Adams, C. M., Larkin, S. L., Hoagland, P., & Sancewich, B. (2018). Assessing the Economic Consequences of Harmful Algal Blooms: A Summary of Existing Literature, Research Methods, Data, and Information Gaps. In S. E. Shumway, J. M. Burkholder, & S. L. Morton (Eds.), Harmful Algal Blooms (pp. 337–354). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118994672.ch8 This chapter summarizes an extant literature that seeks to evaluate many of the economic consequences associated with marine HABs. The discussion utilizes a report by Adams and Larkin (2013) containing an annotated bibliography of both peer-reviewed and "gray" (no formal peer review) research papers. That bibliography is supplemented with publications from the more recent literature, focusing on the peer-reviewed literature and adding examples from the methodologically rigorous gray literature. Specifically, this chapter discusses methodologies that have been used to measure economic losses, review the types and sources of data, depict the spatial distribution of examples where economic impacts have been estimated in the United States, discuss the complexities of addressing the scopes of HAB events, and identify research gaps and areas for focusing future socioeconomic research efforts.

Alvarez, S., Lupi, F., Solís, D., & Thomas, M. (2019). Valuing Provision Scenarios of Coastal Ecosystem Services: The Case of Boat Ramp Closures Due to Harmful Algae Blooms in Florida. Water, 11(6), 1250. https://doi.org/10.3390/w11061250 Ecosystem service flows may change or disappear temporarily or permanently as a result of environmental changes or ecological disturbances. In coastal areas, ecological disturbances caused by toxin-producing harmful algae blooms can impact flows of ecosystem services, particularly provisioning (e.g., seafood harvesting) and cultural services (e.g., recreation). This study uses a random utility model of recreational boating choices to simulate changes in the value of cultural ecosystem services provided by recreation in coastal ecosystems resulting from prolonged ecological disturbances caused by harmful algae blooms. The empirical application relies on observed trips to 35 alternative boat access ramps in Lee County, an important marine access destination in southwest Florida. Results indicate that reduced boating access from harmful algae blooms may have resulted in losses of $3 million for the 2018 blooms, which lasted from the end of June to the end of September.

Anderson, D. M. (1989). Toxic algae blooms and red tides: A global perspective. In D. M. Anderson, T. Okaichi, & T. Nemoto (Eds.), Red Tides: Biology, Environmental Science, and Toxicology (pp. 11–16). Elsevier Science Publishing Co., Inc. http://www.whoi.edu/cms/files/ Anderson_1989_global-persp_Okaichi_30809.pdf The literature on toxic algal blooms and red tides documents a global increase in the frequency, magnitude, and geographic extent of these events over the last two decades. Some of this increase is undoubtedly a result of the increased awareness and analytical capabilities of the scientific community, but a strong correlation between the number of red tides and the degree of coastal pollution or utilization of coastal waters for aquaculture argue that there are other contributing factors. It also appears likely that toxic algal species have spread within regions over spatial scales of hundreds of kilometers, moving with major water currents and storms. Long distance transport of species across oceans may have occurred as well, but the evidence is not conclusive and the hypothesis controversial.

Anderson, D. M. (1997). Turning back the harmful red tide. *Nature*, *388*, 513–514. https://doi.org/10.1038/41415 Harmful algal blooms are a serious and increasing problem in marine waters, yet scientists and funding agencies have been slow to investigate possible control strategies.

Anderson, D. M. (2009). Approaches to monitoring, control and management of harmful algal blooms (HABs). *Ocean & Coastal Management*, *52*(7), 342–347. https://doi.org/10.1016/ j.ocecoaman.2009.04.006 Virtually every coastal country in the world is affected by harmful algal blooms (HABs, commonly called "red tides"). These phenomena are caused by blooms of microscopic algae. Some of these algae are toxic, and can lead to illness and death in humans, fish, seabirds, marine mammals, and other oceanic life, typically as a result of the transfer of toxins through the food web. Sometimes the direct release of toxic compounds can be lethal to marine animals. Non-toxic HABs cause damage to ecosystems, fisheries resources, and recreational facilities, often due to the sheer biomass of the accumulated algae. The term "HAB" also applies to non-toxic blooms of

macroalgae (seaweeds), which can cause major ecological impacts such as the displacement of indigenous species, habitat alteration and oxygen depletion in bottom waters. Globally, the nature of the HAB problem has changed considerably over the last several decades. The number of toxic blooms, the resulting economic losses, the types of resources affected, and the number of toxins and toxic species have all increased dramatically. Some of this expansion has been attributed to storms, currents and other natural phenomena, but human activities are also frequently implicated. Humans have contributed by transporting toxic species in ballast water, and by adding massive and increasing quantities of industrial, agricultural and sewage effluents to coastal waters. In many urbanized coastal regions, these inputs have altered the size and composition of the nutrient pool which has, in turn, created a more favorable nutrient environment for certain HAB species. The steady expansion in the use of fertilizers for agricultural production represents a large and worrisome source of nutrients in coastal waters that promote some HABs. The diversity in HAB species and their impacts presents a significant challenge to those responsible for the management of coastal resources. Furthermore, HABs are complex oceanographic phenomena that require multidisciplinary study ranging from molecular and cell biology to large-scale field surveys, numerical modelling, and remote sensing from space. Our understanding of these phenomena is increasing dramatically, and with this understanding comes technologies and management tools that can reduce HAB incidence and impact. Here I summarize the global HAB problem, its trends and causes, and new technologies and approaches to monitoring, control and management, highlighting molecular probes for cell detection, rapid and sensitive toxin assays, remote sensing detection and tracking of blooms, bloom control and mitigation strategies, and the use of large-scale physical/biological models to analyze past blooms and forecast future ones.

Anderson, D. M., Hoagland, P., Kaoru, Y., & White, A. W. (2000). *Estimated annual economic impacts from harmful algal blooms (HABs) in the United States*. Woods Hole Oceanographic Institution. https://doi.org/10.1575/1912/96 We estimate the economic impacts of HABs for events where such impacts were measurable with a fair degree of confidence during the six-year interval of 1987-92. Due to reporting limitations, the selected events are a subset of all outbreaks that occurred during the 1987-92 study period, and thus our aggregate economic impact underestimates the the impacts. “Economic impact” is defined broadly to mean either lost gross revenues in the relevant product or factor markets, expenditures for environmental monitoring and management, or other costs that would not have been incurred in the absence of HABs. In general, this measure is consistent with published estimates made for other natural catastrophes, such as hurricanes or earthquakes. Economic multipliers, often used to approximate the full ramifications of costs or losses as they are transferred though a local economy, are not used here. The calculation of economic multipliers in the absence of detailed data on market structure and interactions can be misleading, as multipliers can be sensitive to local market structure characteristics and to the quality of data that describe interactions among market sectors. Developing a description of local and regional markets for specific HAB events was beyond the scope of this project.

Backer, L. C. (2009). Impacts of Florida red tides on coastal communities. *Harmful Algae*, *8*(4), 618–622. https://doi.org/10.1016/j.hal.2008.11.008 Over the last few decades, scientific research has helped to describe the disease neurotoxic shellfish poisoning (NSP) by identifying the causative organism, Karenia brevis, and by characterizing the disease-causing toxins, a suite of polyether toxins called brevetoxins. In addition to causing disease in exposed human populations, K. brevis blooms and associated management responses have been linked to other effects on coastal communities. Some of these effects are negative, such as the loss of tourism dollars and the increased burden on local health care services caused by increases in human disease incidence. However, some of the effects are positive, such as the significant improvement in detecting brevetoxins in environmental samples and clinical specimens. This review discusses the health and economic effects from K. brevis blooms on Florida coastal communities and the current efforts to identify the data needed to assess social and cultural effects.

Baldridge, H. D. (1977). *Red Tide Research at the Mote Marine Laboratory: A five-year status report (1972-*

1977). Mote Marine Laboratory. Initiated by an intense. toxic outbreak of the HAB *Karenia brevis* (then known as *Gymnodinium breve*) during the spring and summer of 1971, Mote Marine Laboratory, in collaboration with the University of South Florida, began a five-year program of research on the prediction, monitoring, control, and economic impacts of Kb blooms.

Bauer, M (Ed.). (2006). *Harmful Algal Research and Response: A Human Dimensions Strategy*. National Office for Marine Biotoxins and Harmful Algal Blooms. Harmful Algal Research and Response: A Human Dimensions Strategy (HARR-HD) justifies and guides a coordinated national commitment to human dimensions research critical to prevent and respond to impacts of harmful algal blooms (HABs). Beyond HABs, it serves as a framework for developing human dimensions research as a cross-cutting priority of ecosystem science supporting coastal and oceanmanagement, including hazard research and mitigation planning. Measuring and promoting community resilience to hazards require human dimensions research outcomes such as effective risk communication strategies; assessment of community vulnerability; identification of susceptible populations; comprehensive assessment of environmental, sociocultural, and economic impacts; development of effective decision support tools; and improved coordination among agencies and stakeholders. HARRHD charts a course for human dimensions research to achieve these and other priorities through coordinated implementation by the Joint Subcommittee on Ocean Science and Technology (JSOST) Interagency Working Group on HABs, Hypoxia and Human Health (IWG-4H); national HAB funding programs; national research and response programs; and state research and monitoring programs.

Bauer, Marybeth, Hoagland, P., Leschine, T. M., Blount, B. G., Pomeroy, C. M., Lampl, L. L., Scherer, C. W., Ayres, D. L., Tester, P. A., Sengco, M. R., Sellner, K. G., & Schumacker, J. (2010). The importance of human dimensions research in managing harmful algal blooms. *Frontiers in Ecology and the Environment*, *8*(2), 75–83. https://doi.org/10.1890/070181 Harmful algal blooms (HABs) are natural freshwater and marine hazards that impose substantial adverse impacts on the human use of coastal and marine resources. The socioeconomic and health impacts of HABs can be consid- erable, thereby making a case for "human dimensions" research to support HAB response. Human dimensions research is multidisciplinary, integrating social science, humanities, and other fields with natural science to enhance resource management by addressing human causes, consequences, and responses to coastal environmen- tal problems. Case studies reported here illustrate the importance of human dimensions research. Incorporating such research into the scientific agenda – as well as into management decisions of public agencies concerned with natural resource management, environmental protection, and public health and welfare – requires the development of both strategic guidance and institutional capacity. The recent development of a multi-agency research strategy for HAB response and a strategic plan for human dimensions research represent two important steps in this direction.

Bean, J. A., Fleming, L. E., Kirkpatrick, B., Backer, L. C., Nierenberg, K., Reich, A., Cheng, Y. S., Wanner, A., Benson, J., Naar, J., Pierce, R., Abraham, W. M., Kirkpatrick, G., Hollenbeck, J., Zaias, J., Mendes, E., & Baden, D. G. (2011). Florida red tide toxins (brevetoxins) and longitudinal respiratory effects in asthmatics. *Harmful Algae*, *10*(6), 744–748. https://doi.org/10.1016/j.hal.2011.06.008 Having demonstrated significant and persistent adverse changes in pulmonary function for asthmatics after 1h exposure to brevetoxins in Florida red tide (Karenia brevis bloom) aerosols, we assessed the possible longer term health effects in asthmatics from intermittent environmental exposure to brevetoxins over 7 years. 125 asthmatic subjects were assessed for their pulmonary function and reported symptoms before and after 1h of environmental exposure to Florida red tide aerosols for up to 11 studies over seven years. As a group, the asthmatics came to the studies with normal standardized percent predicted pulmonary function values. The 38 asthmatics who participated in only one exposure study were more reactive compared to the 36 asthmatics who participated in ≥4 exposure studies. The 36 asthmatics participating in ≥4 exposure studies demonstrated no significant change in their standardized percent predicted pre-exposure pulmonary function over the 7 years of the study. These results indicate that stable asthmatics living in areas with intermittent Florida red tides do not exhibit chronic respiratory effects from intermittent environmental exposure to aerosolized brevetoxins over a 7 year period.

Bechard, A. (2019). Red tide at morning, tourists take warning? County-level economic effects of HABS on tourism dependent sectors. *Harmful Algae*, *85*, 101689. https://doi.org/10.1016/j.hal.2019.101689
A tourism dependent state such as Florida relies on its environment and climate to attract visitors and generate revenue. HABs can certainly have an impact on the coastal waters of the Gulf, but does this necessarily drive away tourist related activity? To determine not only if the impact of HABs is significant, but also at what magnitude, a time series econometric model was used to study effects of persistent and severe blooms on counties in Southwestern Florida, particularly Sarasota County, hit hardest by blooms in 2006 and 2018 that lasted multiple months. Lodging and restaurant sectors of the economy were found to have monthly losses of 15% and 1.75% respectively, during months when red tide was present. Neighboring counties unaffected by severe blooms did not experience significant losses to these sectors. These results support the intuition that effects of HABs reach far beyond the waters of the Gulf, and as red tide grows in frequency and severity, more economic loss could lie ahead.

Bechard, A. (2020a). External costs of harmful algal blooms using hedonic valuation: The impact of karenia brevis on Southwest Florida. *Environmental and Sustainability Indicators*, *5*, 100019. https://doi.org/10.1016/j.indic.2020.100019 We use a hedonic valuation method to measure the costs of harmful algal blooms to properties in Southwest Florida. Persistent blooms of "red tide" have lasted for over months at a time and can render the appeal of the Gulf Coast useless, usually a valuable amenity to property prices in the area. We study property prices over a sixteen-year period during which, four major blooms plagued the coast. We find property prices within five miles of the coast decline about 10% during a persistent bloom. Property prices also decrease more, in a non- linear fashion as blooms persist for additional months. Our estimate of local costs, although the first of its kind for this region and this type of algae, is similar to those found elsewhere in the literature for different algae across the country. Our results show the importance of mitigation, as counties face tight budgets and must realize the full external costs of these blooms.

Bechard, A. (2020b). Gone with the Wind: Declines in Property Values as Harmful Algal Blooms Are Blown Towards the Shore. *The Journal of Real Estate Finance and Economics*. https://doi.org/10.1007/s11146-020-09749-6 Florida's Gulf Coast is known as a retirement hotspot, with property values along the coast rising faster than almost anywhere else in the country. However, the coastal amenities that help boost prices, quickly turn to dis-amenities when there is a prolonged red tide bloom in the Gulf. Using a difference in differences hedonic valuation model, we examine six Southwestern Florida counties heavily impacted by four major algal bloom in the past 20 years. We find that affected properties within 1 mile of the coast sell for up to 30% less compared to similar homes sold during the same month in an unaffected county. With red tide predicted to increase in frequency and severity, mitigation of the effects must be paramount for these counties. Losses occur in almost all sectors of the economy, and for a state that relies so much on the health of the environment, declines in property values are a sign that action must be taken against these blooms.

Berdalet, E., Fleming, L. E., Gowen, R., Davidson, K., Hess, P., Backer, L. C., Moore, S. K., Hoagland, P., & Enevoldsen, H. (2016). Marine harmful algal blooms, human health and wellbeing: Challenges and opportunities in the 21st century. *Journal of the Marine Biological Association of the United Kingdom*, *96*(1), 61–91. https://doi.org/10.1017/S0025315415001733 Microalgal blooms are a natural part of the seasonal cycle of photosynthetic organisms in marine ecosystems. They are key components of the structure and dynamics of the oceans and thus sustain the benefits that humans obtain from these aquatic environments. However, some microalgal blooms can cause harm to humans and other organisms. These harmful algal blooms (HABs) have direct impacts on human health and negative influences on human wellbeing, mainly through their consequences to coastal ecosystem services (fisheries, tourism and recreation) and other marine organisms and environments. HABs are natural phenomena, but these events can be favored by anthropogenic pressures in coastal areas. Global warming and associated changes in the oceans could affect HAB occurrences and toxicity as well, although forecasting the possible trends is still speculative and requires intensive multidisciplinary

research. At the beginning of the 21st century, with expanding human populations, particularly in coastal and developing countries, mitigating HABs impacts on human health and wellbeing is becoming a more pressing public health need. The available tools to address this global challenge include maintaining intensive, multi-disciplinary and collaborative scientific research, and strengthening the coordination with stakeholders, policymakers and the general public. Here we provide an overview of different aspects of the HABs phenomena, an important element of the intrinsic links between oceans and human health and wellbeing.

Bertram, C., Ahtiainen, H., Meyerhoff, J., Pakalniete, K., Pouta, E., & Rehdanz, K. (2020). Contingent Behavior and Asymmetric Preferences for Baltic Sea Coastal Recreation. *Environmental and Resource Economics*, *75*(1), 49–78. https://doi.org/10.1007/s10640-019-00388-x In this study, we augment the traditional travel cost approach with contingent behavior data for coastal recreation. The objective is to analyze the welfare implications of future changes in the conditions of the Baltic Sea due to climate change and eutrophication. Adding to the literature, we assess the symmetricity of welfare effects caused by improvements and deteriorations in environmental conditions for a set of quality attributes. Responses are derived from identical online surveys in Finland, Germany and Latvia. We estimate recreational benefits using linear and non-linear negative binomial random-effects models. The calculated annual consumer surpluses are considerably influenced by the magnitude of the environmental changes in the three countries. We also observe asymmetries in the effects of environmental improvements and deteriorations on the expected number of visits. In particular, the results indicate that deteriorations lead to larger or more significant impacts than improvements in the case of blue-green algal blooms and algae onshore for Finland, water clarity for Germany, and water clarity and blue-green algal blooms for Latvia. For the remaining attributes, the effects are ambiguous.

Bingham, M., Sinha, S. K., & Lupi, F. (2015). *Economic Benefits of Reducing Harmful Algal Blooms in Lake Erie* (p. 66). Environmental Consulting and Technology, Inc. This project [evaluates] HAB effects to regional economic welfare including effects to recreation, water withdrawals, tourism, and property values. Results of [an earlier] Phase I study indicated that western Lake Erie HABs can affect inter-related economic systems over a broad, geographic area, and that little information has been collected to specifically support economic benefit studies. This study has benefited from the previous work conceptually and methodologically, however, the problem of information limitations persists. For example, certain information such as timing and severity of HABs at a micro-level (beach, marina, neighborhood, etc.) as well as short-run responses of people (such as recreators and/or tourists) and markets (rental, hotel, housing, restaurants) to the HABs are not available. An additional challenge has been that certain responses of people and markets may not result directly from any specific HAB incident. Rather, these responses occur in different places and time periods than HABs, and result from more complex cognitive and economic processes than the comparatively easy to measure (with appropriate data) economic effects that arise from ecological service reductions. As a result of these two factors, it is not currently feasible to quantify the economic effects of HABs using statistically-significant parameters within rigorous econometric models. Not having that capability, this effort relies on available secondary data and studies. To further illustrate possible effects, this information is incorporated by an evaluation of "value at risk," which employs scenarios and sensitivity analyses to characterize ecological service interruptions and their immediate economic effects. In addition, this study presents a HAB severity index, created for 2011 and 2014 events, that varies by week and county. This construct is used to generate estimates of economic effects for these years; it could also be employed to evaluate future HABs events on Lake Erie. Less immediate (i.e., lagged and halo) effects are discussed and quantified in the context of these effects. This study developed scenarios that indicate nearly $71 million in lost economic benefits from the 2011 HAB event, and an additional $65 million in lost benefits from the 2014 event.

Boesch, D. F., Anderson, D. M., Horner, R. A., Shumway, S. E., Tester, P. A., & Whitledge, T. E. (1997). Harmful algal blooms in coastal waters: Options for prevention, control and mitigation. *NOAA Coastal Ocean Program: Decision Analysis Series*. http://www.cop.noaa.gov/pubs/das/das10.pdf This report is the product of a panel of experts in the science of blooms of unicellular marine algae which can cause mass mortalities in a va-

riety of marine organisms and cause illness and even death in humans who consume contaminated seafood. These phenomena are collectively termed harmful algal blooms or HABs for short. As a counterpart to recent assessments of the priorities forscientific research to understand the causes and behavior of HABs, this assessment addressed the management options for reducing their incidence and extent (prevention), actions that can quell or contain blooms (control), and steps to reduce the losses of resources or economic values and minimize human health risks (mitigation).This assessment is limited to an appraisal of scientific understanding, but also reflects consideration of information and perspectives provided by regional experts, agency managers and user constituencies during three regional meetings. The panel convened these meetings during the latter half of 1996 to solicit information and opinions from scientific experts, agency managers and user constituencies in Texas, Washington, and Florida. The panel's assessment limited its attention to those HABs that result in neurotoxic shellfish poisoning, paralytic shellfish poisoning, brown tides, amnesic shellfish poisoning, and aquaculture fish kills. This covers most, but certainly not all, HAB problems in the U.S.

Burford, M. A., Gobler, C. J., Hamilton, D. P., Visser, P. M., Lurling, M., & Codd, G. A. (2019). *Solutions for managing cyanobacterial blooms: A scientific summary for policy makers* (IOC/INF-1382; p. 19). SCOR-IOC Scientific Steering Committee of the Global Ecology and Oceanography of Harmful Algal Blooms research programme GlobalHAB.

Burkholder, J. M. (1998). Implications of Harmful Microalgae and Heterotrophic Dinoflagellates in Management of Sustainable Marine Fisheries. *Ecological Applications*, *8*(1 Supplement), S37–S62. https://esajournals.onlinelibrary.wiley.com/doi/full/10.1890/1051-0761%281998%298%5BS37%3AIOHMAH%5D2.0.CO%3B2 Worldwide increases in the frequency and spatial extent of blooms of harmful marine microalgae and heterotrophic dinoflagellates suggest that these species are becoming an increasingly important influence on year class strength of marine fishes through both direct and indirect mechanisms. Impacts on fish populations from harmful marine microalgae and heterotrophic dinoflagellates have been considered primarily from the limited view of acute or lethal influences. Accumulating evidence indicates that insidious sublethal and chronic impacts to both fish and human health from these organisms, such as long-term behavior alteration, increased susceptibility to cancers and other diseases, depressed feeding, and impaired reproduction, may be substantial and pervasive. For some harmful species, significant indirect impacts that promote critical habitat loss or disrupt the microbial food web balance also have been documented. Because successful models to predict the behavior and growth of most of these species have not yet been developed, and because toxins for many are poorly characterized, a clear anthropocentric focus has guided management strategies for confronting their outbreaks. The extent to which management takes the fundamental step of acknowledging scientifically demonstrated linkages among harmful microalgae, shellfish contamination, fish kills, and human health impacts has also been seriously constrained by political dictates stemming from economic considerations. Without federal involvement, and without catastrophe of human death or widescale serious human illness, little progress historically has been realized in the development of effective management strategies to mitigate lethal impacts to fish or other organisms. Many long-known taxa such as certain '"red tide"' dinoflagellates apparently can increase independently of human influences other than physical transport. However, some newly discovered toxic or otherwise harmful taxa have been correlated with cultural eutrophication in poorly flushed fish nursery grounds such as estuaries and coastal waters. Outbreaks of certain warm-optimal species have coincided with El Nino events, suggesting that warming trends in global climate change may stimulate their growth and extend or shift their range. The available information points to a critical need for a more proactive, concerted effort to determine the full range of chronic/sublethal effects, as well as acute impacts, on marine fish populations by harmful marine microalgae and heterotrophic dinoflagellates, so that their increasingly important influence can be factored into reliable plans for sustainable fisheries management.

Byrne, M. M., Studts, J. L., Kohler, K., & Kirkpatrick, B. (2016). *The Use of Conjoint Analysis for Assessment of Messaging Regarding Environmental 2 Threats: The Case of Florida Red tide*. Working paper. Miami, FL: Miller School of Medicine, University of Miami. Environmental hazards create a suite of decisions regarding

the severity of the hazard and the appropriateness of actions to take to minimize risk for those people confronted with the hazards. Some hazards have very clear risks, such as tsunamis and hurricanes. Other environmental hazards may also present risk, but the urgency and/or clarity of the risk is less. This is the case with Florida red tides, Karenia brevis blooms, where daily changing conditions and visual cues can cause difficulty in deciding how to minimize risk. We used conjoint analysis to assess the attributes important to residents and snowbirds and asthmatics and healthy individuals regarding decisions when to go to the beach and if to eat seafood when a Florida red tide is present. We first conducted semi structured interviews to identify relevant decision attributes. We then survey 303 individuals using 25 conjoint scenarios for going to the beach and 24 for seafood consumption. Our results regarding seafood consumption during a Florida red tide revealed no differences between snowbirds and residents. The two most important factors were government warnings that it is either safe or unsafe to eat seafood and trust in the merchant providing the seafood. Regarding beach going, recommendations for authorities managing beaches during a red tide bloom are to clean the beach of the dead fish, thus removing both attributes (dead fish and odor) that this study demonstrated to be the drivers for beach attendance choices. Asthmatics reported a lower overall general propensity to go to the beach than those without asthma during a Florida red tide. HAB reporting systems, specifically those that report dead fish, respiratory irritation, official warnings about the beach (such as which flags the lifeguards are flying), as well as wind direction are valuable tools for the public to use in making informed choices about not only beach aesthetics but also about their health, particularly for asthmatics . In addition, HAB systems that report these important beach conditions need to be widely disseminated to beach goers. Regarding seafood consumption during a red tide, an aggressive educational program needs to be created, disseminated, and evaluated to provide clear messages that seafood consumption during red tide is safe.

Cardozo, K. H. M., Guaratini, T., Barros, M. P., Falcão, V. R., Tonon, A. P., Lopes, N. P., Campos, S., Torres, M. A., Souza, A. O., Colepicolo, P., & Pinto, E. (2007). Metabolites from algae with economical impact. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*, *146*(1), 60–78. https://doi.org/10.1016/j.cbpc.2006.05.007 In order to survive in a highly competitive environment, freshwater or marine algae have to develop defense strategies that result in a tremendous diversity of compounds from different metabolic pathways. Recent trends in drug research from natural sources have shown that algae are promising organisms to furnish novel biochemically active compounds. The current review describes the main substances biosynthesized by algae with potential economic impact in food science, pharmaceutical industry and public health. Emphasis is given to fatty acids, steroids, carotenoids, polysaccharides, lectins, mycosporine-like amino acids, halogenated compounds, polyketides and toxins.

Carmichael, W. W., & Boyer, G. L. (2016). Health impacts from cyanobacteria harmful algae blooms: Implications for the North American Great Lakes. *Harmful Algae*, *54*, 194–212. https://doi.org/10.1016/j.hal.2016.02.002 Harmful cyanobacterial blooms (cHABs) have significant socioeconomic and ecological costs, which impact drinking water, fisheries, agriculture, tourism, real estate, water quality, food web resilience and habitats, and contribute to anoxia and fish kills. Many of these costs are well described, but in fact are largely unmeasured. Worldwide cHABs can produce toxins (cyanotoxins), which cause acute or chronic health effects in mammals (including humans) and other organisms. There are few attempts to characterize the full health-related effects other than acute incidences, which may go unrecorded. At present these are difficult to access and evaluate and may be ascribed to other causes. Such information is fundamental to measure the full costs of cHABs and inform the need for often-costly management and remediation. This paper synthesizes information on cHABs occurrence, toxicology and health effects, and relates this to past and current conditions in the Great Lakes, a major global resource which supplies 84% of the surface water in North America. This geographic region has seen a significant resurgence of cHABs since the 1980s. In particular we focus on Lake Erie, where increased reporting of cHABs has occurred from the early 1990's. We evaluate available information and case reports of cHAB-related illness and death and show that cHABs occur throughout the basin, with reports of animal illness and death, especially dogs and livestock. Lake Erie has consistently experienced cHABs and cyanotoxins in the last decade with probable cases of human illness,

while the other Great Lakes show intermittent cHABs and toxins, but no confirmed reports on illness or toxicity. The dominant toxigenic cyanobacterium is the genus Microcystis known to produce microcystins. The presence of other cyanotoxins (anatoxin-a, paralytic shellfish toxins) implicates other toxigenic cyanobacteria such as Anabaena (Dolichospermum) and Lyngbya.

Chadsey, M., V.L. Trainer, & T.M. Leschine. (2011). Cooperation of Science and Management for Harmful Algal Blooms: Domoic Acid and the Washington Coast Razor Clam Fishery. *Coastal Management*, 40(1): 33-54. https://doi.org/10.1080/08920753.2011.639865 Harmful algal blooms (HABs) may be increasing in frequency and intensity worldwide. Coastal economies suffer significant income losses when fisheries or beaches are closed to protect human health and subsistence fishing communities are at risk. Despite these hardships, managers must often conservatively close harvests across a wide area or for long periods, because they lack scientific information that would allow them to predict HAB events. The outer coast of Washington State has experienced several closures of the razor clam (Siliqua patula) fishery starting in 1991, due to domoic acid (DA) contamination caused by toxic blooms of the diatom Pseudo-nitzschia. Improved science-based management was needed to minimize the impact of DA on this fishery and the coastal communities that relied on it for income, tourism, and subsistence. The Olympic Region Harmful Algal Bloom (ORHAB) Partnership, comprised of state and tribal managers, scientists, and local stakeholders, evolved in response to this need; it has been successful in its mission. Here we examine ORHAB through the lens of the Institutional Analysis and Development framework, in order to identify key factors contributing to its success. The relevance of our findings for other ORHAB-like institutions in the Pacific Northwest and elsewhere is discussed.

Clark, S., Hubbard, K. A., Anderson, D. M., McGillicuddy, D. J., Ralston, D. K., & Townsend, D. W. (2019). Pseudo-nitzschia bloom dynamics in the Gulf of Maine: 2012–2016. *Harmful Algae*, *88*, 101656. https://doi.org/10.1016/j.hal.2019.101656 The toxic diatom genus Pseudo-nitzschia is a growing presence in the Gulf of Maine (GOM), where regionally unprecedented levels of domoic acid (DA) in 2016 led to the first Amnesic Shellfish Poisoning closures in the region. However, factors driving GOM Pseudo-nitzschia dynamics, DA concentrations, and the 2016 event are unclear. Water samples were collected at the surface and at depth in offshore transects in summer 2012, 2014, and 2015, and fall 2016, and a weekly time series of surface water samples was collected in 2013. Temperature and salinity data were obtained from NERACOOS buoys and measurements during sample collection. Samples were processed for particulate DA (pDA), dissolved nutrients (nitrate, ammonium, silicic acid, and phosphate), and cellular abundance. Species composition was estimated via Automated Ribosomal Intergenic Spacer Analysis (ARISA), a semi-quantitative DNA finger-printing tool. Pseudo-nitzschia biogeography was consistent in the years 2012, 2014, and 2015, with greater Pseudo-nitzschia cell abundance and P. plurisecta dominance in low-salinity inshore samples, and lower Pseudo-nitzschia cell abundance and P. delicatissima and P. seriata dominance in high-salinity offshore samples. During the 2016 event, pDA concentrations were an order of magnitude higher than in previous years, and inshore-offshore contrasts in biogeography were weak, with P. australis present in every sample. Patterns in temporal and spatial variability confirm that pDA increases with the abundance and the cellular DA of Pseudo-nitzschia species, but was not correlated with any one environmental factor. The greater pDA in 2016 was caused by P. australis – the observation of which is unprecedented in the region – and may have been exacerbated by low residual silicic acid. The novel presence of P. australis may be due to local growth conditions, the introduction of a population with an anomalous water mass, or both factors. A definitive cause of the 2016 bloom remains unknown, and continued DA monitoring in the GOM is warranted.

Clay, P., & Dolin, E. (1997). Building Better Social Impact Assessments. *Fisheries*, *22*(9), 12–13. Fisheries management is people management--Influencing people's behavior to promote socially profitable, ecologically sustainable practices. We can better influence future behavior if we understand current behavior and motivations and their interactions with management. Where effects are severe, compliance may be compromised. Knowing probable impacts allows managers to seek alternative tools or plan for more intensive educational efforts about the need for the management action. Yet data required for social impact assessments (SIAs) are

often missing, incomplete, or inconclusive, resulting in SIAs that fall short in replacing confusion with clarity and promoting objectivity over subjectivity. We must improve the quality of SIAs by acquiring more comprehensive, relevant, and useful social and economic data.

Clua, E., Brena, P. F., Lecasble, C., Ghnassia, R., & Chauvet, C. (2011). Prevalence and proposal for cost-effective management of the ciguatera risk in the Noumea fish market, New Caledonia (South Pacific). *Toxicon*, *58*(6–7), 591–601. https://doi.org/10.1016/j.toxicon.2011.08.020 Ciguatera fish poisoning (CFP) is a common intoxication associated with the consumption of reef fish, which constitutes a critical issue for public health in many countries. The complexity of its epidemiology is responsible for the poor management of the risk in tropical fish markets. We used the example of the Noumea fish market in New Caledonia to develop a cost-effective methodology of assessing the CFP risk. We first used published reports and the knowledge of local experts to define a list of potentially poisonous local species, ranked by their ciguatoxic potential. Based on two 1-month surveys in the market, conducted in winters 2008 and 2009, we then calculated the consolidated ratio of biomass of potentially poisonous species vs. total biomass of fish sold on the market. The prevalence of high CFP-risk species in the market was 16.1% and 18.9% in 2008 and 2009, respectively. The most common high CFP risk species were groupers (serranids), king mackerels (scombrids), snappers (lutjanids), barracudas (sphyaraenids), emperors (lethrinids) and wrasses (labrids). The size (age) of the fish also plays a critical role in the potential ciguatoxic risk. According to proposals of average size thresholds provided by experts for high-risk species, we were also able to assess the additional risk induced by the sale of some large fish on the market. The data collected both from experts and from the market allowed us to develop a cost-effective proposal for improving the management of the CFP risk in this market. However, the successful implementation of any regulation aiming to ban some specific species and sizes from the market, with an acceptable economical impact, will require the improvement of the expertise in fish identification by public health officers and, ideally, the commitment of retailers.

Codd, G. A., Meriluoto, J., & Metcalf, J. S. (2017). Introduction: Cyanobacteria, Cyanotoxins, Their Human Impact, and Risk Management. In *Handbook of Cyanobacterial Monitoring and Cyanotoxin Analysis* (pp. 1–8). Wiley-Blackwell. https://doi.org/10.1002/9781119068761.ch1 Although recognized as cosmopolitan, ancient inhabitants of aquatic and terrestrial environments with major involvement in global nutrient cycling, cyanobacteria also present economic, supply, aesthetic, and health problems in the availability of water resources for human and animal use. Cyanobacterial hazards to human and animal health are presented by a wide array of toxins (cyanotoxins). These include long-recognized cyanotoxins with causative actions in investigated waterborne health incidents. Exposure media and routes via which such incidents can occur are summarized. Novel cyanobacterial toxic compounds are also emerging and are a focus of current research. Increasing human demands on water resources, for industry, agriculture, aquaculture, recreation, and domestic uses, plus likely effects of climate change, are leading to increased problems with toxigenic, cyanobacterial mass populations. The effective risk management of such cyanobacterial problems requires feasible, robust methods for the monitoring and analysis of cyanobacteria and cyanotoxins, the subject of this handbook.

Corrales, R. A., & Maclean, J. L. (1995). Impacts of harmful algae on seafarming in the Asia-Pacific areas. *Journal of Applied Phycology*, *7*(2), 151–162. https://doi.org/10.1007/BF00693062 Seafarming to produce human food has recently intensified, particularly in the Asia-Pacific region. Disastrous impacts of harmful phytoplankton blooms, however, have been experienced during the past 20 years. In extreme cases, these render shellfish and finfish toxic or cause massive fish and shrimp kills. Problems from marine algae in the region include paralytic shellfish poisoning, diarrhetic shellfish poisoning, ciguatera, tetrodotoxin poisoning, fish kills and tainting of fish and shellfish. An analysis of 72 incidents since 1934 showed that 57% were fish and shrimp kills; almost all the remainder were PSP events. By mid-1994 there had been 3164 recorded cases of human poisoning and 148 reported deaths from these events in Asia-Pacific. Economic losses may exceed one million US dollars per event, while monitoring costs may be up to $50000 annually for each affected area. Research needs, management strategies and international cooperation are discussed. National action plan con-

siderations include shellfish sanitation programs, public awareness and education, coastal engineering and classification of waters to protect public health.

Council, N. R., Studies, D. on E. and L., Resources, C. on G., Environment and, Board, W. S. and T., Board, O. S., & Eutrophication, C. on the C. and M. of. (2000). *Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution*. National Academies Press. Environmental problems in coastal ecosystems can sometimes be attributed to excess nutrients flowing from upstream watersheds into estuarine settings. This nutrient over-enrichment can result in toxic algal blooms, shellfish poisoning, coral reef destruction, and other harmful outcomes. All U.S. coasts show signs of nutrient over-enrichment, and scientists predict worsening problems in the years ahead. Clean Coastal Waters explains technical aspects of nutrient over-enrichment and proposes both immediate local action by coastal managers and a longer-term national strategy incorporating policy design, classification of affected sites, law and regulation, coordination, and communication. Highlighting the Gulf of Mexico's "Dead Zone," the Pfiesteria outbreak in a tributary of Chesapeake Bay, and other cases, the book explains how nutrients work in the environment, why nitrogen is important, how enrichment turns into over-enrichment, and why some environments are especially susceptible. Economic as well as ecological impacts are examined. In addressing abatement strategies, the committee discusses the importance of monitoring sites, developing useful models of over-enrichment, and setting water quality goals. The book also reviews voluntary programs, mandatory controls, tax incentives, and other policy options for reducing the flow of nutrients from agricultural operations and other sources.

Deshazo, R. (2018). *The Economic Ripple Effects of Florida Red Tide*. Tampa Bay Regional Planning Council.Diaz, R. E., Friedman, M. A., Jin, D., Beet, A., Kirkpatrick, B., Reich, A., Kirkpatrick, G., Ullmann, S. G., Fleming, L. E., & Hoagland, P. (2019). Neurological illnesses associated with Florida red tide (Karenia brevis) blooms. *Harmful Algae*, *82*, 73–81. https://doi.org/10.1016/j.hal.2018.07.002 Human respiratory and gastrointestinal illnesses can result from exposures to brevetoxins originating from coastal Florida red tide blooms, comprising the marine alga Karenia brevis (K. brevis). Only limited research on the extent of human health risks and illness costs due to K. brevis blooms has been undertaken to date. Because brevetoxins are known neurotoxins that are able to cross the blood-brain barrier, it is possible that exposure to brevetoxins may be associated with neurological illnesses. This study explored whether K. brevis blooms may be associated with increases in the numbers of emergency department visits for neurological illness. An exposure-response framework was applied to test the effects of K. brevis blooms on human health, using secondary data from diverse sources. After controlling for resident population, seasonal and annual effects, significant increases in emergency department visits were found specifically for headache (ICD-9 784.0) as a primary diagnosis during proximate coastal K. brevis blooms. In particular, an increased risk for older residents (≥55 years) was identified in the coastal communities of six southwest Florida counties during K. brevis bloom events. The incidence of headache associated with K. brevis blooms showed a small but increasing association with K. brevis cell densities. Rough estimates of the costs of this illness were developed for hypothetical bloom occurrences.

Dodds, W. K., Bouska, W. W., Eitzmann, J. L., Pilger, T. J., Pitts, K. L., Riley, A. J., Schloesser, J. T., & Thornbrugh, D. J. (2009). Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages. *Environmental Science & Technology*, *43*(1), 12–19. https://doi.org/10.1021/es801217q Human-induced eutrophication degrades freshwater systems worldwide by reducing water quality and altering ecosystem structure and function. We compared current total nitrogen (TN) and phosphorus (TP) concentrations for the U.S. Environmental Protection Agency nutrient ecoregions with estimated reference conditions. In all nutrient ecoregions, current median TN and TP values for rivers and lakes exceeded reference median values. In 12 of 14 ecoregions, over 90% of rivers currently exceed reference median values. We calculated potential annual value losses in recreational water usage, waterfront real estate, spending on recovery of threatened and endangered species, and drinking water. The combined costs were approximately $2.2 billion annually as a result of eutrophication in U.S. freshwaters. The greatest economic losses were attributed to lakefront property values

($0.3−2.8 billion per year, although this number was poorly constrained) and recreational use ($0.37−1.16 billion per year). Our evaluation likely underestimates economic losses incurred from freshwater eutrophication. We document potential costs to identify where restoring natural nutrient regimes can have the greatest economic benefits. Our research exposes gaps in current records (e.g., accounting for frequency of algal blooms and fish kills) and suggests further research is necessary to refine cost estimates.

Dolah, F. M. V., Roelke, D., & Greene, R. M. (2001). Health and Ecological Impacts of Harmful Algal Blooms: Risk Assessment Needs. *Human and Ecological Risk Assessment: An International Journal*, *7*(5), 1329–1345. https://doi.org/10.1080/20018091095032 The symposium session, Indicators for Effects and Predictions of Harmful Algal Blooms, explored the current state of indicators used to assess the human health and ecological risks caused by harmful algal blooms, and highlighted future needs and impediments that must be overcome in order to provide a complete risk assessment of their impacts. Six recognized human poisoning syndromes resulting from algal toxins (paralytic, neurotoxic, amnesic, diarrhetic shellfish poisonings, ciguatera fish poisoning, and putative estuary associated syndrome) impact human health through consumption of contaminated seafood, direct contact with bloom water, or inhalation of aerosolized toxin. Thorough health risk assessment for the variety of algal toxins is hampered to varying degrees because either the toxin has not been identified or indicators for exposure and effects remain poorly defined. Predicting the occurrence and determining the impacts of harmful algal blooms in coastal ecosystems are the two major ecological risk assessment needs. In the former case, the hazard is the suite of conditions that trigger bloom initiation, magnify bloom intensity or support bloom longevity, whereas in the latter case, the hazard is the algal toxin. In both cases, indicators (of triggering mechanisms, exposure, and effects) are better defined for some HAB species and toxins than others, but are by no means complete.

Dortch, Q. (2009). Progress in understanding the causes and impacts of the Florida red tide and improving management and response. *Harmful Algae*, *8*(4), 547–548. https://doi.org/10.1016/j.hal.2008.11.001 A scientific workshop, State of the Research on Red Tide in the Gulf of Mexico, sponsored by the National Oceanic and Atmospheric Administration, Mote Marine Laboratory (MML), and Florida Fish and Wildlife Conservation Commission's Fish and Wildlife Research Institute and held July 17–20, 2006 at MML,summarized and synthesized existing research on K. brevis and developed priorities for future research. This special issue demonstrates how much progress has been made in understanding K. brevis blooms and their impacts and the improvements in management and response.

Dyson, K., & Huppert, D. D. (2010). Regional economic impacts of razor clam beach closures due to harmful algal blooms (HABs) on the Pacific coast of Washington. *Harmful Algae*, *9*(3), 264–271. https://doi.org/10.1016/j.hal.2009.11.003 Visitor spending in the recreational razor clam fishery positively impacts the coastal economies of Grays Harbor and Pacific counties in Washington State. Since 1991 the fishery has frequently closed due to harmful algal blooms (HABs). These events reduce or eliminate recreational clam-related visitor spending. We develop an economic impact model, based on recreationists' spending, to estimate the economic impacts of these closures. To estimate visitor expenditure patterns, questionnaires were distributed in April of 2008 to an on-site sample of clammers at four beaches on Washington's Pacific coast: Mocrocks, Copalis, Twin Harbors, and Long Beach. Based upon responses from 240 parties, the average expenditure per party ranged from $268.77 at Mocrocks beach to $412.67 at Long Beach. Overall expenditures for the 2007–2008 season were estimated at $24.4 million. A regional input–output model was used to estimate that the fishery had the local economic impact of supporting 404 full-time equivalent jobs and $12.6 million in labor income. To estimate negative impacts of HAB closures, expected visitor expenditures are adjusted to account for visitors' stated intentions when razor clamming is unavailable. For a full year closure of all four beaches, the estimated negative economic impact is a loss of support from the razor clam fishery impacting 339 full-time equivalent jobs and $10.6 million of labor income in the two counties. Further, impacts were calculated for beach closures ranging from a single (2–5 days) season opening to a full year, for individual beaches and combinations of beaches. As expected, the closing of a single opening at one

beach had the smallest economic impacts, while whole season closures at multiple beaches had the largest impact.

Ekstrom J, Moore SK, & Klinger T. (2020). Examining harmful algal blooms through a disaster risk management lens: a case study of the 2015 U.S. West Coast domoic acid event, *Harmful Algae*, 94. https://doi.org/10.1016/j.hal.2020.101740 The human dimensions of harmful algal blooms (HABs) are becoming increasingly apparent as they grow in frequency and magnitude in some regions of the world under changing ocean conditions. One such region is the U.S. West Coast, where HABs of toxigenic species of Pseudo-nitzschia have been found to coincide with or closely follow periods of warming. In 2015, the region experienced a massive HAB of Pseudo-nitzschia that was associated with the 2014-16 Northeast Pacific marine heatwave. The HAB event delayed the opening of the lucrative commercial Dungeness crab fishery for up to 5 months and closed the popular recreational razor clam fishery, resulting in fishery failures and disaster declarations and causing significant sociocultural and economic impacts to coastal communities. Here, management actions are examined that were taken by federal and state government agencies and responses of coastal residents to this extreme HAB event using a disaster risk management framework consisting of four phases: 1) prediction and early warning, 2) event response, 3) recovery and reconstruction, and 4) mitigation and prevention. Clear differences in management actions at the state level were evident in California, Oregon, and Washington during every phase, producing vastly different perceptions of management by coastal residents. A history of trusted relationships and coordination among agencies and with the fishing industry in Washington State was associated with more transparent and accepted management responses. The examination found that additional education, outreach, and trust-building exercises would provide benefits to communities affected by extreme HAB events. Our findings contribute to an understanding of climate change adaptation in coastal communities dependent on fishery resources.

Evans, G., & Jones, L. (2001). *Economic Impact of the 2000 Red Tide on Galveston County, Texas: A Case Study*. https://tpwd.texas.gov/landwater/water/environconcerns/hab/redtide/media/report/economicimpact.pdf The purpose of this case study was to estimate the economic impact of the 2000 Red Tide on Galveston, Texas. Three activities were identified as important components of the Galveston economy that were most likely to be affected by a harmful algal bloom: tourism, commercial oyster harvests, and beach cleanup costs. The 2000 Red Tide had an estimated minimum direct economic impact on Galveston County of $9.9 million, and a maximum direct economic impact of $11.5 million. Employment impacts ranged between 367 and 425 jobs. Output and employment impacts are probably temporary, persisting with the duration of the red tide. The majority of this impact was on businesses within the Food Stores sector (40% of the total estimated impact).

Falconer, I. R. (1999). An Overview of problems caused by toxic blue–green algae (cyanobacteria) in drinking and recreational water. *Environmental Toxicology*, *14*(1), 5–12. https://doi.org/10.1002/(SICI)1522-7278(199902)14:1<5::AID-TOX3>3.0.CO;2-0 Toxic blue–green algae present a hazard to human populations that are exposed through drinking water or recreational activities. The toxins include hepatotoxic peptides, a cytotoxic alkaloid, neurotoxic alkaloids, and saxitoxin derivatives, with allergens and lipopolysaccharides also present. The recorded outbreaks of hepatoenteritis through drinking water have occurred in chlorinated supplies at the time of either natural or copper-induced lysis of blue–green algal water blooms. Recent deaths of dialysis patients were from liver injury caused by blue–green algal toxins contaminating a water supply carried by tanker from an algal infested reservoir source. Recreational exposures to water containing toxic blue–green algae have caused illnesses ranging from acute pneumonia and hepatoenteritis to mild skin irritation and gastroenteritis. Water safety guidelines for cyanobacterial toxins are under development by WHO, and a provisional guideline for microcystin-LR of 1 μg/L has been approved. ©1999 John Wiley & Sons, Inc. Environmental Toxicology 14: 5–12, 1999

Fleming, L. E., Broad, K., Clement, A., Dewailly, E., Elmir, S., Knap, A., Pomponi, S. A., Smith, S., Solo Gabriele, H., & Walsh, P. (2006). Oceans and human health: Emerging public health risks in the marine environ-

ment. *Marine Pollution Bulletin*, *53*(10), 545–560. https://doi.org/10.1016/j.marpolbul.2006.08.012 There has been an increasing recognition of the inter-relationship between human health and the oceans. Traditionally, the focus of research and concern has been on the impact of human activities on the oceans, particularly through anthropogenic pollution and the exploitation of marine resources. More recently, there has been recognition of the potential direct impact of the oceans on human health, both detrimental and beneficial. Areas identified include: global change, harmful algal blooms (HABs), microbial and chemical contamination of marine waters and seafood, and marine models and natural products from the seas. It is hoped that through the recognition of the inter-dependence of the health of both humans and the oceans, efforts will be made to restore and preserve the oceans.

Fleming, Laura E., Baden, D. G., Bean, J. A., Weisman, R., & Blythe, D. G. (1998). Marine seafood toxin diseases: Issues in epidemiology and community outreach. *Environmental Health*, 5. https://www.oceandocs.org/bitstream/handle/1834/758/?sequence=1 In addition to increased seafood consumption and tourism, recent studies link global climate change with an apparent increasing incidence of the Marine Seafood Toxin diseases. However, the epidemiology of the human diseases caused by the harmful marine phytoplankton is still in its infancy. In general, the epidemiology of these diseases has consisted ofcase reports of acute illness, sometimes as epidemic outbreaks, associated with the ingestion of suspicious seafood. Furthermore, even these outbreaks are highly under-reported, especially in poorer countries and in traditionally non-endemic areas. True incidence data are not available due to the lack of disease and exposure biomarkers in humans, as well as the global lack of routine exposure and disease surveillance. Without true incidence data to establish background population rates, it is impossible to evaluate the impact of Global Change or the apparent increasing incidence. Using Ciguatera as an example, general principles of the epidemiology of these diseases will be presented. The issue of disease surveillance as an essential component in the epidemiologic study and public health control of the marine seafood toxin diseases in human populations will be discussed. Recommendations will be made for epidemiologic study and public health control of the marine seafood toxin diseases in human populations.

Fleming, Lora E., Backer, L., & Rowan, A. (2002). The Epidemiology of Human Illnesses Associated with Harmful Algal Blooms. In E. J. Massaro (Ed.), *Handbook of Neurotoxicology: Volume I* (pp. 363–381). Humana Press. https://doi.org/10.1007/978-1-59259-132-9_19 Harmful algal blooms (HABs) are harmful to people predominantly through their elaboration of a wide variety of very potent natural toxins that can accumulate in water or food. The toxins can be acutely lethal, and can cause a wide range of both acute and chronic health effects, including neurologic, dermatologie, pulmonotoxic, hepatotoxic, and immunotoxic illnesses and cancer in humans and other species. Many of these toxins are tasteless, odorless, and heat- and acid-stable; thus normal food preparation methods and conventional water treatment processes will not prevent intoxication if the food or water is contaminated (1–7).

Fleming, Lora E., Kirkpatrick, B., Backer, L. C., Bean, J. A., Wanner, A., Reich, A., Zaias, J., Cheng, Y. S., Pierce, R., Naar, J., Abraham, W. M., & Baden, D. G. (2007). Aerosolized Red-Tide Toxins (Brevetoxins) and Asthma. *Chest*, *131*(1), 187–194. https://doi.org/10.1378/chest.06-1830 Background:With the increasing incidence of asthma, there is increasing concern over environmental exposures that may trigger asthma exacerbations. Blooms of the marine microalgae,Karenia brevis, cause red tides (orharmful algal blooms) annually throughout the Gulf of Mexico.K brevisproduces highly potent natural polyether toxins, calledbrevetoxins, which are sodium channel blockers, and possibly histamine activators. In experimental animals, brevetoxins cause significant bronchoconstriction. In humans, a significant increase in self-reported respiratory symptoms has been described after recreational and occupational exposures to Florida red-tide aerosols, particularly among individuals with asthma. Methods:Before and after 1 h spent on beaches with and without an activeK brevisred-tide exposure, 97 persons ≥ 12 years of age with physician-diagnosed asthma were evaluated by questionnaire and spirometry. Concomitant environmental monitoring, water and air sampling, and personal monitoring for brevetoxins were performed. Results:Participants were significantly more likely to report res-

piratory symptoms afterK brevisred-tide aerosol exposure than before exposure. Participants demonstrated small, but statistically significant, decreases in FEV1, midexpiratory phase of forced expiratory flow, and peak expiratory flow after exposure, particularly among those participants regularly using asthma medications. No significant differences were detected when there was no Florida red tide (ie, during nonexposure periods). Conclusions:This study demonstrated objectively measurable adverse changes in lung function from exposure to aerosolized Florida red-tide toxins in asthmatic subjects, particularly among those requiring regular therapy with asthma medications. Future studies will assess these susceptible subpopulations in more depth, as well as the possible long-term effects of these toxins.

Fleming, Lora E., Kirkpatrick, B., Backer, L. C., Walsh, C. J., Nierenberg, K., Clark, J., Reich, A., Hollenbeck, J., Benson, J., Cheng, Y. S., Naar, J., Pierce, R., Bourdelais, A. J., Abraham, W. M., Kirkpatrick, G., Zaias, J., Wanner, A., Mendes, E., Shalat, S., … Baden, D. G. (2011). Review of Florida red tide and human health effects. *Harmful Algae*, *10*(2), 224–233. https://doi.org/10.1016/j.hal.2010.08.006 This paper reviews the literature describing research performed over the past decade on the known and possible exposures and human health effects associated with Florida red tides. These harmful algal blooms are caused by the dinoflagellate, Karenia brevis, and similar organisms, all of which produce a suite of natural toxins known as brevetoxins. Florida red tide research has benefited from a consistently funded, long-term research program, that has allowed an interdisciplinary team of researchers to focus their attention on this specific environmental issue—one that is critically important to Gulf of Mexico and other coastal communities. This long-term interdisciplinary approach has allowed the team to engage the local community, identify measures to protect public health, take emerging technologies into the field, forge advances in natural products chemistry, and develop a valuable pharmaceutical product. The review includes a brief discussion of the Florida red tide organisms and their toxins, and then focuses on the effects of these toxins on animals and humans, including how these effects predict what we might expect to see in exposed people.

Friedman, M., Fernandez, M., Backer, L., Dickey, R., Bernstein, J., Schrank, K., Kibler, S., Stephan, W., Gribble, M., Bienfang, P., Bowen, R., Degrasse, S., Flores Quintana, H., Loeffler, C., Weisman, R., Blythe, D., Berdalet, E., Ayyar, R., Clarkson-Townsend, D., … Fleming, L. (2017). An Updated Review of Ciguatera Fish Poisoning: Clinical, Epidemiological, Environmental, and Public Health Management. *Marine Drugs*, *15*(3), 72. https://doi.org/10.3390/md15030072

Given, S., Pendleton, L. H., & Boehm, A. B. (2006). Regional Public Health Cost Estimates of Contaminated Coastal Waters: A Case Study of Gastroenteritis at Southern California Beaches. *Environmental Science & Technology*, *40*(16), 4851–4858. https://doi.org/10.1021/es060679s We present estimates of annual public health impacts,both illnesses and cost of illness, attributable to excess gastrointestinal illnesses caused by swimming in contaminated coastal waters at beaches in southern California. Beach-specific enterococci densities are used as inputs to two epidemiological dose-response models to predict the risk of gastrointestinal illness at 28 beaches spanning 160 km of coastline in Los Angeles and Orange Counties. We use attendance data along with the health cost of gastrointestinal illness to estimate the number of illnesses among swimmers and their likely economic impact. We estimate that between 627,800 and 1,479,200 excess gastrointestinal illnesses occur at beaches in Los Angeles and Orange Counties each year. Using a conservative health cost of gastroenteritis, this corresponds to an annual economic loss of $21 or $51 million depending upon the underlying epidemiological model used (in year 2000 dollars). Results demonstrate that improving coastal water quality could result in a reduction of gastrointestinal illnesses locally and a concurrent savings in expenditures on related health care costs.

Grattan, L., Holobaugh, S., & Morris, J. G. (2013). Chapter 31—Seafood Intoxications. In J. G. Morris & M. E. Potter (Eds.), *Foodborne Infections and Intoxications (Fourth Edition)* (pp. 419–434). Academic Press. https://doi.org/10.1016/B978-0-12-416041-5.00031-7 Seafood consumption is the leading cause of foodborne illness with known etiology. It is anticipated that the number of cases will continue to rise over the next dec-

ade with shifting preferences to heart-healthy diets, increased travel to coastal destinations, increased consumption of imported fish, the growth of coastal urban communities, and growing segments of the population involved in marine recreation. The greatest seafood intoxication risks in the United States today are ciguatera fish poisoning (CFP), diarrheic shellfish poisoning (DSP), neurotoxic shellfish poisoning (NSP), paralytic shellfish poisoning (PSP), amnesic shellfish poisoning (ASP), puffer fish poisoning, and scombroid fish poisoning. Effective prevention, early diagnosis, symptom management, and case reporting of these illnesses are important to mitigate the potential impact from some of the most potent naturally occurring toxins known to date.

Grattan, L. M., Holobaugh, S., & Morris, J. G. (2016). Harmful algal blooms and public health. *Harmful Algae*, *57*, 2–8. https://doi.org/10.1016/j.hal.2016.05.003 The five most commonly recognized Harmful Algal Bloom-related illnesses are ciguatera poisoning, paralytic shellfish poisoning, neurotoxic shellfish poisoning (NSP), amnesic shellfish poisoning, and diarrhetic shellfish poisoning. Although these exposures result from exposure to different toxins or toxin congeners, these clinical syndromes have much in common. Exposure occurs through the consumption of fish, shellfish, or through exposure to aerosolized NSP toxins. Routine clinical tests are not available for the diagnosis of harmful algal bloom related illnesses, there is no known antidote for exposure, and the risk of these illnesses can negatively impact local fishing and tourism industries. The absence of exposure risk or diagnostic certainty can also precipitate a chain of events that results in considerable psychological distress for coastal populations. Thus, illness prevention is of paramount importance to minimize human and public health risks. To accomplish this, further transdisciplinary research, close communication and collaboration are needed among HAB scientists, public health researchers, and local, state and tribal health departments at academic, community outreach, and policy levels.

Haab, T. C., Whitehead, J. C., & Parsons, G. R. (2001). The Effect of Information Conveyance on Behavioral Changes from Perceived Risks: An Application to Seafood Consumption and Pfiesteria Piscicida. 33. This paper reports on a study of the effect of alternative information conveyance mechanisms on perceived seafood risks from Pfiesteria Piscicida (hereafter, Pfiesteria) associated fish kills and seafood consumption. The empirical application stems from a Mid Atlantic (North Carolina, Virginia, Maryland and Delaware) survey of approximately 1800 coastal seafood consumers. As the available economic impact studies show, the seafood industry in the Mid-Atlantic has been significantly impacted by recent outbreaks of Pfiesteria in Maryland and North Carolina (Lipton, Diaby). Popular media coverage of Pfiesteria outbreaks has lead to substantial decreases in seafood purchases despite lack of scientific evidence linking these outbreaks to human illness. Because the scientific links between Pfiesteria and human health effects are not fully understood, the risk perceptions and changes in behavior from outbreaks are driven by information conveyed to consumers through the popular media and word of mouth.

Haab, T. C., Whitehead, J. C., Parsons, G. R., Kirkley, J., & Lipton, D. (2002). *The Economic Effects of Pfiesteria in the Mid-Atlantic Region* (p. 272) [National Sea Grant College Program Final Report]. Ohio State University. This report summarizes a Mid-Atlantic (North Carolina, Virginia, Maryland and Delaware) study of seafood consumption combining both revealed and contingent behavior questions. As the available economic impact studies show, the seafood industry has been significantly impacted by recent Pfiesteria outbreaks in Maryland and North Carolina. Popular media coverage of Pfiesteria outbreaks has lead to substantial decreases in seafood purchases despite lack of scientific evidence linking these outbreaks to human illness. Because, at the time of this study, the scientific links between Pfiesteria and human health effects are not fully understood, the changes in behavior from outbreaks are driven by the information conveyed to the consumers through the popular media and word of mouth. As such, this study provides a better understanding of how consumers in the mid-Atlantic region respond to negative information about the risks associated with seafood consumption and what types of counter-information can be successful in alleviating the uncertainty associated with these risks.

Habas, E. J., & Gilbert, C. K. (1974). The Economic Effects of the 1971 Florida Red Tide and the Damage it Presages for Future Occurrences. *Environmental Letters*, *6*(2), 139–147. https://doi.org/10.1080/00139307409437354 A conservative estimate places the economic damage at $20,000,000 from the effects of the 1971 Red Tide on the seven afflicted counties which border the west coast of Florida. A future Red Tide of equal severity could cause up to 40% more economic damage. One of greater severity could easily triple the damage.

Hall, E. R., Nierenberg, K., Boyes, A. J., Heil, C. A., Flewelling, L. J., & Kirkpatrick, B. (2012). The art of red tide science. *Harmful Algae*, *17*, 1–5. https://doi.org/10.1016/j.hal.2012.02.002 Over the years, numerous outreach strategies by the science community, such as FAQ cards and website information, have been used to explain blooms of the toxic dinoflagellate, Karenia brevis that occur annually off the west coast of Florida to the impacted communities. Many state and federal agencies have turned to funded research groups for assistance in the development and testing of environmental outreach products. In the case of Florida red tide, the Fish and Wildlife Research Institute/Mote Marine Laboratory (MML) Cooperative Red Tide Agreement allowed MML to initiate a project aimed at developing innovative outreach products about Florida red tide. This project, which we coined "The Art of Red Tide Science," consisted of a team effort between scientists from MML and students from Ringling College of Art and Design. This successful outreach project focused on Florida red tide can be used as a model to develop similar outreach projects for equally complex ecological issues.

Hallegraeff, G. M. (1993). A review of harmful algal blooms and their apparent global increase. *Phycologia*, *32*(2), 79–99. https://doi.org/10.2216/i0031-8884-32-2-79.1 The microscopic planktonic algae of the world's oceans are critical food for filter-feeding bivalve shellfish (oysters, mussels, scallops, clams) as well as the larvae of commercially important crustaceans and finfish. In most cases, the proliferation of plankton algae (so-called "algal blooms"; up to millions of cells per liter) is therefore beneficial for aquaculture and wild fisheries operations. However, in some situations algal blooms can have a negative effect, causing severe economic losses to aquaculture, fisheries and tourism operations and having major environmental and human health impacts. Among the 5000 species of extant marine phytoplankton, some 300 species can at times occur in such high numbers that they obviously discolor the surface of the sea (so-called 'red tides'),

Hamilton, D. P., Wood, S. A., Dietrich, D. R., & Puddick, J. (2013). Costs of harmful blooms of freshwater cyanobacteria. In *Cyanobacteria* (pp. 245–256). Wiley-Blackwell. https://doi.org/10.1002/9781118402238.ch15 Some toxin-producing genera form dense surface blooms (e.g., Microcystis and Anabaena), whilst others form sub-surface blooms (e.g., Planktothrix and Cylindrospermopsis). The economic costs of harmful cyanobacterial blooms (cyanoHABs) are mainly associated with these genera and relate to both the precautionary measures taken to avoid more severe impacts and the direct effects of toxins. This chapter categorizes the different types of economic impacts that arise from cyanoHABs. It provides information from studies across the globe that have attempted to quantify the monetary costs of blooms. The authors seek a blueprint for the future in terms of how economic costs may change with continued environmental pressures, as well as what might be done to mitigate these effects. The economic impacts of harmful freshwater cyanobacterial blooms may be related to direct water consumption to contact and non-contact recreational activities, including commercial and non-commercial fisheries.

Heil, C. A., Dixon, L. K., Hall, E., Garrett, M., Lenes, J. M., O'Neil, J. M., Walsh, B. M., Bronk, D. A., Killberg-Thoreson, L., Hitchcock, G. L., Meyer, K. A., Mulholland, M. R., Procise, L., Kirkpatrick, G. J., Walsh, J. J., & Weisberg, R. W. (2014). Blooms of Karenia brevis (Davis) G. Hansen & Ø. Moestrup on the West Florida Shelf: Nutrient sources and potential management strategies based on a multi-year regional study. *Harmful Algae*, *38*, 127–140. https://doi.org/10.1016/j.hal.2014.07.016 Identification and quantification of the nutrient sources supporting large, extended duration Karenia brevis blooms on the West Florida Shelf (WFS) in the eastern Gulf of Mexico are critical steps for effective bloom management and mitigation. Previous research

had identified multiple (>12) potential nutrient sources available to K. brevis blooms on the WFS, which vary with bloom stage, location, biomass and bloom toxicity. This current study newly identified and quantified additional nitrogen (N) sources including water column nitrification, photochemical nutrient production, pelagic unicell N2 fixation by diazotrophs other than the colonial cyanobacterium Trichodesmium, and remineralization from seasonal Trichodesmium biomass decay and microzooplankton grazing (and estimated regeneration). Newly identified phosphorus (P) sources include remineralization from Trichodesmium biomass decay and microzooplankton grazing. In estuarine environments, benthic nutrient flux, mixotrophic consumption of picoplankton, nutrient release from zooplankton and microzooplankton grazing, photochemical nutrient production, and nitrification all can contribute up to 100% of the N and/or P requirements of small (<105cellsL−1) K. brevis blooms. During average estuarine flow years, combined estuarine sources contribute up to 17 and 69% of the N and P needs of these blooms, however local estuarine contribution can increase to 100% for exceptional, high flow years. In coastal and offshore environments, regenerated nutrient sources become increasingly important to blooms, with zooplankton excretion, nitrification, decay and regeneration of nutrients from dead fish and pelagic N2 fixation potentially providing 100% of bloom N and P needs. During the largest observed coastal blooms (14.0×106cellsL−1) N2 fixation and release and decay of seasonal Trichodesmium bloom biomass were the only sources of N and P that were completely sufficient to support blooms of that magnitude. Given the complexity of K. brevis bloom dynamics, the multiple available nutrient sources on the WFS and the importance of regenerated N forms in supporting blooms, efforts to reduce potentially controllable nearshore nutrient inputs should be undertaken with the understanding that while they may lead to enhanced coastal water quality, they may not have an immediate impact on the frequency or magnitude of nearshore K. brevis blooms. Additionally, time lags in ecosystem responses or differences in the time scales on which various process operate may require multi-year assessments to determine how effective management practices are in relation to K. brevis blooms. Timely red tide related monitoring products that allow for effective focusing of monitoring needs for short-term prediction of impacts and targeted communication of scientific results to the public and stakeholders, remains the most effective means of K. brevis management.

Heil, C. A., & Steidinger, K. A. (2009). Monitoring, management, and mitigation of Karenia blooms in the eastern Gulf of Mexico. *Harmful Algae*, *8*(4), 611–617. https://doi.org/10.1016/j.hal.2008.11.006 Annual blooms of the toxic dinoflagellate Karenia brevis in the eastern Gulf of Mexico represent one of the most predictable global harmful algal bloom (HAB) events, yet remain amongst the most difficult HABs to effectively monitor for human and environmental health. Monitoring of Karenia blooms is necessary for a variety of precautionary, management and predictive purposes. These include the protection of public health from exposure to aerosolized brevetoxins and the consumption of toxic shellfish, the protection and management of environmental resources, the prevention of bloom associated economic losses, and the evaluation of long term ecosystem trends and for potential future bloom forecasting and prediction purposes. The multipurpose nature of Karenia monitoring, the large areas over which blooms occur, the large range of Karenia cell concentrations (from 5×103cellsL−1 to >1×106cellsL−1) over which multiple bloom impacts are possible, and limitations in resources and knowledge of bloom ecology have complicated K. brevis monitoring, mitigation and management strategies. Historically, K. brevis blooms were informally and intermittently monitored on an event response basis in Florida, usually in the later bloom stages after impacts (e.g. fish kills, marine mammal mortalities, respiratory irritation) were noted and when resources were available. Monitoring of different K. brevis bloom stages remains the most practical method for predicting human health impacts and is currently accomplished by the state of Florida via direct microscopic counts of water samples from a state coordinated volunteer HAB monitoring program. K. brevis cell concentrations are mapped weekly and disseminated to stakeholders via e-mail, web and toll-free phone numbers and provided to Florida Department of Agriculture and Consumer Services (FDACS) for management of both recreational and commercial shellfish beds in Florida and to the National Oceanic and Atmospheric Administration (NOAA) for validation of the NOAA Gulf of Mexico HAB bulletin for provision to environmental managers. Many challenges remain for effective monitoring and management of Karenia blooms, however, including incorporating impact specific monitoring for

the diverse array of potential human and environmental impacts associated with blooms, timely detection of offshore bloom initiation, sampling of the large geographic extent of blooms which often covers multiple state boundaries, and the involvement of multiple Karenia species other than K. brevis (several of which have yet to be isolated and described) with unknown toxin profiles. The implementation and integration of a diverse array of optical, molecular and hybrid Karenia detection technologies currently under development into appropriate regulatory and non-regulatory monitoring formats represents a further unique challenge.

Heil, D. C. (2009). Karenia brevis monitoring, management, and mitigation for Florida molluscan shellfish harvesting areas. *Harmful Algae*, *8*(4), 608–610. https://doi.org/10.1016/j.hal.2008.11.007 The purpose of this paper is to describe the State of Florida Karenia brevis monitoring, management and mitigation procedures for the harvesting of safe molluscan shellfish. Monitoring and management to prevent public health impacts of due to brevetoxins from K. brevis in shellfish has worked successfully for over forty years. Over the past forty years there have been no reports of human illness resulting from the consumption of commercial or recreational harvest harvested of shellfish from Florida waters that were classified as open. Therefore, this monitoring and management program has been a highly successful public health program. In addition, opportunities exist for mitigation which may allow for limited shellfish harvesting and safe consumption during blooms. The key elements of the Florida program are provided as a '"model"' or '"ideal"' monitoring, management, and mitigation program.

Henrickson, S. E., Wong, T., Allen, P., Ford, T., & Epstein, P. R. (2001). Marine swimming-related illness: Implications for monitoring and environmental policy. *Environmental Health Perspectives*, *109*(7), 645–650. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1240366/ There is increasing evidence that environmental degradation may be contributing to an increase in marine-related diseases across a wide range of taxonomic groups. This includes a growing number of reports of both recreational and occupational users of marine waters developing gastrointestinal, respiratory, dermatologic, and ear, nose, and throat infections. The duration and type of exposure, concentration of pathogens, and host immunity determine the risk of infection. Public health authorities may not be able to accurately predict the risk of waterborne disease from marine waters due to the limitations of conventional monitoring, as well as erroneous perceptions of pathogen life span in marine systems. Pathogens undetectable by conventional methods may remain viable in marine waters, and both plankton and marine sediments may serve as reservoirs for pathogenic organisms, which can emerge to become infective when conditions are favorable. In this paper we address the environmental factors that may contribute to illness, the types of associated economic costs, the issues of water quality monitoring and the policy implications raised by the apparent rise in incidence of marine water-related illnesses.

Hinder, S. L., Hays, G. C., Brooks, C. J., Davies, A. P., Edwards, M., Walne, A. W., & Gravenor, M. B. (2011). Toxic marine microalgae and shellfish poisoning in the British isles: History, review of epidemiology, and future implications. *Environmental Health*, *10*(1), 54. https://doi.org/10.1186/1476-069X-10-54 The relationship between toxic marine microalgae species and climate change has become a high profile and well discussed topic in recent years, with research focusing on the possible future impacts of changing hydrological conditions on Harmful Algal Bloom (HAB) species around the world. However, there is very little literature concerning the epidemiology of these species on marine organisms and human health. Here, we examine the current state of toxic microalgae species around the UK, in two ways: first we describe the key toxic syndromes and gather together the disparate reported data on their epidemiology from UK records and monitoring procedures. Secondly, using NHS hospital admissions and GP records from Wales, we attempt to quantify the incidence of shellfish poisoning from an independent source. We show that within the UK, outbreaks of shellfish poisoning are rare but occurring on a yearly basis in different regions and affecting a diverse range of molluscan shellfish and other marine organisms. We also show that the abundance of a species does not necessarily correlate to the rate of toxic events. Based on routine hospital records, the numbers of shellfish poisonings in the UK are very low, but the identification of the toxin involved, or even a confirmation of a poisoning event is extremely difficult to diagnose. An effective shellfish monitoring system, which shuts

down aquaculture sites when toxins exceed regularity limits, has clearly prevented serious impact to human health, and remains the only viable means of monitoring the potential threat to human health. However, the closure of these sites has an adverse economic impact, and the monitoring system does not include all toxic plankton. The possible geographic spreading of toxic microalgae species is therefore a concern, as warmer waters in the Atlantic could suit several species with southern biogeographical affinities enabling them to occupy the coastal regions of the UK, but which are not yet monitored or considered to be detrimental.

Hoagland, P., Anderson, D. M., Kaoru, Y., & White, A. W. (2002). The economic effects of harmful algal blooms in the United States: Estimates, assessment issues, and information needs. *Estuaries*, *25*(4), 819–837. https://doi.org/10.1007/BF02804908 During the last several decades, harmful algal bloom (HAB) events have been observed in more locations than ever before throughout the United States. Scientists have identified a larger number of algal species involved in HABs, more toxins have been uncovered, and more fisheries resources have been affected. Whether this apparent increase in HAB events is a real phenomenon or is the result of increased sampling and monitoring is a topic of intense discussions within the scientific community. We also have an inchoate understanding of the reasons for the apparent increase, particularly concerning the role of anthropogenic nutrient loadings as a causal factor. Whatever the reasons, virtually all coastal regions of the U.S. are now regarded as potentially subject to a wide variety and increased frequency of HABs. It is important to begin to understand the scale of the economic costs to society of such natural hazards. It is a common, but not yet widespread, practice for resource managers and scientists in many localities to develop rough estimates of the economic effects of HAB events in terms of lost sales in the relevant product or factor markets, expenditures for medical treatments, environmental monitoring and management budgets, or other types of costs. These estimates may be invoked in policy debates, often without concern about how they were developed. Although such estimates are not necessarily good measures of the true costs of HABs to society, they may help to measure the scale of losses and be suggestive of their distribution across political jurisdictions or industry sectors. With adequate interpretation, our thinking about appropriate policy responses may be guided by these estimates. Here we compile disparate estimates of the economic effects of HABs for events in the U.S. where such effects were measured during 1987–1992. We consider effects of four basic types: public health, commercial fisheries, recreation and tourism, and monitoring and management. We discuss many of the issues surrounding the nature of these estimates, their relevance as measures of the social costs of natural hazards, and their potential for comparability and aggregation into a national estimate.

Hoagland, P., & Scatasta, S. (2006). The Economic Effects of Harmful Algal Blooms. In E. Granéli & J. T. Turner (Eds.), *Ecology of Harmful Algae* (Vol. 189, pp. 391–402). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-32210-8_30 30.8 Conclusions: Much work remains to develop reliable estimates of the economic effects of HABs. As this work proceeds, attention should be directed at the rationale for developing these estimates. While government officials and others might solicit economic estimates of any kind in order to justify idiosyncratic public health or scientific agendas, attention should be directed at developing estimates of true economic losses, i.e., surplus changes. Based upon our experience with the field, although the number of studies of economic losses or impacts is limited, they outnumber studies of the economic costs of societal responses to HAB events. In other words, societal responses to HABs have been debated, formulated, and implemented with an inadequate understanding of the net benefits of such responses. Further efforts on the economics of HABs should focus on identifying the array of societal responses and characterizing the cost minimizing combination of management actions.

Hoagland, Porter. (2008). *From Jubilees to Halos: Clarifying the Economic Effects of Harmful Algal Blooms on Commercial Fisheries*. *64*, 12. Harmful algal blooms (HABs) are widely thought to have negative economic effects on commercial fisheries. Over the years, many studies have been carried out to estimate these effects, using a variety of methodologies, from simple to complex. While some of these studies are useful, many others ignore some of the important characteristics of the biology of fish stocks, the behavior of firms in the harvesting sector, the exvessel markets for fresh or partially processed fish, and the characteristics of wholesale

markets and markets of substitute seafood products. Accounting for these important features of fisheries can make a difference in terms of the occurrence and scale of economic effects. Further, in order to develop appropriate mitigation strategies, it is important to characterize correctly the size and distribution of economic effects. In this paper, I present an overview of some of the most important considerations when undertaking estimates of the economic effects of HABs on commercial fisheries. I discuss fishery closures, untapped resources, capital and labor malleability, processing costs, halo effects, and some of the issues of efficiency and distribution that arise in these contexts. I illustrate the discussion using real-world examples from HAB-impacted fisheries around the nation. I conclude with some recommendations for estimating the economic impacts of HABs in commercial fisheries in the future.

Hoagland, Porter. (2014). Coupled Nature-Human (CNH) Systems: Generic Aspects of Human Interactions with Blooms of Florida Red Tide (Karenia brevis) and Implications for Policy Responses. In *Toxins and Biologically Active Compounds from Microalgae* (Vol. 2). CRC Press. https://hdl.handle.net/1912/8585 We review first the characteristics of K. brevis blooms, focusing on what is known about the occurrences and effects of the blooms. Second, we sketch the dynamics of human populations that are exposed to the blooms. Third, we investigate the generic aspects of the couplings between K. brevis and humans along the Gulf coast of Florida. We consider some plausible, but non-exhaustive, examples of each of these aspects, and we consider their implications for the incentives that humans face to respond to the HAB hazard. Fourth, we examine an array of policy responses, and we outline an economic approach to policy selection. We finish with a subjective prognosis of the likely implementation of appropriate policy responses, given the characteristics of the hazard, the micro-motives of humans, and the interactions between the two.

Hoagland, Porter, Jin, D., Beet, A., Kirkpatrick, B., Reich, A., Ullmann, S., Fleming, L. E., & Kirkpatrick, G. (2014). The human health effects of Florida Red Tide (FRT) blooms: An expanded analysis. *Environment International*, *68*, 144–153. https://doi.org/10.1016/j.envint.2014.03.016 Human respiratory and digestive illnesses can be caused by exposures to brevetoxins from blooms of the marine alga Karenia brevis, also known as Florida red tide (FRT). K. brevis requires macro-nutrients to grow; although the sources of these nutrients have not been resolved completely, they are thought to originate both naturally and anthropogenically. The latter sources comprise atmospheric depositions, industrial effluents, land runoffs, or submerged groundwater discharges. To date, there has been only limited research on the extent of human health risks and economic impacts due to FRT. We hypothesized that FRT blooms were associated with increases in the numbers of emergency room visits and hospital inpatient admissions for both respiratory and digestive illnesses. We sought to estimate these relationships and to calculate the costs of associated adverse health impacts. We developed environmental exposure–response models to test the effects of FRT blooms on human health, using data from diverse sources. We estimated the FRT bloom-associated illness costs, using extant data and parameters from the literature. When controlling for resident population, a proxy for tourism, and seasonal and annual effects, we found that increases in respiratory and digestive illnesses can be explained by FRT blooms. Specifically, FRT blooms were associated with human health and economic effects in older cohorts (≥55 years of age) in six southwest Florida counties. Annual costs of illness ranged from $60,000 to $700,000 annually, but these costs could exceed $1.0 million per year for severe, long-lasting FRT blooms, such as the one that occurred during 2005. Assuming that the average annual illness costs of FRT blooms persist into the future, using a discount rate of 3%, the capitalized costs of future illnesses would range between $2 and 24 million.

Hoagland, Porter, Jin, D., Polansky, L. Y., Kirkpatrick, B., Kirkpatrick, G., Fleming, L. E., Reich, A., Watkins, S. M., Ullmann, S. G., & Backer, L. C. (2009). The Costs of Respiratory Illnesses Arising from Florida Gulf Coast Karenia brevis Blooms. *Environmental Health Perspectives*, *117*(8), 1239–1243. https://doi.org/10.1289/ehp.0900645 Background: Algal blooms of Karenia brevis, a harmful marine algae, occur almost annually off the west coast of Florida. At high concentrations, K. brevis blooms can cause harm through the release of potent toxins, known as brevetoxins, to the atmosphere. Epidemiologic studies suggest

that aerosolized brevetoxins are linked to respiratory illnesses in humans. Objectives: We hypothesized a relationship between K. brevis blooms and respiratory illness visits to hospital emergency departments (EDs) while controlling for environmental factors, disease, and tourism. We sought to use this relationship to estimate the costs of illness associated with aerosolized brevetoxins. Methods: We developed a statistical exposure–response model to express hypotheses about the relationship between respiratory illnesses and bloom events. We estimated the model with data on ED visits, K. brevis cell densities, and measures of pollen, pollutants, respiratory disease, and intra-annual population changes. Results: We found that lagged K. brevis cell counts, low air temperatures, influenza outbreaks, high pollen counts, and tourist visits helped explain the number of respiratory-specific ED diagnoses. The capitalized estimated marginal costs of illness for ED respiratory illnesses associated with K. brevis blooms in Sarasota County, Florida, alone ranged from $0.5 to $4 million, depending on bloom severity. Conclusions: Blooms of K. brevis lead to significant economic impacts. The costs of illness of ED visits are a conservative estimate of the total economic impacts. It will become increasingly necessary to understand the scale of the economic losses associated with K. brevis blooms to make rational choices about appropriate mitigation.

Hoagland, Porter, Kirkpatrick, B., Jin, D., Kirkpatrick, G., Fleming, L. E., Ullmann, S. G., Beet, A., Hitchcock, G., Harrison, K. K., Li, Z. C., Garrison, B., Diaz, R. E., & Lovko, V. (2020). Lessening the Hazards of Florida Red Tides: A Common Sense Approach. *Frontiers in Marine Science*, *7*. https://doi.org/10.3389/fmars.2020.00538 Along the southwest Florida coast, blooms of the dinoflagellate Karenia brevis are a coastal natural hazard. The organism produces a potent class of toxins, known as brevetoxins, which are released following cell lysis into ocean or estuarine waters or, upon aerosolization, into the atmosphere. When exposed to sufficient levels of brevetoxins, humans may suffer from respiratory, gastro-intestinal, or neurological illnesses. The hazard has been exacerbated by the geometric growth of human populations, including both residents and tourists, along Florida's southwest coast. Impacts to marine organisms or ecosystems also may occur, such as fish kills or deaths of protected mammals, reptiles, or birds. Since the occurrence of a severe Karenia brevis bloom off the southwest Florida coast three-quarters of a century ago, there has been an ongoing debate about the best way for humans to mitigate the impacts of this hazard. Because of the importance of tourism to coastal Florida, there are incentives for businesses and governments alike to obfuscate descriptions of these blooms, leading to the social amplification of risk. We argue that policies to improve the public's ability to understand the physical attributes of blooms, specifically risk communication policies, are to be preferred over physical, chemical, or biological controls. In particular, we argue that responses to this type of hazard must emphasize maintaining the continuity of programs of scientific research, environmental monitoring, public education, and notification. We propose a common-sense approach to risk communication, comprising a simplification of the public provision of existing sources of information.

Horner, R. A., Garrison, D., & Plumley, F. G. (1997). Harmful algal blooms and red tide problems on the U.S. west coast. *Limnology and Oceanography*, *42*(5, part 2), 1076–1088. https://aslopubs.onlinelibrary.wiley.com/doi/abs/10.4319/lo.1997.42.5_part_2.1076 On the U.S. west coast, the main toxin-producing algal species are dinoflagellates in the genus Alexandrium that cause paralytic shellfish poisoning (PSP) and diatoms in the genus Pseudo-nitzschia that produce domoic acid and cause domoic acid poisoning (DAP). Other harmful species, including the raphidophyte Heterosigma uknshiwo and the diatoms Chaetoceros convolutus and Chaetoceros concavicornis, kill fish at aquaculture sites, but arc not harmful to humans. Water discolorations (red tides) caused by nontoxic dinoflagellates also occur throughout the area. Early records, partially based on local native lore, suggest that algal toxins have been present along this coast for hundreds of years, but actual scientific information is sparse. WC review what is now known about harmful algal blooms in this vast area, including the hydrographic regimes that induce and(or) support blooms, bloom dynamics, and the biology of the causative species.

Hudnell, H. K. (2010). The state of U.S. freshwater harmful algal blooms assessments, policy and legislation. *Toxicon*, *55*(5), 1024–1034. https://doi.org/10.1016/j.toxicon.2009.07.021 The incidence of harmful algal

blooms (HABs) is increasing in the United States and worldwide. HAB toxins cause a substantial but unquantified amount of human and animal morbidity and mortality from exposures in recreational, commercial, drinking-source and potable waters. HAB biomass and toxins threaten the sustainability of aquatic ecosystems. U.S. Congressional legislation mandated the establishment of a National Research Plan for Coastal Harmful Algal Blooms, but no similar plan exists for freshwater HABs (FHABs). Eutrophication and FHABs are conservatively estimated to cost the U.S. economy 2.2–4.6 billion dollars annually. A National Research Plan for Freshwater Harmful Algal Blooms is needed to develop U.S. policy and regulations or guidelines to confront FHAB risks. This report reviews the state of FHAB occurrence, risk and risk management assessments in the U.S. Research is identified that must be accomplished to characterize occurrence and risks, and develop cost effective strategies for preventing, suppressing and mitigating FHABs. U.S. Congressional legislation is needed to mandate a National Research Plan for FHABs, establish a timeline for developing policy and fund competitive research-grant programs. The research results will provide a sound scientific basis for making policy determinations and implementing risk management strategies. Successfully confronting FHAB risks will strengthen the U.S. economy, protect human and animal health and help ensure the sustainability of our Nation's freshwater bodies.

Imai, I., Yamaguchi, M., & Hori, Y. (2006). Eutrophication and occurrences of harmful algal blooms in the Seto Inland Sea, Japan. *Plankton & Benthos Research*, *1*(2), 71–84. https://www.jstage.jst.go.jp/_article/pbr/1/2/1_2_71/_article/-char/ja/ The Seto Inland Sea is the largest enclosed coastal sea in Japan and is also a major fishing ground including aquacultures of fish, bivalves and seaweeds. The incidents of red tides dramatically increased in frequency and scale in the Seto Inland Sea along with serious eutrophication in the 1960s and 1970s. The maximum incident of 299 was recorded in 1976, but the incident has since shown a clear decreasing trend, reaching about 100 per year in the late 1980s by virtue of regulation by law, and this level has been maintained thereafter with the level of nutrients supporting red tide occurrences. The "Law Concerning Special Measures for Conservation of the Environment of the Seto Inland Sea" was legislated in 1973 and industrial loading was decreased to half the level of 1972. The important red tide organisms causing huge fishery damages by fish-kill are Chattonella antiqua, C. marina, C. ovata and Heterosigma akashiwo (Raphidophyceae), and Karenia mikimotoi and Cochlodinium polykrikoides (Dinophyceae). The maximum fishery damage (death of 14.2 million yellowtails) was 7.1 billion yen (about US $60 million) caused by C. antiqua in Harima-Nada in 1972. In 1988, a novel red-tide dinoflagellate species Heterocapsa circularisquama appeared for the first time, and has repeatedly killed both natural and aquacultured bivalves, with the highest damage of 3.9 billion yen to cultured oysters in Hiroshima Bay in 1998. Among the important red-tide organisms, C. antiqua, H. circularisquama and C. polykrikoides are rated as extremely harmful species that can easily reach the warning level of fishery damage by consuming only small amounts of nutrients. In toxic blooms, the dinoflagellate Alexandrium tamarense has become dominant in the Seto Inland Sea in the spring season, causing toxicity in short-necked clams and cultured oysters almost every year. Many countermeasures have been applied for harmful algal blooms in Japan. Laws for the regulation of water quality have been most effective in decreasing red-tide occurrences. No physical and chemical controls have been successful except for clay treatments. Clay spraying has been investigated and implemented in Kyushu and Korea for the removal of C. polykrikoides red tides. As environment-friendly mitigation strategies for red tides, biological controls using algicidal bacteria and viruses are proposed. A new finding of the abundant existence of algicidal bacteria on the surface of seaweeds suggests that co-culturing fish and seaweed is a prevention strategy for harmful algal blooms by virtue of the continuous release of many algicidal bacteria to the surrounding seawater. The artificial development of seaweed beds would also be effective as a prevention strategy for red tides.

Interorganizational Committee on Principles and Guidelines for Social Impact Assessment. (2003). Principles and guidelines for social impact assessment in the USA. *Impact Assessment and Project Appraisal*, *21*(3), 231–250. https://doi.org/10.3152/147154603781766293 The 2003 version of Principles and Guidelines for Social Impact Assessment (SIA) in the USA provides guidance for the conduct of SIA within the context of the US National Environmental Policy Act of 1970. Guidelines are integrated within six principles focusing on: un-

derstanding of local and regional settings; dealing with the key elements of the human environment; using appropriate methods and assumptions; providing quality information for decision making; ensuring that environmental justice issues are addressed; and establishing mechanisms for evaluation/ monitoring and mitigation. A social impact assessment model is outlined followed by suggested social impact assessment variables. The document concludes with the detailed steps in the SIA process.

Jardine, S. L., Fisher, M. C., Moore, S. K., & Samhouri, J. F. (2020). Inequality in the Economic Impacts from Climate Shocks in Fisheries: The Case of Harmful Algal Blooms. *Ecological Economics*, *176*, 106691. https://doi.org/10.1016/j.ecolecon.2020.106691 Climate impacts disproportionately affect people that are most vulnerable and least able to adapt. The extent to which these equity impacts extend to fishing communities in the developed world is a question that has received surprisingly little attention. Here we explore the distributional impacts of a climate shock in one of the largest and most valuable fisheries on the West Coast of the United States. Specifically, we examine whether a series of two harmful algal blooms (HABs), occurring during the 2014–2016 Northeast Pacific Marine Heatwave, differentially affected small and large vessels in the commercial California Dungeness crab fishery. The HAB events were managed with localized fishery closures in response to elevated levels of the HAB toxin, domoic acid, in crab tissue. We find evidence that large vessels had a greater ability to mitigate losses from the HAB events. Thus, the proportion of total revenue going to small-vessel operators and the proportion of small-vessel participation in the fishery fell in response to the HAB events in several California fishing ports. Our results, therefore, offer empirical evidence that climate impacts on fishing communities are not uniform and offer insights into potential alternative adaptation strategies for different ocean user groups.

Jin, D., & Hoagland, P. (2008). The value of harmful algal bloom predictions to the nearshore commercial shellfish fishery in the Gulf of Maine. *Harmful Algae*, *7*(6), 772–781. https://doi.org/10.1016/j.hal.2008.03.002 In this study, we develop a framework for measuring the value of harmful algal bloom (HAB) predictions. The framework captures the effects of both private and public responses to HABs. Using data from the New England nearshore commercial shellfish fishery and impact estimates for a large-scale HAB event in 2005, we illustrate how the potential value of HAB forecasts may be estimated. The results of our study suggest that the long-term value of a HAB prediction and tracking system for the Gulf of Maine is sensitive to the frequency of HAB events, the accuracy of predictions, the choice of HAB impact measures, and the effectiveness of public and private responses.

Jin, D., Thunberg, E., & Hoagland, P. (2008). Economic impact of the 2005 red tide event on commercial shellfish fisheries in New England. *Ocean & Coastal Management*, *51*(5), 420–429. https://doi.org/10.1016/j.ocecoaman.2008.01.004 Over the last several decades, harmful algal bloom (HAB) events have been observed in more locations than ever before throughout the United States. The 2005 bloom of Alexandrium fundyense was the most widespread and intense in New England waters since a similar event more than three decades ago. In this study, using historical data from the National Marine Fisheries Service, the Massachusetts Division of Marine Fisheries, and other sources, we develop estimates of the direct economic impacts of the 2005 event on commercial shellfish fisheries in Maine and Massachusetts. Results of our regression analyses suggest that the 2005 event had broad spatial and temporal effects on the shellfish market. In response to a supply shortage resulting from local closures, there was an increase in shellfish imports to New England during the red tide. Further, shellfish closures in Maine were the most likely cause of observable price changes on the Fulton Fish Market in New York.

Kahn, J., & Rockel, M. (1988). Measuring the Economic Effects of Brown Tides. *Journal of Shellfish Research*, *7*(4), 677–682. This paper develops behavioral models for examining the reactions of marine resource users to reduced resource quality associated with brown algal blooms. Models of recreational and commecial fishing are developed, as well as other recreational uses. These models emphasize the concept that the presence of brown tides at certain sites will cause the commercial and recreational activity to substitute other sites and

other species. These substitutions will have additional implications for economic welfare. After developing the conceptual models, preliminary estimates of economic losses are made for the bay scallop fishery, Annual economic losses are on the order of two million dollars.

Kirkpatrick, B., Bean, J. A., Fleming, L. E., Kirkpatrick, G., Grief, L., Nierenberg, K., Reich, A., Watkins, S., & Naar, J. (2010). Gastrointestinal emergency room admissions and Florida red tide blooms. *Harmful Algae*, *9*(1), 82–86. https://doi.org/10.1016/j.hal.2009.08.005 Human exposure to brevetoxins during Florida red tide blooms formed by Karenia brevis has been documented to cause acute gastrointestinal, neurologic, and respiratory health effects. Traditionally, the routes of brevetoxin exposure have been through the consumption of contaminated bivalve shellfish and the inhalation of contaminated aerosols. However, recent studies using more sensitive methods have demonstrated the presence of brevetoxins in many components of the aquatic food web which may indicate potential alternative routes for human exposure. This study examined whether the presence of a Florida red tide bloom affected the rates of admission for a gastrointestinal diagnosis to a hospital emergency room in Sarasota, FL. The rates of gastrointestinal diagnoses admissions were compared for a 3-month time period in 2001 when Florida red tide bloom was present onshore to the same 3-month period in 2002 when no Florida red tide bloom occurred. A significant 40% increase in the total number of gastrointestinal emergency room admissions for the Florida red tide bloom period was found compared to the non-red tide period. These results suggest that the healthcare community may experience a significant and unrecognized impact from patients needing emergency medical care for gastrointestinal illnesses during Florida red tide blooms. Thus, additional studies characterizing the potential sources of exposure to the toxins, as well as the dose/effect relationship of brevetoxin exposure, should be undertaken.

Kirkpatrick, B., Fleming, L. E., Backer, L. C., Bean, J. A., Tamer, R., Kirkpatrick, G., Kane, T., Wanner, A., Dalpra, D., Reich, A., & Baden, D. G. (2006). Environmental exposures to Florida red tides: Effects on emergency room respiratory diagnoses admissions. *Harmful Algae*, *5*(5), 526–533. https://doi.org/10.1016/j.hal.2005.09.004 Human exposure to Florida red tides formed by Karenia brevis, occurs from eating contaminated shellfish and inhaling aerosolized brevetoxins. Recent studies have documented acute symptom changes and pulmonary function responses after inhalation of the toxic aerosols, particularly among asthmatics. These findings suggest that there are increases in medical care facility visits for respiratory complaints and for exacerbations of underlying respiratory diseases associated with the occurrence of Florida red tides. This study examined whether the presence of a Florida red tide affected the rates of admission with a respiratory diagnosis to a hospital emergency room in Sarasota, FL. The rate of respiratory diagnoses admissions were compared for a 3-month time period when there was an onshore red tide in 2001 (red tide period) and during the same 3-month period in 2002 when no red tide bloom occurred (non-red tide period). There was no significant increase in the total number of respiratory admissions between the two time periods. However, there was a 19% increase in the rate of pneumonia cases diagnosed during the red tide period compared with the non-red tide period. We categorized home residence zip codes as coastal (within 1.6km from the shore) or inland (>1.6km from shore). Compared with the non-red tide period, the coastal residents had a significantly higher (54%) rate of respiratory diagnoses admissions than during the red tide period. We then divided the diagnoses into subcategories (i.e. pneumonia, bronchitis, asthma, and upper airway disease). When compared with the non-red tide period, the coastal zip codes had increases in the rates of admission of each of the subcategories during the red tide period (i.e. 31, 56, 44, and 64%, respectively). This increase was not observed seen in the inland zip codes. These results suggest that the healthcare community has a significant burden from patients, particularly those who live along the coast, needing emergency medical care for both acute and potentially chronic respiratory illnesses during red tide blooms.

Kirkpatrick, B., Fleming, L. E., Squicciarini, D., Backer, L. C., Clark, R., Abraham, W., Benson, J., Cheng, Y. S., Johnson, D., Pierce, R., Zaias, J., Bossart, G. D., & Baden, D. G. (2004). Literature review of Florida red tide: Implications for human health effects. *Harmful Algae*, *3*(2), 99–115. https://doi.org/10.1016/j.hal.2003.08.005 Florida red tides are a natural phenomenon caused by dense aggregations of single cell or several species of

unicellular organisms. Patches of discolored water, dead or dying fish, and respiratory irritants in the air often characterize these algal blooms. In humans, two distinct clinical entities, depending on the route of exposure, are associated with exposure to the Florida red tide toxins (particularly the brevetoxins). With the ingestion of brevetoxin-contaminated shellfish, neurotoxic shellfish poisoning (NSP) presents as a milder gastroenteritis with neurologic symptoms compared with other marine toxin diseases such as paralytic shellfish poisoning (PSP) or ciguatera fish poisoning. With the inhalation of the aerosolized red tide toxins (especially the brevetoxins) from the sea spray, respiratory irritation and possibly other health effects are reported in both humans and other mammals [Nat. Toxins Drugs (1995) 141; Fleming, L.E., Baden, D.G., 1988. Neurotoxic shellfish poisoning: public health and human health effects. White Paper for the Proceedings of the Texas Conference on Neurotoxic Shellfish Poisoning. In: Proceedings of the Texas NSP Conference, Corpus Christi, TX, pp. 27–34; Travel Med, 2 (10) (1998b) 1; Travel Med. 3 (10) (1999a) 1; Toxins Pathol. 26 (2) (1998) 276; J. Allergy Clin. Immunol. 69 (1982) 418; Arch. Intern. Med. 149 (1989) 1735; Toxicon 24 (1986) 955; Florida Med. J. 60 (11) (1773) 27; J. Nat. Toxins 4 (1995) 181; J. Nat. Toxins 4 (1995) 181; Sci. Am. 271 (4) (1994) 62]. This paper reviews the literature on the known and possible human health effects of exposure to the Florida red tides and their toxins. The review includes discussion of the red tide organisms and their toxins, as well as the effects of these toxins on both wild and laboratory animals as they relate to possible human health effects and exposures.

Kirkpatrick, B., Kohler, K., Byrne, M., Fleming, L. E., Scheller, K., Reich, A., Hitchcock, G., Kirkpatrick, G., Ullmann, S., & Hoagland, P. (2014). Human responses to Florida red tides: Policy awareness and adherence to local fertilizer ordinances. *Science of The Total Environment*, *493*, 898–909. https://doi.org/10.1016/j.scitotenv.2014.06.083 To mitigate the damages of natural hazards, policy responses can be beneficial only if they are effective. Using a self-administered survey approach, this paper focuses on the adherence to local fertilizer ordinances (i.e., county or municipal rules regulating the application of fertilizer to private lawns or facilities such as golf courses) implemented in jurisdictions along the Southwest Florida coast in response to hazardous blooms of Florida red tides (Karenia brevis). These ordinances play a role in the context of evolving programs of water pollution control at federal, state, water basin, and local levels. With respect to policy effectiveness, while the strength of physical linkages is of critical importance, the extent to which humans affected are aware of and adhere to the relevant rules, is equally critical. We sought to understand the public's depth of understanding about the rationales for local fertilizer ordinances. Respondents in Sarasota, Florida, were asked about their fertilizer practices in an area that has experienced several major blooms of Florida red tides over the past two decades. A highly educated, older population of 305 residents and "snowbirds" reported relatively little knowledge about a local fertilizer ordinance, its purpose, or whether it would change the frequency, size, or duration of red tides. This finding held true even among subpopulations that were expected to have more interest in or to be more knowledgeable about harmful algal blooms. In the face of uncertain science and environmental outcomes, and with individual motivations at odds with evolving public policies, the effectiveness of local community efforts to decrease the impacts of red tides may be compromised. Targeted social-science research on human perceptions about the risks of Florida red tides and education about the rationales for potential policy responses are warranted.

Kirkpatrick, B., Kohler, K., Byrne, M. M., & Studts, J. (2014). Florida red tide knowledge and risk perception: Is there a need for tailored messaging. *Harmful Algae*, *32*, 27–32. https://doi.org/10.1016/j.hal.2013.09.008 Harmful algal blooms of the toxic dinoflagellate, Karenia brevis, occur throughout the Gulf of Mexico. Recent research efforts sponsored by the National Institute of Environmental Health Sciences (NIEHS) and others found that Florida red tide causes both acute and possibly chronic health effects from the toxic aerosols. Florida red tide also demonstrated significant social and economic impacts to both coastal residents and visitors. In conjunction with the research, persistent outreach efforts were conducted over the 11-year period. The goal of this project was to assess potential needs for tailored messaging needed among different red tide information user groups. Survey participants included 303 local residents, both with asthma and without, and 'snowbirds (seasonal residents that reside in the Sarasota area for more than 3 months but less than 6

months/year), also both with asthma and without. The questionnaire assessed Florida red tide knowledge and risk perception regarding Florida red tide using items drawn from two previously published surveys to allow comparison. Our results reveal that overall knowledge of Florida red tide has not changed. We found that knowledge was consistent across our selected groups and also did not vary by age, gender and education level. However, knowledge regarding consumption of seafood during Florida red tide has declined. Risk perception increased significantly for people who have asthma. Individuals responsible for public health communication regarding Florida red tide and human health concerns need to continue to pursue more effective outreach messages and delivery methods.

Kite-Powell, H. L., Fleming, L. E., Backer, L. C., Faustman, E. M., Hoagland, P., Tsuchiya, A., Younglove, L. R., Wilcox, B. A., & Gast, R. J. (2008). Linking the oceans to public health: Current efforts and future directions. *Environmental Health*, *7*(2), S6. https://doi.org/10.1186/1476-069X-7-S2-S6 We review the major linkages between the oceans and public health, focusing on exposures and potential health effects due to anthropogenic and natural factors including: harmful algal blooms, microbes, and chemical pollutants in the oceans; consumption of seafood; and flooding events. We summarize briefly the current state of knowledge about public health effects and their economic consequences; and we discuss priorities for future research.

Kouakou, C. R. C., & Poder, T. G. (2019). Economic impact of harmful algal blooms on human health: A systematic review. *Journal of Water and Health*, *17*(4), 499–516. https://doi.org/10.2166/wh.2019.064 Harmful algal blooms (HABs) damage human activities and health. While there is wide literature on economic losses, little is known about the economic impact on human health. In this review, we systematically retrieved papers which presented health costs following exposure to HABs. A systematic review was conducted up to January 2019 in databases such as ScienceDirect and PubMed, and 16 studies were selected. Health costs included healthcare and medication expenses, loss of income due to illness, cost of pain and suffering, and cost of death. Two categories of illness (digestive and respiratory) were considered for health costs. For digestive illness cost, we found $86, $1,015 and $12,605, respectively, for mild, moderate and severe cases. For respiratory illness, costs were $86, $1,235 and $14,600, respectively, for mild, moderate and severe cases. We used QualityAdjusted Life Years (QALYs) to access the loss of well-being due to illness caused by HABs. We found that breathing difficulty causes the most loss of QALYs, especially in children, with a loss of between 0.16 and 0.771 per child. Having gastroenteritis could cause a loss of between 2.2 and 7.1 QALYs per 1,000 children. Misleading symptoms of illness following exposure to HABs could cause bias in health costs estimations.

Kouzminov, A., Ruck, J., & Wood, S. A. (2007). New Zealand risk management approach for toxic cyanobacteria in drinking water. *Australian and New Zealand Journal of Public Health*, *31*(3), 275–281. https://doi.org/10.1111/j.1467-842X.2007.00061.x Cyanobacterial blooms are common seasonal phenomena occurring worldwide in fresh, estuarine and coastal waters, including those used for drinking-water supplies, recreation and stock watering. In New Zealand, the frequency of blooms and their geographic spread is likely to grow with increasing eutrophication and global climate change. The New Zealand Ministry of Health has recently developed national criteria for assessing and managing the risk of toxic cyanobacteria in drinking-water supplies. This paper investigates a cyanobacterial bloom incident in the summer 2002/03 in the Waikato River and hydro lakes, which are a major drinking-water supply for Hamilton City and many other smaller towns along the river. The procedures invoked by the Hamilton City Council and other authorities to deal with this bloom event are considered in terms of the best practice of the day and compared with the Drinking-Water Standards for New Zealand 2005. The presence of cyanobacteria has significant economic effects because of increases in water supply treatment costs or the need to use an alternative source, and there are also social effects from the disruption of recreational use of water bodies and loss of confidence in the quality of reticulated, treated water supplies. Notional evaluation of economic cost of monitoring regimes and control, based on the Waikato River cyanobacterial bloom incident, is also given. The multi-barrier and process-control risk management approach, reliant on good vertical communication systems between central and local

government, is an advanced approach useful for any country that regularly experiences cyanobacterial problems.

Kudela, R. M., Berdalet, E., Bernard, S., Burford, M., Fernand, L., Lu, S., Roy, S., Usup, G., Tester, P., Magnien, R., Anderson, D., Cembella, A. D., Chinain, M., Hallegraeff, G., Reguera, B., Zingone, A., Enevoldsen, H., & Urban, E. (2015). *Harmful Algal Blooms. A scientific summary for policy makers* [Miscellaneous]. http://unesdoc.unesco.org/images/0023/002334/233419e.pdf What is a Harmful Algal Bloom (HAB)? Photosynthetic algae support healthy aquatic ecosystems by forming the base of the food web, fixing carbon and producing oxygen. Under certain circumstances, some species can form high-biomass and/or toxic proliferations of cells (or "blooms"), thereby causing harm to aquatic ecosystems, including plants and animals, and to humans via direct exposure to water-borne toxins or by toxic seafood consumption. Ecosystem damage by high-biomass blooms may include, for instance, disruption of food webs,fish-killing by gill damage, or contribution to low oxygen "dead-zones" after bloom degradation. Some species also produce potent natural chemicals (toxins) that can persist in the water or enter the food web, leading to illness or death of aquatic animals and/or human seafood consumers.

Kuhar, S. E., Nierenberg, K., Kirkpatrick, B., & Tobin, G. A. (2009). Public Perceptions of Florida Red Tide Risks. *Risk Analysis*, *29*(7), 963–969. https://doi.org/10.1111/j.1539-6924.2009.01228.x This research integrates theoretical frameworks of risk perception, social amplification of risk, and the role of place-specific contexts in order to explore the various perceptions surrounding Florida red tides. Florida red tides are naturally occurring events that are increasing in frequency, duration, and severity. This has implications for public health, the local economy, and ecosystem health. While many of the negative impacts of Florida red tides are not easily controlled, some of the secondary impacts may be mitigated through individuals' responses. However, public perception and consequent reactions to Florida red tides have not been investigated. This research uses questionnaire surveys, and semi-structured interviews, to explore the various perceptions of the risk surrounding red tides. Surveys and interviews were conducted along two Florida west coast beaches. The results indicate that the underlying foundations of the social amplification of the risk framework are applicable to understanding how individuals form perceptions of risk relative to red tide events. There are key differences between the spatial locations of individuals and corresponding perceptions, indicating that place-specific contexts are essential to understanding how individuals receive and interpret risk information. The results also suggest that individuals may be lacking efficient and up-to-date information about Florida red tides and their impacts because of inconsistent public outreach. Overall, social and spatial factors appear to be influential as to whether individuals amplify or attenuate the risks associated with Florida red tides.

Landsberg, J. H., Flewelling, L. J., & Naar, J. (2009). Karenia brevis red tides, brevetoxins in the food web, and impacts on natural resources: Decadal advancements. *Harmful Algae*, *8*(4), 598–607. https://doi.org/10.1016/j.hal.2008.11.010 As recently as a decade ago, Karenia brevis red tides and their effects on animal resources in the Gulf of Mexico were principally perceived as acute blooms that caused massive fish kills. Although occasional mortalities of higher vertebrates were documented, it has only been in the past decade that conclusive evidence has unequivocally demonstrated that red tides and their brevetoxins are lethal to these organisms. Brevetoxins can be transferred through the food chain and are accumulated in or transferred by biota at many trophic levels. The trophic transfer of brevetoxins in the food web is a complex phenomenon, one that is far more complicated than originally conceived. Unexplained fish kills and other animal mortalities in areas where red tide is endemic are being increasingly linked with postbloom exposures of biota to brevetoxins. Mass mortality events of endangered Florida manatees (Trichechus manatus latirostris) follow a consistent spatial and temporal pattern, occurring primarily in the spring in southwestern Florida. Persistent blooms can also cause a cascade of environmental changes, affecting the ecosystem and causing widespread die-offs of benthic communities. Ongoing fish kills from sustained blooms can lead to short-term declines in local populations. Although animal populations in areas where red tide is endemic are unquestionably at risk, it remains to be determined to what extent populations can continue to recover from these sus-

tained effects.

Larkin, S. (2010). *Florida Red Tides: A Survey of Coastal Residents* (p. 8). Florida Sea Grant. One of the goals of this study was to determine public preferences for three alternative red tide mitigation, control and prevention strategies. This was accomplished through administering a survey to residents in 12 coastal counties where red tides are a common occurrence. The counties were divided into three geographic regions: the Northeast (St. Johns, Flagler, Volusia and Brevard counties), the Southwest (Manatee, Sarasota, Lee and Charlotte counties) and the Northwest (Bay, Okaloosa, Franklin and Gulf counties). The number of surveys sent to each region was stratified based on the proportion of the study population in each region.

Larkin, S. L., & Adams, C. M. (2007). Harmful Algal Blooms and Coastal Business: Economic Consequences in Florida. *Society & Natural Resources*, *20*(9), 849–859. https://doi.org/10.1080/08941920601171683 The impacts of harmful algal blooms (HABs) on coastal businesses in the Ft. Walton Beach and Destin areas of northwest Florida were estimated for 1995–1999. Separate time-series models for the restaurant and lodging sectors revealed that HABs reduced restaurant and lodging revenues in the localized study area by $2.8 million and $3.7 million per month, respectively, which represents a 29% to 35% decline in average monthly revenues for each sector during months of red tide incidence. By comparison, a tropical storm was found to reduce monthly restaurant revenues by $0.5 million, and each inch of rainfall reduced revenues an additional $41,000. Adverse weather was not found to affect the lodging sector. While the estimates are conservative given the resolution of data, the magnitude of effects indicate that coastal communities have suffered significant revenue losses due to HABs and that these losses are larger than caused by other environmental events.

Larkin, S. L., Lucas, K. M., Adams, C. M., & Stevely, J. (2010). *Strategies to Address Red Tide Events in Florida: Results of a 2010 Survey of Coastal Residents*. 5. EDIS Document FE891, April; rev. Feb. 2014. UF/IFAS Extension, Food and Resource Economics Department, University of Florida, Gainesville. This study sought to gather information on the public's concern for, experience with, and knowledge of red tides in Florida. In addition, this study sought to determine public preferences for three alternative red tide mitigation, control, and prevention strategies. Mitigation strategies are those that aim to reduce the negative impacts of a red tide once it has been detected. Control strategies aim to shorten the duration of a red tide once it has been detected. Prevention strategies aim to take action to reduce the probability that a red tide will occur in the future. In this study, the following three types of new programs were proposed as prevention strategies: a fertilizer tax to improve general water quality (prevention strategy that is uncertain for red tides), a trust fund donation for a beach conditions reporting service (mitigation strategy designed to change behavior), and a property tax to fund pilot biological or chemical control programs.

Lassus, P., Chomérat, N., Hess, P., & Nézan, E. (2016). *Toxic and harmful microalgae of the World Ocean* (No. 68; IOC Manuals and Guides, p. 525). International Society for the Study of Harmful Algae. https://unesdoc.unesco.org/ark:/48223/pf0000247767?locale=en Intergovernmental Oceanographic Commission of UNESCO, International Society for the Study of Harmful Algae. We reviewed literature to examine factors that may contribute to the changing distribution of harmful algal blooms around the planet. In addition to straightforward environmental factors such as nutrient loads and ratios, we also consider a number of more complex issues such as increased awareness and monitoring, ballast water discharges, climate change (including global warming) and overfishing. Subsequently, the literature was examined for occurrence of individual species, and any apparent distributional changes. In this second part, a short taxonomic description is given for each species as well as its global distribution, major regional harmful or poisoning events and information on toxins produced, as appropriate. Overall, studies converge to conclude that blooms are on the increase in many areas world-wide. An interesting finding of this review was that large uncertainty exists for most ichthyotoxic species concerning the compounds responsible for their toxicity to fish. The systematic literature search on taxa, toxins and regional events includes publications up to December 2014.

Lazensky, R., Reich, A., Faris, J., Jin, D., Fleming, L. E., Kirkpatrick, B., Watkins, S., Backer, L., Ullmann, S., Kirkpatrick, G., Hitchcock, G., Kohler, K., Stumpf, R., Rudge, K., & Hoagland, P. (2015). *Assessing the Impact of Shellfish Harvesting Area Closures on Neurotoxic Shellfish Poisoning (NSP) Incidence during Florida Red Tide (Karenia brevis) Blooms*. Neurotoxic shellfish poisoning (NSP) is caused by the consumption of molluscan shellfish meat contaminated with brevetoxins produced by the dinoflagellate, Karenia brevis (K. brevis). During a prolonged and intermittent K. brevis bloom starting in 2005 lasting through early 2007 in the Gulf of Mexico off southwest Florida coast, there were 24 confirmed cases of NSP linked to the consumption of clams recreationally harvested in, or in close proximity to, regulated shellfish harvesting areas; these shellfish beds had already been officially closed to harvesting due to the presence of the K. brevis bloom. The majority of NSP cases (78%) were in '"visitors,"' either non-Florida residents or Florida residents living outside the county of harvest. The number of confirmed NSP cases was likely an underestimate of the actual number of cases. Current management strategy appears to be effective in limiting the number of NSP cases associated with shellfish harvested commercially during red tide events.

Legat, A., French, V., & McDonough, N. (2016). An economic perspective on oceans and human health. *Journal of the Marine Biological Association of the United Kingdom*, *96*(1), 13–17. https://doi.org/10.1017/S0025315415001319 Human health and wellbeing are intrinsically connected to our seas and oceans through a complex relationship comprising both positive and negative influences. Although significant public health impacts result from this relationship, the economic implications are rarely analysed. We reviewed the literature to assess current knowledge on the economic valuation and impacts of ocean and human health interactions in a European context. Quantitative analyses on the economic impacts of varying ocean-health interactions were limited. Common challenges to economic assessment included the difficulty in obtaining estimates for indirect healthcare costs, under-reporting of illness and the lack of standardization of surveillance data on illnesses, when available. It was also evident that non-market values, such as health promotion and psychological benefits are underrepresented in economic assessments, most likely because of the lack of standardized valuation methods for such non-market values. We provide recommendations to improve knowledge of ocean and human health linkages and progress future assessment of its economic implications in Europe.

Leggett, C. G., & Bockstael, N. E. (2000). Evidence of the Effects of Water Quality on Residential Land Prices. *Journal of Environmental Economics and Management*, *39*(2), 121–144. https://doi.org/10.1006/jeem.1999.1096 We use hedonic techniques to show that water quality has a significant effect on property values along the Chesapeake Bay. We calculate the potential benefits from an illustrative (but limited) water quality improvement, and we calculate an upper bound to the benefits from a more widespread improvement. Many environmental hedonic studies have almost entirely ignored the potential for omitted variables bias—the possibility that pollution sources, in addition to emitting undesirable substances, are likely to be unpleasant neighbors. We discuss the implications of this oversight, and we provide an application that addresses this potential problem.

Lewitus, A. J., Horner, R. A., Caron, D. A., Garcia-Mendoza, E., Hickey, B. M., Hunter, M., Huppert, D. D., Kudela, R. M., Langlois, G. W., Largier, J. L., Lessard, E. J., RaLonde, R., Jack Rensel, J. E., Strutton, P. G., Trainer, V. L., & Tweddle, J. F. (2012). Harmful algal blooms along the North American west coast region: History, trends, causes, and impacts. *Harmful Algae*, *19*, 133–159. https://doi.org/10.1016/j.hal.2012.06.009 Along the Pacific coast of North America, from Alaska to Mexico, harmful algal blooms (HABs) have caused losses to natural resources and coastal economies, and have resulted in human sicknesses and deaths for decades. Recent reports indicate a possible increase in their prevalence and impacts of these events on living resources over the last 10–15 years. Two types of HABs pose the most significant threat to coastal ecosystems in this "west coast" region: dinoflagellates of the genera Alexandrium, Gymnodinium, and Pyrodinium that cause paralytic shellfish poisoning (PSP) and diatoms of the genus Pseudo-nitzschia that produce domoic acid (DA), the cause of amnesic shellfish poisoning (ASP) in humans. These species extend throughout the region,

while problems from other HABs (e.g., fish kills linked to raphidophytes or Cochlodinium, macroalgal blooms related to invasive species, sea bird deaths caused by surfactant-like proteins produced by Akashiwo sanguinea, hepatotoxins from Microcystis, diarrhetic shellfish poisoning from Dinophysis, and dinoflagellate-produced yessotoxins) are less prevalent but potentially expanding. This paper presents the state-of-knowledge on HABs along the west coast as a step toward meeting the need for integration of HAB outreach, research, and management efforts.

Li, Z., Garrison, B., Ullmann, S. G., Kirkpatrick, B., Fleming, L. E., & Hoagland, P. (2015). Risk in Daily Newspaper Coverage of Red Tide Blooms in Southwest Florida. *Applied Environmental Education & Communication*, *14*(3), 167–177. https://doi.org/10.1080/1533015X.2015.1067579 This study investigated newspaper coverage of Florida red tide blooms in four metropolitan areas of Southwest Florida during a 25-year period, 1987–2012. We focused on how journalists framed red tide stories with respect to environmental risk, health risk, and economic risk. We determined risk to be a key factor in this news coverage, being an aspect of coverage of red tide itself in terms of environmental risk, tourism risk, and public health risk. The study found that red tide news coverage is most often framed as an environmental story.

Loftin, K. A., Graham, J. L., Hilborn, E. D., Lehmann, S. C., Meyer, M. T., Dietze, J. E., & Griffith, C. B. (2016). Cyanotoxins in inland lakes of the United States: Occurrence and potential recreational health risks in the EPA National Lakes Assessment 2007. *Harmful Algae*, *56*, 77–90. https://doi.org/10.1016/j.hal.2016.04.001 A large nation-wide survey of cyanotoxins (1161 lakes) in the United States (U.S.) was conducted during the EPA National Lakes Assessment 2007. Cyanotoxin data were compared with cyanobacteria abundance- and chlorophyll-based World Health Organization (WHO) thresholds and mouse toxicity data to evaluate potential recreational risks. Cylindrospermopsins, microcystins, and saxitoxins were detected (ELISA) in 4.0, 32, and 7.7% of samples with mean concentrations of 0.56, 3.0, and 0.061 mg/L, respectively (detections only). Co-occurrence of the three cyanotoxin classes was rare (0.32%) when at least one toxin was detected. Cyanobacteria were present and dominant in 98 and 76% of samples, respectively. Potential anatoxin-, cylindrospermopsin-, microcystin-, and saxitoxin-producing cyanobacteria occurred in 81, 67, 95, and 79% of samples, respectively. Anatoxin-a and nodularin-R were detected (LC/MS/MS) in 15 and 3.7% samples (n = 27). The WHO moderate and high risk thresholds for microcystins, cyanobacteria abundance, and total chlorophyll were exceeded in 1.1, 27, and 44% of samples, respectively. Complete agreement by all three WHO microcystin metrics occurred in 27% of samples. This suggests that WHO microcystin metrics based on total chlorophyll and cyanobacterial abundance can overestimate microcystin risk when compared to WHO microcystin thresholds. The lack of parity among the WHO thresholds was expected since chlorophyll is common amongst all phytoplankton and not all cyanobacteria produce microcystins.

Lucas, K. M., Larkin, S. L., & Adams, C. M. (2010). Willingness-to-Pay for Red Tide Prevention, Mitigation, and Control Strategies: A Case Study of Florida Coastal Residents. Working paper presented at the Southern Economics Association Annual Meeting, Orlando Florida. Gainesville, FL: Department of Food and Resource Economics, University of Florida, 18pp. The goal of this study is to determine public preferences for three alternative Florida red tide mitigation, control and prevention strategies. This is done through administration of 14,400 mail surveys and an online survey invitation sent to the email addresses of 692,431 residents in 12 coastal counties where red tides are a common occurrence. The survey is used to gather data on the public's concern for, experience with, and knowledge of red tides. In addition, a series of three willingness-to-pay (WTP) scenarios are presented in random order for evaluation: a fertilizer tax to improve general water quality (prevention strategy that is uncertain for red tides), a trust fund donation for a beach conditions reporting service (mitigation strategy designed to change behavior), and a property tax to fund pilot control programs (biological or chemical). A dichotomous choice (DC) format is used to determine the WTP for each scenario. In additions, each scenario is followed by follow-up questions asking the respondent to provide a level of certainty about their response. The results of this study will be used to help summarize public opinion, inform policy makers, and evaluate specific programs intended to address the potentially harmful effects of red tide

events in Florida.

Mao, J., & Jardine, S. L. (2020). Market Impacts of a Toxic Algae Event: The Case of California Dungeness Crab. *Marine Resource Economics*, *35*(1), 1–20. https://doi.org/10.1086/707643 Perceptions of seafood safety are a known driver of seafood demand, and misinformation about seafood safety has generated documented welfare losses in seafood markets. Welfare losses known as avoidance costs can occur when consumers respond to imperfect information about a contamination event, perceiving a health risk from seafood consumption where one does not exist. Furthermore, contamination events can enable other indirect economic impacts in the form of welfare transfers within the seafood supply chain. Here we explore the indirect economic impacts generated by the prolonged 2015 harmful algal bloom event in California. During this event, harmful algae produced high levels of domoic acid (a neurotoxin), resulting in closures for all commercial Dungeness crab fisheries in California that lasted roughly four and a half months. To estimate the impacts of the event, we investigate whether Dungeness crab prices, both at the ex-vessel and consumer levels, were negatively impacted by the event after the closures were lifted and the crab was declared safe to eat. We find ex-vessel prices fell by at least 9.6% while consumer prices were not impacted. We put forth three competing theories to explain these outcomes and discuss the efficiency and distributional implications of each alternative.

Matsuyama, Y. (2012). Impacts of the harmful dinoflagellate Heterocapsa circularisquama bloom on shellfish aquaculture in Japan and some experimental studies on invertebrates. *Harmful Algae*, *14*, 144–155. https://doi.org/10.1016/j.hal.2011.10.019 The dinoflagellate, Heterocapsa circularisquama Horiguchi is known to cause massive marine shellfish deaths in coastal waters of Japan. During the last two decades, proliferation of H. circularisquama across western portions of Japan hampered the production of shellfish cultivation, resulting in economic consequences. In this chapter, the ecophysiology and toxicology of H. circularisquama and subsequent damage to aquaculture are discussed, with special emphasis on the effects of H. circularisquama on the physiology of shellfish.

Mazzillo, F., Pomeroy, C., Kuo, P., Raimondi, P., Prado, R., & Silver, M. (2010). Exposure of anglers to domoic acid-contaminated fish caught in Monterey Bay, California. *Aquatic Biology*, *9*(1), 1–12. Domoic acid (DA) is a neurotoxin that causes amnesic shellfish poisoning, and fish are recognized vectors of DA to marine fauna. However, the exposure of anglers through consumption of DA-contaminated fish is unknown. We measured DA in 11 fish species targeted by Santa Cruz Wharf (SCW) anglers in Monterey Bay, California, USA, and surveyed anglers regarding their fish consumption patterns. In addition, we used California mussel Mytilus californianus DA data provided by the state of California and our measurements of DA in seawater to examine the associations between DA in fish viscera versus in mussels and seawater. DA was detected in the viscera of 7 fish species commonly consumed by anglers, and toxin uptake in fishes varied according to their diet. DA was almost entirely in the viscera, with low DA concentrations detected in muscle tissue. The majority of anglers (58% of 565) reported consuming their catch, with a small fraction ingesting the viscera. Total DA concentrations in fish decreased significantly after 11 mo storage at –20°C. DA concentration in seawater and California mussels was correlated with DA in the viscera of some but not all fish groups. We conclude that SCW anglers who consume their catch are exposed to asymptomatic DA doses, and that exposure is a function of the species and parts consumed, as well as storage methods and DA levels in the seawater when the fish are caught.

Moore, S. K., Cline, M. R., Blair, K., Klinger, T., Varney, A., & Norman, K. (2019). An index of fisheries closures due to harmful algal blooms and a framework for identifying vulnerable fishing communities on the U.S. West Coast. *Marine Policy*, *110*, 103543. https://doi.org/10.1016/j.marpol.2019.103543 Harmful algal blooms (HABs) are a significant threat to coastal communities and their economies. They cause economic losses associated with lost fisheries landings and tourism revenue, food insecurity from loss of subsistence harvest activities, disruption of cultural practices, and loss of community identity and social interactions tied to coastal resource use. In 2015, an unprecedented bloom of Pseudo-nitzschia occurred along the U.S. West

Coast, producing record high concentrations of the toxin domoic acid (DA). Widespread and prolonged fisheries closures resulted, including closures of the lucrative Dungeness crab fishery, generating an economic shock for fishery-dependent communities. To estimate the socioeconomic impacts of the closures and to compare the 2015 DA event with other events, an index was constructed that quantifies lost fishing opportunities due to toxic HABs for 17 fishing communities on the West Coast from 2005 through 2016. An examination of the HAB index shows that the 2015 DA event caused the longest duration and most geographically widespread fisheries closures on record. Communities most vulnerable to the closures of the Dungeness crab fishery were identified using indices of community social vulnerability and fishery dependence. Of the 17 fishing communities examined here, the communities of Crescent City, Fort Bragg and Moss Landing in California had the highest social vulnerability, were the most dependent on the Dungeness crab fishery, and were the most deprived of their Dungeness crab fishing opportunities; as such, these communities may have been the least resilient to the economic shock generated by the 2015 DA event.

Morgan, K. L., Larkin, S. L., & Adams, C. M. (2009). Firm-level economic effects of HABS: A tool for business loss assessment. *Harmful Algae*, *8*(2), 212–218. https://doi.org/10.1016/j.hal.2008.05.002 While the economic consequences of HABs may seem obvious, there is little empirical evidence to support the assertion or its magnitude relative to other environmental effects. As scientists learn more about the effectiveness of alternative HAB prevention, mitigation, and control strategies and agencies prepare for a suite of environmental events, information on potential economic losses are needed at the firm level to evaluate and justify continued HAB-related expenditures. To determine the extent of monetary losses that some firms may have incurred due to blooms of Karenia brevis (red tides) in Southwest Florida, 7 years of daily proprietary data were obtained from three beachfront restaurants and supplemented with environmental data from nearby weather stations. The statistical models revealed that reductions in daily sales ranged from $868 to $3734 (13.7%–15.3% on average) when red tide conditions were present. Estimated losses are compared to other environmental events and were found to coincide with those from other studies. The incidence of red tide events (as noted by each restaurant manager) corresponded with cell counts that averaged 180,853cells/l as measured within 6 miles. Collectively this information supports the hypothesis of localized economic losses and provides a threshold cell count for future loss projections.

Morgan, K. L., Larkin, S. L., & Adams, C. M. (2010). Red tides and participation in marine-based activities: Estimating the response of Southwest Florida residents. *Harmful Algae*, *9*(3), 333–341. https://doi.org/10.1016/j.hal.2009.12.004 Blooms of Karenia brevis (red tide) can kill marine life and irritate human respiratory systems. Knowing how and why participation in marine-based activities (beach-going, fishing, and coastal restaurant patronage) is affected during a red tide is fundamental to estimating the changes in use that occur. Using a sample of residents in Southwest Florida, participant choice models for each activity were estimated to determine the likelihood of alternate behavioral decisions during a red tide event. We find that factors influenced by extension activities have a larger impact than socioeconomic factors commonly hypothesized to affect individual response behavior.

Morgan, K. L., Larkin, S. L., & Adams, C. M. (2011). Empirical analysis of media versus environmental impacts on park attendance. *Tourism Management*, *32*(4), 852–859. https://doi.org/10.1016/j.tourman.2010.07.010 This study examined whether park attendance was affected by red tide events. The analysis found that the presence of red tide, objectively measured with four models including nearby cell counts, did not affect park attendance. However, the appearance of the search phrase “red tide” in local newspapers revealed significant reductions in average daily park attendance of 398 (21 percent) visitors, representing revenue losses of $16,955. An effective red tide impact mitigation strategy may be to educate members of the press regarding the public response resulting from red tide coverage.

National Research Council. (2006). *Facing Hazards and Disasters: Understanding Human Dimensions*. National Academies Press. https://doi.org/10.17226/11671 Social science research conducted since the late 1970s has

contributed greatly to society's ability to mitigate and adapt to natural, technological, and willful disasters.However, as evidenced by Hurricane Katrina, the Indian Ocean tsunami, the September 11, 2001 terrorist attacks on the United States, and other recent events, hazards and disaster research and its application could be improved greatly. In particular, more studies should be pursued that compare how the characteristics of different types of events— including predictability, forewarning, magnitude, and duration of impact—affect societal vulnerability and response.

Nierenberg, K., Byrne, M. M., Fleming, L. E., Stephan, W., Reich, A., Backer, L. C., Tanga, E., Dalpra, D. R., & Kirkpatrick, B. (2010). Florida red tide perception: Residents versus tourists. *Harmful Algae*, *9*(6), 600–606. https://doi.org/10.1016/j.hal.2010.04.010 The west coast of Florida has annual blooms of the toxin-producing dinoflagellate, Karenia brevis with Sarasota, FL considered the epicenter for these blooms. Numerous outreach materials, including Frequently Asked Question (FAQ) cards, exhibits for local museums and aquaria, public beach signs, and numerous websites have been developed to disseminate information to the public about this natural hazard. In addition, during intense onshore blooms, a great deal of media attention, primarily via newspaper (print and web) and television, is focused on red tide. However to date, the only measure of effectiveness of these outreach methods has been counts of the number of people exposed to the information, e.g., visits to a website or number of FAQ cards distributed. No formal assessment has been conducted to determine if these materials meet their goal of informing the public about Florida red tide. Also, although local residents have the opinion that they are very knowledgeable about Florida red tide, this has not been verified empirically. This study addressed these issues by creating and administering an evaluation tool for the assessment of public knowledge about Florida red tide. A focus group of Florida red tide outreach developers assisted in the creation of the evaluation tool. The location of the evaluation was the west coast of Florida, in Sarasota County. The objective was to assess the knowledge of the general public about Florida red tide. This assessment identified gaps in public knowledge regarding Florida red tides and also identified what information sources people want to use to obtain information on Florida red tide. The results from this study can be used to develop more effective outreach materials on Florida red tide.

Nierenberg, K., Kirner, K., Hoagland, P., Ullmann, S., LeBlanc, W. G., Kirkpatrick, G., Fleming, L. E., & Kirkpatrick, B. (2010a). Changes in work habits of lifeguards in relation to Florida red tide. *Harmful Algae*, *9*(4), 419–425. https://doi.org/10.1016/j.hal.2010.02.005 The marine dinoflagellate, Karenia brevis, is responsible for Florida red tides. Brevetoxins, the neurotoxins produced by K. brevis blooms, can cause fish kills, contaminate shellfish, and lead to respiratory illness in humans. Although several studies have assessed different economic impacts from Florida red tide blooms, no studies to date have considered the impact on beach lifeguard work performance. Sarasota County experiences frequent Florida red tides and staffs lifeguards at its beaches 365 days a year. This study examined lifeguard attendance records during the time periods of March 1 to September 30 in 2004 (no bloom) and March 1 to September 30 in 2005 (bloom). The lifeguard attendance data demonstrated statistically significant absenteeism during a Florida red tide bloom. The potential economic costs resulting from red tide blooms were comprised of both lifeguard absenteeism and presenteeism. Our estimate of the costs of absenteeism due to the 2005 red tide in Sarasota County is about $3000. On average, the capitalized costs of lifeguard absenteeism in Sarasota County may be on the order of $100,000 at Sarasota County beaches alone. When surveyed, lifeguards reported not only that they experienced adverse health effects of exposure to Florida red tide but also that their attentiveness and abilities to take preventative actions decrease when they worked during a bloom, implying presenteeism effects. The costs of presenteeism, which imply increased risks to beachgoers, arguably could exceed those of absenteeism by an order of magnitude. Due to the lack of data, however, we are unable to provide credible estimates of the costs of presenteeism or the potential increased risks to bathers.

Nierenberg, K., Kirner, K., Hoagland, P., Ullmann, S., LeBlanc, W. G., Kirkpatrick, G., Fleming, L. E., & Kirkpatrick, B. (2010b). Corrigendum to "Changes in work habits of lifeguards in relation to Florida red tide" [Harmful Algae 9 (2010) 419–425]. *Harmful Algae*, *9*(6), 647. https://doi.org/10.1016/j.hal.2010.05.003

Nierenberg, K., Reich, A., Currier, R., Kirkpatrick, B., Backer, L. C., Stumpf, R., Fleming, L., & Kirkpatrick, G. (2009). Beaches and HABs: Successful Expansion of the Florida Red Tide Reporting System for Protection of Public Health through Community Education and Outreach. *Florida Journal of Environmental Health*, *203*, 18–24. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3163452/ The NOAA HAB Bulletin (http://coastwatch.noaa.gov/hab/bulletins_ns.htm) is a valuable tool for public health managers, resource managers and environmental scientists. It showsbloom location, forecast of short-term bloom movement, and likelihood of adverse healtheffects due to near or onshore impacts (Figure 2). Access to the imagery is delayed one week for public access to ensure accuracy of bloom characterization. Real time beach reporting can improve asthmatics' and local coastal residents' quality of life as well as tourists visiting the area. The Florida tourism promotion agency notes that 80% of people who visit the state come for the beaches (www.visitFlorida.com). The tourism industry has supported a system that provides real time beach conditions to guide visitors to areas not impacted by blooms. With increasing evidence that these inhaled toxins can compromise the health of beachgoers, particularly on days when there are high amounts of toxins in the air, a system that provides frequent and timely reporting on beach conditions is needed. Ideally, this reporting system would consist of objective data such as the amount of brevetoxins in the air. However, there is not currently a method of toxin detection that provides rapid analysis. This article reports on the implementation and expansion of a community- based beach conditions reporting system.

Nunes, P. A. L. D., & van den Bergh, J. C. J. M. (2004). Can People Value Protection against Invasive Marine Species? Evidence from a Joint TC–CV Survey in the Netherlands. *Environmental & Resource Economics*, *28*(4), 517–532. https://doi.org/10.1023/B:EARE.0000036777.83060.b6 Harmful algal-bloom species (HABs) are invasive exotic species that are primarily introduced in North European waters through ballast water of ships. Some produce important damages to the marine ecosystem such as the red tides that cause a massive destruction of marine living resources, including fish and bottom-living animals. Others are responsible for the production of thick foams with repellent odors and the coloration of the beach water, causing important damages on beach recreation. This article reports a monetary valuation study of a marine protection program. This program focuses on the prevention of HABS along the coastline of the Netherlands. It entails the construction of a ballast water disposal treatment in the Rotterdam harbor and the implementation of a monitoring program of the water quality in the open sea along the North-Holland beaches. The valuation study is based on a questionnaire undertaken at Zandvoort, a famous Dutch beach resort. The economic value of the marine protection program includes non-market benefits associated with beach recreation, human health and marine ecosystem impacts. Both contingent-valuation and travelcost methods are used. These valuation techniques have not yet been applied to value HABs damages. The valuation results indicate that the protection program makes sense from an economic perspective as long as its cost is, in any case, less than 225 million euro, and possibly less than 326 million euro, depending on how survey refusals are dealt with.

Núñez-Vázquez, E. J., Gárate-Lizarraga, I., Band-Schmidt, C. J., Cordero-Tapia, A., Lopez-Cortes, D. J., Sandoval, F. E. H., Postal, A., Paz, L., Heredia-Tapia, A., & Bustillos-Guzman, J. J. (2011). *Impact of harmful algal blooms on wild and cultured animals in the Gulf of California*. 11. Historical documents and classic works together with recent specialized literature have described Harmful Algal Blooms (HABs) in the Gulf of California. This is a review of HABs impact (qualitative and quantitative) during the last decades in the Gulf of California on wild (mammals, birds, fishes, and invertebrates) and cultured animals (shrimps and fishes). Microalgal species responsible of noxious effects are Noctiluca scintillans, Cochlodinium polykrikoides, Gymnodinium catenatum, Prorocentrum minimum, Akashiwo sanguinea, Chattonella subsalsa Ch. marina, Chattonella sp., Heterocapsa sp., Dinophysis sp., Fibrocapsa japonica, Heterosigma akashiwo, Thalassiosira sp., Chaetoceros spp., Pseudo-nitzschia australis, P. fraudulenta, Pseudo-nitzschia sp., Trichodesmium erythraeum and Schizotrix calcicola. Emphasis is given to the necessity to continue with interdisciplinary studies in oceanography, ecology, toxicology and toxinology interrelated with biomedical sciences such as physiology, pathology, epidemiology and animal health.

O'Neil, J. M., Davis, T. W., Burford, M. A., & Gobler, C. J. (2012). The rise of harmful cyanobacteria blooms: The potential roles of eutrophication and climate change. *Harmful Algae*, *14*, 313–334. https://doi.org/10.1016/j.hal.2011.10.027 Cyanobacteria are the most ancient phytoplankton on the planet and form harmful algal blooms in freshwater, estuarine, and marine ecosystems. Recent research suggests that eutrophication and climate change are two processes that may promote the proliferation and expansion of cyanobacterial harmful algal blooms. In this review, we specifically examine the relationships between eutrophication, climate change and representative cyanobacterial genera from freshwater (Microcystis, Anabaena, Cylindrospermopsis), estuarine (Nodularia, Aphanizomenon), and marine ecosystems (Lyngbya, Synechococcus, Trichodesmium). Commonalities among cyanobacterial genera include being highly competitive for low concentrations of inorganic P (DIP) and the ability to acquire organic P compounds. Both diazotrophic (= nitrogen (N2) fixers) and non-diazotrophic cyanobacteria display great flexibility in the N sources they exploit to form blooms. Hence, while some cyanobacterial blooms are associated with eutrophication, several form blooms when concentrations of inorganic N and P are low. Cyanobacteria dominate phytoplankton assemblages under higher temperatures due to both physiological (e.g. more rapid growth) and physical factors (e.g. enhanced stratification), with individual species showing different temperature optima. Significantly less is known regarding how increasing carbon dioxide (CO2) concentrations will affect cyanobacteria, although some evidence suggests several genera of cyanobacteria are well-suited to bloom under low concentrations of CO2. While the interactive effects of future eutrophication and climate change on harmful cyanobacterial blooms are complex, much of the current knowledge suggests these processes are likely to enhance the magnitude and frequency of these events.

O'Shea, T. J., Rathbun, G. B., Bonde, R. K., Buergelt, C. D., & Odell, D. K. (1991). An epizootic of Florida manatees associated with a dinoflagellate bloom. *Marine Mammal Science*, *7*(2), 165–179. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1748-7692.1991.tb00563.x Over a 10-wk period in early 1982, 39 Florida manatees (Trichechus manatus latirostris) were found dead in the lower Caloosahatchee River and nearby waters of southwestern Florida. Two were killed by boats. The remainder showed no evidence of trauma. Lesions indicative of infectious agents were not identified,and bacteriological and contaminant residue findings were unremarkable. Nonspecific lesions of congestion and hemorrhage were identified in brain tissue. Numerous reports were also received of manatee morbidity. Some distressed manatees showed no biochemical lesions in clinical analyses of blood samplesand recovered quickly. Timing of manatee illnesses coincided with fish and double-crested cormorant (Phalacrocorax auritus) mortality and morbidity. Awidespread bloom of the dinoflagellate red tide organism (Gymnodinium breve) also coincided with these incidents. G. breve produces potent neurotoxins (brevetoxins). Circumstantial evidence links these events, and possible routes of exposure may include ingestion of filter-feeding ascidians. Ecological conditions that magnified the extent of the epizootic included an early dispersal of manatees intothe area from a nearby winter aggregation site and unusually high salinities that

Paerl, H. W., Fulton, R. S., Moisander, P. H., & Dyble, J. (2001). Harmful Freshwater Algal Blooms, With an Emphasis on Cyanobacteria. *The Scientific World Journal*. https://doi.org/10.1100/tsw.2001.16 Suspended algae, or phytoplankton, are the prime source of organic matter supporting food webs in freshwater ecosystems. Phytoplankton productivity is reliant on adequate nutrient supplies; however, increasing rates of nutrient supply, much of it manmade, fuels accelerating primary production or eutrophication. An obvious and problematic symptom of eutrophication is rapid growth and accumulations of phytoplankton, leading to discoloration of affected waters. These events are termed blooms. Blooms are a prime agent of water quality deterioration, including foul odors and tastes, deoxygenation of bottom waters (hypoxia and anoxia), toxicity, fish kills, and food web alterations. Toxins produced by blooms can adversely affect animal (including human) health in waters used for recreational and drinking purposes. Numerous freshwater genera within the diverse phyla comprising the phytoplankton are capable of forming blooms; however, the blue-green algae (or cyanobacteria) are the most notorious bloom formers. This is especially true for harmful toxic, surface-dwelling, scum-

forming genera (e.g., Anabaena, Aphanizomenon, Nodularia, Microcystis) and some subsurface bloom-formers (Cylindrospermopsis, Oscillatoria) that are adept at exploiting nutrient-enriched conditions. They thrive in highly productive waters by being able to rapidly migrate between radiance-rich surface waters and nutrient-rich bottom waters. Furthermore, many harmful species are tolerant of extreme environmental conditions, including very high light levels, high temperatures, various degrees of desiccation, and periodic nutrient deprivation. Some of the most noxious cyanobacterial bloom genera (e.g., Anabaena, Aphanizomenon, Cylindrospermopsis, Nodularia) are capable of fixing atmospheric nitrogen (N2), enabling them to periodically dominate under nitrogen-limited conditions. Cyanobacteria produce a range of organic compounds, including those that are toxic to higher-ranked consumers, from zooplankton to further up the food chain. Both N2- and non-N2-fixing genera participate in mutualistic and symbiotic associations with microorganisms, higher plants, and animals. These associations appear to be of great benefit to their survival and periodic dominance. In this review, we address the ecological impacts and environmental controls of harmful blooms, with an emphasis on the ecology, physiology, and management of cyanobacterial bloom taxa. Combinations of physical, chemical, and biotic features of natural waters function in a synergistic fashion to determine the sensitivity of water bodies. In waters susceptible to blooms, human activities in water- and airsheds have been linked to the extent and magnitudes of blooms. Control and management of cyanobacterial and other phytoplankton blooms invariably includes nutrient input constraints, most often focused on nitrogen (N) and/or phosphorus (P). The types and amount of nutrient input constraints depend on hydrologic, climatic, geographic, and geologic factors, which interact with anthropogenic and natural nutrient input regimes. While single nutrient input constraints may be effective in some water bodies, dual N and P input reductions are usually required for effective long-term control and management of harmful blooms. In some systems where hydrologic manipulations (i.e., plentiful water supplies) are possible, reducing the water residence time by enhanced flushing and artificial mixing (in conjunction with nutrient input constraints) can be particularly effective alternatives. Implications of various management strategies, based on combined ecophysiological and environmental considerations, are discussed.

Park, T. G., Lim, W. A., Park, Y. T., Lee, C. K., & Jeong, H. J. (2013). Economic impact, management and mitigation of red tides in Korea. *Harmful Algae*, *30*, S131–S143. https://doi.org/10.1016/j.hal.2013.10.012 Over the past three decades, a total of USD $121 million in economic losses (fish/shellfish kills) has occurred in the Korean aquaculture industry due to harmful algal blooms (HABs). Paralytic shellfish poisoning (PSP) has also been noted almost every year, closing shellfish farms, and 46 people were poisoned including five people killed by consuming wild mussels. Since 1980, PSP has been officially monitored and managed, and the nationwide control of fish/shellfish kills by HAB species began in 1995. Management and control strategies include both precautionary and emergency measures. Precautionary management includes establishing an observation network and prediction system, an early warning system, and mitigating damage to aquafarms. Along with regular HAB monitoring including species, chlorophyll a, and associated water quality and meteorological parameters, automatic HAB alarm systems equipped with chlorophyll a and turbidity sensors are used in aquafarms as early HAB warnings. Emergency management is essential after a HAB outbreak to prevent fisheries damage. This method includes supplying oxygen to fish, stopping feeding, transferring fish to a safe area, and clay dispersal. Clay dispersion is the prime mitigation technique for HABs in Korea, because clay is natural, nontoxic, inexpensive, and easy to use in field operations. Clay is dispersed over the sea surface using a clay dispensing device to efficiently remove HABs. A third generation (3G) clay dispenser has been developed recently, combining an electrolytic water generator and a clay dispenser, significantly reducing the amount of clay used, resulting in high removal efficiencies. Since using this device, the economic losses from HAB fish kills have dropped >80% in Korea, although the frequency of HABs has increased since 1980. Clay is a natural component, but using too much clay may cause negative impacts on marine organisms and environments. In addition, clay dispersal is not an effective method to control poisoning of fish/shellfish from algal toxins that accumulate in fish and shellfish at low density toxic blooms. Future studies of HAB control should include control of HABs using minimum amounts of clay and practical use of biological control agents.

Parsons, G. R., Morgan, A., Whitehead, J. C., & Haab, T. C. (2006). The Welfare Effects of Pfiesteria-Related Fish Kills: A Contingent Behavior Analysis of Seafood Consumers. *Agricultural and Resource Economics Review*, *35*(2), 348–356. https://doi.org/10.1017/S106828050000678X We use contingent behavior analysis to study the effects of pfiesteria-related fish kills on the demand for seafood in the Mid-Atlantic region. We estimate a set of demand difference models based on individual responses to questions about seafood consumption in the presence of fish kills and with different amounts of information provided about health risks. We use a random-effects Tobit model to control for correlation across each observation and to account for censoring. We find that (i) pfiesteria-related fish kills have a significant negative effect on the demand for seafood even though the fish kills pose no known threat to consumers through seafood consumption, (ii) seafood consumers are not responsive to expert risk information designed to reassure them that seafood is safe in the presence of a fish kill, and (iii) a mandatory seafood inspection program largely eliminates the welfare loss incurred due to misinformation.

Quilliam, M. A., & Wright, J. L. C. (1989). The Amnesic Shellfish Poisoning Mystery. *Analytical Chemistry*, 61(18): 1053A-1060A. https://pubs.acs.org/doi/pdf/10.1021/ac00193a002 In late 1987 a mysterious and serious outbreak of food poisoning occurred in Canada. Symptoms of the poisoning included vomiting and diarrhea, followed in some cases by confusion, memory loss, disorientation, and coma. Three elderly patients died, and other victims still suffer from neurological problems. The term amnesic shellfish poisoning has been proposed for this clinical syndrome. Epidemiologists from Health and Welfare Canada (HWC) attributed the illnesses to restaurant meals of cultured blue mussels (Mytilus edulis L.). Using the Association of Official Analytical Chemists' mouse bioassay for "red-tide" paralytic shellfish poison, HWC and Department of Fisheries and Oceans (DFO) scientists demonstrated that these mussels did contain toxic material and traced the problem to mussels harvested from a localized area of eastern Prince Edward Island. Intraperitoneal injections of acidic aqueous extracts of suspect mussels into mice caused death with some unusual neurotoxic symptoms very different from those of paralytic shellfish poison and other known toxins. It was not known whether the toxic agent was a man-made pollutant or a natural toxin. The scientific detective story that unfolded was followed closely by a concerned Canadian public and made front-page newspaper headlines for several weeks. For health, political, and economic reasons, scientists in Canadian government laboratories were eager to solve the mystery quickly. On December 12,1987, a team of scientists was assembled at the AtlanticResearch Laboratory (ARL) of the National Research Council in Halifax, Nova Scotia. This team consisted of all available chemists and marine biologists from ARL as well as some scientists from DFO, including personnel experienced with the mouse bioassay procedure. This team developed a strategy based on bioassay-directed separations and analyses that led to the identification of the toxin on the afternoon of December 16, just 102 h after the start of the concerted investigation.

Ralston, E. P., Kite-Powell, H., & Beet, A. (2011). An estimate of the cost of acute health effects from food- and water-borne marine pathogens and toxins in the USA. *Journal of Water and Health*, *9*(4), 680–694. https://doi.org/10.2166/wh.2011.157 Large and growing segments of the United States population consume seafood or engage in marine recreation. These activities provide significant benefits but also bring risk of exposure to marine-borne illness. To manage these risks, it is important to understand the incidence and cost of marine-borne disease. We review the literature and surveillance/monitoring data to determine the annual incidence of disease and health consequences due to marine-borne pathogens from seafood consumption and beach recreation in the USA. Using this data, we employ a cost-of-illness model to estimate economic impacts. Our results suggest that health consequences due to marine-borne pathogens in the USA have annual costs on the order of US$900 million. This includes US$350 million due to pathogens and marine toxins specifically identified as causing food-borne disease, an estimated US$300 million due to seafood-borne disease with unknown etiology, US$30 million from direct exposure to the Vibrio species, and US$300 million due to gastrointestinal illness from beach recreation. Although there is considerable uncertainty about the degree of underreporting of certain pathogen-specific acute marine-related illnesses, the conservative assumptions we

have used in constructing our estimate suggest that it should be considered a lower bound on true costs.

Reich, A., Lazensky, R., Faris, J., Fleming, L. E., Kirkpatrick, B., Watkins, S., Ullmann, S., Kohler, K., & Hoagland, P. (2015). Assessing the impact of shellfish harvesting area closures on neurotoxic shellfish poisoning (NSP) incidence during red tide (Karenia brevis) blooms. *Harmful Algae*, *43*, 13–19. https://doi.org/10.1016/j.hal.2014.12.003 Neurotoxic shellfish poisoning (NSP) is caused by the consumption of molluscan shellfish meat contaminated with brevetoxins produced by the dinoflagellate, Karenia brevis (K. brevis). During a prolonged and intermittent K. brevis bloom starting in 2005 lasting through early 2007 in the Gulf of Mexico off southwest Florida coast, there were 24 confirmed cases of NSP linked to the consumption of clams recreationally harvested in, or in close proximity to, regulated shellfish harvesting areas; these shellfish beds had already been officially closed to harvesting due to the presence of the K. brevis bloom. The majority of NSP cases (78%) were in '"visitors,"' either non-Florida residents or Florida residents living outside the county of harvest. The number of confirmed NSP cases was likely an underestimate of the actual number of cases.

Ritzman, J., Brodbeck, A., Brostrom, S., McGrew, S., Dreyer, S., Klinger, T., & Moore, S. K. (2018). Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 U.S. West Coast harmful algal bloom. *Harmful Algae*, *80*, 35–45. https://doi.org/10.1016/j.hal.2018.09.002 In the spring of 2015, a massive harmful algal bloom (HAB) of the toxin-producing diatom Pseudo-nitzschia occurred on the U.S. West Coast, resulting in the largest recorded outbreak of the toxin domoic acid and causing fisheries closures. Closures extended into 2016 and generated an economic shock for coastal fishing communities. This study examines the economic and sociocultural impacts of the Dungeness crab and razor clam fisheries closures on two fishing-dependent communities. Semi-structured interviews were conducted with 36 community members from two communities impacted by the event – Crescent City, California and Long Beach, Washington. Interviewees included those involved in the fishing, hospitality, and retail industries, local government officials, recreational harvesters, and others. Interviews probed aspects of resilience in economic, social, institutional, and physical domains, based on the contention that community resilience will influence the communities' ability to withstand HAB events. Dimensions of vulnerability were also explored, encompassing sensitivity of the communities to HAB events and their adaptive capacity. Common themes that emerged from the interview responses indicate that economic hardships extended beyond fishing-related operations and permeated through other sectors, particularly the hospitality industry. Significant barriers to accessing financial and employment assistance during extended fisheries closures were identified, particularly for fishers. Long-held traditions surrounding crab and shellfish harvest and consumption were disrupted, threatening the cultural identities of the affected communities. Community members expressed a desire for clearer, more thorough, and more rapid dissemination of information regarding the management of fisheries closures and the health risks associated with HAB toxins. The likelihood of intensifying HABs under climate change heightens the need for actions to increase the resilience of fishing communities to the economic and sociocultural impacts caused by HAB-related fisheries closures.

Rongo, T., & van Woesik, R. (2012). Socioeconomic consequences of ciguatera poisoning in Rarotonga, southern Cook Islands. *Harmful Algae*, *20*, 92–100. https://doi.org/10.1016/j.hal.2012.08.003 For the last 20 years, the world's highest incidence of ciguatera poisoning has been reported in Rarotonga, which is located in the southern Cook Islands. Therefore, Rarotonga is an ideal location to understand the socioeconomic consequences of ciguatera poisoning on small-island communities. In 2011, information on protein consumption preferences was collected from 179 Rarotongan households and compared with previous food consumption studies. This study showed that ciguatera poisoning halved the per-capita fresh fish consumption, from 149g/person/day in 1989 to 75g/person/day in 2006. Consequently, the consumption of alternative proteins, particularly imported meats, increased from 1989 to 2006. The cost-savings-and-avoidance valuation technique, used to estimate the direct loss in value of marketable goods and services, showed that the economic consequences of ciguatera poisoning amounted to approximately NZD $750,000 per year. Approximate costs

associated with dietary shifts amounted to NZD $1 million per year. With the decline in cases of ciguatera poisoning in recent years, fresh fish has returned to the menu of residents, and the per-capita fresh fish consumption increased to 104g/person/day in 2011. Yet over the last two decades, the impact of ciguatera poisoning on the local Rarotongan community may have had long-term health-related consequences, and may have changed the social, cultural, and traditional characteristics of a once subsistence fishing lifestyle.

Sanseverino, I., Conduto, D., Dobricic, S., & Lettieri, T. (2016). *Algal bloom and its economic impact*. *JRC101253*(EUR 27905 EN), 52. https://doi.org/10.2788/660478

Harmful algal blooms (HABs) represent a natural phenomena caused by a mass proliferation of phytoplankton (cyanobacteria, diatoms, dinoflagellates) in waterbodies. Blooms can be harmful for the environment, human health and aquatic life due to the production of noxic toxins and the consequences of accumulated biomass (oxygen depletion). These blooms are occurring with increased regularity in marine and freshwater ecosystems and the reasons for their substantial intensification can be associated with a set of physical, chemical and biological factors including climate changes and anthropogenic impacts. Many bloom episodes have significant impacts on socio-economic systems. Fish mortality, illnesses caused by the consumption of contaminated seafood and the reluctance of consumers to purchase fish during HABs episodes represent only some of the economic impacts of HABs. The aim of this report is to evaluate the economic losses caused by HABs in different sectors. This was achieved by collecting data that exist in the technical literature and group them into four categories: (1) human health impacts; (2) fishery impacts; (3) tourism and recreation impacts; (4) monitoring and management costs. The data analyzed refer to both marine and freshwater HABs. Among the sectors examined in this study, human health impacts appear less investigated than the other three categories. This is probably caused by the difficulty to assess the direct effects of toxins on human health because of the wide range of symptoms they can induce. Looking at the data, the interest in mitigating the economic losses associated with blooms is particularly demonstrated by studies aimed to develop monitoring and management strategies to reduce HABs episodes. Indeed, the water monitoring, when accompanied by appropriate management actions, can assure the mitigation of ongoing HABs and the reduction of negative impacts. During data collection, it has been more difficult to find economic data about blooms in Europe than in United States of America (USA). A reason may be the lack of European reports or publicly available data about HABs and their socio-economic impacts. Much studies still have to be performed in this field, but the reported increase in HABs frequency will surely increase not only scientific analysis about HABs but also economic studies to report whether safeguards taken have succeeded in mitigating the economic impact associated with blooms.

Scatasta, S., Stolte, W., Granéli, E., Weikard, H. P., & van Ierland, E. (2003). *HARMFUL ALGAL BLOOMS IN EUROPEAN MARINE WATERS: SOCIO-ECONOMIC ANALYSIS OF SELECTED CASE STUDIES* (No. 3; ECOHARM: THE SOCIO-ECONOMIC IMPACT OF HARMFUL ALGAL BLOOMS IN EUROPEAN MARINE WATERS). In this study we analyze the socio economic impact of harmful algal blooms (HABs) in European marine waters for some specific case studies. The European Union regions analyzed in this study are: Galicia (Spain), the province of Rimini (Italy), Galway (Ireland), Zandvoort (The Netherlands), and Hanko (Finland) and Les Pradet, Hyéres, and Corquieranne (France). Because of data availability we focused on the impact of harmful algal blooms on mussel aquaculture and tourism. The analysis reveals that the impact of HABs in the mussel aquaculture sector in Galicia was between 56 and 255 million Euro per year from 1989 to 1998. In Riminirevenue losses in the mussel sector were estimated at about 1.67 million Euro per year. In the other case studies this impact could not be calculated because of lack of data. With respect to the impact of HABs in the tourism sector, we found the impact on welfare of coastal tourists to be between 0.9 and 4.8 million Euro per year in Riccione (Italy), between 8.8 and 16.1 million Euro per year in Galway (Ireland), between 9.6 and 16.8 million Euro per year in North-Holland (The Netherlands), between 85 and 538 thousands Euros per year in Hanko (Finland), and between 4 thousands and 433 thousands Euros per year in Le Pradet, Hyéres and Corquieranne (France). The impact of HABs on tourism was found to be positively related to income and positively related to the percentage of the population having experienced problems with

high-biomass non toxic blooms. Given average income of the sample the impact of HABs on tourism varies between 10 and 71 Euro per tourist per year.

Schantz, E. J. (1975). Poisonous Red Tide Organisms. *Environmental Letters*, *9*(3), 225–237. https://doi.org/10.1080/00139307509435851 The purpose of this paper is to describe (1) the poisonous organisms that cause the destructive red tides, (2) the poisons they produce and the effect of these poisons on people, and (3) the public health problems associated with these red tides.

Sengco, M. R. (2009). Prevention and control of Karenia brevis blooms. *Harmful Algae*, *8*(4), 623–628. https://doi.org/10.1016/j.hal.2008.11.005 With the recurrent and potentially severe impacts of Karenia brevis blooms in the Gulf of Mexico, new management approaches have been examined to potentially prevent and control these blooms. This paper summarizes past and present research and strategies for the prevention and control of K. brevis blooms. Prevention presumes a certain level of understanding about the cause or causes of these blooms. This may not yet be available, however, for K. brevis in the Gulf of Mexico. Some efforts to synthesize the current understanding of bloom dynamics for the region were recommended. The earliest attempts to control K. brevis blooms in the field used copper sulfate minerals seeded from ships and crop-dusting planes. Although effective for short term applications, the method was abandoned as it provided only temporary relief at a high cost with unknown collateral damage to the ecosystem. Results from chemical screenings and ozone treatments were also presented. Algicidal bacteria have shown some promise in controlling K. brevis in laboratory experiments, either through direct contact or release of algicidal compounds. Finally, the state of the research into the use of natural clays was presented, beginning with laboratory and mesocosm tests, to larger-scale experiments and flume studies. Several impacts studies were reviewed. While much progress has been made in examining control methods in recent years, more research in the field is needed to fully evaluate the efficacy and impacts of these strategies. Furthermore, the social and human dimensions of this potentially controversial area of research may have to be explored more fully to gauge the receptiveness of the public to these management approaches.

Shaw, J. A. (2004). Troubled Waters under the Bridge: Red Tide, Aquatic Pollution, and the Prince Edward Island Shellfish Poisoning of 1987. *Dalhousie Journal of Legal Studies*, *13*, 31. https://heinonline.org/HOL/Page?handle=hein.journals/dalhou13&id=35&div=&collection= Toxic red tides, such as the one that poisoned PEI in 1987, are a coastal aquatic phenomenon that cause harm to wildlife and humans alike, seemingly with increasing frequency. They appear tied to nutrient pollution of aquatic habitats, especially by the food-producing industries, such as aquaculture and industrial farming. Canada has made (nonbinding) global commitments to protect marine waters from such landbased pollution, resulting in its 'National Program of Action'. To date, however, Canada's attempts to meet this goal have been hampered by the federal division of powers, and by an overall fragmented legal protection for the aquatic environment. Respecting no legal boundaries, aquatic habitats are practically a metaphor for environmental interconnectedness, yet Canada's legal framework ignores this holistic picture. The current legislation perpetuates the historical view of food production as environmentally benign and of food security as having higher priority than environmental integrity. Ultimately though, a healthy, safe food supply depends entirely upon a healthy environment. Red tides are thus a dangerous reminder that Canada must urgently begin to deal with the interconnectedness of its lands, waters and human activities in future legal protections for aquatic habitats.

Showalter-Otts, S. (2016). Domoic Acid Issue in California. NSGLC-16-04-05. University, MS: National Sea Grant Law Center, 6pp. Memorandum responding to an advisory request to the National Sea Grant Law Center regarding legal and policy questions related to the fishery closures triggered by elevated levels of domoic acid in crab samples during the 2015-2016 fishing season. The memorandum discusses FDA guidance, state interpretation, implementation, and procedures, and warning labels.

Shumway, S. E. (1990). A Review of the Effects of Algal Blooms on Shellfish and Aquaculture. *Journal of the*

World Aquaculture Society, *21*(2), 65–104. https://doi.org/10.1111/j.1749-7345.1990.tb00529.x Toxic algal blooms occur worldwide and in some areas they are a common and seasonal occurrence. Historically, attention has been focused on blooms of toxic dinoflagellates (e.g., Protogonyaulax tamarensis). More recently, attention has been turned to other species (e.g., Dinophysis, Aureococcus, Gymnodininum). These blooms often present problems with respect to optimal utilization of the shellfish resources, and the magnitude of economic losses can be catastrophic. Nevertheless, successful culture facilities and commercial harvests persist in areas prone to toxic algal blooms. This paper reviews the literature available on occurrences of toxic algal blooms, discusses the means by which harvesters, managers, and industry cope with the problems associated with toxic algal blooms, and makes recommendations for the most efficient and successful utilization of resources in the face of environmental instability.

Shumway, S. E., & Cembella, A. D. (1993). The impact of toxic algae on scallop culture and fisheries. *Reviews in Fisheries Science*, *1*(2), 121–150. https://doi.org/10.1080/10641269309388538 Harmful algal blooms occur worldwide and their associated phycotoxins are accumulated by filter-feeding bivalve molluscs. Because only the adductor muscle of scallops has been traditionally marketed, scallops are not usually included in routine monitoring programs. A renewed interest in marketing both whole and "roe-on"; scallops from various geographic regions along with intensified aquaculture ventures in areas prone to toxic blooms have provoked public health concerns regarding the safety of this resource. Our studies have focused on the sequestering and biotransformation of phycotoxins in scallops. Our results, coupled with a review of historic data, indicate that (1) toxins are not distributed evenly throughout the scallop tissues—more toxin is usually concentrated in the mantle and digestive gland; (2) some scallop tissues, e.g., digestive glands and mantles, remain highly toxic throughout the year; (3) toxicity varies considerably (43.5% coefficient of variation) between individual animals collected in the same area; (4) no correlations could be made between toxicity levels in gonadal tissue and other tissues. Scallop culture and commercial fisheries can thrive in areas prone to toxic algal blooms if only the adductor muscle is utilized. Safe marketing of roe-on scallops is feasible only under strict regulatory regimes. Marketing of mantles or whole scallops poses a high risk to public health and should be undertaken only after extensive monitoring. Scallop mariculturists should be acutely aware of the potential risks associated with phycotoxins. Furthermore, public health guidelines, with particular emphasis on toxin levels in individual tissues, is necessary if scallops are to be marketed whole or in conjunction with tissues other than adductor muscles.

Skinner, M. P., Brewer, T. D., Johnstone, R., Fleming, L. E., & Lewis, R. J. (2011). Ciguatera Fish Poisoning in the Pacific Islands (1998 to 2008). *PLoS Neglected Tropical Diseases*, *5*(12), e1416. https://doi.org/10.1371/journal.pntd.0001416 Background: Ciguatera is a type of fish poisoning that occurs throughout the tropics, particularly in vulnerable island communities such as the developing Pacific Island Countries and Territories (PICTs). After consuming ciguatoxincontaminated fish, people report a range of acute neurologic, gastrointestinal, and cardiac symptoms, with some experiencing chronic neurologic symptoms lasting weeks to months. Unfortunately, the true extent of illness and its impact on human communities and ecosystem health are still poorly understood.Methods: A questionnaire was emailed to the Health and Fisheries Authorities of the PICTs to quantify the extent of ciguatera. The data were analyzed using t-test, incidence rate ratios, ranked correlation, and regression analysis.Results: There were 39,677 reported cases from 17 PICTs, with a mean annual incidence of 194 cases per 100,000 people across the region from 1998–2008 compared to the reported annual incidence of 104/100,000 from 1973–1983. There has been a 60% increase in the annual incidence of ciguatera between the two time periods based on PICTs that reported for both time periods. Taking into account under-reporting, in the last 35 years an estimated 500,000 Pacific islanders might have suffered from ciguatera.Conclusions: This level of incidence exceeds prior ciguatera estimates locally and globally, and raises the status of ciguatera to an acute and chronic illness with major public health significance. To address this significant public health problem, which is expected to increase in parallel with environmental change, well-funded multidisciplinary research teams are needed to translate research advances into practical management solutions.

Smith, R. B., Bass, B., Sawyer, D., Depew, D., & Watson, S. B. (2019). Estimating the economic costs of algal blooms in the Canadian Lake Erie Basin. *Harmful Algae*, *87*, 101624. https://doi.org/10.1016/j.hal.2019.101624 Over the past two decades there has been a re-emergence of regular harmful algal blooms in Lake Erie due to increasing phosphorus loading, mainly from non-point agricultural sources. The Canadian and United States governments have jointly agreed to reduce phosphorus loadings to the lake in order to control the extent and severity of the blooms. Citizens on both sides of the border face a number of economic costs, both market and non-market, as a result of the blooms. This study values these costs for the Canadian portion of the Lake Erie basin economy using standard economic approaches that are widely applied within the world of cost-benefit analysis. The results suggest that algal blooms will impose equivalent annual costs equal to $272 million in 2015 prices over a 30-year period if left unchecked. The largest market costs will be imposed on the tourism industry ($110 million in equivalent annual costs) and the largest non-market costs will be borne by recreational users and those who place inherent value on the lake's quality ($115 million in equivalent annual costs). Management action to reduce phosphorus loadings is found to be justified on economic grounds if the 30-year net present value of the reduction program is less than $1294 million (2015 Canadian dollars).

Steffensen, D. A. (2008). Economic cost of cyanobacterial blooms. In H. K. Hudnell (Ed.), *Cyanobacterial Harmful Algal Blooms: State of the Science and Research Needs* (pp. 855–865). Springer New York. https://doi.org/10.1007/978-0-387-75865-7_37 Cyanobacterial blooms impact upon the water quality, environmental and ecological status of water bodies and affect most of the uses we make of water. The extent of the impact depends upon the type, size and frequency of the blooms, the size of the water body affected, the uses made of the water and the treatment options available to respond to the blooms. The impacts therefore vary considerably from place to place. Overall costs should also account for the planning and remedial actions taken to prevent future blooms.

Steidinger, K. A. (2009). Historical perspective on Karenia brevis red tide research in the Gulf of Mexico. *Harmful Algae*, *8*(4), 549–561. https://doi.org/10.1016/j.hal.2008.11.009 Research on Karenia brevis blooms in the Gulf of Mexico started with the 1946–1947 red tide along the Florida west coast. Early research was on the organism itself, its tolerances and requirements, and the environment in which it lived and grew. Control of blooms, as a management option, was pursued in the 1950s with little success. However, in the 1960s–1970s, new regulation of shellfish growing areas was a public health management success. Research on K. brevis blooms followed funding cycles and was sporadic until the late 1990s when the National Oceanic and Atmospheric Administration (NOAA) and the Environmental Protection Agency (EPA) funded the Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) and NOAA Monitoring and Event Response of Harmful Algal Blooms (MERHAB) programs. These particular funding programs, augmented by State of Florida appropriations, provided the opportunity to study K. brevis blooms on different temporal-spatial scales and consequently advanced the science. This review looks at historical research results in the light of today's advances.

Stumpf, R. P., Tomlinson, M. C., Calkins, J. A., Kirkpatrick, B., Fisher, K., Nierenberg, K., Currier, R., & Wynne, T. T. (2009). Skill assessment for an operational algal bloom forecast system. *Journal of Marine Systems*, *76*(1–2), 151–161. https://doi.org/10.1016/j.jmarsys.2008.05.016 An operational forecast system for harmful algal blooms (HABs) in southwest Florida is analyzed for forecasting skill. The HABs, caused by the toxic dinoflagellate, Karenia brevis, lead to shellfish toxicity and to respiratory irritation. In addition to predicting new blooms and their extent, HAB forecasts are made twice weekly during a bloom event, using a combination of satellite derived image products, wind predictions, and a rule-based model derived from previous observations and research. These forecasts include: identification, intensification, transport, extent, and impact; the latter being the most significant to the public. Identification involves identifying new blooms as HABs and is validated against an operational monitoring program involving water sampling. Intensification

forecasts, which are much less frequently made, can only be evaluated with satellite data on mono-specific blooms. Extent and transport forecasts of HABs are also evaluated against the water samples. Due to the resolution of the forecasts and available validation data, skill cannot be resolved at scales finer than 30 km. Initially, respiratory irritation forecasts were analyzed using anecdotal information, the only available data, which had a bias toward major respiratory events leading to a forecast accuracy exceeding 90%. When a systematic program of twice-daily observations from lifeguards was implemented, the forecast could be meaningfully assessed. The results show that the forecasts identify the occurrence of respiratory events at all lifeguard beaches 70% of the time. However, a high rate (80%) of false positive forecasts occurred at any given beach. As the forecasts were made at half to whole county level, the resolution of the validation data was reduced to county level, reducing false positives to 22% (accuracy of 78%). The study indicates the importance of systematic sampling, even when using qualitative descriptors, the use of validation resolution to evaluate forecast capabilities, and the need to match forecast and validation resolutions.

Taft, W. H., & Martin, D. F. (1986). The potential for managing a Florida red tide. *Journal of Environmental Science and Health . Part A: Environmental Science and Engineering*, *21*(2), 107–127. https://doi.org/10.1080/10934528609375279 The potential for management of a Florida red tide outbreak is considered. Control agents that have been considered in the past are reviewed, and most are rejected in favor of a natural product ("Aponin" produced by a marine green alga Nannochloris sp.) or in favor of biocontrol, i.e., direct seeding with Nannochloris sp. or similar species. The economics of biocontrol are compared with the reported cost of a typical red tide on the west coast of Florida.

Taylor, T., & Longo, A. (2009). Valuation of Marine Ecosystem Threshold Effects: Application of Choice Experiments to Value Algal Bloom in the Black Sea Coast of Bulgaria. Algal bloom arises in part from anthropogenic emissions of nutrients into the coastal zone. Increased interest in water quality in coastal and marine areas stemming from the Water Framework Directive and the Marine Strategy Framework Directive leads to important questions in terms of policies to address nutrient loadings. This paper presents the results from a choice experiment for the valuation of algal blooms in Varna Bay, Bulgaria. Varna Bay is an important tourist destination and a large port city on the Black Sea coast of Bulgaria. Algal bloom events have been experienced frequently in this area. A choice experiment questionnaire was developed to be applied in Varna Bay. The key attributes used were visibility, duration of bloom and the amount of congestion on the beach. The amount of bloom is found to be important: respondents are willing to pay for a program that entails 1 week of algal bloom about 33 Leva (s.e. 8.09) when there is high visibility; 21 Leva (s.e. 5.75) with medium visibility and 9 Leva (s.e. 3.48) with low visibility. Respondents are willing to pay more for programs that offer shorter duration of algal bloom. The marginal price for one metre of extra space between the respondent and the nearest person is equal to 0.38 Leva.

Tester, P. A., Stumpf, R. P., Vukovich, F. M., Fowler, P. K., & Turner, J. T. (1991). An expatriate red tide bloom: Transport, distribution, and persistence. *Limnology and Oceanography*, *36*(5), 1053–1061. https://doi.org/10.4319/lo.1991.36.5.1053 In November 1987, the toxic dinoflagellate Gymnodinium breve bloomed in North Carolina nearshore waters. This occurrence was the first record of G. breve north of Florida, a range extension of >800 km. We propose the (Gulf of Mexico) Loop Current-Florida Current-Gulf Stream system as the transport mechanism for G. breve cells from a late summer bloom off the southwest coast of Florida (Charlotte Harbor-Sarasota). The estimated transit time for cells around the peninsula and northward to the continental shelf off North Carolina is 22–54 d. About 30 d after the Charlotte Harbor-Sarasota bloom, satellite images of sea-surface temperature substantiated the shoreward movement of a filament of Gulf Stream water onto the narrow continental shelf between Cape Hatteras and Cape Lookout. This filament, the likely source of G. breve cells, remained in nearshore waters and was identifiable in satellite images for >19 d. Once the bloom was inshore, both windspeed and direction were important in determining its distribution.

Tibbetts, J. (1998, July). Toxic tides. *Environmental Health Perspectives*, *106*(7), A326–A331. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1533123/ Topical magazine article.

Todd, E. C. D. (1994). Emerging Diseases Associated with Seafood Toxins and Other Water-borne Agents. *Annals of the New York Academy of Sciences*, *740*(1), 77–94. https://doi.org/10.1111/j.1749-6632.1994.tb19855.x Few attempts have been made to estimate the number of food-borne or water-borne cases in a country or their costs. Even though these estimates may be limited in accuracy, they do give a measure for the effectiveness of existing control programs and whether the benefit-cost ratio justifies the need for new programs. There are three types of costs associated with seafood toxins: 1) costs associated with human illness; 2) costs of monitoring potentially toxic areas and inspection and analysis of finished products; and 3) loss of product sales because of closure of harvest areas (short- or long-term), embargo of imported product, or less demand through decrease in purchasers through adverse publicity and loss of tourism. Illness costs include those to society for health care and investigation of the cause of illness, to the individualwho loses both the opportunity for work and leisure (lost productivity), and to the fishing, processing and foodservice industries for lost business. In Canada, costs have been calculated for seafood toxins.82 Those with most impact are PSP, ASP, scombroid poisoning, and ciguatera.

Tomerlin, T., & Adams, C. M. (1999). *The Economics of Harmful Algal Blooms (HABs): An Annotated Bibliography* (Tech. Pap. 98; p. 14). Florida Sea Grant College Program. http://nsgl.gso.uri.edu/flsgp/flsgpl99001.pdf The purpose of this report is to briefly outline literature which addresses HAB economic impacts.

Trainer, V. L. (ed.). (2020). GlobalHAB. Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies. *PICES Scientific Report* No. 59, 107 pp. https://meetings.pices.int/publications/scientific-reports/Report59/Rpt59.pdf Over the last two decades, several efforts have been addressed to compile what is known about the economic impacts of harmful algal blooms (HABs). One study estimated the annual cost of HABs in the European Union at $800 million, but most of that cost was extrapolated from very few HAB organisms. In China, a single Karenia mikimotoi event in 2012 caused up to $330 million loss to the mariculture industry, mostly cultivated abalone. Although past reports have attempted to gather comprehensive economic impact data, both the type and amount of information were limited, highlighting the need for collaboration between HAB scientists and economists. Furthermore, most countries have neither conducted economic analyses of HABs nor collected data that can be used to generate reliable quantitative estimates of net economic losses and impacts. The lack of data, appropriate and standardized protocols, and the dearth of peer-reviewed studies hamper efforts to quantify the societal costs of regionally frequent, intense, and long-lasting HAB events and to help evaluate the cost of various strategies being developed for HAB prevention, control, and mitigation. To strategize how specific economic studies can be used to assess the economic impacts of HABs and mitigate their associated risks, a Marine Environmental Quality (MEQ) sponsored Workshop on GlobalHAB: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies was held on October 17–19, 2019, at the Annual Meeting of the North Pacific Marine Science Organization.

Trainer, V., Davidson, K., Wakita, K., Berdalet, E., Suddleson, M., Myre, G., & Trethewey, D. (2019, December). IOC-SCOR Global HAB Workshop: Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies. *Harmful Algae News*, 63, 3–4. www.ioc-unesco.org/hab In September 2019 the Intergovernmental Panel on Climate Change (IPCC) approved and accepted the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) at its 51st Session [1]. This report was notable for many reasons, but of particular note was that an IPCC report identified “increased frequency in coastal areas since the 1980s of harmful algal blooms, attributed to both climatic and non-climatic drivers, with high confidence”, meaning that experts agreed that there was medium to high agreement and robust evidence for this statement.

Trainer, V. L., Kudela, R. M., Hunter, M. V, Adams, N. G., & McCabe, R. M. (2020). Climate extreme seeds a new domoic acid hotspot on the US west coast. *Frontiers in Climate* 2:571836. https://www.frontiersin.org/articles/10.3389/fclim.2020.571836 A heatwave that blanketed the northeast Pacific Ocean in 2013–2015 had severe impacts on the marine ecosystem through altered species composition and survival. A direct result of this marine heatwave was a sustained, record-setting harmful algal bloom (HAB), caused by the toxigenic diatom, Pseudo-nitzschia, that led to an unprecedented delay in harvest opportunity for commercial Dungeness crab (Metacarcinus magister) and closure of other recreational, commercial and tribal shellfish harvest, including razor clams. Samples collected during a cruise in summer 2015, showed the appearance of a highly toxic "hotspot" between Cape Mendocino, CA and Cape Blanco, OR that was observed again during cruises in the summers of 2016–2018. The transport of toxic cells from this retentive site northward during wind relaxations or reversals associated with storms resulted in economically debilitating delay or closure of Dungeness crab harvest in both northern California and Oregon in 2015–2019. Analyses of historic large-scale Pseudo-nitzschia HABs have shown that these events occur during warm periods such as El Niño, positive phases of the Pacific Decadal Oscillation, or the record-setting marine heatwave. In order to reduce the impacts of large-scale HABs along the west coast of North America, early warning systems have been developed to forewarn coastal managers. These early warning systems include the Pacific Northwest and California HAB Bulletins, both of which have documented elevated domoic acid and increased risk associated with the northern California hotspot. These early warnings enable mitigative actions such as selective opening of safe harvest zones, increased harvest limits during low risk periods, and early harvest in anticipation of impending HAB events. The aims of this study are to show trends in nearshore domoic acid along the US west coast in recent years, including the recent establishment of a new seed bed of highly-toxic Pseudo-nitzschia, and to explore how early warning systems are a useful tool to mitigate the human and environmental health and economic impacts associated with harmful algal blooms.

Trainer, V. L., & Yoshida, T. (eds.). (2014). Proceedings of the Workshop on Economic Impacts of Harmful Algal Blooms on Fisheries and Aquaculture. *PICES Scientific Report* No. 47, 85 pp. https://meetings.pices.int/publications/scientific-reports/Report47/Rpt47.pdf Over the past decades, serious damage caused by HABs has been reported with increasing frequency in the North Pacific. These blooms have adverse economic and social impacts on the aquaculture industry, human health, coastal economies, and wild fisheries. HABs have prompted routine closures of both commercial and recreational shellfish harvesting and have contributed to the deaths of aquaculture finfish, resulting in financial losses in coastal communities. However, the economic impacts generated by these events extend far beyond the industry itself. Obtaining more realistic estimates of HAB economic impacts, and the costs of preventing and managing them, calls for an integrated assessment approach that comprises the following: the economic impact of HABs on the aquaculture industry, the secondary integrated industries, and consumers, on both local and regional scales; some valuation of the costs and benefits of taking any recognized steps to lessen the HAB problem (e.g., reducing coastal pollution and other human-related activities); and weighing the costs and benefits of enhanced monitoring and surveillance that potentially reduces the magnitude of the impacts (e.g., by limiting shellfish harvesting closure windows or alteration in the timing of finfish harvesting). This publication includes presentations made at a workshop on "Economic impacts of harmful algal blooms on fisheries and aquaculture" co-convened by Drs. Chang Hoon Kim (Korea) and Vera Trainer (USA) on October 11, 2013 at the PICES 2013 Annual Meeting in Nanaimo, Canada (see Appendices 1 and 2 for a summary of the workshop and list of participants), and three additional papers on the topic submitted by scientists who were planning but were unable to attend the workshop (Appendix 3). The following reports detail what is known about the economic and social impacts of HABs in the eastern and western Pacific by PICES and NOWPAP researchers who describe cutting edge approaches and methodologies for assessment of HABs. The thrust of the workshop, and the findings and insights that were derived, directly address two research themes of the PICES' integrative science program FUTURE (Forecasting and Understanding Trends, Uncertainty, and Responses of North Pacific Marine Ecosystems), namely: (1) What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing? and (2) How do ecosystems respond to natural and anthropogenic forcing,

and how might they change in the future?US Environmental Protection Agency. (2015). *A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution* (Reports and Assessments EPA 820-F-15-096). Office of Water. https://www.epa.gov/nutrient-policy-data/compilation-cost-data-associated-impacts-and-control-nutrient-pollution Cost is a major factor in the management and control of nutrient pollution. External costs – costs borne by the public more generally – associated with the impacts from uncontrolled or under controlled nutrient pollution and delayed action are important considerations. The adverse biological and ecological effects of nutrient pollution can result in economic losses across multiple industries and economic sectors. Managing and controlling nutrient pollution must also include consideration of the costs associated such actions, including the development, implementation, and enforcement of pollution control plans, wastewater treatment plant upgrades, municipal storm-water controls, agricultural best management practices, homeowner septic system improvements, and other actions. Although it may not be appropriate to directly compare the costs of controlling nutrients to the economic impacts associated with nutrient pollution because the studies vary in their analyses, methodologies, starting conditions and initial assumptions, the document will help users to understand the substantial economic costs of not controlling nutrient pollution. The data and information compiled for this report are instructive in that they provide relative order of magnitude estimates appropriate for screening or feasibility analyses, and can be used to add perspective to the costs of not implementing controls. The information suggests that nitrogen and phosphorus may be expensive to control after they are released to the environment. Preventing them from entering the system is potentially a more cost-effective strategy for addressing nutrient pollution and its impacts.

Usman, R. A., Olorunfemi, F., Awotayo, G. P., Tunde, A. M., & Usman, B. A. (2013). Disaster Risk Management and Social Impact Assessment: Understanding Preparedness, Response and Recovery in Community Projects. *Environmental Change and Sustainability*, *Chapter 10*, 259–274. https://doi.org/10.5772/55736 Social impact assessment can play an important role in the understanding of the consequences and social outcome of projects that are meant to tackle poverty, enhance community development or designed to reduce vulnerability to disasters during environmental emergencies. As well as helping to explain how a proposed action will change the lives of people in communities, SIA indicates how alternative actions might mitigate harmful changes or implement beneficial ones. [This chapter] is devoted to the clarification and definition of major conceptual issues with a view to establishing a link between each of the concepts and providing a framework for the entire paper. We also provide a discussion on the ways disaster risk can be minimized in community development projects. The next two sections examine respectively the livelihood contexts in disaster management and the need for a process that integrate disaster risk into community projects through social impact assessment. In this section, the paper provides a typical example from previous projects. The SIA process is also discussed as a series of interrelated steps and how hazards and disaster risk typically require a SIA. Finally the last section is devoted to examining the critical challenges to the success of adoption of SIA in community projects.

van den Bergh, J. C. J. M., Nunes, P. A. L. D., Dotinga, H. M., Kooistra, W. H. C. F., Vrieling, E. G., & Peperzak, L. (2002). Exotic harmful algae in marine ecosystems: An integrated biological–economic–legal analysis of impacts and policies. *Marine Policy*, *26*(1), 59–74. https://doi.org/10.1016/S0308-597X(01)00032-X Harmful algal blooms (HABs) are the cause of important damages to marine living resources and human beings. HABs are generated by micro-algae. These marine species are primarily introduced through ballast water of ships and, to a lesser extent, through import of living fish, in particular shellfish. Effective and efficient regulation of HABs requires an integration of insights from biological, economic and legal sciences. Such an integration consists of (a) a clear identification of the bio-ecological pathways and overall consequences related to the damages of HABs; (b) an assessment of monetary costs of HABs; and (c) an understanding of the set of complementary legal-institutional and economic instruments dealing with HABs through prevention, restoration and amelioration. This paper discusses each element in detail, in which biological, economic and legal aspects come together, drawing conclusions for decision making in marine management. In order to move away from the general level of discussion, an example of HABs is presented in which, biological, economic and legal aspects are combined.

Van Dolah, F. M. (2000). Marine algal toxins: Origins, health effects, and their increased occurrence. *Environmental Health Perspectives 108*(Supp. 1):133–141. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1637787/ Certain marine algae produce potent toxins that impact human health through the consumption of contaminated shellfish and finfish and through water or aerosol exposure. Over the past three decades, the frequency and global distribution of toxic algal incidents appear to have increased, and human intoxications from novel algal sources have occurred. This increase is of particular concern, since it parallels recent evidence of large-scale ecologic disturbances that coincide with trends in global warming. The extent to which human activities have contributed to their increase therefore comes into question. This review summarizes the origins and health effects of marine algal toxins, as well as changes in their current global distribution, and examines possible causes for the recent increase in their occurrence.

Watkins, S., Reich, A., Fleming, L., Hammond, R., Watkins, S. M., Reich, A., Fleming, L. E., & Hammond, R. (2008). Neurotoxic Shellfish Poisoning. *Marine Drugs*, *6*(3), 431–455. https://doi.org/10.3390/md6030431 Neurotoxic shellfish poisoning (NSP) is caused by consumption of molluscan shellfish contaminated with brevetoxins primarily produced by the dinoflagellate, Karenia brevis. Blooms of K. brevis, called Florida red tide, occur frequently along the Gulf of Mexico. Many shellfish beds in the US (and other nations) are routinely monitored for presence of K. brevis and other brevetoxin-producing organisms. As a result, few NSP cases are reported annually from the US. However, infrequent larger outbreaks do occur. Cases are usually associated with recreationally-harvested shellfish collected during or post red tide blooms. Brevetoxins are neurotoxins which activate voltage-sensitive sodium channels causing sodium influx and nerve membrane depolarization. No fatalities have been reported, but hospitalizations occur. NSP involves a cluster of gastrointestinal and neurological symptoms: nausea and vomiting, paresthesias of the mouth, lips and tongue as well as distal paresthesias, ataxia, slurred speech and dizziness. Neurological symptoms can progress to partial paralysis; respiratory distress has been recorded. Recent research has implicated new species of harmful algal bloom organisms which produce brevetoxins, identified additional marine species which accumulate brevetoxins, and has provided additional information on the toxicity and analysis of brevetoxins. A review of the known epidemiology and recommendations for improved NSP prevention are presented.

Wessells, C. R., Miller, C. J., & Brooks, P. M. (1995). Toxic Algae Contamination and Demand for Shellfish: A Case Study of Demand for Mussels in Montreal. *Marine Resource Economics*, *10*(2), 143–159. https://doi.org/10.1086/mre.10.2.42629107 Toxic algae blooms are a worldwide phenomena, which appear to be increasing in frequency and severity. These natural events cause product contaminations that often have significant economic consequences, including supply interruptions due to closed fishing grounds, losses from human illness, and losses due to a decline in demand for the affected products. This paper evaluates the impacts of a toxic algae bloom contamination event on demand for unaffected shellfish. As an empirical example of the economic losses the shellfish industry experiences for these events, demand for mussels in Montreal is estimated using firm-level data and proxies for consumer information, during and after domoic acid contamination of Prince Edward Island mussels. Sales losses due to decreased demand are calculated. Implications of this issue for seafood safety and management policies are discussed.

Whitehead, J. C., Haab, T. C., & Parsons, G. R. (2003). Economic effects of Pfiesteria. *Ocean & Coastal Management*, *46*(9–10), 845–858. https://doi.org/10.1016/S0964-5691(03)00070-X Pfiesteria is a single-celled microorganism that is a toxic predator of a number of fish species. We measure the effects of information about Pfiesteria on three related decision processes of the consumer: risk perceptions, seafood demand, and willingness to pay for a mandatory seafood inspection program. Using responses to a survey on seafood consumption and hypothetical Pfiesteria-related fish kills, we find that announcement of a fish kill increases the perceived risks of seafood and decreases the demand for seafood. Information policies that assure the safety of seafood have little effect in restoring consumer confidence in seafood. Perceived negative information tends to decrease welfare by more than the counter effects of perceived positive information. Welfare losses

are recovered through a mandatory seafood inspection program rather than safety announcements.

Wilson, M. A., & Carpenter, S. R. (1999). Economic Valuation of Freshwater Ecosystem Services in the United States: 1971–1997. *Ecological Applications*, *9*(3), 772–783. https://doi.org/10.1890/1051-0761(1999)009[0772:EVOFES]2.0.CO;2 The purpose of this paper is to provide ecologists and resource managers with a sense of where the economic science of ecosystem valuation has come from and where it might go in the future. To accomplish this, the paper provides a comprehensive synthesis of peer-reviewed economic data on surface freshwater ecosystems in the United States and examines major accomplishments and gaps in the literature. Economic value has been assigned to nonmarket goods and services provided by surface freshwater systems in the United States by 30 published, refereed articles in the scientific literature from 1971 to 1997. These studies have used variations of three approaches for a quantitative assessment of economic value: travel cost methods, hedonic pricing methods, and contingent valuation methods. To determine the economic value of nonmarket ecosystem goods and services, each method focuses on a different aspect of social benefit associated with lakes, streams, rivers, and wetlands. Valuation methodologies work from different underlying assumptions while possessing unique limitations and uncertainties. Dollar benefit estimates derived for nonmarket freshwater ecosystem goods and services from these studies tend to be specific to a particular method, ecosystem, and socioeconomic circumstance. Creative interdisciplinary research is needed on the quantitative measurement of surface freshwater ecosystem goods and service values, the relation of these values to key limnological variates, and communication of limnological insights to the public and social scientists in ways that facilitate and improve future management and research.

Wolf, D., & Klaiber, H. A. (2017). Bloom and bust: Toxic algae's impact on nearby property values. *Ecological Economics*, *135*, 209–221. https://doi.org/10.1016/j.ecolecon.2016.12.007

Woodhouse, J. N., Rapadas, M., & Neilan, B. A. (2013). Cyanotoxins. In *Cyanobacteria* (pp. 257–268). Wiley-Blackwell. https://doi.org/10.1002/9781118402238.ch16 This article discusses the economic implications of toxin production by aquatic cyanobacteria, predominantly within the context of freshwater reservoirs. It presents an overview of the various cyanobacterial bloom compositions and toxin profiles typically encountered in these ecosystems. The chapter provides a brief overview of the major cyanotoxin toxocological subgroups, including the hepatotoxins, the neurotoxins, the cytotoxins, and the dermatoxins. The economic costs associated with toxic cyanobacterial blooms are complex and difficult to fully evaluate. If successful, a monitoring program can drastically reduce the economic costs associated with cyanobacterial blooms and their toxins by allowing for early intervention and prevention of exposure of individuals.

Workshop on Economic Impacts of Harmful Algal Blooms on Fisheries and Aquaculture, Trainer, V. L., Yoshida, T., & North Pacific Marine Science Organization (Eds.). (2014). *Proceedings of the Workshop on Economic Impacts of Harmful Algal Blooms on Fisheries and Aquaculture*. The Section on Ecology of Harmful Algal Blooms in the North Pacific (S-HAB) was established in October 2003, under the direction of the Marine Environmental Quality Committee, to promote the sharing of information among PICES member countries on HAB occurrences in the North Pacific. Since its formation, the Section has studied the characteristics of HAB occurrences and the differences between them in the eastern and western Pacific, including historical changes, and has provided scientific information to PICES member countries and relevant stakeholders. Over the past decades, serious damage caused by HABs has been reported with increasing frequency in the North Pacific. These blooms have adverse economic and social impacts on the aquaculture industry, human health, coastal economies, and wild fisheries. HABs have prompted routine closures of both commercial and recreational shellfish harvesting and have contributed to the deaths of aquaculture finfish, resulting in financial losses in coastal communities. However, the economic impacts generated by these events extend far beyond the industry itself. Obtaining more realistic estimates of HAB economic impacts, and the costs of preventing and managing them, calls for an integrated assessment approach that comprises the following: the economic impact of HABs on the aquaculture industry, the secondary integrated industries, and consumers, on both local and re-

gional scales; some valuation of the costs and benefits of taking any recognized steps to lessen the HAB problem (e.g., reducing coastal pollution and other human-related activities); and weighing the costs and benefits of enhanced monitoring and surveillance that potentially reduces the magnitude of the impacts (e.g., by limiting shellfish harvesting closure windows or alteration in the timing of finfish harvesting). This publication includes presentations made at a workshop on "Economic impacts of harmful algal blooms on fisheries and aquaculture" co-convened by Drs. Chang Hoon Kim (Korea) and Vera Trainer (USA) on October 11, 2013 at the PICES 2013 Annual Meeting in Nanaimo, Canada (see Appendices 1 and 2 for a summary of the workshop and list of participants), and three additional papers on the topic submitted by scientists who were planning but were unable to attend the workshop (Appendix 3). Introduction page 1.

Zingone, A., & Oksfeldt Enevoldsen, H. (2000). The diversity of harmful algal blooms: A challenge for science and management. *Ocean & Coastal Management*, *43*(8–9), 725–748. https://doi.org/10.1016/S0964-5691(00)00056-9 A broad spectrum of events come under the category of harmful algal blooms (HABs), the common denominator being a negative impact on human activities. Harmful algal blooms involve a wide diversity of organisms, bloom dynamics, and mechanisms of impact. Here we review the e€ ects of natural and man-induced environmental ¯uctuations on the frequency and apparent spreading of these phenomena. This article highlights the need for interdisciplinary research aimed at shedding light on basic mechanisms governing the occurrence and succession of microalgae in coastal seas. Information integrated from various discipline coupled with improved, sustained monitoring systems, will help predict and manage problems caused by HABs over a wide range of space and time scales. # 2000 Elsevier Science Ltd. All rights reserved.