Harmful algal blooms in western Canadian coastal waters

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Introduction

British Columbia (B.C.), the Pacific province of Canada, has one of the longest documented histories of the severest form of harmful algal blooms, paralytic shellfish poisoning (PSP), along its entire 27,000 km coastline. The first documented case was in 1793 when four of Capt. George Vancouver's survey crew became ill after a meal of mussels while charting the central coast (Mussel Inlet, originally named Mussel Canal, a side-arm of Mathieson Channel; see Fig. 23). The location where they had the toxic breakfast of mussels was named Poison Cove by Vancouver. One of them died five and a half hours later and the location of his burial was named Carter's Bay. Their symptoms, described in detail by Vancouver (1798, quoted by Quayle 1969), are unmistakably characteristic of PSP. Earlier illnesses from the consumption of mussels in Europe differ in detail from classic PSP, most notably in the struggle to breath before the cessation of respiration. In PSP breathing stops gradually without struggle (Taylor 1992). In 1799, only a few years after the Capt. Vancouver incident, a major poisoning episode with many fatalities involving Aleut Indians working with Alexander Baranoff in the Russian-American sea-otter fur trade occurred in nearby southern Alaska (detailed by Trainer, this volume).

Ever since monitoring of shellfish for the presence of toxins began in 1942, following a severe outbreak with fatalities in B.C. and adjacent Washington State, PSP has been recorded primarily in filter-feeding shellfish on the coast (Quayle 1969). These include mussels, various species of clams, oysters, geoducks and scallops (Anderson 1960; Quayle 1969). PSP toxins and domoic acid have been found in the guts of Dungeness crabs (Wekell *et al.* 1994).

Since 1965, when one of the authors began to focus on HABs on the B.C. coast (Prakash and Taylor 1965), most other forms of HABs, or the species known to produce them (Taylor *et al.* 1994), have been recorded from B.C., including domoic acid poisoning (also known as amnesic shellfish poisoning or APS) and fish kills. Further summaries have been provided by Taylor (1994) and Taylor and Horner (1994), the latter limited to the Strait of Georgia and its tributary inlets. The present report provides a summary of current knowledge of HABs in western Canada.

Shellfish poisoning

This is the potentially fatal poisoning of humans by the consumption of shellfish that have accumulated toxins from their phytoplankton diet. It exists in several forms, some of which are known from British Columbia.

Paralytic shellfish poisoning (PSP)

This phenomenon, caused by the concentration of saxitoxin and its derivatives by shellfish consumed by humans, is severe and chronic on the B.C. coast. Since monitoring began in the late 1940s, there has not been a year in which toxicity has not occurred and virtually everywhere on the coast has been toxic at one time or another. Some areas are toxic every year. The worst single fatality episode recorded in B.C. was in May 1942, in which three native Indians died in Ucluelet and Bamfield, on either side of Barkley Sound on the west coast of Vancouver Island, and three near Port Angeles close by in Washington State (details are provided in an appendix by Quayle 1969). Since records were first officially kept (1942) and a monitoring program established, there has not been a single year in which shellfish did not become toxic, the years differing only in the extent and duration of the closures (a complete summary of data from 1942-1965 was provided by Quayle and Bernard 1966). Further fatalities occurred in 1965 (Theodosia Inlet; details in Prakash and Taylor 1965 and Quayle 1969) and in 1980 at Health Harbour on Gilford Island (southern Queen

Charlotte Sound). Illnesses and near-fatalities are common (Fig. 23).

Although it did not result in fatalities, there was a particularly severe incident in the Comox area on eastern Vancouver Island in 1957, with 61 human illnesses and seven domestic cat fatalities. Although mussels and clams were involved, the majority became ill after eating oysters. At this time, toxin levels reaching 19,840 Mouse Units (MU, roughly equivalent to 3200 µg per 100g) were measured (for details see Quayle 1969). A severe, potentially fatal incident, summarized by Taylor (1992), occurred in Kingcome Inlet (on the mainland not far from Gilford Island) in 1992, when two individuals were poisoned sufficiently

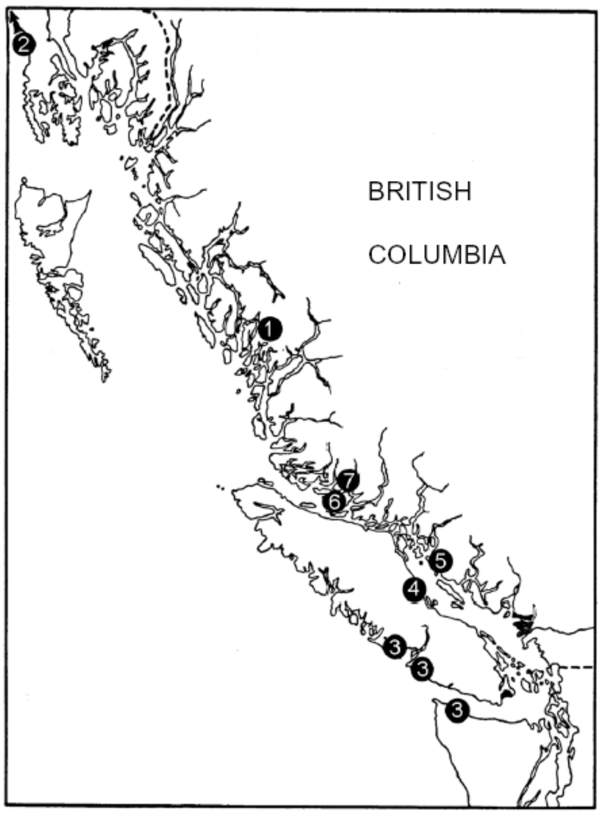

Fig. 23 Fatalities and severe incidents of paralytic shellfish poisoning (PSP) ion the B.C. coast and adjacent waters (see text and U.S. report for details). 1. Vancouver, 1793. 2. Baranoff, 1799 (Peril Strait, near Sitka, Alaska). 3. The 1942 outbreak. 4. Comox, 1957. 5. Theodosia Arm, Malaspina Inlet, 1965. 6. Health Harbour, Gilford Island, 1980. 7. Kingcome Inlet, 1994.

to cause rapid death (one stopped breathing twenty minutes after consuming less than one butter clam). Although there is no antidote to saxitoxin they were both saved by continuous artificial respiration. Recovery was complete after several days on respirators in hospital. This is the first known case in which the importance of artificial respiration in saving severely poisoned individuals was demonstrated.

An interesting feature of PSP occurrence on the B.C. coast is that it frequently occurs earliest in this part of the coast (Fisheries statistical areas 12 and 13), as early as April or May, whereas it usually appears in June in the Strait of Georgia and later off the west coast of Vancouver Island. Most recently (1999-2001) the closures in southern B.C. were extensive and persisted in some areas of Vancouver Island until November (Canadian Food Inspection Agency reports). Because butter clams *(Saxidomus giganteus)* retain toxin in their black siphon tips potentially for more than a year (Quayle 1969), and because the current monitoring program relies on mussel toxicity, butter clams are now permanently prohibited from collection along the entire coast. Other shellfish that become potentially fatal to humans include mussels, other clams, scallops, oysters, moonsnails and geoducks. The guts of crustaceans such as barnacles, Dungeness crabs and sand crabs *(Emerita analoga)* have been found to contain PSP, as well as ASP (see below).

Schallié (2001) has discussed the philosophy, nature and limitations of the current B.C. shellfish monitoring program. The locations of monitoring sites for PSP toxins in shellfish (during 1999) are shown in Figure 24. The north coast can be subject to prolonged toxicity but is logistically very difficult to monitor effectively and has been permanently closed since 1964 to the collection of bivalves except at a few monitoring sites (see Purkis 2001; Purkis in Martin 2002). Some data from the north coast suggests that it differs from the south in that high levels of toxin can persist in winter (Gaines end Taylor 1985). Anecdotal information from local inhabitants (Taylor, unpubl.) suggests otherwise, with avoidance of shellfish consumption confined to the summer months.

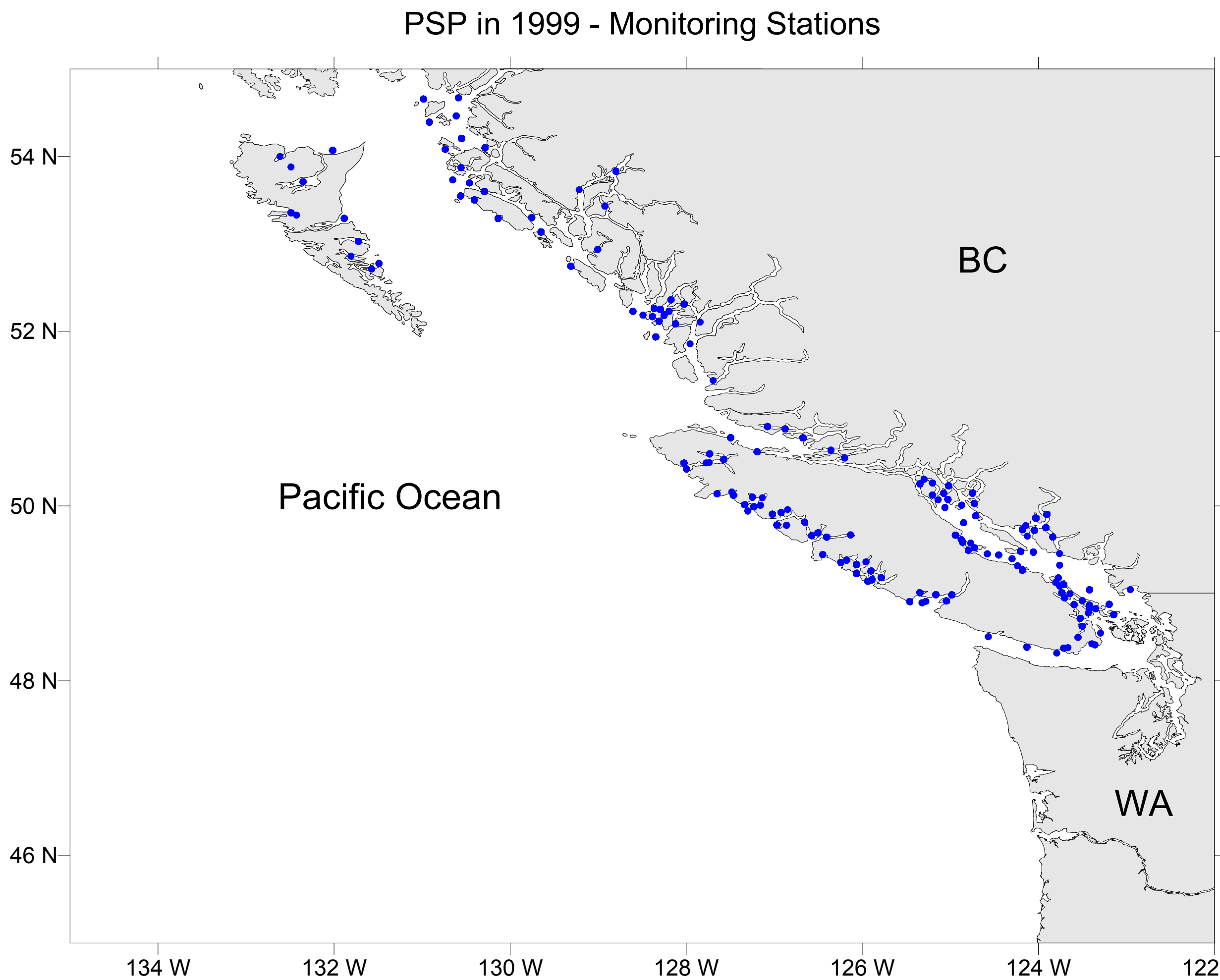

Fig. 24 Shellfish testing sites sampled for PSP toxins in 1999 (Canadian Food Inspection Agency, Shellfish Inspection).

The link to species of the dinoflagellate, genus *Alexandrium* (formerly attributed to the genera *Gonyaulax* and *Protogonyaulax;* see illustrations of some of the species elsewhere in this report*)* in British Columbia, was made unequivocally by Prakash and Taylor (1966): the Theodosia Inlet episode was the first recorded instance anywhere in which human fatality was coincident, not only with toxic shellfish, but also with a bloom of toxic *Alexandrium (A. acatenella).*

Usually when poisoning occurs the bloom has already passed. A. *catenella* also occurs in B.C., where it is the chief source of PSP off the west coast and eastern Vancouver Island. In more estuarine waters, such as the east side of the Strait of Georgia, *A. tamarense* is the dominant taxon (Taylor 1984, see Figure 25). A. *minutum,* also known to be toxic, is present in English Bay near Vancouver although a bloom of it has not been recorded so far (Taylor, unpubl.), as well as several non-toxic species of *Alexandrium,* such as *A. pseudogoniaulax* and *A. hiranoi. A. ostenfeldii* is present in English Bay, Vancouver (Haigh end Taylor, unpubl.), but not in bloom quantities. Canadian east coast populations of the latter have been shown to produce spirolides causing rapid death in mice, but spirolides have not been demonstrated in B.C. shellfish.

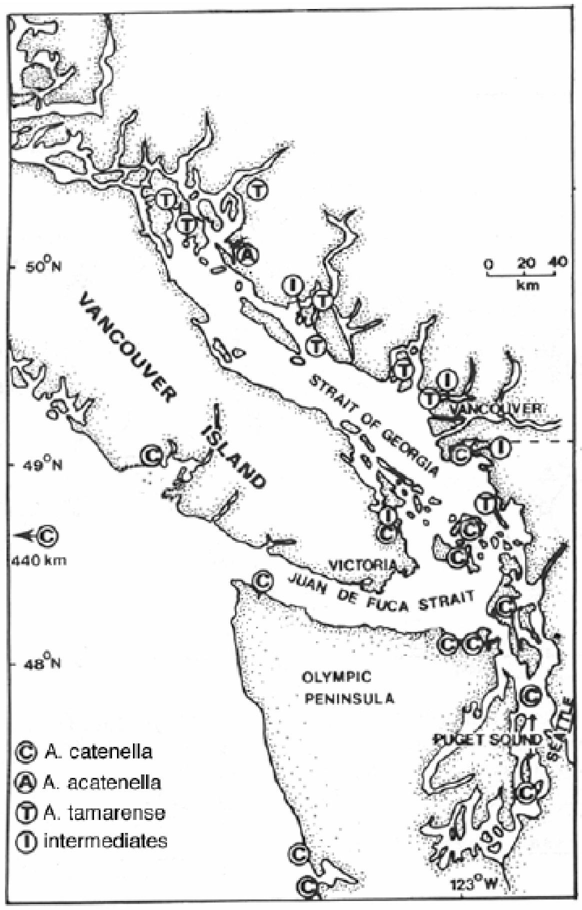

Fig. 25 Distribution of three toxic species of *Alexandrium* and intermediate forms in the Strait of Georgia and adjacent Washington State waters (slightly modified from Taylor 1984).

Ecology of PSP species in B.C.

Alexandrium blooms have been observed repeatedly in several studies in B.C. waters although there has not been a large-scale effort focused specifically on their outbreaks. In English Bay, multi-year sampling at Jericho Pier (Haigh and Taylor 1993) has shown that blooms first appear subsurface (1-3 m) in May or June, coincident with surface *Heterosigma* blooms, and persist throughout the summer months.

The blooms are initiated from benthic cysts, as is well known elsewhere, but studies have shown that there is no simple spatial correlation with cyst density in sediments. In B.C., blooms seem to originate in shallow, nearshore localities and spread into adjacent, larger bodies of water, *e.g.*, in Barkley Sound where cells are first seen in the inner northern corner (Taylor *et al.* 1994). In Barkley Sound, cells appear at depth sooner than indicated by intertidal toxicity values, with the blooms rising nearer to the surface as the season progresses.

Although PSP is present every year, there are clear oscillations in intensity (Fig. 26). There is a problem comparing years with widespread, medium-level toxicity, to years with isolated intense toxicity, and Chiang (1985) created a "PSP activity scale" formula in an attempt to make these comparisons. Using a simpler method, Gaines and Taylor (1985) found a cyclical periodicity that seemed to be roughly five to seven years. Often these years have been El Niño years (Erickson end Nishitani 1985) but the recent high toxicity around Vancouver Island, reaching more than 9000 μg per 100 g of shellfish in Barkley Sound, in October 2000 (K. Schallie, pers. comm.), was during an inter-year. Prolonged calm, sunny weather late in the season may have contributed to prolongation of *Alexandrium* blooms past the summer.

There appears to be no link to pollution (Taylor and Horner 1994), because *Alexandrium* species usually occurring subsurface during the growing season (Taylor and Haigh 1994). They are thus able to take nutrients from below. PSP is worst in many of the least inhabited parts of the coast. There is no positive correlation of PSP with aquaculture activities in B.C. judging by a detailed, multiyear study in Sechelt Inlet (Taylor *et al.* 1994). Blooms are not apparent in surface waters, at least in early stages of bloom development. They often occur in dense layers close to the nutricline. In Barkley Sound, Taylor and Haigh (1994) observed that *A. catenella* was present at depth long before toxicity was recorded in intertidal shellfish.

An interesting anomaly in the PSP data is the unusually early appearance of toxicity in the inlets and around the islands at the southern end of Queen Charlotte Strait, extending through to the northern Strait of Georgia. This is also where several of the fatalities or serious illnesses have occurred, *e.g.*, Gilford Island, Kingcome Inlet, Theodosia Inlet (see Fig. 23).

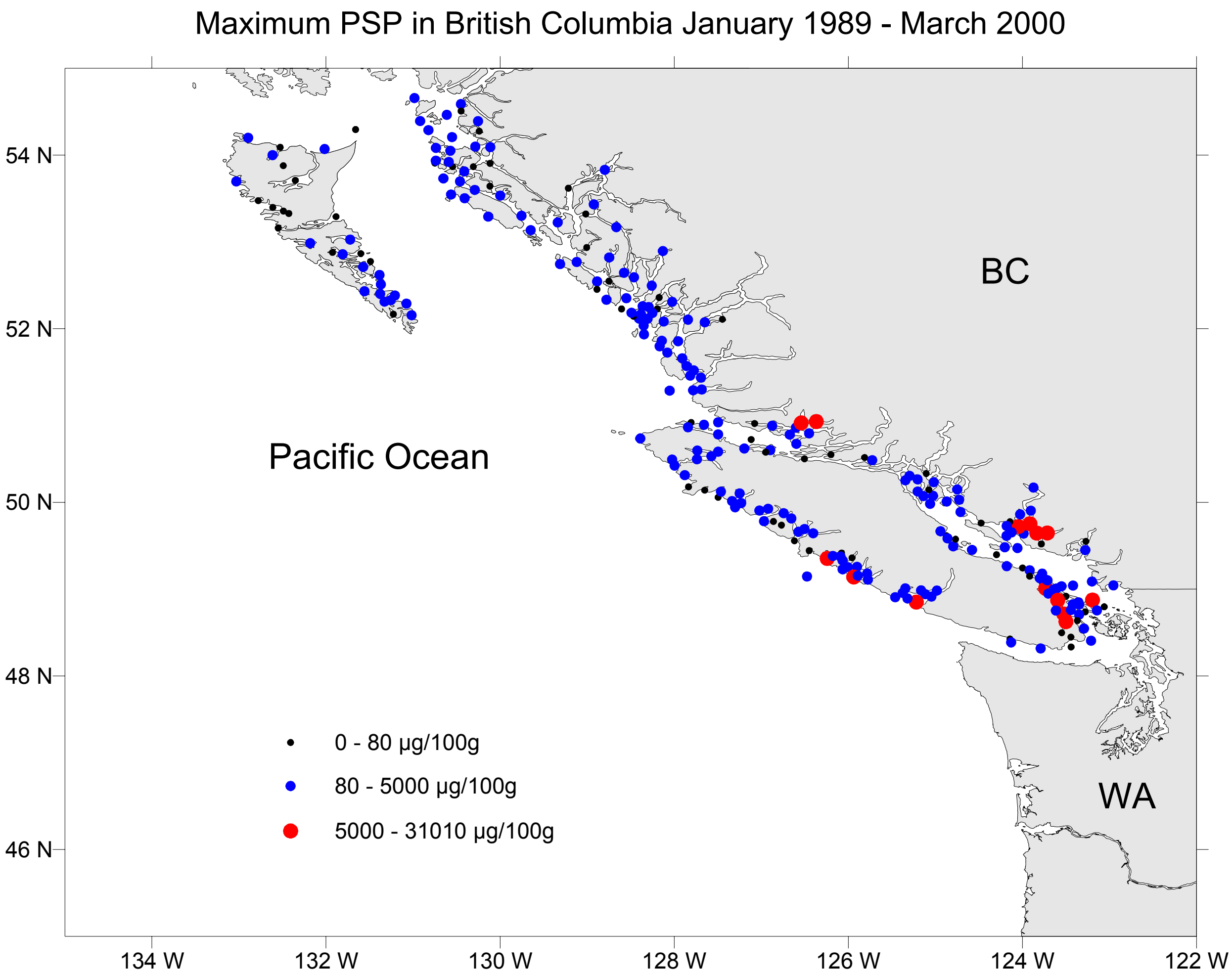

Fig. 26 Historic highs in saxitoxin equivalent concentrations on the B.C. coast. Note that sampling intensity is much higher in the south, which probably skews the picture.

Domoic acid poisoning **(**DAP or Amnesic shellfish poisoning, ASP)

Domoic acid production has been linked to blooms of several species of the diatom genus *Pseudo-nitzschia,* notably *P. multiseries, P. australis* and *P. pseudodelicatissima.* The toxin is retained the longest by razor clams but also occurs in mussels, used in the B.C. monitoring program (K. Schallie, pers. comm.) and in Dungeness crab guts. Cooking of the latter whole causes the toxin to spread into the flesh.

Pseudo-nitzschia spp. are present and often abundant in all B.C. marine water bodies throughout the summer and fall, *e.g*., Sechelt Inlet (Taylor *et al.* 1994) but the biggest blooms seem to occur over the outer continental shelf (Forbes and Denman 1991; see Fig. 25). Taylor and Haigh (1996) observed that blooms enter Barkley Sound from the open coast and appear to sink out. Taylor (2001) has suggested that this may be necessary for the sexual cycle since *Pseudo-nitzschia* like other pennate diatoms, requires direct contact of compatible cells and movement is only possible on a hard surface.

There is a provocative timing series along the west coast of North America in terms of the first appearance of domoic acid toxicity, with that in British Columbia appearing later than further south. So far, southern outbreaks have invariably

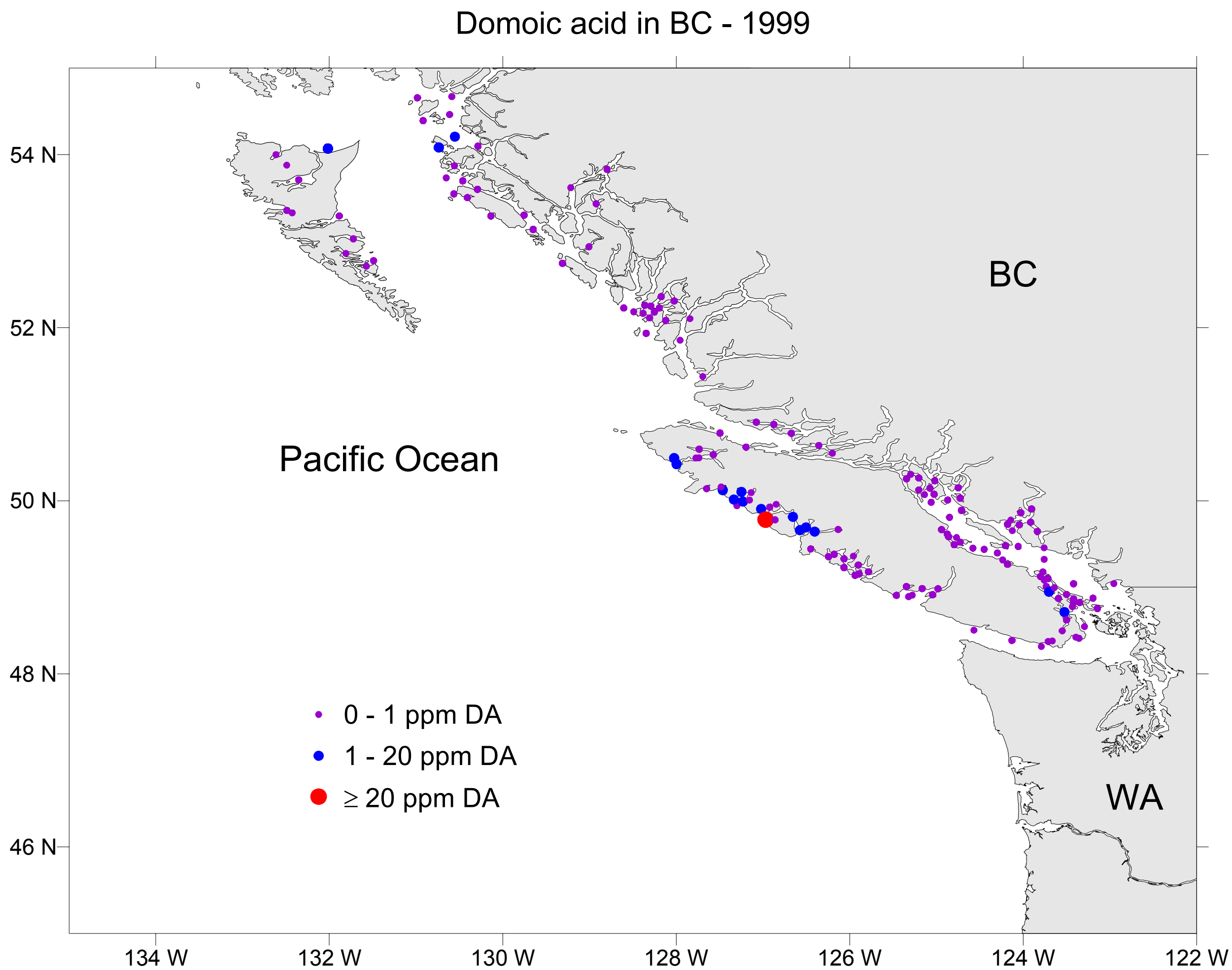

Fig. 27 Domoic acid levels in 1999 (Canadian Food Inspection Agency, Shellfish Inspection).

preceded those further north in B.C. and Alaska. This provides forewarning, allowing increased vigilance and raises interesting questions regarding possible advection (Taylor and Haigh 1996) or a seasonal wave of altered environmental conditions (discussed in Summary and conclusions).

Other potential shellfish toxin producers

Species of the dinoflagellate genus *Dinophysis* have been linked to diarrheic shellfish poisoning (DSP). In particular *D. fortii, D, acuta. D. acuminata* and *D. norvegica*, all of which have been linked to DSP elsewhere are common, but never abundant.

However, it has been claimed that prolonged presence in concentrations of thousands per litre or less may cause levels sufficient to cause illness. No DSP has been diagnosed in humans in B.C. but, given its resemblance to diarrhea caused by bacterial contamination (*Vibrio haemolyticus* in particular), would DSP be detected without testing specifically for okadaic acid or dinophysistoxin? *Prorocentrum lima,* a known okadaic acid producer, has been recorded as common in benthic environments (sand) in B.C. (Taylor, unpubl.) but local strains have not been tested for toxin production.

Most recently the common temperate dinoflagellate species *Protoceratium reticulatum,* also known as *Gonyaulax grindleyi,* has been shown to reproduce yessotoxins which have contaminated shellfish in New Zealand. This species is very common and occasionally abundant in British Columbia coastal waters (its benthic cyst stage is the commonest dinoflagellates cyst in B.C. coastal sediments (Dobell, Ph.D. thesis, UBC)) but no illnesses have been linked to this species in this region so far. It should be noted that yessotoxins are not part of the standard monitoring program. Like the potential DSP producers, local culture isolates need to be made for toxin testing. This is also true for potential spirolide production by *A. ostenfeldii.*

A disturbing development was the discovery of microcystins in samples of fouling on farmed salmon pens in the Strait of Georgia (Andersen, Kent, Taylor REF.). Microcystins are tumor promoters so far known only to be produced by fresh-water cyanobacteria. Their presence in sea samples in B.C. is a mystery at present.

Fish killers

In general wild fish are not harmed by HABs in B.C. This is probably due to the high tidal exchange preventing the hyper-bloom concentration and subsequent plankton death and decay which causes mass mortalities elsewhere. Also, there is possibly behavioural adaptation, such as avoidance by swimming around or under surface blooms, arising from long-term exposure (thousands of years or more) to the same HABs that occur now. On the other hand, farmed fish are more vulnerable to such blooms because they are kept in pens in the ocean where they cannot avoid the noxious plankton concentrations. The loss to salmon aquaculture in B.C. between 1986 and 1990 was estimated to be CDN$ 15 million (Black 1990).

Chaetoceros concavicomis, Ch. convolutus

Bell (1961) first showed that spines of the common, chain-forming diatom *Ch. convolutus* (probably including the closely similar *Ch. concavicornis*) could lethally damage the gills of ling-cod held in cages near Nanaimo. Relatively low concentrations of cells (5000 l^{-1}) of these two diatom species, particularly *Ch. concavicornis*, can also kill farmed salmon by physically damaging their gills. Small spines on their setae cause them to irreversibly penetrate the gill tissue and cause capillary damage. This also makes the fish more vulnerable to *Vibrio* infections. Quite often the fish produce large quantities of mucus in their gills. The diatoms are most abundant in the summer and fall in the Strait of Georgia (Haigh and Taylor 1990) and coastal inlets (Taylor et al. 1994) in waters above 25‰ for *Ch. convolutus* and 17‰ for *Ch. concavicornis* (Albright *et al.* 1992, Harrison *et al.* 1993).

Heterosigma akashiwo (= H. carterae)

This small species of chloromonad (raphidophyte) flagellate has been the principal killer of farmed salmon in British Columbia since 1986. Blooms can be extremely extensive in B.C. coastal waters (Taylor end Haigh 1993).

In 1989, the entire Strait of Georgia was covered by the reddish brown of a bloom of this organism (E. Black and F. Taylor, unpubl.obs.). The precise mechanism of death is uncertain although the organism is presumed to release harmful substances into the water which cause gill and/or liver damage in salmon. Black *et al.* (1991) could not observe gill damage in fish killed in their experiments. Excessive gill mucus production is sometimes also observed with *Heterosigma* blooms, but not always.

Regular, multi-year monitoring of bloom development in English Bay, Vancouver (Taylor and Haigh 1993), has shown that cells abruptly appear in the water when the temperature reaches 15°C (usually in June), apparently due to excystment from shallow sediments. Blooms are most extensive in the Strait of Georgia during summers with strong, shallow stratification due to high runoff from the Fraser River, in turn resulting from a higher than normal snow-pack the previous winter. A drop in salinity in English Bay to 15‰ coincides with 15°C in severe bloom years in this area. A prerequisite to strong blooms is that the spring diatom bloom must be over (usually by late May) and the surface water depleted of nitrate.

Cochlodinium sp.

In the summer of 1999 a series of salmon kills at farms on the west coast of Vancouver Island was linked to a bloom of the naked dinoflagellate *Cochlodinium* sp. (Whyte *et al.* 2001). The cells resembled *C. polykrikoides,* the major fish killer of Korea and in Japan (see this report) but showed less chain formation, usually occurring in pairs or singly. The initial outbreak was estimated to cause losses of approximately CDN$ 2 million. This phenomenon has recurred less severely in subsequent years with a suggestion of southward spread along the coast of Vancouver Island. The cause of death is unknown although a similar mechanism to that in Korea and Japan (oxygen radical production leading to gill, and perhaps also liver damage) is suspected.

Others

Visible discolourations due to blooms of many other species of phytoplankton are common in B.C. waters during spring and summer (reviewed for the Strait of Georgia by Harrison *et al*. 1983). There is a regular spring bloom of diatoms, primarily consisting of *Thalassiosira nordenskioldii*, *Skeletonema costatum* and several species of *Chaetoceros*, notably *Ch. debilis*. This is often followed by the heterotrophic dinoflagellate *Noctiluca scintillans* which regularly blooms intensely enough to strongly discolour the water an orange-red (see cover photograph). In these waters it is usually not harmful. Esquimalt Lagoon near Victoria on Vancouver Island is frequently intensely discoloured by late summer blooms of *Akashiwo sanguinea* (formerly *Gymnodinium sanguineum*) which is also not harmful unless trapped in a decaying state. Watanabe and Robinson (1979) studied an intense bloom of it in September-October 1978.

Another very common discolouration is caused by intense, maroon, surface blooms of the photosynthetic ciliate *Mesodinium rubrum,* which aggregates particularly at downwelling fronts or in internal waves in the Strait of Georgia (reviewed by Taylor *et al.* 1971). It has been invariably harmless although it can cause a red discolouration in shellfish. AVHRR imagery has detected large reflective blooms off B.C., particularly off the coasts of Vancouver Island and the Queen Charlotte Islands (Gower 1997). These are probably caused by harmless coccolithophorids but this has not been properly "ground-truthed" yet. We do not include such harmless blooms in our HAB data.

In 1990, a particularly extensive and intense bloom of the dinoflagellate *Gonyaulax spinifera* was implicated by Heath and Lindsay (1993) in the mass mortality of shellfish such as oysters, clams and mussels in tributary inlets to Barkley Sound on the west coast of Vancouver Island. This non-specific mortality was attributed to oxygen depletion accompanying collapse of the bloom. Usually blooms are not as concentrated as this in local areas due to strong tidal exchange. Such non-specific kills due to high B.O.D. are known from other parts of the world where other species of *Gonyaulax* and also *Ceratium*, have caused fish and shellfish kills without the involvement of toxin release.

In Japan, the commonest fish killers are species of the chloromonad genera *Chattonella* and *Fibrocapsa.* A few cells of an unidentifiable species of *Chattonella* have been seen in preserved samples from open west coast waters (Taylor, unpubl. obs.) but never a bloom. Sea temperatures on the B.C. coast are generally colder than areas commonly subject to *Chattonella* blooms, such as the Inland Sea of Japan. This is also true of the fish- killing dinoflagellate *Pfiesteria.*

Discussion

Given that reports have been increasing and new species implicated in HABs in B.C. and on many coastlines, it is reasonable to wonder if this is due to human activities, such as eutrophication. Taylor *et al.* (1994) and Taylor and Horner (1994) concluded that there was no evidence for links between HABs and salmon aquaculture in B.C. waters. The sites usually chosen for salmon farming are deep and the large tidal range flushes the surface waters well. Many of the highest PSP sites are along very lightly populated coasts. On the other hand there is evidence of cyclical interannual variation that is presumably due to interannual climatic variation. In the case of

Heterosigma there is a clear link to snow pack accumulation the previous winter and subsequent runoff. Also, Taylor (in press) has argued that the natural adaptation of local fauna, such as the avoidance of toxic shellfish by sea otters or *Heterosigma* blooms by Pacific salmon, is strong evidence for the presence of particular HABs over evolutionary time.

Another question is whether some local HAB species have been introduced by, for example, the discharge of foreign ballast water. Again, Taylor (in press) has drawn attention to the general biogeographic phenomenon of "latitudinal cosmopolitanism" exhibited by groups such as dinoflagellates (Taylor 1987).

Management at present consists of monitoring shellfish, primarily mussels, for the presence of saxitoxins and domoic acid, by the Canadian Food Inspection Agency, Fish Inspection Branch, with closures declared when levels reach or exceed 80 µg saxitoxin equivalents per 100 grams of shellfish meat. This program is aided in collection and sample preparation for toxin testing by the North Coast Water Quality and Biotoxin Program, a private agency based in Prince Rupert (see Purkis in Martin 2002). While the use of mussels as indicators of the presence of toxins is favourable for a variety of reasons (see Schallié 2001) including their rapid uptake abilities relative to other shellfish, their rapid depuration abilities make them unreliable as indicators of the state of shellfish in general. As noted above, butter clams retain saxitoxins for longer and oysters only accumulate PSP slowly, requiring longer exposure to reach dangerous levels. In the case of domoic acid it is known that razor clams retain the toxin the longest. At present plankton monitoring is not part of the Food Inspection Agency activities although it could be a valuable adjunct to shellfish testing, as shown on the east coast, *e.g.*, Prince Edward Island and New Brunswick. A consortium of fish farmers, aided by staff of the Department of Fisheries and Oceans at the Pacific Biological Station in the Nanaimo, participate in a Harmful Algae Monitoring Program (HAMP) that does include plankton sampling from farm sites, resulting in warnings of potentially fish-killing blooms. However, because it is restricted to near-shore sites, it is of limited ecological value. Some plankton monitoring is also being done at a few northern sites near Prince Rupert by the North coast plankton identification and monitoring program (Shaw 2001).

It is clear that the siting of aquaculture sites in particular should require a prior investigation of the broad aspects of the phytoplankton community of the area. So far this has not been the case, often to the cost of the farmers. Much remains to be done, both to understand and effectively manage HABs in British Columbia and this will be most effective if it is integrated with the confluent waters of its neighbours, Washington State and Alaska.

Specific questions needing near-future examination

- What is the causal nature of the multi-year (six- to eight-year) cycles on the coast? Is there a direct link between El Niño (ENSO) and higher levels of PSP?
- Are *Alexandrium* blooms in B.C. coastal waters all locally triggered events or is long-shore transport also important?
- What is the source of extensive blooms visible by satellite off the east coast of the Queen Charlotte Islands and in Queen Charlotte Strait?
- Why is the southern Queen Charlotte Strait region (Gilford Island, Kingcome Inlet, Johnstone Strait area) the earliest in southern B.C. to experience high PSP toxicity?
- Is PSP more persistent in the winter months in the north than the south?
- How many toxin-producing species and strains of *Alexandrium* and *Pseudo-nitzschia* are there in B.C. waters?
- Is there a hydrographic link between off-shore blooms of *Pseudo-nitzschia* along the west coast of North America?
- Are *Cochlodinium* and *Heterosigma* blooms relatively recent developments or have aquaculture activities drawn attention to their presence? Are they spreading?
- Blooms of *Heterosigma* in the Strait of Georgia are apparently strongly linked to river runoff and stratification but how are blooms on other parts of the coast regulated?

- What is the source of microcystins in salmon net pen fouling organisms?
- Do viruses play a role in the collapse of *Heterosigma* or other B.C. HABs?
- Are HAB species responsible for "summer die-off" in cultivated mussels or oysters?
- Have there been any introduced HAB species due to ballast water or other sources in B.C. waters?

Acknowledgments

The authors wish to acknowledge the assistance of the Canadian Food Inspection Agency and Klaus Schallié in particular, for discussions and use of their toxicity data. The charts were produced with the assistance of the NOAA Northwest Fisheries Science Center, Seattle, and the manuscript was reviewed and discussed with Vera Trainer.

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