

## *Pfiesteria*: Harmful Algal Blooms as Indicators of Human: Ecosystem Interactions

Ellen K. Silbergeld,<sup>1</sup> Lynn Grattan, David Oldach, and J. Glenn Morris

Program in Human Health and the Environment, University of Maryland, 10 South Pine Street, MSTF 9-34, Baltimore, Maryland 21201

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As man continues to expand and to develop large land areas near surface waters the pollution of these waters will intensify. Historically man has used lakes and rivers for waste disposal with little regard to the effects of these wastes on the receiving waters... With the predicted population growth and subsequent demands on the environment, the frequency with which recreational and municipal waters will become dominated by algae can be expected to increase. The opportunities for exposure can be expected to increase with man's increased utilization of surface waters for recreation and municipal purposes. This increased utilization will also be responsible for accelerating natural eutrophication processes which in turn will favor the development of noxious [algal] blooms. In order to avoid the potential health hazards that these algae present, man will have to take steps necessary to prevent alterations in aquatic environments known to enhance the growth of these organisms.

J. H. Gentile, "Blue Green and Green Algal Toxins," 1971

### Introduction

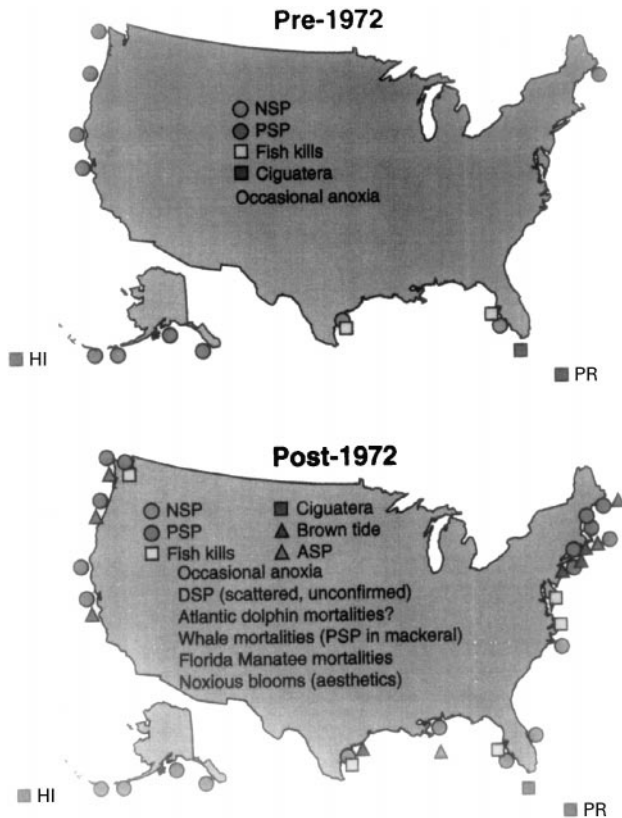
Harmful algal blooms are episodes of rapid, explosive growth of populations of microorganisms, including dinoflagellates and bacteria, that make and secrete highly toxic biomolecules. Some of these natural toxins are among the most potent and selective neurotoxins known (Baden *et al.*, 1995; Shimizu, 1996). Knowledge of their hazards has been dated back to the Tang Dynasty in China; in 1774, Captain Cook recorded his own intoxication after eating a snapper caught near the New Hebrides islands (cited by Watters, 1997). While the existence of marine microorganisms that produce toxins is a natural phenomena, the extent and impact of these events have increased dramatically in recent years (Hallgraeff, 1993). As shown in Fig. 1, over the past 10 years, the frequency and apparent severity of these blooms (especially *Gymnodinium breve*, *Alexandrium tamarense*, *Aureococcus anophagefferens*,

*Pseudo-nitzschia*) have increased in most coastal regions throughout the United States (WHOI, 1998). The economic impacts of these events are significant. One outbreak of *A. tamarense* in the coastal waters of southern Maine cost over \$6 million in losses to seafood-related industries. Farther south, blooms of *A. anophagefferens*, or "brown tides," have been reported from Rhode Island to Long Island with increasing frequency over the past two decades. Economic losses for one brown tide outbreak in New York waters in 1989 were estimated to cost \$2 million in losses to the scallop industry of Long Island (WHOI, 1998).

As noted by Gentile (1971), the rise and fall of algal populations are influenced by many factors, some of which are related to human activities. The recent *Pfiesteria* episodes in estuaries of the middle and southern Atlantic coast suggest that anthropogenic stresses on the environment may also influence the impacts of these blooms on fish and humans. Thus, harmful algal blooms may be considered a dramatic indicator of the deteriorating relationship between humans and ecosystems like the Chesapeake Bay. In this paper, we review the discovery of the dinoflagellate *Pfiesteria piscicida*, the chronology of its recent appearances, factors thought to be related to its blooms, its effects on fish, and the recent discovery of its effects on human health. At the outset it should be noted that the term "*Pfiesteria*" represents one or more organisms that have been causally related to outbreaks of fish and human poisoning. As discussed below, it is not yet clear that these outbreaks are associated with only one organism or even with a dinoflagellate rather than an opportunistic pathogen. We conclude with a discussion of policy options in a period of unresolved uncertainties.

Although species of dinoflagellates have been recognized to be harmful to humans for some time

<sup>1</sup>To whom correspondence and reprint requests should be addressed.



**FIG. 1.** HAB outbreaks known before (top) and after (bottom) 1972. Neurotoxic shellfish poisoning, NSP; paralytic shellfish poisoning, PSP; and amnesic shellfish poisoning, ASP. From Anderson *et al.*, 1993.

(Schantz, 1971), it is clear that the dramatic reports of *Pfiesteria* toxicity in humans have raised public awareness and induced government response to the issue of harmful algal blooms generally. Several agencies of the U.S. government—the Environmental Protection Agency, the National Oceanographic and Atmospheric Administration, the Centers for Disease Control, the Department of Interior, the Department of Agriculture, the Food and Drug Administration, and the National Institutes of Health—have announced a coordinated strategy to support research and monitoring for national harmful algal blooms. The concept of this multiagency response is appropriate, given the cross-cutting issues associated with harmful algal blooms, which range from understanding estuarine ecology to evaluating impacts on food safety. If successful, this strategy will avoid the potential for compartmentalizing both our understanding of and our response to these events. The NIH-funded research project underway at the University of Maryland and the Johns Hopkins University exemplifies the

involvement of scientists from molecular biology, neurobiology, ecology, microbiology, epidemiology, neuropsychology, and clinical medicine. National coordination of surveillance and research may also mitigate the inconsistencies that have characterized state-level responses to the *Pfiesteria* crisis over the past decade.

### *Pfiesteria* in the Chesapeake Bay and Atlantic Coast

Whether *P. piscicida* is a new or newly recognized danger is still unknown. Fish kills have occurred in U.S. coastal waters for as long as records are available. *Pfiesteria* is estimated to be responsible for many more fish kills than those in which it has been identified, in part because of the difficulties in positive identification (Steidinger *et al.*, 1995). From 1994 to 1997, it is estimated that *Pfiesteria* was probably involved in as many as 50% of the major fish kills in large estuaries of the Albermarle-Pamlico system in North Carolina (WHOI, 1998). As shown in the timetable in Table 1, beginning in 1974, massive fish kills in North Carolina estuaries were reported, usually in the hot summers, involving millions of fish.

The dead fish had a characteristic lesion, often found in small menhaden (Fig. 2) (Kane *et al.*, 1998).

The *Pfiesteria* story took a dramatic turn with the reports, first by Burkholder, that during these episodes, a toxin could be produced that was highly dangerous to humans. As described in three lab personnel at North Carolina State University, the symptoms associated with exposure to this toxin included a broad spectrum of affected systems: neurological, immunological, and musculoskeletal (Glasgow *et al.*, 1995). Although these represent a limited set of case reports, the description of neurotoxic effects is consistent with our later findings. One person developed severe symptoms as a consequence of chronic exposure. Personality changes, abnormal olfaction, and abnormal reflexes were also found. Possible axonopathy was also reported. Another case who experienced acute exposures, reported confusion, irritability, personality changes, and disorientation. Problems in neuropsychometric performance were found, as well as ataxia. The third case, who was also acutely exposed, experienced confusion and memory disturbance. These reports were not widely accepted, owing to the highly political nature of harmful algal blooms in North Carolina (see below).

In 1996, characteristic fish kills were reported in the estuaries of the Eastern Shore of Maryland, as well as among fish in laboratories and in fish farms

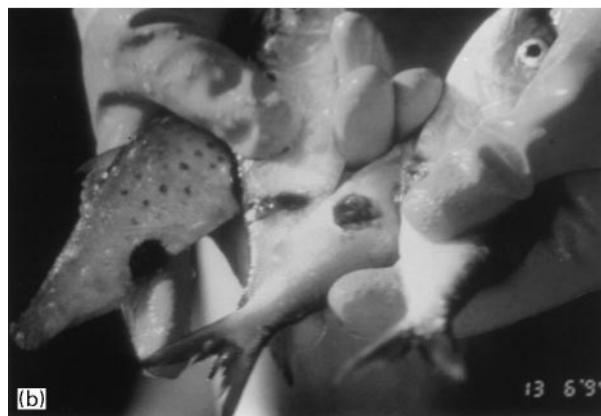
**TABLE 1**  
**Chronology of *Pfiesteria*-Related Events**

1974–1992	Episodic, severe fish kills reported in North Carolina estuaries; characteristic “punched out” lesions reported on dead and dying fish; anecdotal reports of adverse health effects in watermen
1991	Identification of <i>Pfiesteria piscicida</i> as an “ambush predator” by J. M. Burkholder (Burkholder <i>et al.</i> , 1992; Steidinger <i>et al.</i> , 1995)
1992	<i>Pfiesteria piscicida</i> identified in Jenkins Creek on Choptank River, MD
1994	<i>Pfiesteria</i> associated with fish mortality at Benedict Estuarine Research Laboratory, Patuxent River, MD
1994–1995	Cases of intoxication among members of Burkholder’s lab at North Carolina State University <i>Pfiesteria</i> associated with lab fish mortalities and fish farms
1996	First <i>Pfiesteria</i> -like fish kills reported in Pocomoke River, MD Some unconfirmed reports of human illness
1997	Increasingly frequent episodes of fish kills in lab and fish farms and in Pocomoke River and Chicamacomico River involving lesioned fish in Maryland, culminating in massive fish kills in August
August 7, 1997	Pocomoke River ordered closed after large fish kill
August 22, 1997	Fish health investigation of watermen exposed to Pocomoke River during fish kills
September 1997	Further neurocognitive assessment of exposed and unexposed watermen at the University of Maryland and Johns Hopkins

(see map, Fig. 3). Anecdotal reports from watermen suggested that human health effects were also occurring, but no systematic clinical examinations or collection of data was undertaken. In 1997, the fish kills recurred in estuaries of the Chesapeake Bay, starting in the spring. Reports of health difficulties—fatigue, headache, respiratory problems, diarrhea, weight loss, skin irritation, and memory difficulties—were made by watermen to the country health department, which were referred to the Maryland State Department of Health and Mental Hygiene (DHMH). In August 1997, DHMH asked the state’s two medical institutions to undertake a formal assessment. A report on this investigations has been published (Grattan *et al.*, 1998); its findings are summarized below.

### Toxicology of *Pfiesteria* to Fish and Humans

*Fish.* Our knowledge of fish toxicity is more complete than our knowledge of human toxicity, but there are still many gaps. It is reported that over 20 species of fish are susceptible to *Pfiesteria* (WHOI, 1998). The origin of the characteristic lesion is not yet fully understood, and some still question its association with *P. piscicida*. One hypothesis suggests that *Pfiesteria* (or related organisms) secrete a toxin that is in some way able to damage the



**FIG. 2.** External lesions observed on menhaden sampled from the Chicamacomico River in 1997 suspected to be associated with toxic dinoflagellates. Note the chronic ulcerative lesions with necrotic centers which penetrate the epidermis, dermis, and musculature, at the anus, mid-abdomen, trunk, and dorsal fin area, respectively, taken from Kane *et al.*, 1998. (B) Lesions in dead fish collected from the Pocomoke River in 1997, with a characteristic punched-out presentation.

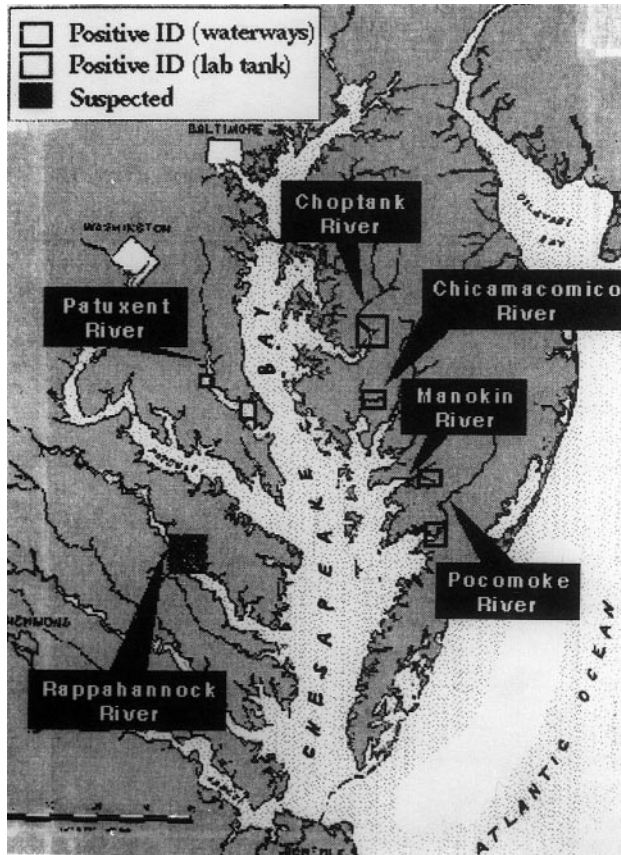


FIG. 3. Location of *Pfiesteria* outbreaks in the Chesapeake Bay, 1996–1997.

dermal mucus or skin of fish, allowing the penetration and unchecked growth of bacterial, fungal, and mycobacterial species present in water, which are the proximate cause of the lesion (Nogan and Dykstra, 1986). The failure to find *Pfiesteria* in the lesioned tissue is cited in support of this hypothesis (Kane *et al.*, 1998). Others (Burkholder *et al.*, 1997) indicate that the appearance of the lesion can be very rapid and represents a direct effect of *Pfiesteria* toxins. Others (Baden, personal communication) have suggested that the lesion originates internally, resulting from ingestion of *Pfiesteria* and its toxin by fish and a toxic effect on the internal organs. Less well characterized are the other effects of *Pfiesteria* on fish. Anecdotally, North Carolina and Maryland watermen and scientists report that prior to the appearance of fish with lesions, fish are disoriented, lose the ability to swim upright or in a forward direction, and exhibit respiratory problems. In aquaria, fish exhibit disorientation and impaired swimming behavior after contact with water from aquaria containing *Pfiesteria* (Burkholder *et al.*, 1992; Noga *et al.*, 1993).

Laboratory studies have provided further insight on the events involved in *Pfiesteria* toxicity. In response to the presence of fish, possibly triggered by some substances secreted or excreted by fish, *Pfiesteria* are stimulated to transform from nontoxic stages to toxic zoospores (Burkholder and Glasgow, 1997). In this stage, the organism releases toxin(s) that narcotize fish, slough fish epidermis, and may also cause formation of open bleeding sores. The dinoflagellate then consumes the epidermal tissue and blood cells from affected fish. During this, they produce gametes that complete the reproductive cycle in or near dying (necrotizing) fish. In the absence of fish, the toxic form reverts to nontoxic stage, including a cyst form that can survive for long periods of time in sediments at lowered temperatures.

*Humans.* When systematic health investigations began in Maryland in August 1997, there was relatively little information upon which to design a field study of potential *Pfiesteria* intoxication among Maryland watermen. Both the description of lab intoxication in North Carolina and the reports from watermen in 1996 and 1997 suggested a wide range of symptoms, many of which were difficult to assess objectively. Lack of information on the toxin(s) involved was also a major problem. The study was conducted amid extraordinary public concern and controversy—the newspaper headlines cited “*Pfiesteria* hysteria,” and intensifying political controversies over appropriate responses did not make this investigation any easier.

There were major methodological challenges to identifying exposures and outcomes. Without identification of the toxin(s) involved, or information on relevant routes of exposure, human exposure could only be inferred. The presence of fish with the characteristic lesion were used as the indicator of *Pfiesteria* toxin(s) in water; contact with affected waters was used as the “dosimeter” for relative exposures. (Scanning electron microscopy was later used to determine the presence of *Pfiesteria* by microbial ecologists in Maryland and elsewhere). The study group was thus defined as persons having direct contact with the Pocomoke River or other affected estuaries during periods of fish kills. “Direct contact” was defined as activities involving water contact, even though observations during the course of the study indicated that intoxication could also be associated with inhalation of aerosols. No data as yet support the possibility of intoxication via consumption of fish or shellfish. Because of the nonspecific nature of reported symptoms, a range of outcome measures

was applied to assess many different systems. A symptom questionnaire was used, along with as many objective measures as possible: skin biopsies in persons with lesions or rashes; and pulmonary function testing, immunologic workup, complete blood count, clinical assessment, and neuropsychological assessment, including brain imaging. The psychometric tests were specifically designed to evaluate attention, concentration, learning, and memory because of complaints by watermen of forgetfulness, confusion, and difficulties in short-term memory.

### Results of the 1997 Investigation of *Pfiesteria* Intoxication in Maryland

The results of the Maryland-Hopkins investigation provide the first information confirming an objective set of symptoms and deficits among watermen having contact with waters where *Pfiesteria*-related fish kills occurred. Both symptoms and objective signs were more frequent and more severe in highly "exposed" watermen. Among the reported symptoms, headaches, skin lesions, and skin "burning" upon contact with water were more frequently reported in highly and moderately exposed watermen, as compared to low exposure and control groups (Grattan *et al.*, 1998) (Table 2). None of

the clinical evaluations or tests of respiratory, immunologic, or other functional tests showed any relationship to apparent *Pfiesteria* exposure. The "exposed" watermen showed consistent and apparently dose-related deficits in neuropsychological performance, particularly related to divided attention, new learning, and memory (Grattan *et al.*, 1998), consistent with the symptom reports of forgetfulness, disorientation, and acute confusion. Results are shown in Figs. 4A and 4B.

These findings are consistent with the symptom reports of forgetfulness, disorientation, and acute confusion. Some of the reported episodes were dramatic and frightening. Disorientation and confusion were also observed acutely in several state lab personnel sent to investigate a fish kill; they had no direct contact with the water. The consistency and apparent dose-relatedness of these findings and the failure to detect evidence of malingering psychogenic illness or other functional and behavioral disturbances convinced us that *Pfiesteria*-related intoxication is likely to occur in humans (Greenberg *et al.*, 1998; Tracey *et al.*, 1998). In this first group, the degree of impairment on neuropsychological performance has ameliorated, to a large extent, although those found most severely affected in August 1997 are still performing below norms.

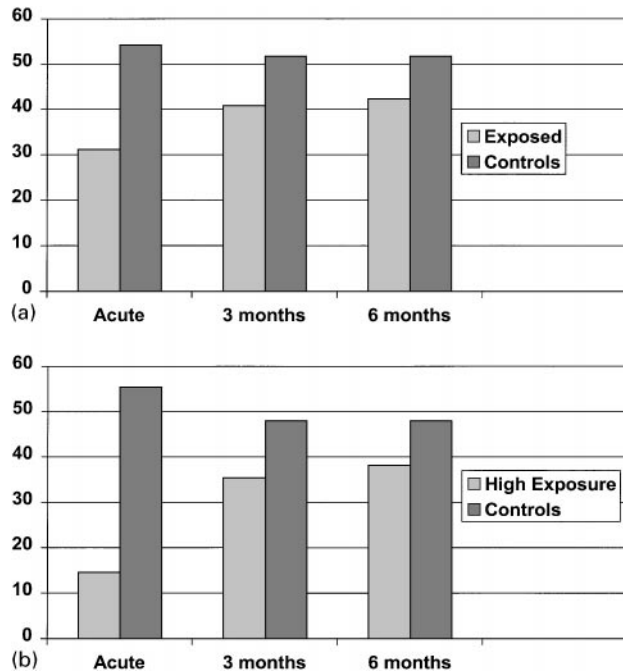
**TABLE 2**  
Symptoms of Persons Examined in Maryland 1997

Symptom	High exposure ( <i>n</i> = 11)	Moderate exposure ( <i>n</i> = 7)	Low exposure ( <i>n</i> = 4)	Controls ( <i>n</i> = 8)
Neuropsychological Symptoms	9 (82%)	6 (86%)	2 (50%)	1 (13%)*
Confusion, episodes of disorientation, new or increasing "forgetfulness" or problems concentrating				
Headache	9 (82%)	5 (72%)	2 (50%)	1 (13%)*
Skin lesions	8 (73%)	4 (57%)	1 (25%)	1 (13%)**
Skin burning on contact with water	5 (45%)	6 (86%)	1 (25%)	2 (25%***)
Diarrhea	5 (45%)	4 (57%)	2 (50%)	1 (13%)
Nausea/vomiting	7 (64%)	4 (57%)	0	1 (13%)
Abdominal cramps	5 (45%)	2 (29%)	1 (25%)	1 (13%)
Joint pain	5 (45%)	2 (29%)	1 (25%)	2 (25%)
Muscle/leg cramps	8 (73%)	2 (29%)	1 (25%)	2 (25%)
Eye irritation	6 (55%)	2 (29%)	2 (50%)	4 (50%)
Sinusitis	5 (45%)	5 (71%)	3 (75%)	3 (32%)
Shortness of breath	2 (18%)	4 (57%)	1 (25%)	2 (25%)
Pneumonia	2 (18%)	1 (14%)	0	0

\* $P < 0.01$ , Fisher's exact test, two tail.

\*\* $P < 0.05$ , Fisher's exact test, two tail.

\*\*\*Control waterman reported seeing sea nettles in association with the sensation of burning skin; case persons denied sea nettle contact. If the two control persons with complaints of skin burning are presumed to have had contact with sea nettles and are excluded,  $P < 0.05$ , Fisher's exact test, two tail.



**FIG. 4.** Neuropsychological assessment of Maryland watermen exposed to *Pfiesteria*: Recovery of performance over time. (A) Recovery of new learning and memory for exposed and non-exposed (Trial 5, Rey AVLT). (B) Recovery of new learning and memory for high exposure group and occupational controls (Trial 5, Rey AVLT).

Experience in 1998 and in 1999 was substantially different from 1997. For reasons not yet fully understood, but possibly related to differences in weather patterns, no major fish kills occurred in the Chesapeake estuaries of the Eastern shore. Data have been collected on a cohort of watermen and matched controls; preliminary results suggest that there may be a low level syndrome associated with the presence of *Pfiesteria* in waters. These data will be useful in determining if there are “subclinical” effects of *Pfiesteria* exposure, as well as assessing the persistence of effects described earlier.

### Unanswered Questions

#### 1. Is it *Pfiesteria*?

In many ways “*Pfiesteria*” is a stand in for what is still unknown. There may be more than one species of dinoflagellate involved in the fish kills and human intoxication; some or all of the toxic effects may be due to toxins produced by associated bacteria: the Maryland events may be due to a specific organism or organisms present in Maryland waters, as distinct from Virginia or North Carolina.

Until axenic cultures of *P. piscicida* and other species are established and molecular methods of identification developed, it will be difficult to answer these questions.

#### 2. Why is it toxic?

Several marine microorganisms, or associated pathogens, can under certain circumstances synthesize and secrete potent neurotoxins. Other neurotoxins of similar origin include ciguatoxin, tetrodotoxin, domoic acid, anatoxin, and saxitoxin (Watters, 1997; Morris, 1995; Perl *et al.*, 1990; Mahmood and Carmichael, 1986; Carmichael *et al.*, 1975). As shown in Table 3, these natural products are very toxic to birds, humans, and other mammals.

These toxins are characterized by highly specific mechanisms of action within neural systems, and for this reason, they have been useful tools in neurobiology research (e.g., Mahmood and Carmichael, 1986; Matthews *et al.*, 1979). Although our knowledge of the toxin(s) involved in *Pfiesteria*-related illness is limited at present, there are some intriguing differences between these well-studied marine neurotoxins and the phenomena we have observed in well-studied *Pfiesteria* episodes, including the lab exposures in North Carolina and experience in Maryland in 1997–1998. First, there is no evidence to date that human intoxication can occur as a consequence of consuming fish or shellfish. Intoxication is induced apparently by exposure to waters in which characteristic fish kills are occurring and possibly also by inhalation of aerosols from such waters. In contrast, human intoxication by most of the toxins listed in Table 3 is associated with consumption of fish and shellfish that accumulate the neurotoxins (Morris, 1995; Watters, 1997). Second, the description of *Pfiesteria* neurotoxicity in humans is not consistent with actual cytotoxicity in the nervous system. The apparent reversibility of most symptoms in the Maryland group studied in 1997, as well as the lack of overt neuropathology upon MRI and PET examination, distinguishes this intoxication from domoic acid.

It also appears that the production of toxin(s) by *Pfiesteria* is episodic. Although its life cycle is not fully understood, this complex organism exists in as many as 24 different states, some of which are quiescent (encysted) and some of which are active. Laboratory observations also indicate that *Pfiesteria* only intermittently secretes toxin, and that apparent toxin production can be elicited by the presence of fish or fish excreta or blood (Burkholder and Glasgow, 1997). The presence of fish also induces rapid

**TABLE 3**  
**Marine Neurotoxins—Source, Exposures, and Toxicity<sup>a</sup>**

Toxin	Source (organism)	Exposures	Toxicity
CTX	<i>Gambierdiscus toxicus</i>	Via consumption of fish especially carnivores	GI; paresthesias; motor dysfunction LOW MORTALITY
STX	<i>Gonyaulax Alexandrinum</i> spp	Via shellfish (red tide)	GI, paresthesias; motor flaccidity; apnea; neuropathy MODERATE MORTALITY
TTX	Unknown	Via fish, amphibians, shellfish	GI, paresthesia, bulbar and motor signs; apnea HIGH MORTALITY
Brevetoxins	<i>Gymnodinium breve</i>	Via shellfish	GI, paresthesia, rhinorrhea, bronchospasm LOW MORTALITY
Domoic Acid	<i>Nitzschia pungens</i>	Via shellfish and crabs	GI; paresthesia; neuropathy; seizure; soma; amnesia LOW MORTALITY
Okadaic acid	<i>Diophysia</i> spp	Via shellfish	GI, diarrhea, nausea, chills; NO MORTALITY
"Pfiesteria toxin"	<i>Pfiesteria piscicida</i> (?)	Contact with water	Paresthesias; amnesia; psychological disturbance; impaired psychometric function NO MORTALITY REPORTED

<sup>a</sup>Taken from Watters (1997) and Shimizu (1996) in part.

reproduction in the organism (Brown, 1997). It is not known if these conditions are actually associated with toxin production, since without chemical identification of the toxin(s) produced by *Pfiesteria*, this cannot be directly measured. The nature of signaling between fish or excreta and other organic material is not known. It is also not known whether other environmental cues elicit toxin production, or how this is accomplished. It is possible that some environmental conditions cause production of "supertoxins," increasing the impacts of the organisms involved. This possibility is not entirely speculative. There is a range of saxitoxin-gonyautoxin biomolecules that vary in toxicity (Shimizu, 1996).

### 3. Why does it "bloom"?

Critical to the development of appropriate preventive policies, with implications for agriculture and waste management, is an understanding of the factors that govern the periodically explosive blooms of *Pfiesteria* sp. *Pfiesteria* is found in estuarine ecosystems in the mid- to south Atlantic coast (Kane *et al.*, 1998). In general, water salinity, pH, nutrients, and temperature are important factors controlling dinoflagellate cycles (Schantz, 1971; Anderson, 1993). Studies in North Carolina indicate that *Pfiesteria* is more abundant in waters near sources of organic phosphates, such as sewage treatment plant outfalls (Burkholder and Glasgow, 1997). Nutrient loading is undoubtedly critical. However, the relative

importance of runoff from land-based sources, aquatic deposition of nitrogen, and water discharge of organic wastes is unknown. As the Blue Ribbon Citizens Commission of Maryland concluded:

Simply stated, it appears that excessive nutrient loadings help create an environment rich in microbial prey and organic matter that the *Pfiesteria* use as a food supply. By increasing the concentration of *Pfiesteria*, nutrient loads increase the likelihood of a toxic outbreak when adequate numbers of fish are present. *However, just as not every toxic outbreak of Pfiesteria occurs in nutrient-enriched environments, not every nutrient-enriched environment contains a high population of Pfiesteria* [emphasis added]. (Hughes Commission, Final Report, November 1997)

Over the past 3 years (1996–1998) in Maryland, an experiment of nature has occurred resulting in significant differences each year in *Pfiesteria* density (and toxicity to fish); intensive research is now underway to understand how variability in critical environmental factors might explain the rise and fall of *Pfiesteria* in Maryland estuaries.

### 4. How does *Pfiesteria* affect fish and humans?

The nature of *Pfiesteria* toxicity is largely unknown. Even the careful study undertaken last year in Maryland raises more questions than it answers. Can *Pfiesteria* cause dermal lesions in humans? Can *Pfiesteria* cause neurotoxicity in fish? Or are fish and humans differently affected? Does *Pfiesteria* secrete more than one toxin? What are the critical routes of

exposure? Is dermal contact alone sufficient, or do both fish and humans have to ingest toxin? Can intoxication occur from inhalation? Is it true that humans cannot be intoxicated via consumption of seafood from affected waters? These questions await identification of the toxins produced by *Pfiesteria* so that careful studies can be conducted in appropriate animal models. Preliminary data suggested that *Pfiesteria* can produce a toxin that affects rodent behavior (Levin *et al.*, 1997). Marine dinoflagellates and cyanobacteria can produce an extraordinary range of complex neurotoxic molecules, including relatively simple amino acids (domoic acid), long-chain macrolides (maia toxin produced by the organism involved in ciguatera), linear polycyclic ethers (brevetoxins), and peptides (kahalalide F) (Shimizu, 1996). When we identify the biomolecules produced by *Pfiesteria*, we can examine their effects under lab conditions, to determine issues such as route to exposure, dose, and nature of toxicity to skin and nervous system.

#### Policy-Making under Uncertainty

The *Pfiesteria* issue presents policymakers and stakeholders, including the public and industry, with a situation characterized by both urgency and uncertainty. The potential for human toxicity necessitates a rapid response capacity, but lack of information makes immediate response measures difficult to devise: Can river closings be based upon surveillance of fish for lesions? If so, what signals can be used to base reopening of these waters? How can detection of the organism be utilized, if the organism is not always toxic? What are the "early warning signals" of human exposure? More long-term policy questions are also difficult to resolve with the current state of knowledge: Should nutrient loadings of certain estuaries be reduced? Which nutrients, and nutrient sources, should be targeted for control? What is the relative importance of point and nonpoint sources? How should large agricultural production facilities be managed? What are the implications for land farming of nutrient containing wastes and sludges in ecosystems like the Chesapeake Bay?

The Maryland Citizens Commission reached 45 specific recommendations, the most significant of which were acted upon by the legislature in 1997: identification of vulnerable watersheds and implementation of improved nutrient management (including advanced waste water treatment) at these sites; adoption of a phosphorus and nitrogen

management system involving farmers and the poultry industry; alternative uses for chicken manure to protect watersheds on the Eastern Shore; support of research on biology and ecology of *Pfiesteria*, human health impacts, and methods to reduce nutrient loadings of critical ecosystems.

Some of these issues are of special local interest, but the *Pfiesteria* episodes point to the critical importance of developing a national policy on harmful algal blooms. In 1996–1998, three of the major states impacted by *Pfiesteria*—North Carolina, Virginia, and Maryland—responded very differently to the events of these summers. These differences arose in part because of the relative economic importance of agriculture and fishing. In North Carolina, for instance, hog farming has grown exponentially in the coastal regions over the past decade; some facilities house millions of animals generating tons of organic waste each day (EDF). In Maryland and Virginia, poultry production has also become a major industry. However, for these two states, the viability of the Chesapeake Bay for fishing and recreation is at least as important economically and politically. Maryland's stronger commitment to environmental protection and the response of its poultry industry leader, the Perdue Corporation, were probably determinants of its activist response first by the governor and then by the legislature.

The combination of uncertainty and urgency is not unusual for environmental issues. In analyses of global climate change, some observers have suggested that prudent policymaking should emulate the concept of insurance in assessing the appropriateness of making present investments to avoid future risk. Moreover, as Davis *et al.* (1998) noted in discussing the same issue, there are often more well-defined benefits from policy change that can justify taking actions with less certain impact on reducing future risk. The same analytic approach is useful to consider in the *Pfiesteria* issue. Protecting the Chesapeake estuaries and coastal rivers of the United States from nutrient loading has real short-term benefits for the health of these rivers and the Bay. Improved management of agricultural wastes and prevention of runoff from farms on the Eastern Shore will also be beneficial. Thus, it is likely that the near-term benefits apart from avoiding *Pfiesteria* blooms may well offset the costs of these changes in management practice by farmers, poultry producers, and the state. The necessity of further change will require improvements in our knowledge of the complex interactions among humans, land management, and ecosystem response.

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