Ecology of Marine Infectious Diseases (EMID) Workshop Report

Report of a Workshop on the Ecology of Marine Infectious Diseases (EMID) to Explore the State of the Science and Develop Recommendations for the National Science Foundation

Workshop Conveners
Rachel Noble, University of North Carolina at Chapel Hill
James W. Porter, University of Georgia

Sheraton Hotel, San Juan, Puerto Rico

February 12-13, 2011

Table of Contents

Cover photo: Water sample from Neuse River Estuary (mid estuary) in weeks following Tropical Storm Nicole in 2010. Microscope photograph of Cryptomonas sp., Leptocylindrus minimum, single centric diatoms, and several small flagellates from surface water sample (0.5 m depth) (Photo credit: Nathan S. Hall, UNC Chapel Hill Institute of Marine Sciences).

Executive Summary

Our understanding of infectious disease dynamics in aquatic ecosystems (i.e., freshwater, estuarine, and marine) lags behind that of terrestrial ecosystems. Despite the ever increasing recognition of its importance (Harvell et al., 1999, 2004; Porter et al., 2001; McCallum et al., 2004; Ward and Lafferty, 2004; Stewart et al., 2008; Bienfang et al., 2011), research targeting the ecology of aquatic diseases has received less funding compared to land-based studies. Yet, the concepts and models developed for the terrestrial examples are not specifically transferable to aquatic ecosystems because of fundamental differences in community structure, species diversity, life-history phenomena, and dispersal mechanisms. Aquatic ecosystems consist of complex relationships among hosts and pathogens that challenge traditional views of disease processes. As a result, research on aquatic diseases requires innovative and interdisciplinary strategies to identify, monitor, and model them. Furthermore, impending global climate changes such as rising temperatures, ocean acidification, eutrophication, increased runoff, and inland intrusions of salt water will impact the ecology and distribution of aquatic pathogens and consequently, all the populations of organisms they influence. Ultimately, without a better understanding of aquatic disease dynamics, we will not be able to predict impacts of global climate change or mitigate their effects. To address these topical issues, a 2-day workshop was organized.

The Ecology of Marine Infectious Diseases (EMID) workshop was convened to review the state of science regarding disease ecology in marine systems, identify novel research areas, ascertain challenges and impediments to progress, and suggest recommendations for advancing this interdisciplinary field. The EMID workshop was held (February 12-13, 2011) in conjunction with the 2011 American Society for Limnology and Oceanography (ASLO) Aquatic Sciences meeting (San Juan, Puerto Rico) in order to tightly interface with the Ecology of Infectious Diseases (EID) in Marine Systems Special Session chaired by the NSF workshop conveners. The combination of the workshop, special session, and meeting promoted synergism within the scientific community by stimulating EMID related discussions among diverse scientists who regularly attend this internationally acclaimed meeting.

The EMID workshop included plenary talks on current EID research coupled with structured breakout discussions. A poster session provided an additional opportunity for participants to discuss their work and network with others. Overarching recommendations highlighted through rigorous discussion within the breakout groups included a pressing need to: (1) quantify the importance of marine disease processes to the health and survival of marine and human populations; (2) encourage investigations which characterize EMID responses to climate change; (3) increase capacity building of marine researchers through hands-on graduate training; and finally (4) increase collaboration between marine and terrestrial disease researchers. In addition, participants recommended modifying the current EID evaluation process by restructuring the review panels and including seed grants, rapid response research (RAPID) grants, and more cross-disciplinary training opportunities. The workshop agenda, participant list, and summaries from each breakout group are provided in the appendices. Insights gleaned from this workshop are expected to increase the number and quality of competitive proposals submitted by the marine/coastal scientific community to the existing EID Program. This Program is currently supported by the Biological Sciences and Geosciences (Ocean Sciences Division) Directorates of the National Science Foundation (NSF) and by the National Institutes of Health (NIH).

Overarching Recommendations from the Workshop

1) **Quantify the importance of marine disease processes to health and survival of marine and human populations:**

   - Integrate current knowledge of micro- and macro-scale processes to systematically connect pathogenic strains with environmental sources and pathways that include both marine and human populations (Figure 1);
   - Minimize the deficits between hydrodynamic modeling inputs and disease ecology monitoring data;
   - Advance the design and deployment of biological sensors on the Ocean Observing Systems for rapid detection of ecologically or economically important pathogens that are important in coastal, estuarine, and marine systems;
   - Support investigations of major disease outbreaks even when the etiological agent of the disease has not yet been identified.

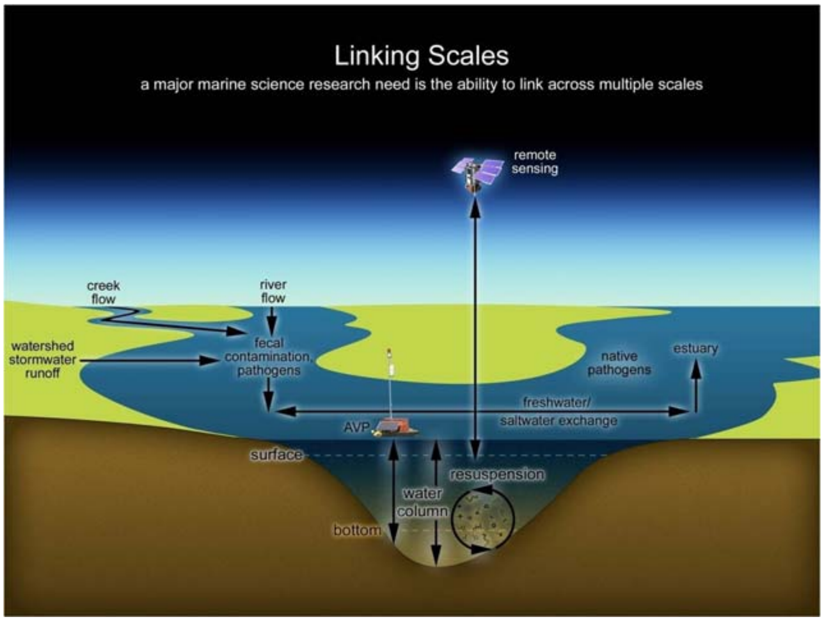

Figure 1. Linking micro and macro environmental scales to predict disease outbreak (*Figure credit: Alan Joyner, UNC Chapel Hill*).

2) **Encourage investigations which characterize EMID responses to climate change:**

   - Support long-term research on the basic biology and ecology of aquatic pathogens and hosts to document and accrue baseline data;
   - Elucidate mechanisms of dispersal and transmission because the predicted changes in climate will influence chemical and physical properties of water, increase or decrease flooding and run-off, and distress infrastructures due to sea-level rise;
   - Consider ocean acidification's differential effects on host and parasite relationships;
   - Improve the usefulness of data collected by considering linkage across multiple scales and spatial and temporal sampling frequencies necessary for developing useful models.

3) Capacity Building for Marine Infectious Disease Researchers:

- Develop an EMID website (e.g., https://extwiki.nsf.gov/signup.action);
- Develop graduate courses and networks to build diagnostic and modeling expertise in the next generation;
- Develop a framework for model and data inter-comparisons (e.g., National Center for Ecological Analysis and Synthesis);
- Coordinate bi-annual interdisciplinary workshops to bring together marine scientists and others interested in infectious diseases (e.g.. oceanographers, ecologists, microbiologists, physicians, veterinarians, epidemiologists, pathologists, public health officials, modelers, and mathematicians);
- Further develop availability of funding for field, bench-top and *in silico* training of the next generation of students, specifically incorporating plans for underrepresented minorities.

4) Increase collaboration between marine and terrestrial disease researchers:

- Summarize commonalities among systems with the goal of developing broad theories and general patterns that encapsulate the dynamics of different disease types, including identifying important types of hosts, pathogens, and environmental factors;
- Support research in areas identified as unique to aquatic ecosystems such as poly-microbial disease ecology, diseases of colonial and sessile populations, and dispersed infectious agents (i.e., transported by currents);
- Support more research for projects at the land-sea interface.

5) Modify the current EID evaluation process:

- Establish seed grants (i.e., one-year, modest-funding exploratory grants in order to generate preliminary data) within the existing EID program to enhance EMID proposals;
- Establish a rapid response grant system to respond to marine disease outbreaks;
- Expand training opportunities to support cross training of students, post-doctoral researchers, and other specialists (e.g., training in modeling for microbiologists, training in pathology for mathematicians) including cross agency support for similar efforts (e.g., NOAA’s training consortia in oceans and human health or NSF/NIEHS Centers for Oceans and Human Health);
- Require more review panel members with experience in marine systems, provide a tutorial for panel members regarding conceptual differences of pathogen dynamics and transmission between marine and terrestrial systems, and identify external review expertise to evaluate EMID projects.

Introduction

Both anecdotal and quantitative studies have identified an increase in the prevalence and severity of marine diseases (Lafferty et al., 2004; Ward and Lafferty, 2004). Yet, our understanding of these diseases continues to lag behind that of terrestrial ones (Harvell et al., 1999; McCallum et al., 2004; Bienfang et al., 2011). More research is needed in aquatic systems because most of our understanding of disease processes was gained from the study of terrestrial organisms. The application of this knowledge to marine systems is challenged by fundamental differences in aquatic community structure, species diversity, life-history phenomena, and fluid dispersal mechanisms. For example, the stunning complexity of host-parasite interactions that is commonly understood to occur in terrestrial systems has not even begun to be revealed in marine systems where phyletic diversity is much greater. Of the 34 described animal phyla, 25 are exclusively aquatic, and 19 of these are exclusively marine whereas only 1 phylum is exclusively terrestrial. In addition, marine organisms appear to have more complex life histories, and their pathogens have a greater number of intermediate host species than is typical for terrestrial diseases (McCallum et al., 2004). Evaluating the appropriate level of complexity needed to fully understand transmission and transport of infectious agents is essential to build predictive models. Finally, some marine pathogens violate common assumptions and generalizations made in terrestrial systems, such as the specificity of infection. For instance, the host range of marine viruses appears to be much broader than for their terrestrial counterparts (McCallum et al., 2004). Consequently, major differences should be expected in infectious disease dynamics between aquatic and terrestrial ecosystems.

All commonly accepted Global Climate Change models predict rising temperatures, elevated aqueous CO_2 concentrations, and increased storm intensities. All of these factors will impact aquatic pathogens, and mostly to increase the prevalence, severity, and lethality of marine diseases. There are also expected to be synergistic effects between elevated nutrients and rising temperatures on microbial growth and survival (Harvell et al., 1999; Looney et al., 2010). For example, bleached corals subjected to stressful temperatures suffered higher rates of disease even after recovery (Sutherland et al., 2004; Muller et al., 2008), than corals that were not heat stressed. Neither maritime modeling nor coastal zone management has addressed disease phenomena, and as our waters continue to warm, diseases will take increasing tolls on marine ecosystems. Lastly, the magnitude and duration of several marine epizootics has demonstrated that disease phenomena have basin-wide effects which may actually be substantially greater and longer lasting than physical disturbances such as hurricanes (e.g., the massive die-off of the grazing sea urchin, *Diadema*, in the Caribbean).

The EID is being effectively studied in some marine, coastal and estuarine systems. Excellent examples of cross collaborative work are beginning to emerge and include innovative research and modeling on diseases of scleractinian corals (e.g., elkhorn coral, Figure 2; Porter et al., 2008), sea fans (Harvell et al., 2004; Bruno et al., 2011), crustaceans (e.g., spiny lobsters; Behringer et al. 2006), mollusks (e.g., oysters and clams; Ford et al., 1999; Lyons et al., 2005), fish (e.g., salmonids; Wargo and Kurath, 2011), marine mammals (sea otters, Figure 3; Conrad et al., 2005), and humans (e.g., *Vibrio*) along with overall estuarine health risk research being conducted by Noble and others (Lafferty, 2008; Stewart et al., 2008; Wetz et al. 2008). The EMID workshop was designed to create a platform for future development of the ecology of diseases in the marine environment by providing salient background information on our current state of knowledge regarding EMID research. Case studies were presented to highlight successful projects and identify newly emerging paradigms. Inclusion of ecological studies from terrestrial disease projects provided insight into potential challenges facing the EMID community. Ultimately the workshop proposed new structural and scientific approaches to the development of this interdisciplinary field, identified novel questions and research areas, and recommended strategies for overcoming the challenges.

Figure 2. White-pox disease on a frond of the endangered elkhorn coral on Carysfort Reef, Florida Keys *(Photo credit: James W. Porter, University of Georgia).*

Figure 3. Sea otter mother and pup *(Photo credit: Bryant Austin).*

Novel Research Areas for EID in Marine Systems

- Understand and categorize marine disease systems by identifying commonalities with the goal of developing broad theories that encapsulate the general dynamics of different disease types. This includes recognition of what types of host, pathogen, and environmental factors are common to specific disease complexes.
- Understand how marine systems are fundamentally different from terrestrial systems in terms of their ability to incubate and convey pathogens, including the identification of reservoirs, vectors, and cascading effects of diseases on other organisms within a system (Figure 4).
- Understand how disease propagates through the environment by identifying transport mechanisms of both hosts and pathogens and developing predictive models to anticipate timing and rate of disease outbreaks and declines.
- Investigate pathogen biology, ecology, and evolution with a focus on viability, virulence, and persistence in varying environments because transmission probabilities ultimately depend on time, environmental characteristics, and the micro-distribution of pathogen populations.
- Explore polymicrobial disease ecology (i.e., community ecology of disease consortia) and the mechanisms associated with pathogen-to-pathogen interactions.
- Understand the role of host surface microbial associates in both resistance to disease and transition to disease.
- Investigate the synergistic effects of a changing climate on invertebrate surface microbial associates, particularly the effects of increasing temperature and acidification through both small scale experimental studies and large geographical scale studies interfaced with remotely sensed temperature and ocean color.

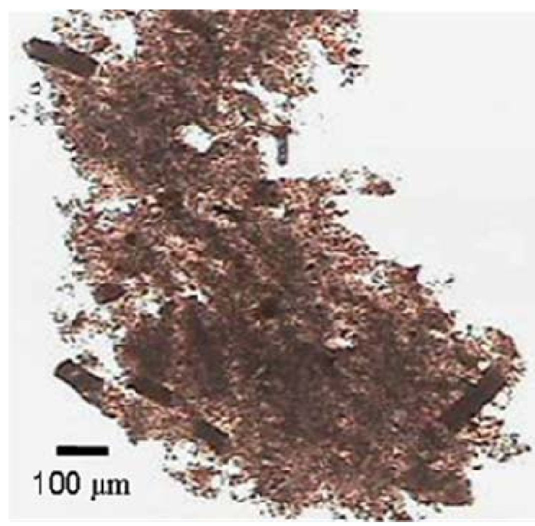

Figure 4. Marine aggregate with fecal pellets, detritus and living organisms. Recent studies on aggregates demonstrate they can serve as both reservoirs and vectors of microorganisms that cause diseases of marine organisms ***(Photo credit: Maille Lyons and Evan Ward, University of Connecticut).***

- Investigate complex life histories of marine hosts (all life stages) including sessile animals (e.g., oysters and corals, Figures 5 and 6) compared t mobile social animals (e.g., lobsters), and singular life forms compared to colonial life forms (uncommon in terrestrial ecosystems). Target host biology including genetics and immunological responses along with host population dynamics and evolutionary responses to disease pressure.

- Explore globalization effects on marine diseases including how the effects of transporting potential pathogens to naïve hosts through aquaculture, ballast water, cruise ships, and the aquarium trade impacts marine populations.

- Investigate the relative the importance of endogenous and exogenous controls of disease dynamics by identifying physical, chemical and biological stressors and perturbations that may contribute to disease processes (e.g., temperature, pH, CO_2 concentration, salinity, precipitation, currents, water quality, contaminated sediments, changing food assemblies, nutritional status, intra- and inter-species competition, host physiology, predation).

- Explore the role of disease in the population dynamics of endangered and invasive species.

- Explore the ecological role of pathogenic organisms when they are not causing disease (i.e., investigate the natural ecology of opportunistic pathogens) and investigate non-pathogenic relationships (e.g., *Vibrio* -squid symbiosis). Continue studies of natural disease systems without anthropogenic ties as "baselines" to better understand and predict epidemics.

Figure 5. A healthy stand of the endangered elkhorn coral on Molasses Reef in the Florida Keys. In the past 15 years, more than 90% of this once common coral has disappeared in the Florida Keys. *(Photo credit: James W. Porter, University of Georgia).*

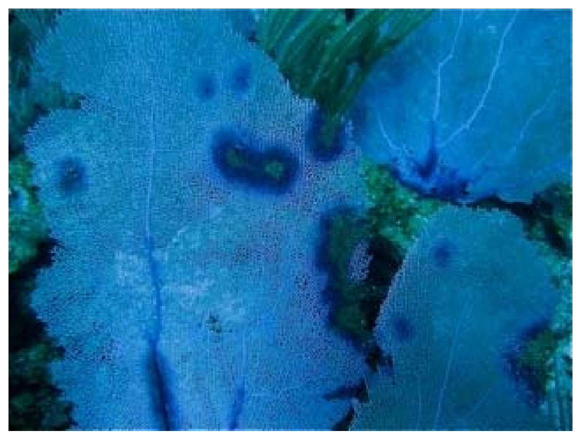

Figure 6. Possible fungal (*Aspergillus* spp.) lesions on the seafan *Gorgonia ventalina* from 50' in Puerto Rico. The purpling surrounding the lesions is part of the amoebocyte-facilitated inflammatory response of the seafan *(Photo credit: Drew Harvell, Cornell University).*

Challenges for Addressing Novel Research Areas

Funding for Research on EMID

- Budget and funding levels often limit the ability to assemble a large, diverse interdisciplinary team, which is necessary to tackle the cross-disciplinary issues in complex marine systems;

- Lack of seed grants for EID to collect preliminary data, conduct exploratory experiments or explore simple models needed for more competitive EID grants from the marine community;

- Lack of an EID-RAPID grant system to respond to outbreaks and emerging disease phenomena.

Limitations in Sampling, Diagnostic Tools, and Long-term Monitoring Data

- Substantial variation in the spatial and temporal scales on which the parameters (i.e., biological, ecological, chemical, and physical variables) can be measured;
- Expense (e.g., funds, time, and labor) of ecological field studies that require good diagnostic tools coupled with adequate sampling frequency and spatial coverage (Figures 7 and 8);
- Expensive and yet-to-be developed molecular diagnostic tools required to account for viable but non-culturable (VBNC) phenomenon common in environmental microbiology, including aquatic pathogens;
- Lack of basic information on the etiological agent (or inability to satisfy Koch's postulates) precludes a proposal from being rated as competitive;
- Lack of long-term, base-line data for model development coupled with lack of biological sensors on Ocean Observing Systems for rapid collection of real-time (or near real-time) data on pathogens.

Figure 7. Studying the ecology of marine infectious disease requires the development of new sampling techniques for remote locations *(Photo credit: James W. Porter, University of Georgia).*

Figure 8. Autonomous vertical profiler deployed in the Neuse River Estuary as a key component for tracking the impact of extreme storm events (*Photo credit: Rachel T. Noble, UNC Chapel Hill).*

Limitations in Model Development

- Lack of ability to integrate multi-scale models requiring a balance between "*parameter* based mechanistic understanding" and "*pattern* based mechanistic understanding";
- Lack of generalization to specific systems. Model quality and usefulness depend on quality of empirical data used and incorporation of the temporal element in models, specifically the behavior of the "infective particles" in such models needs to be tailored to each pathogen of interest;
- Basic disconnects between modeling inputs and monitoring data require better communication between diverse disciplines (e.g., coastal circulation modelers, disease ecologists, and microbiologists).

Recommendations to Overcoming Challenges

Funding for Research on EMID

- Establish seed grants within the EID Program to facilitate data gathering and investigator cohesion;
- Establish an EID-RAPID grant system attuned to outbreaks and emerging phenomena;
- Expand interagency collaboration to leverage additional funding within the context of developing research, monitoring and modeling of EID in marine systems (e.g., NIH, NOAA, USDA and EPA);
- Engage physical oceanographers to participate in EID proposals and then request that the physical oceanography section at NSF contribute funds to the EID Program.

Sharing Concepts to Advance the Field

- Draft a review paper summarizing our current knowledge regarding a census of aquatic pathogens which could be grouped by phyla, hosts, habitats, and ocean processes, and include impacts of physical, chemical, and other non-biological stresses;
- Develop an EMID website and listserv to enhance the ability of scientists to initiate professional collaborations;
- Designate National or Regional Center(s) for Marine Infectious Diseases which would coordinate interdisciplinary workshops for stakeholders, and disseminate information about other workshop and workgroup funding opportunities;
- Continue and expand support of data synthesis and of a framework for model inter-comparison (e.g., National Center for Ecological Analysis and Synthesis);
- Evaluate the use of the Ecology and Oceanography of Harmful Algal Blooms (EcoHAB) research program as a model system to facilitate linkages for EID;
- Evaluate the use of the One Health multi-agency initiative (www.onehealthinitiative.com) to address human and eco-system health interactions.

Sharing Data to Advance the Field

- Improve baseline data collection by standardization of protocols and reporting methods;
- Support a coordinated expansion of existing data sources (e.g., USGS Wildlife disease information network database, wildlifedisease.nbii.gov, environmental health tracking networks, coral disease registry);
- Share and archive all data from EID funded projects in appropriate data center(s) with a web portal created for purposes of disseminating information;
- Authorize resources for EID projects in collaboration with existing studies (e.g., NSF Long-Term Ecological Research (LTER) Network and the National Ecological Observatory Network (NEON)) to add pathogen and disease-relevant data.

Establishing Partnerships to Bridge Interfaces and Developing Cross-Collaborative Work

- Assemble working groups of EMID oriented individuals and institutions with the following expertise:
  - ◊ Scientists: physical, chemical, and biological oceanography, ecology, marine biology, microbiology, molecular biology, botany, environmental sciences, terrestrial disease ecology, statistics, environmental health sciences. Target social scientists to understand and incorporate local community needs in the project, and to improve communication of findings to the public;
  - ◊ Modelers: (1) modelers studying and capturing the dynamics of the physical environment that influence disease transmission; and (2) modelers that study and define the disease dynamics within and among populations (Susceptible-Infected-Recovered (SIR) model focused);
  - ◊ Medical researchers or public health scientists: trained in relevant medical fields, veterinary sciences, epidemiology, pathology;
  - ◊ Agency officials: representation by all funding agencies with potential interests.
- Engage wildlife veterinarians who have expertise in dealing with the difficulty of monitoring animal populations and their diseases;
- Engage plant pathologists in developing a framework for model systems for sessile marine organisms. Applying the wealth of knowledge and understanding of terrestrial plant disease dynamics to certain marine diseases, particularly those sessile organisms (e.g., colonial corals and oysters), may be enlightening for understanding disease dynamics;
- Improve training opportunities with more funding to support interdisciplinary opportunities for students and post-doctoral researchers. Identify 4-5 crucial disciplines and create special programs to support cross-training of students and post-doctoral researchers in these areas;
- Facilitate training of PIs in scientific interpretation and advisory work (e.g., training through the Aldo Leopold Institute or Compass).

Fostering Collaboration and Building the Scientific Community

- Create an "EID Match.com" to develop mechanisms to link investigators with different expertise to improve quality of grants by better matching up investigators (the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET) is an example). A Wiki network could be established for EMID through https://extwiki.nsf.gov/signup.action.

Disseminating Research Findings to Refine Management Strategies

- Encourage interaction with local managers and public health agencies to facilitate development of useful predictive tools and science-based management protocols;
- Utilize disease and disease transmission information to affect management strategies, with an emphasis in the fisheries management community as this has both human health and resource implications;
- Review research from terrestrial environments and marine protected areas (MPAs) for relevance and ideas for management of diseases in marine communities.

Tools and Infrastructure

- Increase accessibility of molecular and microbiological facilities at field sites, especially where laboratories are non-existent or ill equipped (e.g., production of Biosafety certified, mobile laboratories overseen by NSF that can be moved around to facilitate funded projects in those areas;
- Develop, advertise, and coordinate access to "service" laboratories for molecular and microbial processing of samples;
- Establish a centralized marine pathogen/host tissue sample repository to augment existing electronic data repositories (NSF Biological Oceanography data centers, GenBank, International Registry of Coral Pathology, etc.). Similarly, extend these current data repositories to better handle different kinds of data sets (e.g., time series of various pathogens and diseases) that do not fit the current geo-referenced monitoring data model;
- Review the capacity of the University-National Oceanographic Laboratory System (UNOLS) vessels to support EMID research, especially in the framework of biological safety laboratory related considerations. Consider tasking one of the UNOLS vessels for a 12-month global assessment of EMID. This would increase visibility to EMID related research and might also be a way to bring front line scientific equipment into remote areas.

Suggestions for Improvement of the EID Program

- Modify existing EID Synopsis and/or request for proposals by: (1) adding the importance of physical oceanography, environmental modeling, synergisms with cross cutting disciplines, and other techniques to address the appropriate scales relevant to marine systems (2) specifically mention circulation and mechanistic models in marine systems are of interest; and (3) adding “studies on emerging diseases in marine (aquatic) systems will be considered”;
- Modify the current evaluation process to include more panel members with experience in marine systems, employing external review of proposals, or providing a tutorial for all panel members regarding conceptual differences of pathogen dynamics and transmission between marine and terrestrial systems;
- Designate a percentage of funds to be dedicated to marine diseases within the EID Program.

Concluding Statement

EMID work is especially challenging. Historically, there has been a distinction between quantitative epidemiological research developed in clinical fields, and classical marine biological research that focuses on descriptive biology and ecosystem process. The lack of cross fertilization between these fields has also made EMID related research more difficult to fund.. Although it is recognized that marine research problems are just as important as those in terrestrial environments, the research tools, infrastructure, and preliminary data sets from marine investigations are often not as sophisticated or well developed as materials from traditional epidemiological research laboratories. Finally, since scientists working specifically in EMID frontiers are often on the edge of the state of the science, the research tends to be higher risk, and empirical approaches often have a trial and error nature at the infancy of specific studies of disease dynamics. Marine scientists wishing to conduct this type of research face major hurdles to success, which this workshop was designed to overcome.

Acknowledgement

Our gratitude to Priscilla Viana for her tireless work on the inception of the workshop, planning and logistical assistance with the workshop, organization of written material and contributions to the final workshop report. We are also grateful for the work of Dr. Drew Harvell, Denene Blackwood, and Dr. Maille Lyons in editing and substantial improvement of the workshop document. Thank you to all workshop participants for gathering and spending their time to share research findings, ideas, and thoughts for the future. Thank you to invited speakers who presented the state of the art in the EMID field. Finally, we are grateful to Phil Taylor for the opportunity to conduct this workshop and convene a fantastic community of scientists.

References

Behringer, D.C. Jr., M.J. Butler IV, and J. Shields. 2006. Avoidance of disease in social lobsters. *Nature* **441**: 421.

Bienfang, P.K., S.V. Defelice, E.A. Laws, L.E. Brand, R.R. Bidigare, S. Christensen, H. Trapido-Rosenthal, T.K. Hemscheidt, D.J. McGillicuddy, D.M. Anderson, H.M. Solo-Gabriele, A.B. Boehm, and L.C. Backer. 2011. Prominent Human Health Impacts from Several Marine Microbes: History, Ecology, and Public Health Implications. *Int. J. Microbiol.* **2011**:152815

Bruno, J., S.P. Ellner, I. Vu, K. Kim and D. Harvell. 2011 Impacts of aspergillosis on sea fan coral demography: modeling a moving target. *Ecol. Monogr.* **81**: 123-139

Conrad, P.A., M.A. Miller, C. Kreuder, E.R. James, J. Mazet, H. Dabritz, D.A. Jessup, F. Gulland and M.E. Grigg. 2005. Transmission of Toxoplasma: clues from the study of sea otters as sentinels of *Toxoplasma gondii* flow into the marine environment. *Int. J. Parasitol.* **35**, 1155–1168.

Ford, S., E. Powell, J. Klinck, and E. Hofmann. 1999. Modeling the MSX parasite in Eastern oyster (*Crassostrea virginica*) populations. I. Model development, implementation, and verification. *J. Shellfish Res.* **18**:475–500.

Harvell, C.D., K. Kim, J.M. Burkholder, R.R. Colwell, P.R. Epstein, J. Grimes, E.E. Hofmann, E. Lipp, A.D.M.E. Osterhaus, R. Overstreet, J.W. Porter, G.W. Smith and G. Vasta. 1999. Emerging marine diseases - Climate links and anthropogenic factors. *Science* **285**:1505-1510.

Harvell, D., R. Aronson, N. Baron, J. Connell, A. Dobson, S. Ellner, L. Gerber, K. Kim, A. Kuris, H. McCallum, K. Lafferty, B. McKay, J. Porter, M. Pascual, G. Smith, K. Sutherland, and J. Ward. 2004. The rising tide of ocean diseases: Unsolved problems and research priorities. *Front. Ecol. Environ.* **2**: 375 -382.

Lafferty, K.D., J.W. Porter, and S.E. Ford. 2004. Are diseases increasing in the ocean? *Ann. Rev. Ecol. Syst.* **35**:31-54.

Lafferty, K.D. 2008. Effects of disease on community interactions and food web structure, pp. 205-222. In: R.S. Ostfeld, F. Keesing, and V. Eviner (Eds.) Infectious Disease Ecology. Princeton University Press, Princeton, NJ.

Looney, E.E., K.P. Sutherland, and E.K. Lipp. 2010. Effects of temperature, nutrients, organic matter and coral mucus on the survival of the coral pathogen, *Serratia marcescens* PDL100. *Environ. Microbiol.* **12**:2479-2485.

Lyons, M.M., J.E. Ward, R. Smolowitz, K.R. Uhlinger, and R.J. Gast. 2005. Lethal marine snow: Pathogen of bivalve mollusk concealed in marine aggregates. *Limnol. Oceanogr.* **50**: 1983-1988.

McCallum, H.I., A. Kuris, C.D. Harvell, K.D. Lafferty, G.W. Smith, and J.W. Porter. 2004. Does terrestrial epidemiology apply to marine systems? *Trends Ecol. Evol.* **19**:585-591.

Muller, E.M., C.S. Rogers, A.S. Spitzack, and R. van Woesik. 2008. Bleaching increases likelihood of disease on *Acropora palmata* (Lamarck) in Hawksnest Bay, St. John, U.S. Virgin Islands. *Coral Reefs* **27**:91-195.

Porter, J.W. (Ed.) 2001. *The Ecology and Etiology of Newly Emerging Marine Diseases.* Kluwer Acad. Publ.; Dordrecht, The Netherlands. 201 pp.

Porter, J.W., E.K. Lipp, K.P. Sutherland, and E. Mueller. 2008. The ecology of an infectious disease in the Florida Keys: From pathogens to politics, pp.387-403 In: R.S. Ostfeld, F. Keesing, and V. Eviner (Eds.) Infectious Disease Ecology. Princeton University Press, Princeton, NJ.

Stewart, J.R., R.J. Gast, R.S. Fujioka, H.M. Solo-Gabriele, J.S. Meschke, L.A. Amaral-Zettler, E. del Castillo, M.F. Polz, T.K. Collier, M.S. Strom, C.D. Sinigalliano, P.D.R. Moeller, and A.F. Holland. 2008. The coastal environment and human health: microbial indicators, pathogens, sentinels and reservoirs. *Environ. Health* **2008**, 7(Suppl 2):S5.

Sutherland, K.P., J.W. Porter, and C. Torres. 2004. Disease and immunity in Caribbean and Indo-Pacific zooxanthellate corals. *Mar. Ecol. Prog. Ser.* **266**: 273-302.

Ward, J.R., and K.D. Lafferty. 2004. The elusive base-line of marine disease: Are diseases in ocean ecosystems increasing? *PLoS Biol.* **2**:542-547.

Wargo, A.R., and G. Kurath. 2011. In Vivo Fitness Associated with High Virulence in a Vertebrate Virus Is a Complex Trait Regulated by Host Entry, Replication, and Shedding. *J. Virology* **85**: 3959-3967.

Wetz, J.J., A.D. Blackwood, J.S. Fries, Z.F. Williams, and R.T. Noble. 2008. Trends in total *Vibrio* spp. and *Vibrio vulnificus* concentrations in the eutrophic Neuse River Estuary, North Carolina, during storm events. *Aquat. Microb. Ecol.* **53**:141-149.

Appendix I: Workshop Agenda

Saturday, February 12, 2011

7:30-8AM	**Registration and continental breakfast** *[Hang posters]*	*San Geronimo, 2nd floor*
8-8:10AM	**Welcome and conference goals** *[Phil Taylor, National Science Foundation]*	*San Cristobal, 2nd floor*
8:10-9AM	**Introduction of participants** Objective: Each participant introduces their research interests and/or talks about collaboration opportunities (one minute per participant).	*San Cristobal, 2nd floor*
9-9:25AM	**What can we learn from a case study within a well documented/constrained system?** *[Jim Porter, University of Georgia]*	*San Cristobal, 2nd floor*
9:25-9:50AM	**Linking research on EID in marine systems to EID in terrestrial systems** *[Alan Hastings, University of California - Davis]*	*San Cristobal, 2nd floor*
9:50-10:15AM	**The spectrum of models crucial for EID in marine systems** *[Eileen Hofmann, Old Dominion University]*	*San Cristobal, 2nd floor*
10:15-10:30AM	**Coffee break**	*San Geronimo, 2nd floor*
10:30-10:55AM	**Diagnostic tools and marine diseases** *[Carolyn Friedman, University of Washington]*	*San Cristobal, 2nd floor*
10:55-11:45	**Synthesis of the plenary talks: Pointing to challenges, successes and new directions** *[Drew Harvell, Cornell University]*	*San Cristobal, 2nd floor*
	Breakout session – Charge	*San Cristobal, 2nd floor*
12-1PM	**Lunch**	*San Geronimo, 2nd floor*

1-3:40PM **Breakout groups**

- Groups 1 and 2: What are the critical questions on EID in marine systems not being properly addressed or resolved? What are the major conceptual gaps that prevent fostering work on EID in marine systems? What are the other challenges and impediments? Why are these questions important? What are the most novel questions? What are the most tractable questions? Where can we make the most progress?
  - ◊ Group 1 *[Session Chair – Mark Butler, ODU; Rapporteur - Laurie Raymundo, UG]* *San Felipe, 2nd floor*
  - ◊ Group 2 *[Session Chair – Grieg Steward, U. of Hawaii; Rapporteur - Maille Lyons, ODU]* *San Cristobal, 2nd floor*

- Groups 3 and 4: Is there scope for cross-collaborative work between terrestrial and marine systems, and between medical and marine ecological research communities? How can we facilitate this? How can we come together, share concepts and push the field forward? What are the major differences between research on marine disease ecology and terrestrial disease ecology? Are there major system differences, and how does that impact comparison and collaboration?
  - ◊ Group 3 *[Session Chair – Erin Lipp, U. of Georgia; Rapporteur - Denene Blackwood, UNC Chapel Hill]* *Luna room, 2nd floor*
  - ◊ Group 4 *[Session Chair – Jeff Shields, VIMS; Rapporteur – Greta Smith-Aeby, UH]* *Sol boardroom, 2nd floor*

4-5 PM **Each breakout group summarizes their discussions (5-10 min) followed by a group discussion** *San Cristobal, 2nd floor*
[Facilitator: Rachel Noble, University of North Carolina at Chapel Hill]

5:30-7PM **Evening reception and poster session** *San Geronimo, 2nd floor*

Sunday, February 13, 2011

7:30-8:00AM **Continental breakfast** *San Geronimo, 2nd floor*

8:00-8:30AM **Within-host processes and infectious disease spread: implications for both terrestrial and marine systems** *San Cristobal, 2nd floor*
[Vanessa Ezenwa, University of Georgia]

8:30-9:00AM **Theory and models for infectious disease dynamics: from the land to the sea** *San Cristobal, 2nd floor*
[Mercedes Pascual, University of Michigan]

9:00-9:30AM **A case study of a complex disease system, zoonosis, terrestrial-marine connection, physical-biological interactions** *San Cristobal, 2nd floor*
[John Largier, University of California - Davis]

9:30-9:40AM	**Breakout session – Charge** *[Rachel Noble, University of North Carolina at Chapel Hill]*	*San Cristobal, 2nd floor*
9:40-10:00AM	**Coffee break**	*San Geronimo, 2nd floor*
10AM-12PM	**Breakout groups**	

- Group 1: How can we define EID research? Should all EID research have a pre-identified infectious agent and infection outcome? *San Cristobal, 2nd floor*
  [Session Chair – Rachel Noble, UNC Chapel Hill; Rapporteur - Evan Ward, U. of Connecticut]

- Group 2: How are environmental stressors and perturbations (e.g., climate change, land use, invasive species, water and sediment pollution) affecting dynamics and transmission of marine infectious diseases? *San Cristobal, 2nd floor*
  [Session Chair – Paul Hershberger, USGS; Rapporteur - Colleen Burge, Cornell U.]

- Group 3: Have we succeeded in bringing the right people to the table for EID work? What expertise is missing? What training is missing? *Luna room, 2nd floor*
  [Session Chairs – Jim Bowen, UNC-Charlotte, and Anwar Huq, Univ. MD; Rapporteurs - Marilyn Brandt, U. Virgin Islands, and Helena Solo-Gabriele, U. Miami]

- Group 4: What issues are perceived as limiting model development of disease in marine/coastal systems (e.g., scale; integration between circulation models and laboratory experiments; field and remote sensing satellite data)? *Sol boardroom, 2nd floor*
  [Session Chair – Shafiqul Islam, Tufts University; Rapporteur - John Largier, University of California, Davis]

12-1PM	**Lunch**	
1-2PM	**Each breakout group summarizes their discussions (10 minutes) followed by a group discussion** *[Facilitators: Jim Porter & Rachel Noble]*	*San Cristobal, 2nd floor*
2-3:30PM	**Summary and discussions of recommendations for short and long term research on ecology of marine infectious diseases** *[Facilitator: Drew Harvell, Cornell University]*	*San Cristobal, 2nd floor*
3:30-4:30PM	**Wrap-up** Funding opportunities *[Phil Taylor, NSF; Tracy Collier, NOAA and Peter Johnson, USDA]* Workshop highlights and next steps *[Jim Porter & Rachel Noble]*	*San Cristobal, 2nd floor*
4:30PM	**Adjourn**	

Appendix II: Participant List

Researchers and agency representatives from a range of different disciplines convened on February 12-13, 2011, to share recent findings and diverse perspectives on disease and marine systems. The workshop brought together scientists with different expertise, including those with specific knowledge of diseases affecting marine organisms, those with expertise in relating models of physical oceanography to biological processes, and individuals with expertise in the modeling and study of diseases of terrestrial as well as marine organisms. Included in the participant list were scientists actively conducting research on EID in marine, coastal and estuarine systems as well as others interested in infectious diseases (e.g. biomedical, veterinary, epidemiologists, pathologists, oceanographers and mathematicians).

First name	Last name	Affiliation
Alan	Hastings	University of California, Davis
Anna	Bass	University of New England
Anwar	Huq	University of Maryland
Carolyn	Friedman	University of Washington
Colleen	Burge	Cornell University
Denene	Blackwood	University of North Carolina at Chapel Hill
Diego	Narvaez	Old Dominion University
Drew	Harvell	Cornell University
Eileen	Hofmann	Old Dominion University
Erin	Lipp	University of Georgia
Erin	Bromage	Uni. Massachusetts Dartmouth
Ernesto	Weil	University of Puerto Rico Mayaguez
Greta	Aeby	Hawaii Institute of Marine Biology
Grieg	Steward	University of Hawaii
Helena	Solo-Gabriele	University of Miami
J. Evan	Ward	University of Connecticut
James	Bowen	UNC Charlotte
Jason	Graff	University of Rhode Island
Jeffrey	Shields	VIMS
Jill	Stewart	University of North Carolina - Chapel Hill
Jim	Porter	University of Georgia
John	Largier	University of California, Davis
John	Griffith	SCCWRP
Kathryn	Sutherland	Rollins College
Kevin	Lafferty	US Geological Survey

First name	Last name	Affiliation
Laurie	Raymundo	University of Guam Marine Laboratory
Lisa	Plano	University of Miami
Marilyn	Brandt	University of the Virgin Islands
Mark	Butler	Old Dominion University
Mary Maille	Lyons	Old Dominion University
Mathias	Wegner	Leibniz Institute for Marine Sciences IFM-Geomar
Mercedes	Pascual	University of Michigan
Montira	Pongsiri	USEPA
Mya	Breitbart	University of South Florida
Pam	Morris	University of South Carolina
Paul	Hershberger	USGS - Marrowstone Marine Field Station
Peter	Johnson	USDA-National Institute of Food and Agriculture
Phillip	Taylor	National Science Foundation
Priscilla	Viana	National Science Foundation
Rachel	Noble	UNC Chapel Hill Institute of Marine Sciences
Rebecca	Vega Thurber	Florida International University
Shafiqul	Islam	Tufts University
Tracy	Collier	NOAA
Vanessa	Ezenwa	University of Georgia

Ecology of Marine Infectious Diseases

Report of a Workshop on the Ecology of Marine Infectious Diseases (EMID) to Explore the State of the Science and Develop Recommendations for the National Science Foundation

Workshop Conveners

Rachel Noble
Associate Professor
Institute of Marine Sciences
University of North Carolina at Chapel Hill
Email: rtnoble@email.unc.edu

James W. Porter
Associate Dean
Josiah Meigs Distinguished Professor
Odum School of Ecology
University of Georgia
Email: jporter@uga.edu

Background photo: Pennate diatom (Photo credit: Rachel T. Noble, UNC Chapel Hill).