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The Economic Effects of Harmful Algal Blooms in the United States: Estimates, Assessment Issues, and Information Needs

P. Hoagland[1]*, D. M. Anderson[2], Y. Kaoru[3], and A. W. White[4]

[1] *Marine Policy Center, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543*
[2] *Department of Biology, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543*
[3] *School of Business Administration, Nanzan University, 18 Yamazato-cho, Showa-ku, Nagoya 466 Japan*
[4] *Department of Marine Safety and Environmental Protection, Massachusetts Maritime Academy, 101 Academy Drive, Buzzards Bay, Massachusetts 02532-1803*

ABSTRACT: 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.

Introduction

The term harmful algal bloom or HAB is used to describe the often visible blooms of algae that kill fish, make shellfish poisonous, and cause numerous other problems in marine coastal waters. Some algal species produce potent toxins that accumulate in shellfish that feed on those algae, resulting in poisoning syndromes in human consumers called paralytic, diarrhetic, amnesic, or neurotoxic shellfish poisoning (PSP, DSP, ASP, or NSP, respectively). A related phenomenon called ciguatera fish poisoning (CFP) occurs when toxic algae living on coral reef seaweeds are consumed by herbivorous fish, which pass the toxins on to larger predators and which then deliver the neurotoxins to human consumers. Van Dolah et al. (2001) report that, worldwide, algal toxins of all types may be responsible for as many as 60,000 intoxication incidents per year. All of these toxins can alter marine ecosystem structure and function as they are transferred through the food web, affecting fecundity and survival at multiple levels and in ways that are still largely unquantified.

Some toxic blooms lead to fish kills in both wild and farmed fish populations. Others are associated with irritating and toxic aerosols, due to the transport of toxins in sea spray. Even non-toxic algal species can cause problems through biomass effects—shading of submerged vegetation, disruption of food web dynamics and structure, and oxygen depletion as the blooms decay. The term HAB has traditionally referred to microscopic algae, but its interpretation has now been broadened to include the blooms of macroalgae (seaweeds) that displace indigenous species, destroy habitat, cause oxygen depletion, and alter biogeochemical cycles. The causes and effects of macroalgal blooms are similar in many ways to those associated with harmful microalgae.

* Corresponding author: tele: 508/289-2867; fax: 508/457-2184; e-mail: phoagland@whoi.edu.

During the past several decades, HAB events have been observed in more locations than ever before throughout the United States (Anderson 1989; Smayda 1990; Hallegraeff 1993; Anderson et al. 2002). The number of algal species involved in such events has increased, more toxins have been identified, and more fisheries resources are known to have been affected. Whether or not this apparent increase in HABs is taking place because of enhanced nutrient and pollutant loadings from anthropogenic sources has been a topic of serious debate within the scientific community (e.g., Anderson 1989; Smayda 1990; Anderson et al. 2002). Whatever the reasons for the apparent increases in HABs, virtually all coastal regions of the U.S. are potentially subject to a wide variety and increased frequency of HAB events. The U.S. is not alone in this respect, as nations throughout the world are faced with a bewildering array of toxic or harmful species and effects.

Faced with these hazards, it is important for society to begin to understand the scale of the economic costs of HABs. 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. Surveying the literature, Van Dolah et al. (2001, p. 1336) found that HABs were responsible for ''the loss of millions of dollars to coastal communities through costs associated with beach cleanup, closing of commercially important fisheries, and decreased tourism.'' Estimates of economic effects may be invoked, or even exaggerated, in policy debates, often without concern about how they were developed. As an example, section 602(5) of the U.S. Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 [P.L. 105-383] stated that ''Congress finds that . . . harmful algal blooms have been responsible for an estimated $1,000,000,000 in economic losses during the past decade.''

The focus of this article is on HAB events in the U.S. leading to the measurement of economic effects during 1987 to 1992. (All estimates are converted with the U.S. consumer price index and reported in 2000 U.S. dollars.) Due to inadequate reporting, the events included here should be regarded as only a subset of the HAB outbreaks that occurred during the 6-yr study period. We group economic effects into four basic categories: public health (shellfish poisoning and CFP), commercial fisheries (including untapped fishery resources), recreation and tourism, and monitoring and management. We discuss the difficult problems that arise in attempting to compare estimates of economic effects across these categories and in aggregating these estimates to develop a nationwide estimate of the economic effects of HABs. To our knowledge, this is the first effort to compile estimates of the economic effects of HABs at the national level.

Materials and Methods

Our analysis is based on a survey of experts from individual coastal states, a review of the literature, and our own calculations. Formal letters requesting data and copies of any unpublished economic analyses were mailed in both August 1992 and February 1994 to individuals who were either knowledgeable about HAB effects or likely to know others who could be contacted for more specific details. More than 170 people were contacted by letter and telephone to elicit economic data and to uncover details about individual HAB events. After a preliminary evaluation and synthesis of these data, topics requiring further data or analysis were identified. These were addressed through a new series of telephone calls and correspondence during 1997–1999.

To direct our research, we relied upon reports of HABs in a national database. HAB data are compiled on an annual basis by the U.S. National Office for Marine Biotoxins and Harmful Algal Blooms at the Woods Hole Oceanographic Institution. These data are maintained by that office and are also supplied to the International Council for the Exploration of the Sea (ICES)/International Oceanographic Commission (IOC) Working Group on Harmful Algal Bloom Dynamics, which has entered them into an international database called the Harmful Algal Events Database (HAEDAT), maintained by the IOC HAB Science and Communication Centre in Vigo, Spain.

We define economic effects broadly to mean either lost sales (gross revenues) in the relevant product or factor markets, medical costs and lost productivity, expenditures for environmental monitoring and management, or other costs that would not have been incurred in the absence of HABs. This measure is consistent with published estimates of the economic impacts of other kinds of natural hazards, such as hurricanes or earthquakes (e.g., Pielke and Landsea 1997; Pielke and Pielke 1997). The estimates reported here represent a preliminary, but admittedly rough, approximation of the scale of economic costs to the U.S. from the occurrence of HABs, conditional on a number of critical assumptions.

Most of the figures reported here are equivalent to or approximate direct output impacts of the sort that are used in the methodology of economic impact analysis. Economic impact analysis was developed originally as a purely descriptive technique. Its purpose was to describe the economic structure of a region in order to help understand economic interactions and linkages among sectors. In particular, it is not a form of benefit-cost analysis, which is used to examine changes in economic welfare, and it cannot be used by itself to justify decisions such as the scale of investments in policy responses to mitigate the effects of natural hazards such as HABs (Propst and Gavrilis 1987).

Economic impact analysis also may involve the calculation of multipliers to capture the full ramifications of economic impacts (cf., Loomis 1993). Multipliers can be sensitive to local market structure characteristics and the quality of data that describe interactions among market sectors (Propst and Gavrilis 1987; Archer 1995). Developing a description of local and regional markets for specific HAB events was beyond the scope of our research, and so we did not attempt to calculate multipliers here. Through the literature review, we identified some studies of HAB effects in which multipliers were estimated and used. For example, in September 1980, the entire Maine coastline was closed to shellfishing because of a bloom of the dinoflagellate *Alexandrium tamarense,* a source for PSP toxins. Harvest losses from this event were estimated at $5 million, and total economic impacts were estimated to be $15 million, using a multiplier of 3.0. In the autumn of 1986, a red tide bloom of *Karenia brevis* (formerly known as *Gymnodinium breve*) along the coast of Texas caused the loss of $2 million in oyster (*Crassostrea virginica*) production during the months of November and December, resulting in estimated economic impacts of nearly $6 million, after applying a multiplier of 2.7 (Martin 1987). Although these estimates were the result of careful studies of economic impacts, in other cases, the calculation of economic multipliers in the absence of detailed data on market structure and interactions can be potentially misleading, creating a perception of exaggerated economic costs of HAB events (cf., Hunter 1989).

The economic effects reported here may not be a good measure of the costs of HABs to society. Under ideal circumstances, we would like to obtain measures of lost consumer and producer surpluses in the relevant markets due, for example, to shifts in demand or supply curves. The economic concept of surplus involves the combination of benefits to consumers over and above what they must pay for a good or service and the benefits (profits) to firms arising from the difference between the gross value of their sales and their production costs. Increases or decreases in these surpluses represent gains or losses in economic welfare. The economic effects typically measured and reported in the case of HAB events are changes in the gross value of sales (e.g., lost sales from a closed fishery or vacant hotel rooms). The problem with using sales losses as a measure of welfare change is that the costs of production, which are not necessarily incurred when sales are not made, are not factored out. Further, sales losses do not include surplus losses to the consumer.

Van den Bergh et al. (2002) presented an excellent introduction to the methods for measuring lost surpluses in the case of HABs introduced through ballast water discharges, although they make no attempt at estimating losses. In the only study of which we are aware that has estimated lost surpluses (instead of lost sales) from a HAB event, Kahn and Rockel (1988) calculated annual total consumers' and producers' surplus losses from the elimination of bay scallop (*Argopecten irradians*) populations in Long Island, New York, waters at a level of about $3 million. The Long Island study is an important, but rare, example of the kind of analysis that could be used to help policymakers determine an efficient level of management response to HABs.

The point in time at which effects are measured also must be considered. When a commercial or recreational fishery is closed ex ante, then the appropriate measure of economic effects is the sum of lost consumer and producer surpluses. If commercial shellfish have been harvested already, and the product is subsequently prevented from reaching the market because toxicity exceeds safe levels, then it is appropriate to add harvest costs to the measure of economic losses. In the latter case, harvest costs are included because they are a measure of resources that have been used to no productive effect. Another example is the occurrence of a HAB that affects an operating coastal aquaculture facility that must subsequently incur additional depuration costs or dispose of tainted product. In both examples, there may be additional costs, such as higher tipping fees, associated with the disposal of the tainted seafood.

The ease with which capital or labor can be transferred to other productive activities is a critical consideration. A typical assumption is that fishing vessels, processing plants, and fishers will immediately and costlessly switch to their next best alternative activity. In other words, capital and labor are assumed perfectly malleable. When examining specific cases, however, we may find that this assumption is invalid. Good examples include empty hotel rooms or slower restaurant trade resulting from lower coastal tourism during a HAB event. As another example, it may be costly for fishers to re-rig their boats or to steam to another fishing ground when a HAB closure has been declared. Often, economic impact studies assume that capital and labor is completely non-malleable (i.e., production costs are included in the estimate of lost sales).

Note that some firms in the relevant market actually may benefit from a HAB event. For example, if a fishing location is closed because of a HAB event, a firm fishing for the same species in a location that remains open may actually see an increase in price for its product. Although there is a clear net loss at the market level when fewer fish are supplied, local net gains or net losses may occur, and the distribution of gains and losses may not be uniform across all localities. (Note that the existence and degree of net losses at the market level also may be a function of the status of the fishery and the applicable management institutions. In an economically overexploited fishery, the potential exists for producer surplus gains—in the form of resource rents—to exceed consumer surplus losses after the imposition of a closure, if the fishery is subsequently managed efficiently.) Unless demand is perfectly elastic with respect to price (i.e., there is no surplus for consumers), consumers will unambiguously lose because of price increases when supply is reduced as a consequence of a HAB event. Some will even be unwilling to purchase the fish or shellfish at the new higher price.

The public health effects and monitoring and management activities can be interpreted similarly. For the case of medical costs, such as those associated with shellfish poisoning cases, we focus on the individual. Hospitalization or sickness results in lost individual productivity (the labor services produced by the individual) analogous to lost sales in a seafood market. (There are competing models for making estimates of any productivity losses.) As well, there are increased costs to the individual of doctor visits or hospitalization. HAB events may reduce the level of environmental quality services provided by a marine ecosystem. Expenditures are thereby incurred to monitor changes in ecosystem state, to respond by modifying uses of the ocean or, in some cases, to restore the system to the state that existed before the HAB event. It should be recognized, however, that HABs do not always result in net economic losses. As a form of phytoplankton and as a component of ecosystems, in certain cases, excess algae may contribute positively to biological productivity. The existence of uncertainty about the economic consequences of ecological effects underscores the potential value of investments in further scientific research.

It is interesting that public health effects and monitoring and management activities also help to mitigate the larger potential costs of HAB events. For example, monitoring might prevent the consumption of toxic seafood, and hospitalization might reduce mortality from seafood consumption. As a result, in theory, there may be net benefits from undertaking these activities, but estimating these kinds of potential net benefits was beyond the scope of our research.

Even though our measure of economic effects is not a measure of welfare loss from HABs, it is not without value. Measuring economic effects gives us an idea of the scale of the problem. If these effects are found to be large in any particular instance, we may need to take a closer look at surplus changes. The geographic location of economic effects can also give an estimate of where local losses occur, and the type of effect can help us to identify the relevant market. Compiling and categorizing economic effects can uncover some of the distributional effects of a HAB event.

We examined effects resulting from events occurring mainly during the 6-yr period from 1987 to 1992. We observed substantial variability in the frequency and spatial distribution of HABs, and therefore the choice of a shorter period could result in either under-estimates or over-estimates of economic effects, depending upon when and where HAB events occurred. The 6-yr period is the longest period for which we were able to collect consistent data within the constraints of the project. Although our choices about the timing and duration of the study period were somewhat arbitrary, we believe that it gave us a reasonable interval within which to develop estimates of the annual economic effects of HABs nationwide. We mention some studies of economic effects from HABs that occurred outside of 1987–1992 where such studies illustrate an important issue or assumption about the comparability or aggregation of economic effects.

Although we made an effort to gather economic data as comprehensively as possible, both the type and amount of available data were limited. Most coastal states have neither conducted economic studies of the effects of HABs nor collected data that can be used to generate reliable quantitative estimates of such effects. In many cases, the complex physical and ecological characteristics of the coastal environment made it difficult to determine whether an algal bloom was the immediate and relevant cause of certain coastal phenomena such as fish kills, oxygen depletion, or seagrass die-offs. Local experts often differed substantially in their opinions about the magnitude of economic effects from HABs. We discuss these and other data interpretation issues in the following sections.

Results

Shellfish Poisoning

Human sickness and death from eating tainted seafood results in lost wages and work days. Costs of medical treatment and investigation can also be significant. Further, individuals who are sick may experience pain and suffering. In theory, these feelings could be quantified in economic terms, but we made no attempt to do so here. Cases of sickness and death from shellfish toxins are probably the most clearly documented among the different types of HAB effects. Because of the high level of public interest in seafood safety, these cases are recorded by public health agencies in individual states as well as at the federal level.

Prior to our study period, during 1978–1987, PSP was a minor cause of seafood-borne illness in the U.S., according to data on illness cases reported to the Center for Disease Control (CDC) in Atlanta. Only two deaths due to PSP were reported during this period. Nishitani and Chew (1988) present data on reported PSP cases during 1979–1987 in the four U.S. Pacific Coast states. These data showed that in the more recent years there were far fewer PSP cases than in the earlier years, especially in California. A separate report from the U.S. Food and Drug Administration identified shellfish poisoning cases for 1973–1992 (Rippey 1994). The reported number of PSP sickness cases varied widely across these three sources. For example, the CDC reported no PSP cases in 1987, but Nishitani and Chew (1988) reported seven PSP cases in Alaska in that year. Because reports to CDC are voluntary, we believe that the CDC database may undercount the number of PSP sickness cases in any year. A substantial number of illnesses caused by HABs are likely to remain unreported. No reliable method has been proposed for extrapolating from the reported cases to estimate the true incidence of illness however. Todd (1989a, personal communication) proposes multiplying the number of reported shellfish poisoning cases by a factor of ten to estimate the total, and we adopt this rule-of-thumb.

Although the U.S. Department of Agriculture estimated the costs for some foodborne illnesses in the U.S., we were unaware of any recent estimates, published or otherwise, of the cost of shellfish poisoning illnesses in the U.S. As an approximation, we adopted the estimates developed by Todd (1995) for PSP illnesses (we calculated $1,400 per reported illness and $1,100 per unreported illness) to estimate the costs of disease due to PSP, NSP, and ASP in the U.S. These cost estimates were refinements of earlier estimates made by the same author for both Canada and the U.S. (Todd 1989a,b). These estimates of illness costs included lost productivity due to sick days, costs of medical treatment and transportation, and costs associated with investigations for the cause of the sickness. Unreported illnesses do not, by definition, incur medical and transportation costs. Because cost information was unavailable specifically for NSP or ASP illnesses, we applied the cost estimates for PSP cases to these illnesses as well.

During the study period, one 47 year old male individual died from PSP in Alaska in 1989. Two competing methods exist for assessing the economic loss associated with a mortality from foodborne disease: the human capital and the labor market approaches. The human capital approach evaluates the lost productivity of an individual in terms of foregone earnings (Landefeld and Seskin 1982). The cost of a premature death from foodborne disease can be related to the age at which death occurs (Buzby et al. 1996). Using this approach, the economic loss from the PSP mortality in Alaska is approximately $1 million. An estimate of foregone earnings using the human capital approach is most consistent with the lost productivity estimate incorporated into the morbidity cost developed by Todd (1995), who cited Landefeld and Seskin (1982) as his source for foregone earnings. Alternatively, labor market studies are based upon empirical data that try to measure what people are willing to pay for small reductions in health risks (Viscusi 1993). Using an age-adjusted labor market method designed by the U.S. Department of Agriculture (Frenzen et al. 1999), an estimate of the economic loss from the PSP mortality in Alaska is approximately $6 million. Economists disagree over which method is most appropriate, and the U.S. Department of Agriculture has employed both methods. To be consistent with Todd's (1995) analysis, we employed the human capital estimate, assigning $1 million to the loss associated with the PSP mortality in Alaska. We emphasize that this estimate of loss is an approximation.

Todd's calculation accounted for the likelihood that unreported cases were less serious than reported cases, implying that there may be lower associated medical treatment and investigation costs. Following Todd's (1989a) rule-of-thumb, we multiplied the number of reported cases in Table 1 by a factor of ten to arrive at an estimate of total cases, and we weighted the reported illnesses by the higher cost per illness. We calculated a $400 thousand annual average estimate of the public health costs of illnesses due to shellfish poisoning. This estimate is less than one-quarter of that reported by Todd (1989a) for annual PSP costs in the U.S. in which he employed significantly larger estimates of costs per illness during a different period (1978–1982).

Ciguatera Fish Poisoning

Another problem caused by toxic algae is the syndrome called CFP, which is linked to dinofla-

TABLE 1. Public health effects due to shellfish poisonings (2000 $ thousands; from Nishitani and Chew 1988; Rippey 1994; NOMBHAB 2000).

Year	State	Type	Reported	Unreported[a]	Effects[b]
1987	Florida	PSP	3	27	$633
	North Carolina	NSP	47	423	
	Alaska	PSP	7	63	
1988	Washington	PSP	5	45	$89
	Alaska	PSP	3	27	
1989	New York	PSP	2	18	$44
	California	PSP	2	18	
1990	Massachusetts	PSP	8	72	$1,104
	Alaska[c]	PSP	2	18	
1991	California	PSP	11	99	$488
	Washington/Oregon	ASP	28	252	
	Alaska	PSP	5	45	
1992	Alaska	PSP	1	9	$11

[a] Reported illnesses are estimated to be 10% of all illnesses due to HAB events (Todd 1989a, personal communication).
[b] Economic impacts are estimated at $1,400 per reported illness, $1,100 per unreported illness, and $1 million per mortality.
[c] Includes one mortality in Alaska.

gellate toxins that move through the tropical food chain to higher trophic level predators. Although ciguatera technically is not a bloom phenomenon, we investigate it because it originates with toxic microalgae, and it is generally included in the category of HABs by most specialists. We estimated illness costs for both reported and unreported cases in U.S. tropical jurisdictions. We included U.S. tropical jurisdictions including states (Florida and Hawaii), commonwealths (Puerto Rico and the Northern Mariana Islands), and territories (U.S. Virgin Islands, Guam, and American Samoa). Additional costs, unaccounted for here, may arise due to exports of CFP-tainted tropical fish to the continental U.S. (Ragelis 1984). Further, some seafood importers and processors now purchase insurance to cover potential ciguatera-caused liabilities, and there may be court costs associated with ciguatera-related litigation.

We contacted experts on CFP illnesses in U.S. tropical jurisdictions, finding that expert opinions differed significantly on the ratio of reported to unreported illnesses in each jurisdiction. We have no a priori explanation for the variation in expert opinion across jurisdictions of the incidence of unreported illnesses. We employed the following reported to unreported illness ratios: 1:4 for Florida (Weisman personal communication), 1:10 for the Northern Mariana Islands and American Samoa (our own estimate based on the incidence of ciguatera illnesses in the Marshall Islands [Ruff 1989]), and 1:100 for Hawaii, Guam, Puerto Rico, and the U.S. Virgin Islands (Hokama personal communication; Haddock personal communication; Tosteson personal communication; and our own estimates). In Table 2, we present data on the estimated number of CFP illnesses in these jurisdictions.

To be consistent across all regions, we adopted Todd's (1995) estimate of CFP illnesses of approx-

TABLE 2. Public health effects due to ciguatera poisonings (estimates of reported and unreported illnesses for each jurisdiction).

Year	Florida[a]		Hawaii[b]		Puerto Rico[b,c]		Virgin Islands[b,c]		Guam[b]		American Samoa[d]		Northern Mariana Islands[d]		Totals		Estimated Effects (2,000 $ millions)[e]
1987	250	750	90	8,910	200	19,775	6	593	5	495	30	270	32	290	613	31,084	22
1988	250	750	77	7,623	200	19,775	6	593	15	1,485	30	270	32	290	610	30,787	22
1989	250	750	71	7,029	200	19,775	6	593	4	396	30	270	32	290	593	29,104	21
1990	250	750	28	2,772	162	16,025	5	481	11	1,089	30	270	32	290	518	21,677	15
1991	250	750	61	6,039	162	16,025	5	481	6	594	30	270	32	290	546	24,449	17
1992	250	750	48	4,752	162	16,025	5	481	2	198	30	270	32	290	529	22,766	16

[a] Weisman (personal communication) estimates that only one in four ciguatera cases in Florida are reported.
[b] We assume only one in 100 ciguatera cases are reported in these jurisdictions, based upon Tosteson's (personal communication) estimate for Puerto Rico.
[c] Tosteson (personal communication) estimates reported ciguatera cases are 0.6% of the population during 1987–1989 and 0.5% during 1990–1992.
[d] We estimate that 1 in 10 ciguatera cases are reported in these jurisdictions based upon Ruff's (1989) estimate for the Marshall Islands. We use also the average incidence of ciguatera in the Marshall Islands as a hazard rate for these jurisdictions.
[e] Todd (personal communication) estimates ciguatera illness costs of $1,000 per reported case and $700 per unreported case.

imately $1,000 per reported case and $700 per unreported case. This method may overcount CFP illness costs in Puerto Rico, as Tosteson (personal communication) estimated that the costs per reported case are lower there—possibly as low as $530 per reported case. Our estimate of total economic effects varied from $15 to $22 million per year, averaging $19 million on an annual basis. It is clear from this estimate that the economic effects due to CFP account for the majority of public health effects from HABs and that most of these effects are concentrated in tropical jurisdictions.

Commercial Fishery Effects

HABs can affect commercial fisheries by causing direct fish mortalities (of wild or cultured stocks), causing habitat loss leading to lower ecosystem carrying capacity, forcing managers to establish closures, increasing the costs of processing harvested shellfish, and causing consumer demand to contract. In Table 3, we present HAB events for which commercial fishery effect information was obtained during 1987–1992. These events were described in further detail in Anderson et al. (2000). Annual effects vary from $7 to $19 million. Average annual effects are $12 million.

A few of the events in Table 3 are noteworthy. For example, Tester et al. (1991) estimated total commercial harvest losses during a November 1987 to February 1988 *K. brevis* bloom in North Carolina to be $8 million. We estimated total effects of $18 million arising from the deaths of farmed Atlantic salmon (*Salmo salar*) killed by phytoplankton blooms in Washington in 1987, 1989, and 1990 by multiplying the market price of salmon by the weight of lost fish. Two commercial shellfishing interests, Taylor United and the Coast Oyster Company, estimated a combined $1 million loss incurred during a shellfish recall resulting from the detection of PSP toxins in Washington shellfish.

In 1985, a brown tide (*Aureococcus anophagefferens*) bloom first appeared in the Peconic estuary, Long Island, New York, and has reappeared since on a regular basis. The most significant economic effect has been the eradication of the Peconic's nationally significant bay scallop (*A. irradians*) stocks. The Suffolk County Department of Health Services estimated that the 1982 value of commercial landings of bay scallops from the Peconic estuary was $13 million (Suffolk County Department of Health Services 1992). Tettelbach and Wenczel (1993), however, citing a report by Rose (1987), estimated the value of commercial bay scallop landings from New York waters for the years preceding the 1985 brown tide incident at a much lower level, averaging $3 million.

Some observers have hypothesized that brown tide may have also affected oyster (*C. virginica*) production in the Peconic system. The estimated commercial landings of oysters in the Peconic estuary were about $6 million in 1982, plummeting to $10 thousand per year in 1987 (SCDHS 1992). It is unclear, however, whether these losses were due solely to brown tide and whether they occurred on an annual basis, and we did not therefore incorporate an estimate of these losses in our tabulation.

Beginning in the autumn of 1991, the occurrence of ASP adversely affected the shellfisheries for razor clams (*Siliqua patula*) in both Oregon and Washington. Although these fisheries are primarily recreational, a small commercial fishery exists in Oregon. According to the Oregon Department of Fish and Wildlife, an average of 58,000 pounds of razor clams (at $3.65 per pound) were harvested commercially on an annual basis before closures were imposed. This implies that potential annual harvest sales losses were $210 thousand in the commercial market. Because the ASP events occurred during the fall season of 1991, we used 50% of this estimate of lost sales in 1991 and the full estimate for 1992. In the three states of California, Oregon, and Washington, Nishitani and Chew (1988) argued that shellfishing closures due to PSP have resulted mainly in harvesting delays but not in significant financial losses.

Ralonde (1998) estimated that the cost of PSP to Alaska in terms of lost value in commercial fisheries, closures of recreational shellfishing beds, and mouse bioassays was on the order of $10 million per year. With respect to commercial fisheries effects specifically, Ralonde estimated three types of costs: geoduck (*Panopea abrupta*) processing effects, bitter crab disease (BCD) in tanner crabs (*Chionoecetes bairdi*) caused by dinoflagellate parasites, and a 1992 PSP event in Dungeness crabs (*Cancer magister*). Ralonde calculated the 1996 lost value of geoducks due to the fact that they have to be processed to remove the viscera where the PSP toxin is concentrated. Annual lost income in 1996 was more than $1 million. Because the sales of geoducks in 1996 were approximately equal to the 6-yr average, we used the 1996 estimate of lost sales as an annual estimate for 1989–1992 (the fishery began in 1989). Ralonde estimated the lost value in 1996 of tanner crabs due to BCD at $200 thousand. We assumed that this was the annual lost value due to BCD during 1987–1992. Finally, in 1992, a PSP event resulted in a $500 thousand loss of sales in the Dungeness crab fishery.

Hokama (personal communication) estimated ciguatera effects in Hawaii at $3 million per year based on the dollars per pound of fish that are unmarketable due to ciguatera. This estimate rep-

TABLE 3. Commercial fishery effects (2000 $ millions). ASP = amnesiac shellfish poisoning, BT = brown tide, CFP = ciguatera fish poisoning, HAB = harmful algae bloom (not otherwise identified), NSP = neurotoxic shellfish poisoning, PD = paralytic dinoflagellate, and PSP = paralytic shellfish poisoning.

Year	Incident	Type	State	Estimated Effects	Total Annual Estimated Effects
1987	Harvest losses of clams, oysters, scallops, and finfish	NSP	North Carolina	8.27	
	Lost sales of recreational fish	CFP	Hawaii	3.17	
	Bay scallop mortality	BT	New York	3.27	
	Farmed fish kills	HAB	Washington (Cypress Island)	0.75	
	Bitter crab disease in tanner crabs	PD	Alaska	0.16	
	Closure of surf clam fishery	PSP	Alaska	5.72	21
1988	Lost sales of recreational fish	CFP	Hawaii	3.17	
	Bay scallop mortality	BT	New York	3.27	
	Bitter crab disease in tanner crabs	PD	Alaska	0.16	
	Closure of surf clam fishery	PSP	Alaska	8.29	15
1989	Farmed fish kills	HAB	Washington (Cypress Island)	11.01	
	Lost sales of recreational fish	CFP	Hawaii	3.17	
	Bay scallop mortality	BT	New York	3.27	
	Closure of surf clam fishery	PSP	Massachusetts (Georges Bank)	0.13	
	Lost value of unprocessed geoducks and bitter crab disease in tanner crabs	PSP, PD	Alaska	1.49	
	Closure of surf clam fishery	PSP	Alaska	6.15	25
1990	Farmed fish kills	HAB	Washington (Central Puget Sound)	5.88	
	Lost sales of recreational fish	CFP	Hawaii	3.17	
	Closure of surf clam fishery	PSP	Massachusetts (Georges Bank)	0.00	14
	Bay scallop mortality	BT	New York	3.27	
	Lost value of unprocessed geoducks and bitter crab disease in tanner crabs	PSP, PD	Alaska	1.49	
	Closure of surf clam fishery	PSP	Alaska	0.00	
1991	Lost sales of recreational fish	CFP	Hawaii	3.17	
	Bay scallop mortality	BT	New York	3.27	
	Closure of surf clam fishery	PSP	Massachusetts (Georges Bank)	0.23	
	Harvest losses of razor clams	ASP	Oregon	0.11	
	Lost value of unprocessed geoducks and bitter crab disease in tanner crabs	PSP, PD	Alaska	1.49	
	Closure of surf clam fishery	PSP	Alaska	8.04	16
1992	Lost sales of recreational fish	CFP	Hawaii	3.17	
	Bay scallop mortality	BT	New York	3.27	
	Product recall costs for one firm	PSP	Washington	1.22	
	Closure of surf clam fishery	PSP	Massachusetts (Georges Bank)	0.26	
	Harvest losses of razor clams	ASP	Oregon	0.21	
	Lost value of unprocessed geoducks, bitter crab disease in tanner crabs and PSP event in Dungeness crab fishery	PSP, PD	Alaska	1.99	
	Closure of surf clam fishery	PSP	Alaska	9.14	19

resents potential losses of retail sales (not ex-vessel or farmgate value) from catches made mainly in sport fishing. Note that, in this case, the value of sport fishing recreation is not diminished, but the retail sale is lost. If the act of selling a caught fish is a valued part of the sport fishing experience, then the nonmarket value of recreational fishing also may be reduced. On the other hand, because these figures are based upon retail prices, which include markups, they may not be directly comparable to the ex-vessel values for other fisheries (i.e., they exceed lost ex-vessel sales by the amount of the markups).

For Maine and Massachusetts, it is apparently not feasible to infer fishery effects from a relationship between the frequency of shellfish closures due to PSP (or numbers of shellfish samples testing positive for PSP) and annual harvest values (Anderson et al. 2000). For example, in Maine, 1988 was the year with the greatest number of HAB closures, and 1992 was the year with the least (Lewis personal communication). An examination of the landings, however, revealed higher landings in 1988 and lower landings in 1992. Our informal discussions with several New England commercial shellfishing companies suggested that short-term closures caused few operational problems and that long-term closures caused financial losses only infrequently, e.g., once in every ten years.

Several other things led us to conclude that it would not be easy to estimate commercial fishery effects reliably from closure acreage or shoreline miles affected by toxic blooms in New England. These problems illustrate the difficulties with assessing the economic effects of HABs in other geographic locations as well. First, state officials record neither acreage closed to shellfishing due to HAB events nor shoreline miles affected by HAB closures. Records of shellfish closures or openings are complex, including partial extensions of closures or the reopening of already closed areas. Maine has 50,000 acres of potential shellfish beds, but 90% of the state's total clam harvest is produced on about 10% of its acreage. Second, the co-occurrence of high coliform counts or of shellfish sanitation problems with HABs makes it difficult to factor out the economic effects that are due solely to HAB events. For example, samples collected from certain areas in Massachusetts in 1994 showed high PSP levels, warranting shellfish closures. The same areas had been closed already, however, due to high coliform bacteria levels. Third, it is likely the case that shellfishers are able to switch at low cost to other locations, other fisheries, or other occupations, thereby mitigating the losses associated with closures. Finally, the closure of some shellfish beds could permit stocks to rebuild, individuals to grow larger, or increase diffusion of larvae to open areas elsewhere. These effects may either reduce the losses associated with closures or, in some cases, lead to net benefits, particularly in cases of overexploited stocks.

Concerns are sometimes raised in the media about indirect commercial fishery effects, such as wild fish kills. Wild fish kills were reported in many states, but for numerous reasons, measuring the economic effects of these mortalities is problematic. First, many of these events involve so-called trash fish, which have no market value by definition. Even local officials who regularly investigate fish kill events make no attempt to estimate the economic effects of trash fish mortalities. Second, the ultimate causes of some fish kills are often unclear, making it difficult to attribute them to an algal bloom, although many of the red tide events leading to fish kills in Florida and Texas, for example, were clearly caused by HABs. Fish kills can be the result of oxygen depletion (due to high fish populations, high temperatures, or HABs), disease, bacteria, nutrients, chemical spills, or some combination of these or other factors.

Gorte (1994) reported an estimate of $16 million per year for the potential income loss due to the substantial decline in pink shrimp (*Penaeus duorarum*) harvests from Florida Bay, hypothesized to be the result of a seagrass die-off due, in turn, to blooms of blue-green algae. Using an economic multiplier of 2.3, he also reported an estimate of the total economic impacts of $37 million. There was substantial uncertainty, however, about the real causes of the seagrass die-off and its linkage to blue-green algae (Gorte 1994; Hunt personal communication). Further, economic recession and foreign competition within the shrimp industry were other plausible reasons for the industry's decline. Our loss estimates did not include these uncertain effects.

Our study focused on the years 1987–1992, yet there were a number of significant events in other years that demonstrated the magnitude of the effects that were possible and illustrated some important accounting issues. For example, in 1976, New Jersey suffered an extensive oxygen depletion event in which HABs were implicated in part. A confluence of oceanographic, hydrologic, and meteorological factors led to a bloom of the dinoflagellate, *Ceratium tripos,* which resulted in anoxic conditions and the formation of hydrogen sulfide in the bottom waters of the New York Bight. The bloom affected sedentary commercial stocks of surf clams (*Spisula solidissima*), ocean quahogs (*Artica islandica*), sea scallops (*Placopecten magellanicus*), and some finfish and lobster (*Homarus americanus*). Figley et al. (1979) estimated lost sales for sea scallops and surf clams from harvests during 1976 and for five to seven subsequent years. The largest effects by far occurred in the surf clam market. Effects in the downstream processing and marketing sectors were estimated using a multiplier of 2.5. Total lost sales in all sectors combined were estimated to be more than $1 billion.

Another concern is the so-called halo effect, in which the communication of public health risks resulting from a HAB is impaired, leading to contraction in demand for seafood. An excellent example, occurring outside our period of study, was the bloom in 1997 of *Pfiesteria* spp. that occurred in several Chesapeake Bay tributaries, resulting in the mortality of 30–50,000 menhaden (*Brevoortia tyrrannus*). Although this represented only a very small proportion of the Atlantic menhaden stock, and menhaden are not consumed as seafood, press reports drew public attention to the potential for health effects. After medical testing of fishers who complained of an array of physical and neurological problems, the Governor of Maryland acknowledged the possible human health risks associated with *Pfiesteria* and ordered several Chesapeake tributaries closed to recreation and fishing (Bowman 1997). The demand for seafood from the state of Maryland shrank significantly during the autumn of 1997, even though the state spent at least $500 thousand on a promotional effort to lessen the effect on the market. Lipton (1999) estimated that $48 million in seafood sales were lost to Maryland producers as a consequence of the 1997 *Pfiesteria* event.

Untapped Fishery Resources

Some currently untapped fishery resources may have potential values that could be realized in the absence of HAB events. Examples include the shellfish resources of coastal Alaska (e.g., Neve and Reichardt 1984) and surf clams on Georges Bank. The legislative history to the U.S. Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 cited an estimated $50 million annual shellfish harvest off the coast of Alaska that was unexploited due to HABs. One possible source for this estimate was the workshop report by Lutz and Incze (1979) who valued the annual potential sustainable yield of Alaskan surf clams at $28 to $47 million. In order for such lost opportunities to be counted legitimately as economic effects, however, these fisheries must be demonstrated to be commercially viable. A plausible alternative reason for why these resources were untapped is that they were not perceived by the industry to be profitable fisheries.

The status of Alaskan shellfish stocks and their commercial significance are summarized annually by the Alaska Department of Fish and Game, and they have been reviewed by Foster (1997), Schink et al. (1983), and Jewett and Feder (1981). All commercial shellfish except for the Pinto abalone (*Haliotis kamtschatkana*), chitons (*Katherina tunicata* and *Cryptochiton stelleri*), and limpets (*Lottia* spp.) are threatened by PSP contamination (Foster 1997). Yields of razor clam (*S. patula*), weathervane scallop (*Patinopecten caurinus*), and geoduck (*P. abrupta*) are processed to remove portions of the animal that may be toxic due to PSP. The Pacific oyster (*Crassostrea gigas*), blue mussel (*Mytilus edulis*), and Pacific littleneck clam (*Protothaca staminea*) are cultured species for which bioassays are conducted as they are produced. Historically, significant quantities of butter clams (*Saxidomus giganteus*), in 1946, and cockles (*Clinocardium nuttallii*), in 1962, were produced off the Alaskan coast. More recently only minor harvests have taken place, and, although small markets for these species exist on the west coast of the U.S., it is not clear that historical levels of production could be commercially viable (Ostasz personal communication). A 1977 U.S. National Marine Fisheries Service (NMFS) survey of the southeast Bering Sea revealed significant quantities of great Alaskan tellin clams (*Tellina lutea*; Lutz and Incze 1979; Nelson et al. 1979), but there is no known market for tellin in the U.S.

The 1977 NMFS survey also revealed potentially exploitable quantities of the Alaskan surf clam (*Spisula polynyma*) in the Bering Sea. Hughes and Bourne (1981) estimated an annual maximum sustainable yield (MSY) of 25,017 metric tons for this resource. The Alaskan discovery came at a crucial time in the U.S. surf clam market, as the mid-Atlantic surf clam (*S. solidissima*) resource had just suffered a steep decline due to the *Ceratium* bloom in the New York Bight, and the price of surf clams tripled during 1976 and remained high for the next ten years as the resource recovered. Only small quantities of Alaskan surf clams have been harvested since the 1977 stock assessment was conducted.

The reasons for the lack of a viable Bering Sea surf clam fishery are not completely clear, but several hypotheses have been put forward. First, some of the surf clam resource tested positive for PSP. Neve and Reichardt (1984) argued that persistent PSP was largely responsible for the non-exploitation of this resource. On the other hand, Ostasz (personal communication), citing Hughes and Nelson (1979), noted that only a small proportion (2 out of 185 samples) had detectable levels of PSP toxin in 1978, and no samples tested positive for toxin in 1977. Because Alaska has not classified the Bering Sea according to National Shellfish Sanitation Program standards, harvesting the resource is currently infeasible.

A second plausible reason for the lack of production may be that the fishery is not commercially viable (Foster 1997). Certainly, production of surf clams at the MSY level is likely to drive the price down in the U.S. surf clam market, thereby decreasing the profitability of the fishery or even precluding its initiation. Further, the structure of the market may present an entry barrier into this fishery. With respect to the mid-Atlantic surf clam fishery, Weninger (1998, p. 755) stated that: ''[t]he perishable nature of the clams, scheduling of processing activities, and the need to coordinate with downstream buyers requires tight vertical coordination between fishers and processors.'' Without the establishment first of a costly processing infrastructure, and considering the difficulty of distributing product from a remote location, it may be difficult for a surf clam fishery to become established in Alaska. Ostasz (personal communication) suggested that seasonal closures might be imposed on a potential surf clam fishery to protect juvenile spawning grounds for King crab. It is possible that the timing or area coverage of a closure would increase the cost of surf clam fishing to levels that might not support a fishery.

Finally, there has been concern expressed over the potential effects on walrus stocks from the harvesting of Alaskan surf clams, which are an important food source for walrus (Stoker 1977 as cited by Foster 1997). This concern might express itself in opposition from environmental interests should a commercial operation be explored. The Alaskan Eskimo Walrus Commission has the responsibility for protecting surf clam resources in walrus habitat (Ostasz personal communication).

Critical information on the cost of producing Alaskan surf clams does not exist, but Anderson et al. (2000) roughly estimated the economic effects associated with a hypothetical Bering Sea fishery. To accomplish this, they made the following critical assumptions: the only obstacle to the commercialization of the Alaskan surf clam resource was the potential presence of shellfish poisoning (PSP or ASP), the Alaskan surf clam was a close substitute for the Atlantic surf clam and will compete in the same market, production of the Alaskan (and Georges Bank) resources at estimated MSY levels were likely to affect the price of surf clams in the U.S. market (by driving it down), there was no expansion of existing demand such as might occur, for example, through the opening of an export market, an Alaskan surf clam fishery was financially viable, it was feasible to regulate the fishery so that it produced at MSY, for the years 1989–1992, an Atlantic surf clam fishery on Georges Bank was financially viable and produced at the 1988 level of yield, and fishers in the mid-Atlantic fishery would continue to harvest the same amount of Atlantic surf clams as before. During 1987–1992, Anderson et al. (2000) estimated average annual HAB-related economic effects to the hypothetical Alaskan surf clam fishery of $6 million and to the hypothetical Georges Bank surf clam fishery of $100 thousand, which were much smaller than the $50 million figure that has appeared in policy discussions. Even these lower estimates must be considered speculative, because they rely upon such a large number of strong assumptions.

The traditional offshore scallop (*P. magellanicus*) fishery in the U.S. sector of Georges Bank has not been affected by HABs because the product, the scallop adductor muscle, does not concentrate PSP toxins. Some industry experts feel that the potential may exist for the development of a Georges Bank roe-on-scallop fishery (adductor muscle with the gonad attached), because this product is highly regarded in much of the world. The gonad can accumulate PSP toxins, and therefore the fishery would be affected by the presence of the toxins. A fishery for roe-on-scallops has existed in the Canadian sector of Georges Bank since the late 1980s. The fishery is relatively small, involving about 5,000 pounds of roe-on-scallop landings per week. The fishery was closed from 1992 to 1994 because of high levels of PSP toxins. The roe-on-scallops are not marketed in Canada but are sent overseas, bringing in substantially more revenue per pound than the adductor muscle alone (White personal communication). There is insufficient information about the international demand for the product or of the logistics and expense of toxin testing protocols to evaluate the potential for a roe-on-scallop fishery in the U.S. sector of Georges Bank.

Recreation and Tourism Effects

HABs can adversely affect recreation and tourism in local areas by diminishing the quality of the coastal environment through: massive fish mortalities that lead to dead fish accumulating on beaches, the closure of recreational fisheries, the aerosolization of toxins that lead to respiratory ailments, the promulgation of noxious odors from macroalgae decomposing on beaches, the discoloration of water, and mortalities of protected species and modification of their habitats. Although many experts argue that the effects of HABs on recreation and tourism are important and potentially large, there are few available data describing the size of the effects (Table 4). Estimates of the economic effects on recreation and tourism during 1987–1992 ranged from $0 to $29 million, averaging $7 million per year.

TABLE 4. Recreation and tourism effects (2000 $ millions).

Year	Incident	Type	State	Estimated Effects
1987	tourism and recreation impacts to a coastal community (red tide)	NSP	North Carolina	28
1988				0
1989				0
1990				0
1991	Recreational shellfishing for razor clams	ASP	Oregon	1
	Recreational shellfishing for razor clams	ASP	Washington	1
1992	Recreational shellfishing for razor clams	ASP	Oregon	2
	Recreational shellfishing for razor clams	ASP	Washington	7

Tester et al. (1988) estimated the recreation and tourism effects of $29 million from a 1987 HAB event affecting four coastal counties in North Carolina. This estimate included neither the public health effects nor monitoring and management costs. Note that, as tourists redirected their vacation destinations, negative effects that occurred in these four counties were likely to have been counterbalanced by positive effects in other counties, in North Carolina and elsewhere, thereby mitigating aggregate effects at the national or even at the state level. The estimated tourism and recreation effects of the incident amount to less than 2% of the nearly $2 billion generated by combined hotel, lodging, amusement, and recreation services in the entire state of North Carolina in 1986.

Another major HAB event affected recreational fishing in Oregon and Washington during 1991–1992. In October 1991, these states closed their primarily recreational razor clam (*S. patula*) fisheries because of ASP contamination. In Oregon, prior to the closures, roughly 67,000 trips per year were taken for recreational shellfishing of razor clams (Radke personal communication). On average, recreational shellfishers spent $31 per trip. Therefore, a local estimate the 1992 economic effects of the razor clam shellfish closure was $2 million. Because the onset of ASP contamination occurred during the fall of 1991, we assumed that the 1991 effects were a little more than one-half of this amount, $1 million. In Washington State, the number of razor clam trips fell by 21,333 in 1991, compared with the 3-yr average prior to the ASP event. In 1992, the combined number of trips made during the spring and fall seasons was smaller by 220,666 compared with the 3-yr average. Using the same estimated average per trip expenditure as above, a local estimate the effects on recreation and tourism was $700 thousand in 1991 and $7 million in 1992.

The use of an average trip expenditure does not capture the full value (surplus) to the recreational user, but it is analogous to the direct output impact values already reported. As in the case of the North Carolina HAB event, it was likely that recreational shellfishers substituted their next best recreational activities for razor clamming when the fishery was closed. The net effect on the economy depends upon the relative size of the expenditures for those activities.

Many experts consider the economic effects of HABs on commercial fisheries to be minor in contrast with the size of the effects on recreation and tourism. In Florida, for example, Habas and Gilbert (1975) estimated the economic damage to the tourist industry of a summer 1971 *K. brevis* red tide event at more than $68 million. The most significant effects of this event occurred in the hotel, restaurant, amusement, and retail sectors. *Karenia* blooms occurred after 1971, but there have been few attempts to estimate economic effects. Adams et al. (2000) found a relationship between the occurrence of red tide events and sales in the restaurant sector of two west Florida coastal counties, but these effects were weak and occurred only in that sector, thereby restricting the ability to develop economic impact estimates. Once again, tourists may have redirected their activities, possibly even within the same coastal counties, thereby mitigating economic effects of HAB events.

When mortalities of trash fish result from a HAB, no commercial fishery effect occurs, but dead fish may substantially reduce the recreational experiences of visitors to nearby beaches, forcing them to go elsewhere. Further, the adverse economic effects felt by local tourist industries could persist over several years as vacationers choose other destinations due to a poor experience during a bloom event. In Texas, for example, a severe HAB event was reported during August to October 1986. Most of the dead fish from this event were either trash or underutilized fish, but many of these washed up and decayed on beaches, thereby degrading beach quality. According to an analysis conducted by the Texas A&M Sea Grant Program of declines in sales tax proceeds, the event may have led to declines in coastal tourism (Martin 1987). This effect was difficult to attribute to the red tide bloom, however, because the coastal econ-

TABLE 5. Annual average monitoring and management expenditures (2,000 $ thousands).

State	Type of Cost	Annual Average Expenditures
Alaska	Estimated fees for PSP and ASP costs	321
California	Annual monitoring	213
Connecticut	Annual monitoring	10
Florida	Personnel salaries and associated overhead for monitoring and bioassaying for a 3-month Gymnodinium breve event on west coast, estimated costs for beach clean-ups during each year	184
Maine/New Hampshire	Annual PSP monitoring	292
Massachusetts	Annual monitoring, annual private PSP monitoring by BlueGold Inc. (400 samples annually at $15 per sample)	58
New Jersey	A series of three tests for annual red tide monitoring at $100 per test, individual response investigations by four separate agencies for a Jun–Aug 1988 algal bloom, intensive follow-up survey conducted in 1989 for the Jun–Aug 1988 bloom, individual response investigations by two agencies for a July 1992 algal bloom	30
New York	Annual monitoring	319
North Carolina	Annual monitoring	35
Oregon	Annual monitoring	96
Washington	Annual monitoring	532

omies were already experiencing an economic recession.

Although we expect some level of economic effect from a HAB event, the anecdotal evidence sometimes can be contradictory. As an example, from May 1990 until recently, a brown tide (*Aerumbra langunensis*) developed and then persisted for over seven years in the Laguna Madre, along the southern coast of Texas. Some professional sportfishing guides reported that they lost many customers, but others said that customers were still catching fish by changing fishing methods to cope with a change in the water's transparency level. (Water was clear before the outbreak, so sight casting was possible.) The Texas Parks and Wildlife Department reported that their monthly fish stock assessments indicated the same abundance of adult and juvenile fish in the Laguna Madre when compared with the situation prior to the brown tide, and their sport harvest surveys revealed unchanged levels of sport fishing catches (Spiller personal communication). The Laguna Madre system had suffered two unusually hard freeze seasons, causing widespread fish kills prior to the onset of the brown tide. Sport fishers may have bypassed the Laguna Madre because of poor fishing results at those times.

In Massachusetts, local residents expressed several different opinions about the economic effects of a slimy, dark-brown macroalgae, *Pillayella litoralis*. Since 1987, accounts in the media attributed recurrent accumulations of *P. litoralis* in Nahant Bay and Broad Sound to the eutrophication of Massachusetts Bay, but these accumulations were more likely the result of a pattern of current flow that carried this alga to shore and concentrated it in one particular shoreline location. *P. litoralis*'s abundant growth interferes with swimming, and it generates a sulfurous, rotten-egg odor as it decomposes on beaches. It is conceivable that the property values of houses in the area could be reduced by the concentration of *P. litoralis* on beaches, but realtors we contacted were not in full agreement about this possibility. One Nahant, Massachusetts, realtor told us that prices of some of the houses she sold were depressed because of the algae. In particular, she speculated that a house that sold for $350 thousand in 1994 could have been worth from $30 to $60 thousand more if there had been no *P. litoralis* problem. The negative effect of noxious algae on coastal property values might usefully be explored through the application of hedonic pricing techniques.

Monitoring and Management Costs

In Table 5, we present our findings about the costs of monitoring and managing HABs. Annual average monitoring and management costs totaled $2 million in the U.S. We were able to obtain annual estimates of monitoring and management costs from twelve states. Many states experiencing HABs do not have a regular monitoring program for PSP, NSP, ASP, or HABs. It was often the case that water monitoring tasks, including PSP testing, were spread across different divisions of state government, making it difficult to collect data on costs (Langlois personal communication). Further, monitoring activities for both HABs and other water quality testing, such as shellfish sanitation, often were conducted by the same experts. Consequently, for many other state programs, it was difficult, but not impossible, to factor out those costs related specifically to HAB monitoring and management.

In addition to the annual monitoring and management costs incurred by coastal states, we reported other categories of costs in Table 5. For example, the shellfish processor BlueGold Mussels, formerly based in New Bedford, Massachusetts, used to spend approximately $7,000 per year conducting PSP tests on their own shellfish products. Costs of monitoring or management were also incurred relating to one-time or infrequent events including: survey and investigation costs for two specific HAB events in New Jersey (Olsen personal communication), a cost estimate for a 3-mo NSP event on Florida's west coast (Roberts personal communication), and tests for ASP during the spring of 1994 in Washington (Simons personal communication).

Our estimate for monitoring and management costs in Florida included the annual costs of beach cleanups on the southwest coast of Florida. These costs were incurred by each of the eight counties along that coast, but we had data on recent (1995–1997) estimates of the costs of beach cleanups for Sarasota County only (Conn personal communication). These costs averaged $63 thousand per year, and they applied to the cleanup of dead fish due to HAB events and to the collection and disposal of red seaweed that washed up during storms. A significant portion of the annual costs was the tipping fee. We divided this average cost by the number of miles cleaned (17.5) in Sarasota County to develop a per mile cleanup cost. We assumed that approximately 50 miles of the 200-mile southwest coast of Florida were cleaned each year, accounting for the patchiness of red tide events and the difficulty of accessing certain areas of the coast. We assumed further that the costs per mile for Sarasota County beach cleanups were a good estimate of the cleanup costs in other Florida Counties. The result was an estimate of the cost of beach cleanups for HAB events and washed up seaweed of about $170 thousand per year. Compare this estimate to that of Habas and Gilbert (1975), who estimated the cleanup costs for an extreme 1971 red tide event to be approximately $800 thousand.

Discussion

Our research originated with the goal of developing a credible nationwide estimate of the annual cost to the nation of HABs. After a thorough search of the literature, discussions with numerous scientists and resource managers, and making our own calculations, we identified a number of issues that must be considered when assessing the economic effects of HABs nationwide.

The estimates reported here represent a preliminary approximation of the economic effects from HAB events in the U.S. Nationwide, the average annual effects are on the order of $50 million. While this number appears significant, reflecting some serious poisoning incidents and local HAB events, it is important to keep our estimates in perspective. For example, the coastal counties of U.S. coastal states alone generated more than $5 trillion in gross domestic product in 1995. Out of this total production, the ex-vessel value of marine fish landed by commercial fish harvesters during 1987–1992 averaged nearly $5 billion a year (NMFS 2002). Similarly, saltwater anglers spent possibly as much as $6 billion each year during that period, while averaging about 53 million trips annually (NMFS 2002). The number of cases of food-borne morbidity from the six leading pathogens may range from under four to more than seven million a year, with mortalities ranging from 2,600 to 6,500 a year (Buzby et al. 1996). The low estimate of the costs of Salmonellosis alone (caused by one or more of the non-typhoid serotypes of *Salmonella enteritidis*), using the human capital approach, are an order of magnitude larger than our nationwide average economic effects of HABs across all categories (Frenzen et al. 1999).

Notwithstanding the scale of coastal economies and activities, there is little doubt that the economic effects of specific HAB events can be serious and significant at local levels, although estimates of the scale of effects must still be regarded as uncertain. This fact is due to the difficulty in assigning effects to many of the events that occurred because of a lack of information or even a lack of knowledge as to how to quantify certain types of effects. Due to reporting inadequacies and the large size of the U.S. coastline, the HAB events on which this analysis is based are likely to be a subset of all outbreaks that occurred during the 1987–1992 window. In this way, our estimate may undercount aggregate economic effects.

On the other hand, the diversified nature of the U.S. economy, with its myriad alternative opportunities for consumers and producers, mitigates many types of adverse economic effects. Commercial fishers switch to other locations, fisheries, or occupations. Tourists substitute their next best vacation alternative in place of one with an affected beach. Consumers switch from eating shellfish to other forms of protein. As a consequence, the values that we employ to account for economic effects may, especially in the cases of commercial fisheries and recreation and tourism, overcount aggregate economic effects. Further research on the nature, scale, and redistribution of HAB impacts leading to economic consequences is required to obtain accurate estimates of surplus losses and to place credible confidence intervals on such estimates.

TABLE 6. Summary of economic effects of HABs nationwide (2000 $ millions).

Category	Min	Avg	Max	Economic Effect	Accounting Issues
Shellfish Poisoning	≪1	<1	1	Productivity losses and medical costs of morbidities and mortalities from poisonings	Poisoning incidence uncertain; costs do not include pain and suffering; costs may vary by jurisdiction; mortality costs can dominate; alternative methodologies exist for calculating the implicit value of life
Ciguatera Fish Poisoning	15	19	22	Productivity losses and medical costs of morbidities from poisonings	Poisoning incidence uncertain; costs do not include pain and suffering; costs may vary by jurisdiction
Commercial Fisheries	7	12	19	Direct output impacts of fishery closures in actual fisheries	Malleability of fishing capital and labor uncertain; potential for fish stock investment effect from closure
Untapped Fishery Resources	0	6	9	Direct output impacts of fishery closures in hypothetical (untapped) fisheries	Existence of a viable fishery requires stringent assumptions
Recreation and Tourism	0	7	29	Reduced expenditures from recreational fishery closures; slowed coastal hotel and restaurant trade and tourism	Recreational users and tourists likely to select next best alternative thereby reducing potential losses; tourist industry in other (undetermined) locations may benefit
Monitoring and Management	2	2	2	Government budgets and expenditures associated with environmental sampling, administration of closures and seafood consumption warnings, and beach cleanups	Difficult to factor out HABs costs from environmental monitoring of pathogens; does not include costs of scientific research programs
Total	24	46	83	See categories above, majority of effects across categories are direct output impacts	Aggregation of estimates from different categories is a crude means of estimating nationwide effects; beneficial impacts to some sectors from firms and individuals redirecting their activities are not accounted for—this may lead to an overstatement of economic effects at the national level; not all HABs leading to economic effects have been accounted for—this may lead to an understatement of effects

The compilation of data on the adverse economic effects of HABs is difficult because of the many types of effects, their geographic distributions, and their sporadic occurrences. These data must be considered relatively easy to compile, however, in comparison to the compilation of data on the favorable effects of HABs, i.e., the assessment of the gains in those industries and activities to which firms and individuals turn when faced with a HAB. For very obvious and human reasons, the media, policymakers, resource managers, and even scientists tend to focus attention on the damaging effects of natural hazards, often ignoring the value of decentralized market processes that may mitigate economic loss.

Table 6 is a compilation of our estimates of the annual aggregate economic effects of HABs in the U.S. during 1987–1992. For each of the six main types of effects, we present both the ranges of annual estimated effects during 1987–1992 and the average annual estimated effects. Further, we aggregate estimates across categories to present a nationwide estimate, while recognizing that there are numerous accounting issues and assumptions that render an aggregate estimate uncertain at this time. For each category and for the nationwide aggregate, we list the types of economic effects that are being measured, and we summarize the accounting issues and assumptions that arise in the compilation and aggregation of the estimates.

Public health effects are the largest component, representing, at nearly $20 million annually, about 42% of nationwide average effects. Because poisoned individuals cannot mitigate their losses in the same way as tourists or commercial fishers, these effects could be a larger proportion of a smaller nationwide total. CFP poisonings are the largest element of those public health effects, averaging nearly 20 times those arising as a consequence of shellfish poisonings, even when the size of the losses due to mortalities are influenced by a labor market measure. Uncertainties in the measurement of the economic effects of CFP morbidities include estimates of illness incidence, particularly in the ratio of reported to unreported illnesses, and the possibility of variations across jurisdictions in the costs of medical treatments and individual productivities. Outside the areas we surveyed, illnesses from CFP likely occurred as a result of exports of tropical fish to other jurisdictions. We have been unable to include either the costs of insurance to cover potential ciguatera-caused liabilities or the court costs associated with ciguatera-related litigation.

Commercial fisheries effects are the next largest component averaging $18 million annually, representing nearly 40% of nationwide average effects. The size of commercial fishery effects is very uncertain, as the movement of capital and labor from areas closed due to HABs into other fisheries or occupations is particularly difficult to track. The existence of losses in the Peconic Bay sea scallop fishery and in the sale of Hawaiian recreational catches seem most certain, although estimates of losses in the latter market involve a retail markup. There have also been clear losses in Washington state aquaculture netpen operations. Roughly one third of the nationwide commercial fisheries effects may be due to untapped surf clam fisheries in the Bering Sea and on Georges Bank. While there was an established fishery on the latter's grounds, the potential for a Bering Sea fishery is speculative, relying upon very strict assumptions in order to derive an estimate of possible economic effects. Our data do not include the potential economic effects of PSP closures in several states, including Maine and Massachusetts, where it is difficult to document the acreage closed or the value of the resource that is not harvested during PSP outbreaks.

At an annual average level of $7 million, recreation and tourism effects account for about 15% of nationwide average effects. Economic effects in this category are highly uncertain because recreational users and tourists are likely to switch to alternative activities when faced with a HAB event. In many cases, local firms, including hotels, restaurants, and others, are affected adversely, but firms in locations unaffected by HABs may benefit from the redirected business. In the case of recreational shellfishing on the west coast, we account for economic effects in terms of average per trip expenditures, but when these trips do not take place, the expenditures are not made, or they are made for other activities. As in the case of commercial fisheries, adverse economic effects are concentrated in the geographic area of the bloom, whereas the gains may be dispersed more widely. Our contacts with resource managers suggest that the impacts of HABs on recreation and tourism are more widespread than is currently appreciated, but unfortunately the economic effects are rarely measured.

Monitoring and management costs represent 4% of nationwide average effects at $2 million annually. It can be difficult to factor out the costs devoted specifically to HABs from broad agency environmental monitoring and management budgets, although we have done so for the states in Table 5. Our estimates do not include federal expenditures for scientific research programs on HABs, which have grown significantly in recent years. It is important to note that expenditures made to improve monitoring and management likely result in decreases in effects in the other categories. Likewise, the scientific research sponsored through federal agencies undoubtedly will improve the effectiveness of management programs in the future, thereby further reducing potential economic effects.

During 1987–1992, nationwide average annual effects varied considerably (except for monitoring and management costs). This variation reflects the irregular occurrence of HAB events and the wide variety of resources and human uses that can be affected. We expect that coastal communities and industries are able to manage recurrent outbreaks reasonably well, thereby limiting their economic effects (Shumway et al. 1988). Outbreaks of unexpected or unusual blooms, however, tend to cause more severe economic effects (Bicknell and Walsh 1975; Egan 1990; Tester et al. 1988). The nationwide estimate of economic effects is subject to the data uncertainities that plague the estimates in the individual categories.

Information Needs

Here we offer the first effort to compile nationwide estimates of the economic effects of HABs in the U.S. The process of collecting, compiling, and analyzing the data reveals areas where changes are needed. These changes include those in the reporting process, as well as the development of new approaches to the assignment of effects to certain types of events or situations (e.g., the evaluation of untapped fisheries or the losses associated with closures or harvesting restrictions).

The accounting issues summarized in Table 6 can be used as a guide to information needs. Given the scale of public health effects, relative to other losses caused by HABs, further investigation of the economic costs in this category is a clear priority. For example, in accounting for public health effects, it is important to develop accurate estimates of the incidence of illness, especially the ratio of reported to unreported cases. Further, the variation, if any, in medical costs and productivity losses across jurisdictions should be analyzed carefully. In accounting for the economic effects of commercial fisheries and recreation and tourism, it is crucial to identify any sectors or areas to which firms and individuals may redirect their activities and to characterize associated economic changes. Only then is it possible to estimate the true losses associated with HAB induced fishery and beach closures. Further work is warranted to evaluate the effects of risk communication, such as the contraction of demand for seafood (halo effect) when HAB events result in fish kills or shellfisheries are closed. Finally, close scrutiny of the market potentials for untapped fishery resources would clarify the potential losses in those cases.

At present, information about HAB events is fragmentary and incomplete. The data collection within the different reporting regions of the U.S. relies upon volunteer efforts by academic and government scientists as well as government officials, and thus tends to be uneven in coverage and detail. Efforts are underway to standardize the data collection process, but even with those changes, it is clear that these individuals cannot by themselves provide the type of information needed for assessments of economic effects.

The reporting practice for HABs should be expanded, and the format should be formalized. Local and state governments should place a much higher emphasis on quantifying economic effects. The analysis of economic effects may involve consideration of local environmental and socioeconomic conditions, and local officials are therefore the ones who are most likely to be in the best position to compile information that can later be subject to economic analysis. The duration, affected acreage or shoreline length, average toxicity levels, and economic damages—in terms of lost sales or, ideally, in terms of lost surpluses—to coastal resources should be documented for each bloom in order to describe the overall economic significance of the incident. Until local governments can supply site-specific effect information for each bloom incident, a truly comprehensive and detailed national level aggregation of such effects cannot be fully realized.

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