niño, seasonality, drought, global warming, UV radiation). Do climate change 'events' trigger invasions?

- **What invasions are likely to cause structural/ habitat shifts and what are the consequences?**
  -Unvegetated (tidal flat) to vegetated (*Spartina* or *Zostera* invasion)
  -Vegetated in one form to another (*Salicornia* to *Spartina*, *Spartina* to *Phragmites*)
  -Vegetated to unvegetated (insect pests, *Sphaeroma*)

-Sandflat to mudflat/mat (*Musculista*)
-Bare surface to fouled (*Dreissenia*)

Monitoring Goals

A. Tier 1. Structural Features:

Species list (presence)
Species abundance & distribution (focus on keystone, endangered species)
Habitat cover and distribution

B. Tier 2. Functional Features:

Species genetic structure (track hybridization)
Species size/age structure
Food web structure
Habitat support functions:
- Nursery habitat (focus on endangered or commercially valuable?)
- Refugia for different life stages
- Feeding grounds

Linkages among habitats

Monitoring program

- Time series of aerial digital photos (during growing season, IR), GIS mapping
- Focus on habitat distribution, keystone taxa and associated community
- Ground truthing (regular transects)

Target Taxa: Vascular plants, algae and invertebrates, insects and fish that:
(a) have key roles as habitat modifiers
(e.g., *Spartina, Pharagmites, Sphaeroma, Musculista, Caulerpa, Zostera*)
(b) may hybridize with natives (e.g., *Spartina,* Mytilids)
(c) may destroy habitat-structuring species (insect grazers, parasites etc.)
(d) spread easily (e.g., long distance planktonic dispersal or windborne dispersal)

Target Habitats:

Tidal Flat - most endangered coastal habitat on the Pacific coast.
Vegetated salt marsh
Subtidal Benthos (filterers, foulers)
Water column – changes in food web structure and consumers (fish)
Restoration sites (increased susceptibility to invaders).

Monitoring Considerations

- **Focus on most invasible estuaries and most pristine estuaries**
- **Define habitat linkages involving invaders**
  roles of wrack, ontogenetic migrations, parasite transmission
- **Incorporate regional variation into design of monitoring program**

Different habitats dominate, habitats are of different size with different structure and different major threats and considerations (e.g., endangered species), commercially valuable target species, different key functions (e.g., nursery habitat, endangered species habitat).

Monitoring Methods

Attain uniformity within habitat type – across systems
Accommodate habitat differences
Achieve broad habitat coverage (i.e., not just creeks in salt marsh)
Transects/Quadrats – Intertidal/Subtidal/ Photos, aerial imagery
Plant epibiota, Fouling panels, Coring, Plankton

Use of data

- Identification of hotspots (sites of invasion or spread)
- allow study of invasion at inception
  - early eradication,
  - plan for intensive study
- Knowledge of time since invasion
- Linkage to temporal variation – consequences of dry or wet year, warm or cold etc.

When non-natives are detected:

1. Central team assess threat (rank nature and intensity of threat)
2. For those considered serious threats –
   a. Develop follow-up plan, sampling effort to:
      - Assess finer scale abundance and distribution (map)
      - Track functional consequences (food web etc.)
      - Evaluate eradication methods

   b. Develop response strategy

Benefit to coastal managers

Ecosystem and habitat-linkage focus allows:
- Early warning alert
- Multispecies management
- Multiagency management (including watershed)
- Links to restoration efforts
- Biological control measures

EXAMPLE: *SPARTINA* INVASION AND HYBRIDIZATION IN SAN FRANCISCO BAY

Early identification and eradication in any area might have prevented:

- Spread over mudflat
- Use by endangered species, which now prevents control measures
- Restoration effort in vicinity of invasion
- Allowed pre- invasion monitoring to assess habitat use by critical species

Consequences of *Spartina* invasion

- Shift in habitat type from tidal flat to salt marsh
- Altered light and flow regimes, changing sedimentation, redox conditions
- Changes in microphytobenthos production, microbial activity? (under study)
- Changes in sources of production, lability & cycling of organic matter (under study)
- Shifts in animal community composition, influx of invader associates
- Displacement/potential extinction of native marsh plants

- Altered food webs, reduced access of infauna to migratory shore birds

Benefits of Continued (Post-Invasion) Monitoring

- Prevent spread to /invasion of other bays and estuaries
- Generalized model for consequences of wetland plant invasion
- Experimentation with control measures and control consequences
- Adaptive shifts in resource management strategies
- Evaluation of ecosystem recovery rates and trajectories

CLAUDIA MILLS, Friday Harbor Laboratories, University of Washington & JIM CARLTON, Williams College

(1) **The Program**

We propose a two-part monitoring program. The purpose of the program would be to recognize changes in the species composition of the biota at the NERRs, by identifying both human-mediated invasions of new exotic species as well as "natural" invasions as a result of range extensions mediated by global climate change. (We note the question was phrased as, "A program … to answer a prominent unanswered question in the field of invasion biology". The fundamental "prominent" unanswered questions in invasion biology (such as an understanding of the processes that mediate when and where invasions occur such that predictive invasion science becomes a reality) are not, in our opinion, likely to be answered by a national *monitoring* program, unless such also include long-term (multi-decadal), dedicated, and expensive (in terms of time and human endeavor) *experimental* programs).

(a) **Target Guilds Representing Ecological and Physiological Diversity:** We suggest, given the small staff available at each NERR, that four representative groups of marine animals, namely crabs, bivalve mollusks, ascidians (seasquirts), and fish should be quantitatively sampled within each NERR on a regular seasonal basis in lieu of trying to sample the entire fauna frequently. These groups provide sufficient ecological (habitat) and physiological diversity to provide rigorous signals to biotic changes. They were selected because, by and large, they have relatively limited diversity and can be identified with repeatability, confidence, reliability, and accuracy by succeeding generations of moderately-trained individuals. Ascidians and attached bivalves are sampled using standard fouling panels, free-living bivalves are sampled by benthic quadrats or grabs, and fish and crabs are sampled by traps.

(b) **Rapid Assessment Surveys (RAS):** Rapid assessment of the entire fauna by a team of 10–15 taxonomic and regional experts would be very useful once every 5 years. We note that undertaking even one RAS now as a baseline at each NERR would be an ambitious program, as they require a huge organizational effort. RASs, designed around spending approximately one hour at each of 10–20 sites over 4-6 days, have now been accomplished in San Francisco Bay (1993, 1994, 1996, 1997), southern California (2000), Alaska (1998, 1999, 2000), Washington state (1998, 2000, 2001), and southern New England (2000). No RAS has yet been done in any NERRs. Costs are modest, with one RAS costing about $50,000, including funds to pay participants' stipends as well as money to pay additional systematists to help identify material after the expedition. A critical challenge, however, of RASs is that they threaten to exhaust the small pool of taxonomists. We suggest that new taxonomic expertise might be drawn from the ranks of PEET-trained individuals.

(2) **Data use from above monitoring program.**

Synthesizing the data over space (that is, from *all 25 NERRs*) and over time should give a robust indication of invasions due to both exotic introductions and global climate change. Rigorous documentation of these invasions provides the basis for understanding scientific investigations on the role of invasions in altering community structure and function.

(3) **Usefulness of program to coastal managers (e.g., for designing prevention or control strategies) vs basic scientific interest.**

Both programs that we describe are directly useful to both coastal managers and the general scientific community. For coastal managers, evidence that new or increased human-mediated invasions are occurring may provide the needed signal that new or increased vector activity is in play, and indicate the need for increasing vector management strategies. For scientists, see (2).

(4) **How would these data by useful to coastal managers?**
See (3), second sentence.

INGRID PARKER, University of California, Santa Cruz

CENTRAL QUESTIONS:

- What are the relative impacts of different invaders at the same site?
- How much does the answer to that question depend on how you measure impact?
- Does the impact of a single invader vary greatly among sites, and if it does, what determines the impact in any given site?

WHAT WOULD IT REQUIRE TO ANSWER THESE QUESTIONS?

- Coordinated, large-scale monitoring across introduced ranges.
- Intensive study of multiple invasive species at multiple levels of biological organization: behavior and traits of individual interacting species, community responses such as species richness or total cover or vegetation structure, ecosystem responses such as hydrology, nutrient flow.

A HUGE MONITORING CHALLENGE = How should we measure impact?

- Are different measures of impact correlated?

- Is the informal hunch or aesthetic reaction (e.g. "Arundo: yuck.") predictive of more objective criteria such as cost of control or change in species richness per square meter?
- Is areal extent a good enough measure? (Impact = Area x Density x Per Capita Effect)
- Could coarse-scale techniques like remote sensing help us measure impact?
- Are species that are moving the fastest also the ones with biggest impacts?

AS FOR COMPARING IMPACTS AT DIFFERENT SITES:

- Linked series of sites with coordinated scientific programs (e.g., NERR) are one of the only ways to address this question.

HOW WOULD THIS INFORMATION HAVE BEEN USEFUL TO ME?

- We need better coordinated, multi-dimensional studies over a range of scales.

  (In a recent metaanalysis, we assembled a (small) set of studies that recorded different measures of impact for the same invader (plant diversity plus cation exchange capacity of the soil, for example). We found low correlation among measures. However, the available data were also extremely limited. This study underscored for me the importance of more studies that measure impact across a range of metrics, or a range of sites.)

- Are there identifiable traits of certain species that make them high-impact invaders?

  (Recently, invasion biologists seem to be settling into a general consensus that to explain invasions we need to look at the process as an interaction between the invader and the invaded habitat. Never content with consensus, I'd like to know: is this *always* true (beyond, at least, the completely obvious)? Or is impact driven mostly by life history characteristics of the invader that seem to be consistent across habitats?)

HOW WOULD THIS INFORMATION BE USEFUL TO COASTAL MANAGERS?

- To set priorities at anything but the most local scale, we need to know whether impacts are (usually) consistent across sites.
- Managers are busy. In a busy world, it is probably as useful to know which species do *not* have to be worried about, as which species have to be worried about the most.
- We are never going to be able to eliminate all exotic species. Therefore we need a rational scheme for setting control priorities.

  Ecological impact should be a major factor in this scheme (but not the only factor). Can we use a fast and informal assessment of impact based on our gut feelings? Or do we risk missing something important through lack of methodical study and comparison?

ACKNOWLEDGEMENTS:
These ideas have drawn extensively on discussions from the NCEAS working group "Invasion Biology: Toward a Theory of Impacts." To learn more about the products of this working group, see https://www2.nceas.ucsb.edu/admin/db/web.ppage?projid_in=2117
or refer to:
Parker, I.M., D. Simberloff, W.M. Lonsdale, K. Goodell, M. Wonham, P.M. Kareiva, M.H. Williamson, B. Von Holle, P.B. Moyle, J.E. Byers, and L. Goldwasser. 1999. Impact: Toward a framework for understanding the ecological effects of invaders. Biological Invasions 1(1):3-19.

GREG RUIZ, Smithsonian Environmental Research Center
& CHAD HEWIT, CSIRO Centre for Research on Introduced Marine Pests, Australia

Field-based measures are of central importance to science, management, and policy in the area of biological invasions. Field-based measures provide critical data that are necessary to assess the patterns of invasion in space and time, and to adequately test key hypotheses about underlying mechanisms. For example, invasion ecology and management decisions focus on many fundamental questions, such as: (a) what biological characteristics increase invasion success? (b) what makes a system susceptible to invasion? (c) which habitats are most vulnerable to invasion? (d) which vectors are responsible for invasions? (e) what is the rate of invasions, and (d) how will invasion rate change in response to particular management actions? Without field-based measures, these questions cannot be answered with sufficient confidence to advance basic or applied science, which is needed to both guide and evaluate management actions.

Below we provide a brief overview of design elements for programs to measure (monitor) invasion patterns and outline a possible approach using NERRs. (Note: Much of this discussion is based upon a review article, to be published by Kluwer Academic Press.)

Design Elements of a Monitoring Program

We wish to emphasize the paramount importance of standardized, repeatable measures as the fundamental building blocks for analysis of invasion patterns. In our view, a spatially explicit sampling method is necessary to control for many potential biases that exist in qualitative surveys. In addition, other elements that require attention, having important consequences for the possible analyses and interpretation, include: (a) taxonomic identification, (b) reference or voucher material, (c) geographical information, (d) information management and access, and (e) environmental characteristics. We discuss briefly each of these elements below.

Field Survey. Field measures or surveys are characterized by the specific method of sampling as well as the spatial and temporal scales of sampling, number of samples, and variables measured in each sample. For example, hard substrate communities can be sampled by destructive removal of all organisms in a specific area, by deployment and retrieval of settling plates, or by photographic methods. Samples may be restricted to a particular port or region, a particular habitat type (e.g., depth, substrate, wave exposure), a specific spatial dispersion (random, stratified random, uniform, haphazard), and particular time periods (e.g., seasons or years). Finally, the number of samples collected, method of examination (e.g., use of microscope, inclusion of all taxa), and the type of analysis (species presence, abundance, size structure) may also vary.

Each of these attributes defines functionally the "search effort" and can greatly influence the number or type of species detected. Although search effort should be standardized across space or time, when comparing spatial or temporal patterns (respectively), the most appropriate design will depend upon the goals.

Taxonomy & Reference Material. The quality of data that result from surveys depends greatly upon taxonomic identification and knowledge. Taxonomic expertise is clearly critical to the correct identification of species, as many organisms may go undetected by the untrained observer. Such under-detection can occur even for those with good working knowledge of a local biota who may be unaware of species from other regions that are similar in appearance.

Although the issue of taxonomic identification may appear easily addressed, there are now many groups of organisms for which taxonomic experts are rare or non-existent. Resources and expertise in taxonomy have eroded throughout much of the world in the past decades. As a result, identification of all species may not be immediately available for each survey. This underscores the importance of establishing voucher to provide a curated record of collection, and reference collections which can play a critical role in providing comparative material for both confirmation of known species and resolution of unknown species. Ideally, voucher collections would include both morphological and genetic vouchers, as molecular tools may be particularly effective in resolving taxonomy in some cases.

Geographic Information, Information Management, & Information Access. The utility of surveys can be enhanced greatly by using existing tools to (a) reference all data in a geographically explicit fashion and (b) manage all data in a referential database. Obtaining the latitude and longitude of all sites with a geographical positioning system (GPS), with any additional site descriptions, can be critical for many analyses of temporal or spatial patterns of invasion, especially using results from past surveys or across multiple, independent surveys. Furthermore, databases can provide a powerful tool both to manage survey data, making it possible to rapidly link or share data on a broad scale, and to add further information for analyses.

Although use of databases offers the capacity for information sharing, development and management of such information systems is necessary to achieve this goal. As with surveys, standardized format and syntax will serve to maximize data utility, including synthesis and data access (to public, researchers, and managers).

For example, in a collaborative effort, we have developed a common database format for management of data on marine invasions in our respective survey programs (in Australia and the United States). This tool assures our respective data is collected and managed in similar fashion, and should facilitate the comparisons and analyses across continents that we are now planning. We are also creating web-based access to much of the information, for use by others. We intend to make this database tool freely available to others who may wish to use it, creating opportunities for further collaborations and comparisons.

Environmental Conditions. Environmental conditions may be responsible for, or shape, many invasion patterns. For example, current, temperature, salinity, or nutrient characteristics may play an important role in the invasibility of particular sites or the dominance of particular taxa.

Although the primary focus of many surveys is species detection or measurement of invasion patterns, it is desirable to measure environmental conditions associated with each survey site, and possibly each sample, during the survey period. This approach provides a rich source of information on local conditions, which are not often readily available at the appropriate scale, which can be used to test formally some specific hypotheses about invasion patterns and whether particular covariates explain a significant amount of observed variation.

Example of a Monitoring Program for NERRs

A series of quantitative surveys could be implemented across the network of NERRs sites, designed to measure invasion patterns and rates for any one of multiple habitat types or taxonomic groups. All sites may not be included in each survey type, since all habitats or taxa may not be represented. As an illustrative example, we focus on fouling organisms, for which we have already implemented coordinated surveys for 16 bays and estuaries in North America and four additional sites in Australia.

Survey Design. At each site, a standard number of settling plates (PVC) and wood blocks are deployed in a stratified, random design. Plates are deployed to standard depth, at specific times, and retrieved on a regular schedule. Additional environmental data is collected at each deployment site, using various approaches (e.g., manual readings, automated data-loggers, remote sensing, etc.). Upon retrieval, all organisms present are identified to species.

Various permutations on this basic design are possible. For example, selected core sites could be designated for more intensive analyses (spatial or temporal) of invasion patterns. Sampling strategies can be implemented to test for relationships between invasions and season, depth, salinity, vector activity, etc.

Taxonomic Identification. Although the deployment and retrieval can be accomplished with minimal knowledge of invertebrate taxonomy, the analysis of settling plates is more sensitive to such training. However, one approach is to break the analysis down into multiple steps: (1) collection and vouchering of organisms (via fixation), using a standard approach that does not require specialized knowledge; (2) taxonomic identification and verification by a core group with taxonomic training that is shared among sites (providing consistency and a high level of expertise). We have implemented this approach in current surveys, giving us confidence in its viability.

Voucher specimens should be deposited in properly curated collections (e.g., museums), for ready public access. Additionally, a reference collection of duplicate material should be developed to aid the on-going identification of new material. This reference collection should be maintained by the survey organization and provides working material for comparison.

Data Management & Access. Although each NERRs could maintain data for its own use as well as local / regional use, a great premium should be placed upon (1) implementing a standard database across all participating sites, (2) facilitating linkage and comparison of datasets among sites (ideally through a distributed, web-based network), and (3) access to these data for interested parties.

We wish to emphasize these elements, because the statistical power in testing many key hypotheses about invasions comes from comparisons across sites. Thus, field-based measures must not only be collected in a standard fashion, but maintenance, inter-operability, and access of datasets across sites is also of vital importance.

As discussed above, we have been developing a database structure as a template for this purpose. It presently includes extensive data for North America and Australia, respectively. This may meet NERRs goals, and includes web-based access. However, there are many other means to achieve the same purpose.

Analyses & Purpose. The resulting data would be used to test a broad range of basic and applied hypotheses (questions). For example:

- Comparison across sites allows measurement of spatial pattern of invasion. These spatial data across sites are critical to test for correlation between invasion and a suite of site-based characteristics (e.g., environmental conditions, vector activity, disturbance, diversity).
- Record of the invading species allows for analysis of biological attributes associated with invaders (versus unsuccessful invaders).
- Repeated measures within site provide a sorely needed baseline to estimate rate of invasions over time.
- Comparison of rate of invasion over time, and among sites, is key to assess the effectiveness of management strategies to limit the rate of new invasions. Without such a baseline, it remains impossible to assess which prevention strategies are effective and where further management actions are needed to limit future invasions.

To highlight the importance of such a baseline from a management perspective, we turn to ships' ballast water as an example. At the present time, a great deal of attention and effort is focused on strategies to reduce the risk of ballast-mediated invasion. Guidelines for ballast water exchange are being implemented across the globe, and alternative treatment methods are being advanced. If all ships arriving to U.S. waters today treated their ballast water as requested, how would we know if the strategy was effective? There is no national baseline to measure performance of such management actions, for ballast water or any other vector. We are attempting to build such a baseline in Australia and the U.S. A program of monitoring at NERRs, linked to current efforts, could contribute to an important baseline for this purpose.

BOB WHITLATCH, University of Connecticut

1. What is an ideal national NERRS invasive species monitoring program?

Although there is no 'ideal' invasive species monitoring program (especially given the realities of funding and personnel constraints), focus should likely be placed on: (a) organisms which may have disproportionate impacts on particular habitats (e.g., predators, competitors), native endangered species and ecologically sensitive habitats, and economically important species, (b) organisms which may pose potential public health risks (e.g., diseases, parasites), and (c) habitats which are be unusually susceptible to invasion, and/or act as reservoirs for harboring and/or transmitting invaders.

Establishing an initial inventory list of invaders and habitat/organism relationships is a key first step and conducting regular long-term re-sampling provides a general assessment of the invaders, their relative abundance and the types of habitats in which they are found. The "rapid assessment" approach currently being used to establish inventories seems a reasonable first-step to build upon. Collection of a long-term data-base is essential for establishing baseline conditions as well as patterns of species arrival, types of habitats in which invaders typically occupy and assessing changes in their abundance and dispersion into new habitats. In addition, this information can provide (in conjunction which more detailed process-oriented studies) information on the relative impacts invaders are having and whether management strategies need to be considered reduce/eliminate a particular invader from a given site.

Monitoring programs should be as efficient and routine as possible and specific protocols should be established for data quality assurance and reduce sources of error and variance. Monitoring could be as simple as routine collection of water samples to examine changes in water-column assemblages, exposing fouling panels to monitor fouling species, and large-scale surveys to assess distributions larger invertebrates. Any monitoring program should be geared to specific habitats/regions and it may not be appropriate to always standardize across regions. However, data should be collected in ways that between-region comparisons can be made and quantified. In conjunction with monitoring, focus should also be placed on process-oriented studies geared at answering questions such as: (a) why some species better invaders than others, (b) why are some habitats more invasible than others, and (c) what factors contribute to long-term invasion patterns?

2. Give an example of how monitoring data would be helpful in scientific investigations of invasion?

Our laboratory has been using a local invasive monitoring “network” to assist with designing more specific laboratory and field projects aimed at addressing factors contributing to recruitment dynamics and community structure in shallow water epifaunal assemblages. The monitoring network provides insight into when to conduct certain types of experiments as well as enhances our ability to draw conclusions regarding the importance of factors such as competition and predation in invasion success. Specifically, we are manipulating characteristics of native communities such as species richness, larval supply and the presence and identity of predators and competitors and examine the effects of these manipulations on growth, recruitment and survival of exotic invaders. Critical to these efforts is a continued assessment of the ‘background’ recruitment of native and introduced invertebrates in assessing whether the results of our experiments are likely to be broadly applicable.

3. Would a monitoring program be useful to coastal managers?

Almost any type of invasive species monitoring program should be useful to coastal managers by providing insights into which habitats are particularly vulnerable to invasion, the types and frequencies of aliens entering a region and potentially which species are candidates for control and/or prevention. The latter often requires more specific process-oriented studies as it may be difficult to assess the potential impacts of an invader without more fully understanding life history characteristics, predator-prey interactions, etc.

4. Provide an illustration how monitoring data would be useful to a coastal manager.

Over the last 23 years, mean annual ocean surface temperature has increased in Long Island Sound (Connecticut-New York, USA), with the most pronounced increase in the mean winter water temperature. Similar patterns have been found throughout the New England region over the past 60 years. Over our 11 yr monitoring recruitment record of fouling species, natives species had significantly higher recruitment than invaders. However, invader recruitment was enhanced by warmer winter temperatures (slope = 0.275, $p < 0.01$, $R^2 = 0.49$), whereas native recruitment was decreased (slope = -0.153, $p = 0.10$, $R^2 = 0.32$). Thus, during years with warmer winters, the non-native ascidians out-recruit natives and this, combined with their earlier timing of recruitment, and stronger growth response to temperature, may give them a competitive advantage.

While recruitment onset (date of the arrival of the first recruits) for most marine invertebrates is typically related to the seasonal effects of water temperature on growth and development, we found strong differences in the responses of native and introduced ascidians (sea squirts) to inter-annual variation in temperature. Over the past 11 yr period, recruitment onset of 3 of 4 recently introduced species, (*Botrylloides*, *Diplosoma*, and *Ascidiella*) was negatively correlated with warmer spring water temperatures, indicating recruitment began earlier in warmer years. In contrast, there was no significant relationship between water temperature and onset of recruitment for any of the native species (*Botryllus*, *Ciona*, and *Molgula*). Thus, in warmer years, recruitment begins earlier in the season for introduced species, potentially giving them a "head-start" on the natives.

A concurrent increase in both invasive species abundance and temperature can be confounded with time, and alternative hypotheses underlying the invader success can not be ruled out. Year-to-year recruitment variability associated with temperature suggests over longer time periods (e.g., decades) a warming trend will facilitate the establishment and spread of introduced species, particularly those from warmer climates. These data highlight the fact that even subtle temperature increases can differentially affect resident and invasive species, potentially altering the outcome of species introductions and the composition of biological communities.

It is likely that propagules from the successful invaders arrived via boat traffic and other vectors for much of the 20th century, yet these species did not become established in southern New England until the 1970's and 1980's. This reinforces that propagule supply alone may be insufficient for invader success. Increasing winter water temperatures since the 1970s correlate with the establishment of the four introduced ascidians. Water temperatures in southern New England cover a significant range, from as low as -1°C in the winter to 23°C in the summer, presenting a formidable thermal regime for potential invaders. With the moderation of winter water temperature in the past few decades, warm water invaders are more likely to persist and dominate coastal New England shallow water habitats. Increasing coastal ocean temperatures, coupled with enhanced global transport of species, may be contributing to the observed accelerated invasion rate in these ecosystems.

SUSAN WILLIAMS, Bodega Marine Laboratory, University of California, Davis

Monitoring program for answering a prominent question in invasion biology
Management of invasive species has made strides but remains diffuse, uncoordinated, and terrestrial habitats remain the priority.

NERR monitoring would be a huge advance, especially in combination with ongoing ballast water monitoring authorized under the National Invasive Species Act (NISA).

Why monitor?

- To address basic questions on invasive species ecology (examples listed below)?
  A national system provides a model to tease apart hypotheses re. relative importance of community resistance vs. disturbance because it might be possible to control for bias in sources of invaders. Could also lead to an increased capacity to distinguish dynamics of non-native vs. invasive spp. during lag period of establishment.
  Survey for all non-native species
  For reserve stewardship (to preserve ecological integrity of NERR for research)?
  Requires early detection of species with track records, then eradicate. Requires an *a priori* management commitment/strategy. Early detection monitoring will be intensive and expensive.

  Target known invasive species (example: CA Dept. of Food & Agriculture's semi-quantitative mapping for star thistle)

- To develop monitoring methodology- to establish sensitivity of detection, refine methods? Requires comparison of methods and then adaptive monitoring. Development/ testing of methodology might be one of the most useful contributions that NERR could make to invasive spp. biology.

Questions: We are developing a sense of general attributes of good invaders. Much less is known about the relative importance of invader attributes vs. community vulnerability. Little is known about ecological/economic impacts of invaders; this is required for risk assessment.

- What are the ecosystem attributes that influence invasibility and ecological impacts?
- What is the relative importance of community resistance vs. disturbance in invasibility and ecological impacts?
- How do invasive species rank with other environmental problems in estuaries?
- How does nutrient loading interact with estuarine plant invasions?
- A current hypothesis is that the distribution of invasive species in several small populations leads to faster spread vs. a single large population (Moody & Mack. 1988. J. Appl. Ecol. 25:1009).

National monitoring system might provide a way to control for bias in sources of invaders.

How data from monitoring program would have been/would be useful: in evaluation of the correlation between disturbance and invasibility.

There is evidence that 'healthy' unfragmented seagrass beds are more resistant to a diverse group of invasive species (listed below). In native habitats, some co-exist without overrunning the angiosperm community. A NERR monitoring program including invasive spp. and environmental parameters would have been important to assessing the strength of this correlation.

Asian mussel *Musculista senhousia* (so. CA, Reusch & Williams, 1998, Oecologia 113:428,1999, Oikos 84:398; Japan, SLW pers. obs.); *Bunodeopsis* sp. (Williams & Heck, 2001. In Bertness et al. (eds.), Marine Community Ecology, p. 317-337);

Caulerpa taxifolia- invaded very unnatural degraded habitats in so. CA; evidence from Mediterranean (Chishom et al. 1997, Mar. Poll. Bull. 34:78; Ceccherelli & Cinelli 1997, JEMBE 217:165, 1999, JEMBE 240:19)

Anecdotal accounts suggest that invasive *Codium fragile* ssp. *tomentosoides* invades after kelp or eelgrass are disturbed (Trowbridge, 1998, Ann. Rev. Oceanogr. Mar. Biol.).

Don Strong and colleagues's work in San Francisco Bay suggest that the invasive hybrid of *Spartina alterniflora* and *S. foliosa* are rare in established *S. foliosa* marshes, suggesting a role of disturbance in providing safe sites for hybrid seeds (Ayers et al. 2000, Mole. Biol. 8).

- NERR system is probably large enough for multivariate analysis of environmental parameters, disturbance history, community changes, and invader dynamics. Multivariate analysis of zebra mussel invasions in Europe has lead to a good predictive understanding of which US waterbodies were and will be invaded (Ramchran et al. 1992, Can. J. Fish. Aquat. Sci. 49:1).
- Matter of time before *Musculista* invades Gulf and Atlantic coasts

Monitoring Program:

- Need to involve quantitative/statistical ecologists
- Program must be flexible and undergo periodic review (example: FL Keys Marine Sanctuary monitoring program)
- Beyond mapping- need to have abundance data on wetland plant communities, which are the 'foundation' communities in many NERRs. Monitoring needs to address changes in density; by the time coverage is lost, it is too late to manage.
  Density: estimation can be labor-intensive
  Braun-Blanquet (http://www.eri.nau.edu/applications/lesson 111400.htm): Rapid visual assessment method that estimates abundance using relative categories. Developed/used extensively in Europe and also successfully in assessing decline/recovery of Florida Bay seagrasses.
- Grid-based permanent plots (example: enabled detection of decline in native *Elodea* sp. with increase in non-native *Elodea* sp., Mack, RN in Mooney & Hobbs, Invasive Species in a Changing World)
- Teams of experts- experts are tired!
- Herbarium specimens- can extract DNA
- Monitoring to detect impact is a useful objective because impact will carry program funding
- CRIMP (Centre for Research on Introduced Marine Pests, AU) models (stratified systematic sampling)

Devil's advocate position: Byers & Goldwasser (2001, Ecol. 82:1330) modeled impact of non-native on native snail species and the impact would not have been evident for at least 20 years of monitoring. The impacts of the Asian mussel on eelgrass would not have been evident without manipulative experiments. We need national monitoring program, but will it get us farther faster than strategic experimentation? The potential impact of the species is what carries the message to policy makers and provides information for risk assessments.

Other Needs/Questions:

- Genetic analyses: genetic composition might be critical to invasive plant success. Evidence exists for *Spartina* and is suggested for *Caulerpa.*
- Increased capacity to distinguish dynamics of non-native vs. invasive species during the lag period
- What is the role of physiological stress in limiting invasions in estuaries?
- Estuaries are particularly prone to effects of climate change; programs need to address these effects, including sea level changes.

Economic data should be collected if possible- involving social scientists is important.

APPENDIX 2. Perspectives from the National Sea Grant Office on nonindigenous species research and monitoring.

By Judy Pederson, MIT Sea Grant College Program

Introduction

Introductions of nonindigenous species (NIS) have been identified as the second leading cause of species loss and are responsible for introductions of harmful algal blooms and pathogens. Invasion rates are said to be increasing. The history of regulations largely parallels the presence of species such as the sea lamprey, zebra mussel and other species that cause economic damage. In the Great Lakes and marine environments, shipping has been identified as the most significant vector, however several other vectors also may have a role in recent invasions. Aquaculture, the fresh seafood industry, academia and public aquaria, pet and aquarium stores, recreational boating and fishing, canals, and special activities (e.g. transporting dry docks, oil rigs and barges) have all been identified as potential vectors. Only a small portion of the total available funding for introduced species has been spent on research and monitoring of marine and coastal introductions and most of this has come through NOAA/DOC and sea grant. The policy response on the federal level has been to pass occasional regulations, support research, outreach, and public education, and to establish a Task Force and Invasive Species Council. States have been developing management plans for aquatic nuisance species, preparing clean and dirty lists, and some states have passed ballast water management acts.

The National Sea Grant College Program's Investment in Nonindigenous Species

Since 1990, the National Sea Grant College Program has supported NIS research and outreach projects with a total of $8.0 million dollars during FY 1999/2000 and an expected $2 million more in 2002 (specifically on ballast water technology). The focus of the research has been on patterns of distribution in time and space, ecological and evolutionary consequences, and development and evaluation of prevention and control options. A diverse group of invaders (over 30 taxa including macroinvertebrates, macroalgae, macrophytes and fish) has been included in the investigations. Sea Grant has also supported a major public education component that is intended for a broad audience – from recreational boaters to school age children. In addition, outreach efforts have included support for managing and distributing information through clearinghouses, development of databases, creation of educational materials (such as the zebra mussel trunk) and producing and distributing literally millions of brochures, fact sheets, flyers, videos and other materials intended for a variety of audiences. Sea Grant supports two national/international conferences – the Marine Bioinvasions Conference held biennially and the annual Aquatic Invasive Species Conference.

Prevention and control has been the major focus of recent funding efforts. Some advances realized from the research include development of chemical and mechanical controls, some focused solely on zebra mussels, and others on ballast water in general. Sea Grant has also supported research that tests new ballast water technologies onboard ships, for example, centrifugation, filtration, and various biocides. The testing of new technologies is coordinated with the work of the US Coast Guard's Research and Development Center and the US Environmental Protection Agency's Office of Standards and Technology. But in reality, the amount of funding available is quite limited given the scope of the problem. The elimination of species is rare once they have arrived and even draconian efforts fail to achieve the goal of complete elimination.

What can we learn from monitoring?

We can compare the number of introduced species among regions but numbers do not tell all of it. The total number of introduced species reported for San Francisco Bay is over 210, (including freshwater plants and animals), 139 for the Great Lakes and 100 for the Chesapeake Bay. In a recent rapid assessment survey (funded by Sea Grant and local sponsors) in Massachusetts and Rhode Island, we identified 31 species in the two states with 3 new records of introduced marine species. Are these numbers comparable? Without information on the habitats, areal extent, comparability of methods, time of survey, frequency, and similar taxa, it is difficult to make comparisons with other regions. In Massachusetts another 51 species were identified as cryptogenic and it is likely that some percentage of these are also introduced. In addition there are another 18 introduced brackish and marine species and 7 introduced microscopic organisms that have been identified for the Northwestern Atlantic Ocean (Bay of Fundy to Long Island Sound, J. Carlton unpubl. data). Freshwater plants and animals are not part of this count. What numbers should we be comparing? We know that the Northwestern Atlantic has fewer species and therefore one might expect fewer introductions. Is it the total number of species introduced or the percentage of introduced to native that is relevant? The lack of consistent and comparable data (both from regional and long-term studies) suggests a need for national monitoring.

Another question is, has the number of introductions increased? Similarly do we see an increase in the number within a particular taxa? There is no question that we have recorded an increase in the number of species in recent decades (Cohen and Carlton 1998). However, we have also seen an increase in the number of investigators examining NIS during this same time frame. The increase in particular taxa could also be explained by an increase in the number of investigators studying a particular group. This underscores the need to have long-term monitoring for comparisons of similar taxa in similar habitats. The monitoring of zebra mussels indicates where they are found on floating substrates and where they are found as veligers. The same level of monitoring effort has not been done for marine species.

Is there a need for long-term monitoring? How could the data be used? Information needs identified by Sea Grant are: taxonomic specialists, baseline biodiversity data for marine protected areas, species distributions in time and space, and databases for technology and research keyed by geography, species and technology. Sea Grant is likely to continue funding nonindigenous species research and outreach efforts as well as the design of monitoring programs and data interpretation, but not support implementation of monitoring programs.

Some thoughts on monitoring

Past monitoring programs have not always achieved the goals that were intended for a variety of reasons. One of the best approaches to designing a monitoring program is outlined in the National Research Council (NRC) book (1990). The key to a successful monitoring program is defining the issues, posing testable questions, developing a strategy that can detect meaningful change, and communicating the findings to the public and policy makers. In my opinion, Chapter 4 of the NRC book is a valuable perspective worth reading or rereading as we think about a NERR introduced species monitoring program.

Literature cited

Cohen, Andrew N. and James T. Carlton 1998. Accelerating invasions rate in a highly invaded estuary. Science 270:555-558.

National Research Council 1990. *Managing Troubled Waters: The Role of Marine Environmental Monitoring.* National Academy Press, Washington, D.C.

APPENDIX 3. Compilation of invasion monitoring questions identified by workshop participants.

These questions were generated in break-out group discussions. Each participant was asked to contribute the monitoring question s/he deemed most important, and to briefly explain both the approach required to answer it and the benefit to invasion science or to coastal management of doing so. The questions, approaches, and benefits from various participants have been combined, edited for redundancy, and arranged into broad categories.

SPECIES RICHNESS

Questions include:

- What species are in our estuaries?
- How many non-native species are present in each estuary?
- How is species composition changing over time?
- Which estuaries have the greatest proportion of non-native to native species?
- Which regions have the highest rate of new invasions?
- Which non-native species are present across many or all of our estuaries?
- Which taxa have the highest proportions of non-native to native species?

Approaches include:

- Rapid assessments: brief snapshot surveys by teams of taxonomic experts focusing primarily on non-native species at one estuary at a time
- Thorough, standardized quantitative surveys of particular guilds or taxa carried out by non-experts simultaneously across multiple estuaries (likely in conjunction with abundance assessments)
- Historical research to track long term changes in richness starting with archived museum specimens and early explorer accounts

Benefits include:

- Baseline species lists within and across estuaries
- Prioritization of most heavily invaded estuaries for management attention
- Ability to carry out correlations of invasibility across estuaries, e.g., determining whether polluted estuaries have a higher proportion of non-native to native species
- Prioritization of taxa responsible for most invasions
- Detection of new invasions
- Examination of rates of invasion across time and space
- Comparison and partnership with other agencies carrying out similar surveys in other areas

ABUNDANCE

Questions include:

- What are the relative abundances of native and non-native species within the same habitat type across estuaries?
- What are the relative abundances of native and non-native species within a guild across different habitat types?
- How are relative abundances of native and non-native species changing over time, and how does this differ by region?

Approaches include:

- Quantification of relative abundance of members of a taxon or guild with protocols standardized for methods, search effort, sampling times and sites, etc. so results can be compared across estuaries

Benefits include:

- Comparison of abundance of native indicator species across habitats or estuaries, which may reveal health or vulnerability of different areas
- Comparison of non-native population growth across habitats or estuaries, which gives one measure of relative invasion success
- Better understanding of non-native population trajectories: boom and bust cycles, or time-lags
- Detection of impacts of non-native species on relative abundance of native species, useful for identifying problematic invaders

DISTRIBUTION AND SPREAD

Questions include:

- What is the broad-scale distributional pattern of non-native species of greatest concern?
- What are the rates and patterns of spread of key non-native species?
- Where are incipient invasions occurring?

Approaches include:

- Focused searches (by scientists or general public) for target species
- GIS database on distribution and spread of key invaders

Benefits include:

- Identification of vulnerable locations in advance of invasion through predictive database to be used by managers
- Early detection of new invasions -- early enough for eradication efforts to be worth attempting
- Comparison of rates and patterns of spread may reveal environmental correlates of invasion success

IMPACTS

Questions include:

- What are the impacts of non-native species on ecosystem productivity, biodiversity, community structure, and ecologically sensitive habitats?
- Which non-native species are a particular threat to native communities?
- What classes of invaders cause fundamental shifts in habitat structure and ecosystem function?
- How do impacts of the same non-native species differ across different estuaries?
- What combination of factors (or magnitude of single factor) must change to increase the direct and indirect effects of an non-native species on the habitat?
- How does human-mediated habitat disturbance and hydrological alteration modify the impacts of non-native species?

Approaches include:

- Monitoring of presence and/or abundance of invader in conjunction with physical, chemical, or biological response variables
- BACI (Before, After, Control, Impact) design to compare native community or habitat parameters before and after invasion, in areas with and without invader
- Removal experiments carried out consistently across estuaries
- Habitat monitoring for impact responses, including remote sensing of vegetation from aerial photos
- Evaluation of impacts of invaders on human uses of estuary: public health, fisheries, aesthetics, recreational opportunities

Benefits include:

- Prioritization among different invaders for management and control measures

- Prioritization among different management goals and threats (e.g., determining whether pollution or invasion causes greater harm at an estuary)
- Design of restoration or management strategies by mimicking conditions in estuaries with lesser impacts
- Early warning system for major changes in habitat structure and ecosystem processes, including prediction of future effects

FACTORS THAT MEDIATE INVASION SUCCESS

VECTORS

Questions include:

- How is propagule pressure (number of arriving larvae, seeds, vegetative fragments, etc.) related to invasion success?
- Which vectors are responsible for the most invasions, or those of the most high-impact invaders?
- Are different taxa more likely to be introduced by different vectors?
- How do patterns of invasion over time reflect changes in vectors?

Approaches include:

- Database of non-native species distributions across estuaries, vectors they are likely to be associated with, and intensity with which each vector affects each estuary to determine correlations and make predictions
- Field sampling of arriving propagules (on ship hulls, in ballast tanks, as larvae travelling on currents from nearby ports, etc.)

Benefits include:

- National policy targeting vectors responsible for most new invasions
- Local and regional approaches to understanding and managing relevant vectors
- Prevention of arrival of invaders of particular concern by interfering with transport vector

INTRINSIC CHARACTERISTICS

Questions include:

- How do the intrinsic characteristics (including life history strategy, genetics, etc.) of a species affect its invasive abilities?
- How does the ecological role of a species affect the rate and pattern of its spread?
- What are ecological characteristics of a population in its native vs. non-native habitat?
- Are populations of selected introductions genetically isolated from other populations?

Approaches include:

- Database including traits of invaders and patterns of spread and invasion success
- Short-term biological studies on growth, reproduction and/or life history traits across invaded and native ranges (for some species, could be done across east vs. west coast estuaries)
- Examination of genetic structure at multiple spatial scales

Benefits include:

- Predictive framework for identifying traits of species that make them likely to successfully invade new regions
- Identification of source populations from genetic structure

ENVIRONMENTAL CORRELATES

Questions include:

- How does native diversity affect invasion success and impacts?
- Is invasion success due to release from competition or predation?
- Do invasions facilitate more invasions (the “snowball effect”)?

- How do variation in land use patterns and activity within the watershed contribute to patterns of non-native recruitment, reproduction, growth, etc?
- Do different types of disturbance (human-induced or natural) affect invasibility?
- Are some estuarine habitat types more susceptible to invasions than others?
- What can we learn from restoration projects that will help us control invaders?
- What are the physical and chemical factors that influence invasion success for particular taxa?
- How does proportion of native/non-native species vary along a salinity gradient within estuaries?

Approaches include:

- Simultaneous sampling of non-native species and environmental correlates (e.g., recruitment collectors next to data loggers)
- Database of non-native species composition, native species composition, and environmental parameters (biotic and abiotic) across estuaries
- Sampling within estuaries between habitat types, disturbance regimes, salinity gradients, adjacent human land uses, pollution levels, etc.

Benefits include:

- Identification of factors that make estuaries resistant or vulnerable to invasions
- Predictive framework for determining likelihood of invasion success for particular species according to environmental conditions in recipient area
- Improved management and restoration strategies targeting factors that influence invasion success

APPENDIX 4. Illustrative monitoring programs for priority questions.
The following sections illustrate what a national monitoring program for each of the top four priority monitoring questions would consist of, providing both a general overview and/or specific examples of possible approaches. Each section was written by a different workshop participant reflecting the content of discussions in separate break-out groups during the workshop.

Early detection
Kerstin Wasson, Elkhorn Slough NERR

What and where are the incipient invasions?

NARROWING THE QUESTION
While we ideally want to know about all new invasions, we decided to narrow the question to make answering it more feasible. Since this is primarily a conservation and management issue, we narrowed it to: *what and where are the incipient invasions of species that likely will have severe ecological impacts on the communities they invade, and of species that can potentially be eradicated if detected early after invasion* ?

APPROPRIATE METHODS
Our group determined that there were five interrelated components to a successful methodology for answering this question. Each is briefly outlined below.

Analysis and management planning
The first step is to carry out analyses and strategic planning to determine which non-native species are already present in each region, and then to develop a list of "least wanted" species for each. The former could best be accomplished by a centralized database with information accumulated from multiple agencies. The latter requires making some difficult choices about which non-native species to prioritize. Criteria include: ecological impacts (species known to have created problems elsewhere rank high), ease of identification (macroscopic species with diagnostic traits favored), probability of arrival (a rapidly spreading species found in an adjacent area would rank high), and ability to control if detected (high intertidal species could probably be controlled more easily than subtidal ones, for instance). Examples of the sorts of taxa that would likely be targeted include emergent vascular vegetation (e.g., *Phragmites*, *Arundo*, *Spartina*, taro), submerged vegetation (e.g., *Caulerpa*, *Zostera japonica*, *Egeria*), bivalve molluscs (e.g., *Potamocorbula*, *Corbicula*), decapod crustaceans (e.g., *Carcinus*, *Eriocheir*), and diseases (e.g., cholera). For each "least wanted" invader, some sort of management response plan should be developed so that rapid action can be taken following detection.

Ad hoc information gathering
One approach to early detection would be to involve the public – an inexpensive way of having many more pairs of eyes on the lookout. Fishermen, kayakers, divers and volunteers from environmental organizations could be targeted. This would involve preparation and dissemination of a user-friendly brochure or booklet describing some easy-to-identify "least wanted" invaders likely to be encountered in habitats frequented by the public, and what to do if the invaders are seen (notes taken on exact location, voucher collected if possible, report made to

appropriate authorities). Easy methods of reporting species would be developed (entry on a web-based form; a 1-800-INVADER hotline). Confirmation of each report would be necessary, either by examination of the voucher or by collections at the site where the species was reported.

Targeted surveys
Another approach to early detection would be targeted surveys by trained professionals for particular taxa or in particular habitats. Such surveys would be necessary for taxonomically challenging species, or those found in habitats inaccessible to the general public. Methods would resemble those developed for species richness (see that section in this appendix), but would be more informal ("fast and loose"). Rather than quantitative sampling, these would probably consist of presence/absence surveys, which are quicker and cheaper, and thus can have broader spatial coverage. In some cases surrogates can be effectively employed; for instance, examination of aerial photographs for signatures of habitat change due to invasion of a new emergent plant may be efficient.

Database on spread
To develop a powerful early warning system nationwide, a shared database of invasive species distributions must be created (or existing ones expanded). This requires good coordination between multiple agencies. We envision a web-based set of GIS maps showing distributions of estuarine invaders, and highlighting areas of recent spread. As soon as new reports are made, they can be added to this database, perhaps in two categories: unconfirmed or single individuals taken, or confirmed invasion of multiple individuals. Managers could then use this database to determine which invaders pose an imminent threat to their region. Such a database would feed back into the first step of the methods, analysis and management planning.

Management action
For early detection to be useful, immediate management action must be taken when new invaders are identified in a region. The management response plan developed in the first step of this process should serve as a guideline. After action is taken, effectiveness should be monitored, and results should be communicated. These can then be used to improve and update the management response plans for use elsewhere.

BENEFITS TO CARRYING OUT MONITORING FOR THIS QUESTION
The benefits to a monitoring program designed to detect incipient invasions is the development of an early warning system. Managers can perhaps act to prevent invaders identified from nearby areas from entering their regions. If new invaders are detected within their region, they can attempt to eradicate them during the brief window of opportunity before they become widespread or abundant.

Abundance

Drew Lohrer, North Inlet-Winyah Bay NERR

What are the relative abundances of native and non-native species within estuarine habitats, and how do these change over time?

When deciding upon the most appropriate methods for assessing species abundance, one must obviously consider habitat type and organism type. There simply is no universal method that can be applied to all combinations of habitat and taxon. Thus, the group found it necessary to narrow the focus of the discussion. For the purpose of the exercise, we chose soft-sediment habitats and infauna. We chose to include both intertidal and subtidal elevations as we considered soft-sediment habitats, and we agreed to refine our definition of "infauna" to mean macrofauna retained on a 1 mm mesh screen.

We discussed stratified designs *vs*. probabilistic designs. In a stratified sampling scheme, the same number of samples is collected from each "stratum". In our case, the strata would be based on habitat classifications within each estuary (i.e., by bathymetry [intertidal, shallow, deep], by sediment grain size [mud, sand], by salinity regime [fresh, brackish, saline], etc.). In a probabilistic sampling scheme, samples are allocated according to the relative proportions of each habitat class (i.e., weighted by the amount of habitat area relative to total estuarine area). Both of these sampling schemes require knowledge of (and operational definitions of) the various habitat types in each estuary prior to the first sampling excursions.

The question our group addressed is habitat-based. Therefore, we felt that the data collected from each estuary should be habitat-specific. However, the point of the NERRS Planning Workshop was to design a monitoring program at the national scale (using, at a minimum, all the NERR sites and hopefully many other estuarine sites as well). Thus, the data must also be readily comparable among estuaries. Of the two options described in the paragraph above (stratified designs *vs*. probabilistic designs), the stratified approach best ensures that specific habitats can be compared across a diverse set of estuaries.

We envision that 30 samples could be distributed throughout each estuary each year, at a cost of roughly $30,000 per estuary per year. Small and large estuaries would be subjected to the same number of samples. Because of this, large estuaries will suffer from poor sample coverage relative to smaller ones. Nevertheless, detailed habitat classifications, unambiguous site selection criteria, and a stratified sampling scheme will ensure good comparability among habitats in estuaries of all sizes. Once chosen, the sites should be geo-referenced to facilitate repeated visitation. In each estuary, sampling should be done during the same month, every year, for at least 3-5 years.

Given the comparative nature of the program we envisioned, all data must be derived from a standardized surface area and volume of sediment. In other words, the dimensions of any core or grabbing device should remain constant for all samples collected, regardless of habitat type or estuary type. This will ensure that the number of organisms per sample can be directly converted into an estimate of density (number of individuals per unit area or volume) without any conversions or scaling artifacts. It will also allow us compute and compare estimates of total species richness (derived by rarefaction)[1].

To maximize the amount of information gained during sampling, we decided that field preservation techniques must be compatible with DNA examination. Generally, this means preservation in pure alcohol, as opposed to formalin. The obvious trade-off is poorer long-term preservation of the samples. However, since hybridization and founder effects and source populations are important aspects of invasion genetics, it is worth using alcohol as a field preservative. It may be necessary to have two sample streams, one for quantitative purposes and long-term vouchers, and one for genetic analysis and genetic vouchers.

Sorting and analysis of benthic samples will be sub-contracted to a reputable firm where sorting and taxonomy are rigorously quality-controlled (QA/QC). The group briefly discussed the benefits of size structure data and biomass/biovolume data, but no detailed recommendations were made. Data entry and analysis should be done locally (e.g., at a NERR site). This would improve the odds of early detection of unusual organisms that might be non-native. A periodic check and review by a centralized entity (e.g., NCCOS) would also be valuable. A nation-wide synthesis should be done after the first 5 years to keep the large-scale effort on track and accountable to the central question of the study.

Benefits: First, unlike species lists, this effort would generate abundance data with statistical confidence limits to facilitate inter-estuarine comparisons. Second, though we might only observe a fraction of the total number of species present, we would be able to estimate the total number of species present by using rarefaction techniques. Third, unlike presence-absence data, we could demonstrate trends in abundance over time and, particularly, correlative evidence of invasion-driven trends in native species abundance. Fourth, early detection of non-indigneous species would be possible. Fifth, this type of work (i.e., collecting sediment samples, sieving, sorting, identifying) is regularly done at many labs around the world today and it would not be difficult to find reputable organizations to assist us in our efforts. There are existing NOAA/NOS and EPA databases and sampling programs that we could utilize and/or add on to.

Follow ups: Monitoring will never unambiguously demonstrate the impact of an non-native species. However, quantitative biological monitoring can help identify systems that require experimental scrutiny. Some findings that should serve as triggers for follow-up studies include: (1) great densities of an non-native species at some particular locale, (2) increased density of a non-native species correlated to decreased density of a native species, (3) the detection of an "infamous" non-native species in a new region—i.e., highly predatory animals or habitat-altering plants/animals, (4) knowledge of an non-native range expansion that could lead to *before-after-control-invaded* studies. Monitoring also provides baseline data from which experimentalists can design realistic, manipulative treatments (e.g., the data would indicate appropriate numbers of organisms to use per cage, etc.), and monitoring data allows the scientific community to place findings of impact into the context of natural variability. We view standardized, quantitative monitoring as absolutely critical to progress in the field of invasion ecology.

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[1] While rarefaction provides an estimate of *how many* species are present, rapid assessments (question 3) seek to answer both *how many and which* species are present. However, rapid assessments include no information about the relative abundances of the species found.

Environmental correlates
Maurice Crawford, Estuarine Reserve Division, NOAA

What are the abiotic and biotic characteristics of the recipient environment that affect invasion success?

The guiding question is very broad and can encompass many monitoring techniques. By asking a more specific question we would be better able to develop an illustrative monitoring program. We first discussed how the question could be made more specific by asking what the role of human made *vs* more natural events played in invasion success. After some discussion this led to five potential ways that could address the main question (ranked in ascending order).

i. What are the habitat characteristics that allow species to invade based on the physiology of the non-native species? This would require habitat comparisons both within and across estuaries for all habitats.

ii. Measure species recruitment into different habitats - associated species with habitats. This would require measuring species abundance and richness.

iii. What is the impact of disturbances (e.g., drought condition) on non-native species? But what is a disturbance - it's just a question of magnitude and temporal frequency of changes in the environment.

iv. Is nutrient loading allowing areas to be invaded? Determining the role of nutrients is an important and current issue.

v. What are the physical, chemical, and biological conditions that need to come together to allow certain larvae to settle or planktonic non-native organisms to become established in estuary? This does not address if they survive to reproduce or if a populations will be established. If the monitoring program is well designed it could also address questions two and three.

Our breakout group chose the last two questions as the focus for developing an illustrative monitoring program. Question v was further refined and a specific habitat and taxa were targeted:

What are the conditions (physical/chemical/biological) that allow plankton to persist in the water column? Target habitat: Water column, Target species: Decapods

Approach

- Focus on abundance and distribution
- Quantitative
- Collect samples every 2 weeks for first year and then re-evaluate (perhaps collect only when larvae are present)

- Locate the larval collectors with dataloggers to link with physical parameters (e.g., like the NERRS System-wide Monitoring Program) plus measure current velocity and direction
- Conduct a plankton haul at time of collection
- Sample jellyfish and fish at time of collection
- Locate samplers to include the end points of gradients (e.g., salinity)
- Species identified by taxonomic experts
- Possible to do at multiple estuaries

Benefits

- Hindcasting
- Prediction
- First sentinel of a potential invasion
- Identify forcing functions of larval abundance
- Identify hot spots
- Additional investigations could use these data

The second question chosen was:

Is there a relationship between eutrophication and invasion success? Target habitat: Benthos/soft bottoms, Target species: Submerged aquatic vegetation (SAV)

Approach

- Quantitative
- Measure parameters (e.g., Chlorohyll a, biomass (above/below ground), stem densities)
- Sample native and non-native species
- Temporal sampling
- Spatial sampling
- Remote sensing could be used where applicable
- Any trained individual could collect data but would need experts to analyze geochemistry.

Benefits

- Refine the relationship between eutrophication and non-native species
- Define sensitivity of native SAVs to eutrophication

Taxonomic Richness

Steven Rumrill, South Slough NERR

How many and which native and non-native species occur within specific estuarine habitats, and how does this change over time?

Periodic assessment of the existing, historic, and future taxonomic richness of estuarine communities is a fundamental problem that is critical to our baseline understanding of estuarine biotic diversity. Iterative monitoring of taxonomic richness should be carried out by conducting systematic surveys within different types of estuarine habitats, coupled with accurate and reliable taxonomic identifications of the most representative species. The three key components to this approach are: (1) a common environmental classification scheme that allows for stratification of estuarine habitats into distinctly-recognizable and comparable eco-units, (2) formation of a master species list by Estuarine Rapid Assessment Teams (E-RATs) or other groups that possess sufficient taxonomic expertise to adequately characterize and describe levels of within-habitat (beta) biotic diversity, and (3) periodic monitoring by locally-based teams who conduct repeatable surveys that focus on a sub-set of species that are readily identifiable to non-specialists.

General Considerations: Datasets developed by E-RATs are suitable for estimation of taxonomic richness based on site-level confirmation of species presence and absence. Rapid assessment methods have been established and refined for estuaries throughout the United States, and they are designed to detect the maximum number of species over a short time period. It will be possible to recognize estuarine invasions only when the non-indigenous species can be accurately identified, and first-hand involvement by taxonomic specialists can be essential to detect recent and historic invasions that may have been overlooked, unreported, or misidentified in ecological studies.

There is an acute need for participation in the surveys by local and regional experts who are familiar with local and regional estuarine communities. The most pressing need is for individuals who can consistently identify species present (and absent) during site-based surveys, and for individuals who can accurately identify species in the field. The overall goal is to generate and periodically update the master species list, but it is important to recognize that only a small component (i.e. about 10-20 species) warrant sufficient consideration to offset the costs incurred by monitoring.

The temporal scale of sampling by the assessment team is an important consideration, particularly whenever seasonal differences in environmental conditions impose inherent variability within estuarine communities. It is also important to recognize up front that a fundamental difference exists between the master species list and the subset of species that are monitored in an iterative fashion over time. It will be possible to gain assistance with formation of the master species list from taxonomic experts on an infrequent basis, but temporal repeatability will be lost unless the local survey team can reliably distinguish between new and established species. Proper preservation of archival specimens is also important when on-site taxonomic expertise is lacking for particular groups of estuarine species. Rigorous quality assurance/quality control steps should be taken by non-specialists to include preparation of voucher (reference) specimens and examination of random samples by taxonomic experts.

Whenever possible, the assessment team should establish permanent sampling stations that can be re-visited over time to directly compare changes in community composition. In addition, field teams should base their sampling protocol on methods that are already available so that datasets can be evaluated within the context of other ongoing monitoring activities. Finally, the frequency of sampling will be dependent upon the availability of human and financial resources; biotic surveys of taxonomic richness should be repeated at least every five years, but may require more frequent assessment and/or resampling of priority habitats on a rotational basis.

Habitat Approaches: Specific approaches to assess taxonomic richness were discussed for several different types of estuarine habitats:

A: Emergent Vegetated Salt Marsh

- Target taxa: emergent marsh vegetation, macroalgae, aquatic invertebrates, fish, birds, mammals, terrestrial invertebrates (insects & spiders).
- Approach: develop unified estuarine habitat classification scheme, use recent aerial photography to recognize and delineate the location and spatial extent of distinct and representative salt marsh habitats, conduct ground-truth surveys of taxonomic richness within the marsh habitats at high and low intertidal elevations, conduct ground-based species counts along permanent transects and during walk-about surveys of the salt marsh.

B: Sub-tidal Benthos

- Target taxa: demersal fish, infaunal and epifaunal invertebrates (amphipods, polychaetes, decapods, bivalves, sponges, echinoderms, etc.), and submerged aquatic vegetation (seagrasses & macroalgae).
- Approach: use aerial photography and bathymetric maps to delineate sub-tidal areas, channels, and the spatial extent of submerged aquatic vegetation, conduct ground surveys along transects with SCUBA, remote underwater video (e.g. NOAA Sediment Profile Image camera), extractive cores, baited and passive traps, and bottom trawls.

C: Floating Docks and Buoys

- Target taxa: epifouling invertebrates (e.g. ascidians, bryozoans, sponges, barnacles, hydroids, amphipods, sessile worms, bivalves, gastropods) and macroalgae.
- Approach: make use of existing floating structures (if available), attach standardized fouling panels (and/or other artificial substratum settlement collectors) at different depths levels (each panel is held consistently at a particular depth), standardize deployment time/season and duration, conduct periodic surveys of fouling panel communities (photo-records and individual observation) to recognize and identify species that recruit.

D: Cobble/Gravel/Boulders

- Target taxa: decapod crustaceans, bivalves, gastropods, polychaetes, barnacles echinoderms, tunicates, macroalgae.

- Approach: characterize cobble/gravel/boulder habitat according to unified estuarine habitat classification scheme, establish permanent transects at high, mid, and low intertidal elevations, take photos and conduct visual searches of heterogeneous habitat (e.g. examine tops, sides, and bottoms of rocks), collect and sieve core samples, deploy baited and passive traps.

<u>Benefits of Monitoring Taxonomic Richness</u>: Generation of a master species list for the estuary, biotic diversity lists for specific habitats, and iterative survey information over time to allow for determinations of geographic spread and site-specific rates of colonization by invasive species.