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# Review of the potential effects of climate change on marine harmful algal blooms (HABs)

## Implications for public health in Aotearoa New Zealand

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## Implications for public health in Aotearoa New Zealand

LESLEY L. RHODES AND KIRSTY F. SMITH

Report prepared for the New Zealand Ministry of Health

CAWTHRON INSTITUTE
98 Halifax Street East, Nelson 7010 | Private Bag 2, Nelson 7042 | New Zealand
Ph. +64 3 548 2319 | Fax. +64 3 546 9464
www.cawthron.org.nz

REVIEWED BY:
Laura Biessy

APPROVED FOR RELEASE BY:
Cath McLeod

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# EXECUTIVE SUMMARY

This report reviews the likely effects of climate change on marine harmful algal blooms (HABs) in Aotearoa New Zealand. The main aim is to understand the potential implications for public health.

- Increases in sea water temperature and changes in ocean currents are occurring, particularly in northern coastal waters, and will alter both the occurrence and the geographic range of HABs.
- Increased heavy rainfall events will see more inputs of nutrients and trace metals into coastal waters and this will not only affect microalgal cell concentrations but also their toxin production.
- Coastal and ocean acidification is also of concern. Experimental studies have shown that some HAB species increase their cellular toxin content under acidification conditions, indicating a potential shift to the production of more toxins by HABs.
- Increases in respiratory illnesses and skin/eye irritations from HABs are expected. For example, *Ostreopsis* blooms occur regularly along the north-eastern Aotearoa New Zealand coastline and as the waters warm, a more toxic but uncommon species, *O. ovata*, could become dominant. As it is an epiphyte on macroalgae, its monitoring is problematic, and this needs consideration. Other HAB taxa present in Aotearoa New Zealand, such as the dinoflagellates *Karenia* and *Heterocapsa* and the cyanobacterium *Lyngbya* have been associated with skin, eye, and respiratory irritation.
- It is expected that these HABs will continue to occur and may increase in frequency. *Karenia* spp. already bloom throughout Aotearoa New Zealand and *Alexandrium* spp. and *G. catenatum* may continue to spread to more southern waters.
- One of the main health issues from HABs for public health is through the contamination of non-commercial shellfish harvest, causing neurotoxic and paralytic shellfish poisonings (NSP and PSP, respectively). Regular monitoring is in place for the causative organisms, *Karenia* spp. (NSP), and *Alexandrium* spp. and *Gymnodinium catenatum* (PSP).
- HABs that have occurred in Aotearoa New Zealand but have not yet caused significant health issues include those that may cause amnesic and diarrhetic shellfish poisonings (ASP and DSP, respectively). The diatom *Pseudo-nitzschia* is a common bloom-former throughout Aotearoa New Zealand and many species produce domoic acid (the cause of ASP). The dinoflagellate *Dinophysis* (a cause of DSP) is a frequent bloom-former in temperate waters around Aotearoa New Zealand. The effects of changing climatic conditions are uncertain for these genera, but blooms in more southern regions and increases in toxin production per cell are possible. Additionally, novel species or strains with different toxin profiles may establish in Aotearoa New Zealand waters. The impacts of long-term

low exposure to ASP and DSP toxins are of concern. *Pseudo-nitzschia* and *Dinophysis* spp. are regularly monitored, and risk assessments provided to health regulators.

- A genus that is predicted to become a bloom-former and increase its geographic range is *Gambierdiscus,* the cause of ciguatera poisoning (CP) in humans. Both acute symptoms and chronic illness is of concern. Regular benthic/epiphytic monitoring for this genus, particularly in Northland, is advised.
- *Vulcanodinium* produces pinnatoxins which have the potential to cause spiroimine shellfish poisoning (SSP), although no major human health impacts have been reported to date apart from dermal irritation. Mats of this dinoflagellate occur in sub-tropical Northland and benthic blooms are likely to increase their range to more southern regions as waters warm. Benthic monitoring is not carried out and this needs consideration.
- Potential bloom formers are *Azadinium* and *Amphidoma.* These taxa are present in Aotearoa New Zealand, but cell concentrations have been low to date. They can produce azaspiracids which have been detected at low concentrations in shellfish. Identification is difficult and molecular tools need to play a greater role in monitoring. The optimal environmental conditions for these taxa need to be ascertained to enable predictions on how climate change might affect their growth and toxin production.

## Knowledge gaps and priorities for research include:

1. The influence of climate change on microalgal species composition and community structure is not yet fully understood. Future climate scenarios and associated changes in HAB distribution and abundance need to be modelled so that management plans can be informed. Knowledge on the effect of potential environmental impacts on HABs is needed (e.g., increased trace metal inputs into coastal waters with more heavy rainfall events).
2. Species that can cause respiratory illnesses and skin/eye irritations are understudied. For example, it is likely that as coastal waters become warmer increased mats of the cyanobacterium *Lyngbya*, including toxic strains, may spread to more southern waters or increase in frequency. Very little research has been carried out on any marine cyanobacteria and it is an area to focus on in the future.
3. Knowledge on the impact of chronic exposure to HAB biotoxins on human health is lacking (e.g., domoic acid (DA), ciguatoxins). The common bloom-forming diatom *Pseudo-nitzschia* can produce DA (the cause of ASP) and studies focused on the functional effects of these toxins are needed, especially when considering the new evidence of human health consequences from chronic, low-level exposure.

4. There is a lack of benthic/epiphytic monitoring, particularly in high-risk areas such as Northland. Monitoring for *Gambierdiscus, Ostreopsis, Vulcanodinium, Prorocentrum,* and cyanobacteria would enable predictive risk assessments of toxin production and thus potential health issues. This will require development of cheap and rapid sampling methods, linked to molecular techniques such as quantitative polymerase chain reaction (qPCR) or high-throughput sequencing metabarcoding as potential detection tools.
5. There is a lack of knowledge of open and deep water HABs in Aotearoa New Zealand and how warming seas may impact them. This is a risk for future aquaculture developments.
6. Research into the optimal conditions for bloom development of *Azadinium* and *Amphidoma* is needed. Research will be carried out when cells of these species are detected in regular monitoring samples. More focussed research into cyst beds, which can seed blooms, and into toxin production of *in vitro* cell cultures to determine environmental optima, is required.
7. Correlation of microalgal distribution data with records of toxins in seafood and any human illness, including respiratory and skin issues is needed. This information would enable rapid characterisation of any of the predicted impacts of climate change on the distribution and toxicity of HABs.

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# 1. INTRODUCTION

Harmful algae blooms (HABs) occur world-wide and Aotearoa New Zealand has experienced its share of significant bloom events. The Ministry of Health commissioned the Cawthron Institute to review how climate change will likely impact marine HABs in Aotearoa New Zealand and how these changes could affect public health. This report provides:

- A summary of marine HABs currently impacting recreational activities in Aotearoa New Zealand and how they may change with continued climate change.
- Information on toxic marine microalgae that have the potential to impact public health in Aotearoa New Zealand in the future, particularly those that lead to ciguatera poisoning.
- Notes on how our close connection to the Pacific, and seafood from the Pacific, may cause increased public health incidents in Aotearoa New Zealand with continued climate change.
- Current knowledge gaps and recommended priorities for future research in this area.

The key microalgae of concern produce biotoxins that may be taken up by shellfish or finfish, which then become toxic to human consumers (Figure 1). The toxins may cause mild to serious illnesses depending on their mode of action and can potentially cause both acute and chronic toxicity. Of greatest concern are those that produce saxitoxin (STX) and its derivatives, as STX causes paralytic shellfish poisoning (PSP). Domoic acid causes amnesic shellfish poisoning (ASP), brevetoxins cause neurotoxic shellfish poisoning (NSP), and the okadaic acid-group of toxins (including dinophysis toxins) cause diarrhetic shellfish poisoning (DSP). Other biotoxins reported world-wide include palytoxins, azaspiracids (azaspiracid shellfish poisoning, AZP), ciguatoxins (ciguatera poisoning, CP) and cyclic imines. The cyclic imines are currently not regulated anywhere in the world, although a new toxin class, spiroimine shellfish poisoning (SSP) has been proposed for them. Human exposures to aerosolised or water-borne toxins, and dermatological contact with HABs can also have negative impacts on health. These and other biotoxins are discussed in this report.

The producers of microalgal biotoxins fall into many different classes. Within those groupings each species will have its own optimal physiological parameters. The biological of each harmful species needs to be understood to underpin development of predictive models. Some of the expected impacts of climate change on HABs are:

- a shift in the geographical distributions of HABs
- an increase in the occurrence and frequency of blooms in some regions
- the occurrence of HABs at non-typical times of year
- shifts in toxin profiles with an increase in toxicity expected for some taxa

- an increase in human illnesses, particularly from non-commercial shellfish harvest, and including inhalation and skin irritations.

The likely health impacts of climate change for Aotearoa New Zealanders were collated by the Royal Society of New Zealand in 2017 and, as regards to HABs, the potential for the establishment of *Gambierdiscus* was highlighted. *Gambierdiscus* is a dinoflagellate genus, species of which may produce ciguatoxins (CTXs), and it has been reported in northern coastal waters (refer section 4.1). If toxic species were to establish and bloom, there is a consequent risk of CP occurring in Aotearoa New Zealand (Royal Society Te Apārangi, 2017). *Gambierdiscus* usually occurs in sub-tropical to tropical regions, but has been recorded in the temperate regions of south-eastern Australia in recent years, indicating a potential risk of CP toxins in these cooler ecosystems (www.climatechange.environment.nsw.gov.au). Changes in the direction of the East Australian Current due to warming coastal waters is considered a factor in the arrival and establishment of *Gambierdiscus* in the more southern waters (Australian Fisheries Management Authority 2019).

Reported CP cases in South Pacific nations following consumption of biotoxin contaminated fish show a strong correlation between annual incidence of CP and the local warming of sea surfaces a decade ago. The incidences were linked to El Niño climate conditions and pointed to potential increases in CP due to climate warming (Hales et al. 1999). Other HAB events have been linked to El Niño, for example the major NSP event that occurred in Aotearoa New Zealand in 1993 (refer Section 2.3).

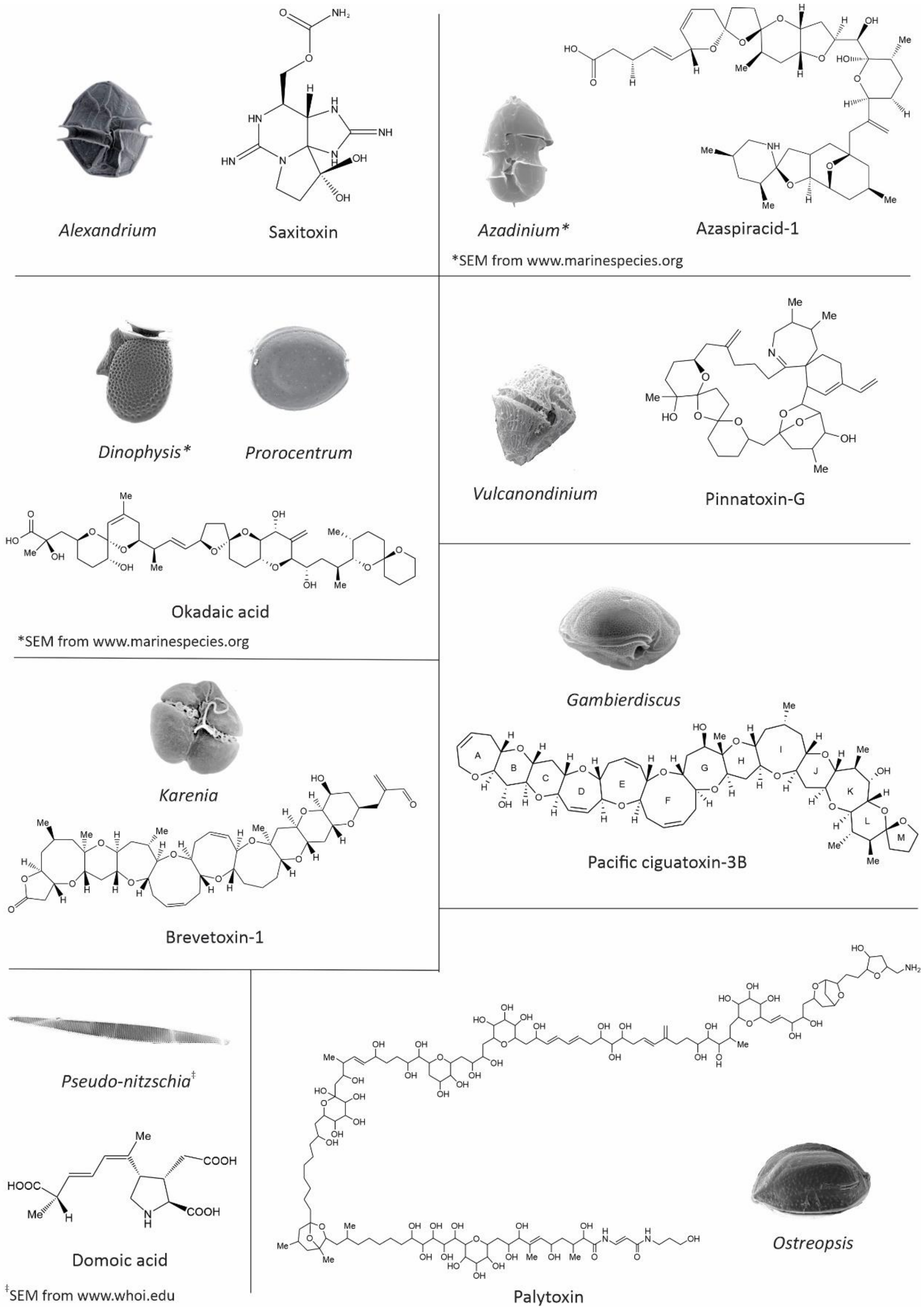


Figure 1. Toxic marine microalgae with the potential to cause human illness and the main biotoxin each produces. Scanning electron micrographs (SEMs) from Cawthron Institute files unless stated otherwise. Figure prepared by Sam Murray, Cawthron Institute.

## 1.1. Evidence of climate change impacts

### 1.1.1. Temperature

Climate change-driven events may see increased microalgal cell concentrations, but may also change HAB toxicity, whether through altered salinity, pH, temperature or through the input of nitrates and trace metals into the coastal environment. As each species will respond to a different combination of impacts in different ways, there is a need to investigate the effects on local and recent HAB species of interest. Methods of detection of both biotoxins and their producers are constantly improving, with molecular approaches complementing microscopic detection of HAB species. There is some debate as to whether more species are being found due to more research being carried out using better methods and more frequent monitoring or whether climate change is already impacting HAB occurrences (Hallegraeff et al. 2021a). Whatever the case, excellent monitoring programmes are in place around Aotearoa New Zealand both for the protection of the seafood industry and its exports (carried out by the concerned businesses) and for the protection of non-commercial seafood gatherers through the Ministry of Primary Industries (MPI).

Temperatures have, without doubt, risen in Aotearoa New Zealand's surface and sub-surface coastal waters in recent years and of concern are 'hot spots', patches of water showing anomalies of +3.7 °C, which have been recorded in the Tasman Sea and Pacific Ocean (Ministry for the Environment 2018; Salinger et al. 2019; Sutton and Brown 2019). Ocean temperatures in Aotearoa New Zealand are highly correlated with air temperatures, largely due to the country's relatively small land mass. If air temperatures continue to rise, so will the temperature of coastal waters. Predictions are for increases of approximately 0.8 °C by 2040, 1.4 °C by 2090, and 1.6 °C by 2110, relative to the 1986–2005 period (Ministry for the Environment 2018). From 2002–2020, there was an estimated 0.2–0.4 °C increase per decade in sea surface temperature in the important, Green-lipped mussel-producing region: the Pelorus Sound, Marlborough Sounds (Broekhuizen et al. 2021).

In Northland, predictions based on modelling carried out by the National Institute of Water and Atmospheric Research (NIWA) in conjunction with the Northland Regional Council suggest that the average summer temperatures may increase by 1.1 °C by 2040 (with warmer summer temperatures lasting for longer). Estimates of future summer temperatures range from 0.5 to 1.6 °C and there is a range of uncertainty in the model results (for more information refer to https://www.nrc.govt.nz/media/i3qnkklo/northland-region-climate-change-projections-and-implications-summary-report_niwa.pdf). Warming sea water temperatures are also leading to changes in the direction of major currents (Figure 2), potentially seeding new regions with toxic HAB species (as has happened in eastern Australia; Kohli et al. 2014). Temperatures in the Tasman Sea have risen by 2 ºC over the past 60 years, three times the average rate of warming in the world's oceans. The warming has been triggered by strengthening wind systems, a result of climate change, which could drive warm ocean currents toward the poles and beyond their usual boundaries.

The warmer temperatures will also lead to an influx of new tropical fish species to Aotearoa New Zealand's northern waters (already being reported). This could lead to changes in the macroalgae habitat becoming 'barrens' due to herbivore grazing and the proliferation of new toxic microalgal species (Rhodes et al. 2020).

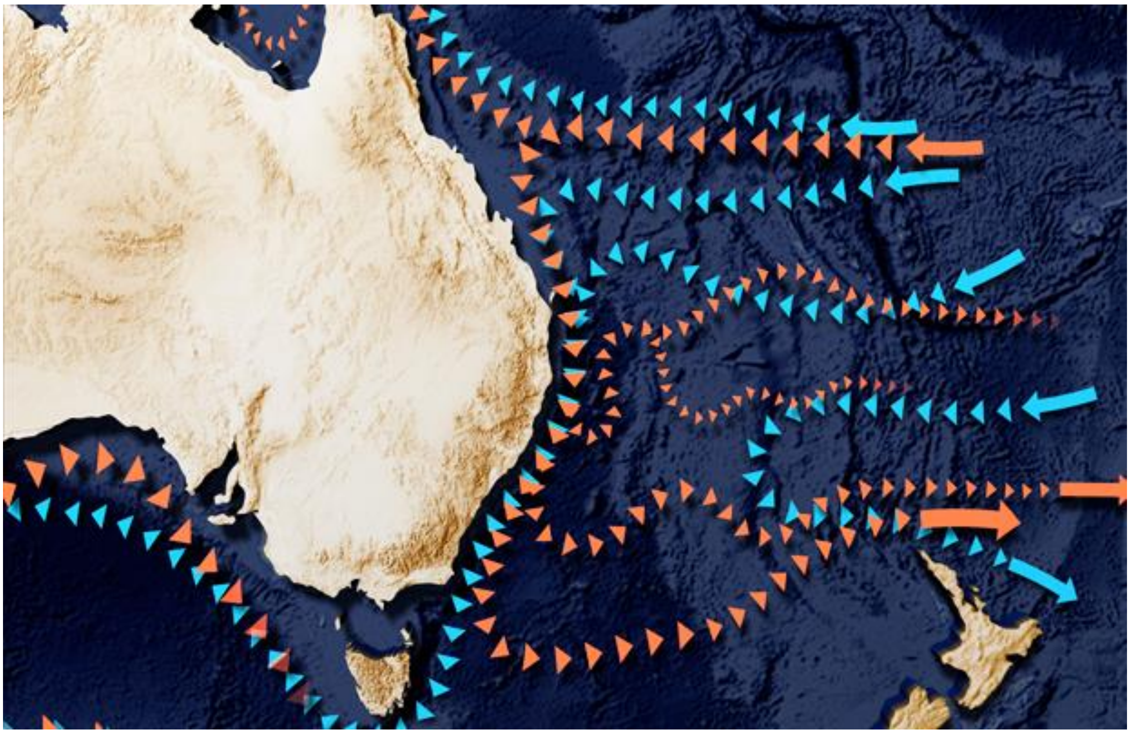

Figure 2. Surface (orange) and deeper (blue) currents along the eastern seaboard of Australia are shifting south as sea temperatures increase, bringing warmer waters to the Tasman Sea and across Northland (credit: The Commonwealth Scientific and Industrial Research Organisation, CSIRO).

### 1.1.2. Rainfall

Another expected outcome of climate change is increased rainfall in some parts of the country, with predictions for increased rainfall on the west coasts of both the North and South Islands and less rain in the east and north (Ministry for the Environment 2018). With an increase in extreme rain events, effects from terrestrial run-off and the associated inputs of trace metals into coastal waters (for example, from roads and car tyres) could also increase. Many landfills around Aotearoa New Zealand are at risk of inundation due to the combination of increased rainfall, rising sea levels and the potential for rising groundwater levels. For example, concerns have been raised about

the Kauri Road landfill beside the Waiarohia Inlet on the Waitematā Harbour, where zinc and arsenic levels are reportedly high (Tonkin & Taylor Ltd. 2018, 2019).
Even minimal increases in copper (Cu) and zinc (Zn) can dramatically affect toxin production by some bloom-forming microalgae. For example, Cu and Zn can cause increases in the production of domoic acid by toxic *Pseudo-nitzschia* species (Rhodes et al. 2006). Increases in Cu alone have led to increases in palytoxin-like compounds being produced by *Ostreopsis* cf. *siamensis* and okadaic acid diol esters by *Prorocentrum lima* in controlled experiments (Rhodes et al. 2006). Cu and Zn from road run-off have been shown to accumulate in shellfish at sites close to major cities in Aotearoa New Zealand (Stewart et al. 2013). The impact of increased metal contamination in the marine environment on biotoxin production is dependent on many complex factors, including the microalgal and shellfish species present and the metal-binding ligands (which allow biotoxin sequestration) present in shellfish. Further research of these factors is needed (Rhodes et al. 2006).

### 1.1.3. Ocean acidification

Some studies suggest that ocean acidification can benefit the dominant HAB taxa—dinoflagellates (Brandenburg et al. 2019)—more than other phytoplankton groups (Beardall et al. 2009) because they require less energy to capture $CO_2$. Experimental evidence shows that key HAB species such as the dinoflagellate *Alexandrium* (paralytic shellfish toxins producer), and the diatom *Pseudo-nitzschia* (domoic acid producer), may increase their cellular toxin content under ocean acidification scenarios (Tatters et al. 2013; Wingert et al. 2021). An understanding of the mechanism underlying this response is still lacking.

Coastal acidification is another concern. There are indications that some coastal waters already experience periods of intense acidification, and these regions may be highly vulnerable to further decreases in pH (Law et al. 2018). This has implications for the habitats of benthic dinoflagellates (substrate-attached), although the free-floating phytoplankton appear relatively resilient (Rhodes et al. 2020).

# 2. HAB EVENTS THAT HAVE IMPACTED PUBLIC HEALTH IN AOTEAROA NEW ZEALAND

## 2.1. Skin irritations caused by harmful algal blooms

In 2003, at Pukehina Beach, Bay of Plenty, a near-shore bloom of *Heterocapsa* caused serious skin irritations for swimmers and the species was later identified as *H. illdefina* (MacKenzie et al. 2004b). At Bream Bay, in sub-tropical Northland, a species most closely resembling *H. cirularisquama* has also been identified. This species is responsible for shellfish mortalities in Japan, but consumers of shellfish that have taken up the dinoflagellate show no signs of poisoning. Five *Heterocapsa* species have been recorded in Aotearoa New Zealand so far (Balci et al. 2020) but any toxic properties remain undescribed.

Large mats of *Lyngbya majuscula* were reported on Ōmana Beach for several years around the turn of the 21st century. No health effects were reported from exposure to the marine cyanobacterium, although strains of this species are known to cause skin, eye, and respiratory irritation (https://dermnetnz.org/topics/seaweed-dermatitis; Fujiki et al. 1984). Two toxins (Lyngbyatoxin-A and Malyngamide-S) have been identified from Ōmana Beach samples (Tricklebank & Hay 2007) and *Lyngbya* has been reported from the northern North Island to Hawke's Bay and is most prevalent in warm temperate to tropical regions (Nelson et al. 2015).

Internationally, blooms of *L. majuscula* have increased in abundance, severity, and duration in tropical and subtropical regions in recent decades (O'Neil et al. (2012). The increase in blooms has been associated with anthropogenic eutrophication and other forms of human disturbance (Nelson et al. 2015).

*Karenia brevisulcata* blooms may cause skin and eye irritations as well as severe headaches, sunburn sensations of the face, and respiratory illness (refer Section 2.3). This is a common dinoflagellate species which caused a major bloom event with associated illnesses in Wellington Harbour in 1998 (Chang et al. 2001).

*It is likely that as coastal waters become warmer, increased mats of* Lyngbya*, including toxic strains occurring in the north, may spread to more southern waters or increase in frequency. Very little research has been carried out on any marine cyanobacteria and it is an area to focus on in the future. The likelihood of increased blooms of the dinoflagellates* Heterocapsa illdefina *and* Karenia brevisulcata *is speculative and requires more research.*

## 2.2. Paralytic shellfish poisoning

Paralytic shellfish poisoning is caused by neurotoxic alkaloids in the STX group, currently the toxins of greatest concern for Aotearoa New Zealand. STX itself and the derivatives neosaxitoxin, decarbamoylsaxitoxin, and gonyautoxins 1,4 and 2,3 are highly toxic (Munday & Reeve 2013; Munday et al. 2013; Selwood et al. 2017) and are reported additively during the regulatory testing for their presence in shellfish in Aotearoa New Zealand. There are numerous (> 30) analogues with varying potency, all of which are based on the parent STX molecule. The STXs have a high affinity for voltage-gated sodium ion channels in nerve cell membranes, where they inhibit the generation of nerve impulses and cause neurological effects, including paralysis (Baden et al. 1995; Table 1).

Aotearoa New Zealand's biotoxin monitoring programme began in 1993 (see Section 2.3 below). It initially relied on a mouse bioassay to test for STXs, but this was replaced in 2010 by the Lawrence method, an AOAC-accredited approach based on liquid chromatography (LC) with fluorescence detection (Harwood et al. 2013). This method was time-consuming and complex for positive samples although it was useful for rapidly screening PSP negative samples. It was replaced in 2015 by a sensitive and selective liquid chromatography-mass spectrometry method for high throughput analysis using graphitised carbon solid phase extraction was recently approved as a regulatory method (Boundy et al. 2015; Turner et al. 2020).

Serious PSP illnesses were reported in the Bay of Plenty and Lakes district health areas in December 2012, when at least 29 recreational shellfish gatherers became ill following consumption of tuatua (surf clams; *Paphies subtriangulata*) collected along the Bay of Plenty coastline. Approximately half of those affected were admitted to hospital and two required intensive care for several days (ESR 2012). The illnesses occurred despite notices warning against harvesting due to the risk of PSP being in force. Shellfish tested contained high concentrations of STX and neoSTX and both toxins were also detected in the urine of one patient (MacKenzie 2014). This has been the most serious documented PSP event in Aotearoa New Zealand to date.

It should be noted that during a neurotoxic HAB event in 1993 (refer Section 2.3), STX positives were detected in tuatua (surf clams) in the Bay of Plenty. It is possible that PSP cases may have occurred then but were indistinguishable from the NSP cases which dominated at that time (Wilson 1996; Wilson and Sim 1996).

The causative dinoflagellates of PSP are species in the genus *Alexandrium*, *Gymnodinium catenatum*, and *Pyrodinium bahamense* (the latter, a tropical species not yet detected in Aotearoa New Zealand). *Alexandrium pacificum* (previously *A. catenella*), *A. minutum* and *G. catenatum* have all been regular bloom-formers around Aotearoa New Zealand's coastline (MacKenzie & Berkett 1997; Hay 2000; Hallegraeff et al. 2021b; MacKenzie et al. 2004a; MacKenzie 2014).

In recent years *Alexandrium pacificum* has caused many harvesting closures in the major green-lipped mussel growing region, the Marlborough Sounds. HABs of *A. pacificum* first appeared in Queen Charlotte Sound in 2011 and since then, large cyst beds have been recorded in Opua Inlet, off the Tory Channel (MacKenzie et al. 2014, 2016). Blooms have since been detected in the neighbouring Pelorus Sound, Tasman Bay and Golden Bay and are moving towards the West Coast of the South Island (Hallegraeff et al. 2021b).

An extensive study of *Alexandrium ostenfeldii* showed that this species occurs around the whole coastline of Aotearoa New Zealand, and while it is known for spirolide production, it may also produce saxitoxins and/or gonyautoxins. Toxin production is variable for *A. ostenfeldii* and some isolates have been non-toxic. The potential for PSP is high due to its widespread presence and the existence of cyst beds, which can give rise to new and extensive blooms (MacKenzie et al. 1996).

Another major HAB species which produces paralytic shellfish toxins is the dinoflagellate *Gymnodinium catenatum* (MacKenzie et al. 2014). Blooms were first detected in the North Island in May 2000 and lasted until 2003, during which time they caused widespread contamination and closure of shellfish harvest areas (MacKenzie and Beauchamp 2001). There have been further blooms since then, and while there were some local accounts of illnesses associated with the bloom, no serious illnesses were reported. This was mainly due to health authorities issuing warnings to the public to avoid harvesting shellfish for over 1500 km of coastline for periods of up to nine months (MacKenzie et al. 2014). *Gymnodinium catenatum* in Aotearoa New Zealand has similar toxin profiles to strains worldwide (Costa et al. 2014, MacKenzie et al. 2014), generally producing low toxicity analogues (‘GC-toxins’) (Negri et al. 2003). However, internationally, instances of serious human illness have resulted from the consumption of shellfish contaminated with *G. catenatum* toxins (e.g., Rodrigues et al. 2012), reinforce the need for appropriate monitoring programmes.

*Major* Alexandrium *blooms already occur in the North Island and more recently novel blooms have occurred in the temperate waters of the Marlborough Sounds. The genus does occur as far south as Rakiura Stewart Island. Blooms could become an issue in the southern regions if climatic conditions continue to favour toxic species. The* G. catenatum *blooms may also become an issue in more southern regions as sea temperatures increase. Regular monitoring for the PSP causing dinoflagellates gives confidence that consumption of toxic shellfish can be prevented as long as public health notifications are followed.*

Table 1. Paralytic shellfish poisoning symptoms*.

- Tingling (pins and needles or paraesthesia)
- Numbness, spreading from lips and mouth to face, neck, and extremities
- Dizziness, headache
- Nausea, vomiting
- Arm and leg weakness, paralysis
- Respiratory failure and in severe cases, death

Note: No antidote - treatment for severe cases is use of life support systems until the toxin passes from the victim's system.

* Encyclopedia of Separation Science: https://www.sciencedirect.com/topics/pharmacology-toxicology-and-pharmaceutical-science/paralytic-shellfish-poisoning.

## 2.3. Neurotoxic shellfish poisoning

A massive bloom, dominated by the dinoflagellate *Karenia mikimotoi*, occurred in the Hauraki Gulf in 1993. A nation-wide shellfish harvesting closure was instigated after 180 cases fitting the case definition of NSP were reported (Table 2). Before the harvest closures were reversed, monitoring programmes were developed and continue to this day. Regulatory closures for the shellfish industry are based on shellfish flesh tests carried out through the biotoxin monitoring programme, but phytoplankton monitoring is also carried out to give risk alerts to the industry, and it is the monitoring approach carried out by MPI for most recreational/non-commercial shellfish harvesting sites.

The origins of the 1993 bloom were traced back to the El Niño climate conditions of 1992 and followed on from a series of earlier HABs, including the ciliate *Mesodinium rubrum*, which caused green-lipped mussels to appear to be bleeding (the bloom was non-toxic, but the shellfish were not acceptable to consumers), and the dinoflagellate *Noctiluca scintillans*, which coloured the water orange (Jasperse 1993; Rhodes et al. 1993; Todd 2002). Concerns arose when cats fed shellfish scraps in Whangārei, Northland (January 1993) were poisoned. It then became evident that human NSP cases had also occurred (Bates et al. 1993). In February 1993, many incidents of eye irritation and dry cough were reported by beach goers in Ōrewa, and this was recognised as NSP when compared with cases in Florida, USA, where *K. brevis* blooms and consequent NSP symptoms were common (Todd 2002).

Brevetoxins were confirmed at low levels in some shellfish, for example Pacific oysters from the Coromandel and green-lipped mussels from Northland (Ishida et al. 1995, 1996). The causative organism was not definitively identified at the time, although the ichthyotoxic species *K. mikimotoi* was the dominant *Karenia* species in the bloom. At the height of the bloom, pāua (*Haliotis iris*) fell from the rocks and mass mortalities of other marine animals were recorded, possibly due to ichthyotoxic compounds (Rhodes et al. 1993; MacKenzie et al. 1995), although low concentrations of brevetoxin-like lipid soluble toxins were reported in pāua (MacKenzie et al. 1995). The impact of *K. mikimotoi* on pāua was supported by the results of *in vitro* larval assays in which paua larvae died after exposure to bloom densities of the dinoflagellate (Shi et al. 2012). While *K. mikimotoi* may produce low levels of brevetoxins and gymnocin-C (Satake et al. 2002), *K. brevisulcata* was also present, although in low numbers (Todd 2002).

*Karenia brevisulcata* caused even greater devastation of marine life in Wellington in January–March 1998, killing a large variety of micro- and macroalgae, invertebrates and vertebrates in the harbour (Chang 1999; Chang et al. 2001). In human health terms, more than 500 cases of respiratory illness were reported with symptoms being a dry cough and sore throat, skin and eye irritation, runny nose, severe headaches and a sunburn sensation of the face. The symptoms resembled those caused by aerosolised brevetoxins and would have been caused by the dinoflagellate toxins being released from cells in sea spray. Considerable research into the causative compound(s) resulted in the characterisation of a suite of polycyclic ether toxins, including brevisulcatic acid (BSXs) and brevisulcenal toxins (KBTs), and some of these were shown to be considerably more toxic than known brevetoxins (Shi et al. 2012; Harwood et al. 2014).

Karenia *blooms have occurred in Aotearoa New Zealand for at least three decades, and it is unclear whether changes in sea temperatures will have an impact on these HAB occurrences. The brevetoxin-producing* K. brevis*, which has had serious impacts on tourism in Florida due to respiratory illnesses in visitors through aerosolisation of blooms, has not yet been detected in Aotearoa New Zealand waters. It does have a higher optimum temperature range (22–28 °C) than is currently found in Aotearoa New Zealand's coastal waters and so if introduced (for example, via ballast water), it could establish in northern waters where temperatures continue to increase above 21 °C.*

Table 2. Neurotoxic shellfish poisoning symptoms*.

| |
|---|
| • Nausea, vomiting, diarrhoea<br>• Paraesthesia of mouth, lips, tongue – may lead to distal paraesthesia<br>• Respiratory distress<br>• Dizziness, headache, vertigo<br>• Myalgia<br>• Ataxia<br>• Reversal of hot and cold sensations (as for ciguatera poisoning) |
| Note: No specific antitoxin available, the illness is generally self-limiting and therapy is supportive and symptom-driven |

*https://www.ncbi.nlm.nih.gov; https://www.floridahealth.gov/environmental-health/aquatic-toxins/_documents/nsp-medical-facts-2014-56kb.pdf.

# 3. MICROALGAE WITH THE POTENTIAL TO IMPACT PUBLIC HEALTH IN AOTEAROA NEW ZEALAND IN ASSOCIATION WITH CLIMATE CHANGE

## 3.1. *Pseudo-nitzschia* and amnesic shellfish poisoning

Domoic acid (DA) is a neurotoxin, an excitotoxic glutamate receptor agonist, produced by species in the diatom genus *Pseudo-nitzschia.* The genus is common throughout Aotearoa New Zealand, but of the sixteen species known to occur in Aotearoa New Zealand waters, only four are designated as high risk (*Ps. multiseries* and *Ps. australis*) or potentially high risk (*Ps. multistriata* and *Ps. pungens*) (Figure 3). Potentially toxic species are those that have many non-toxic strains, but also strains which can be highly toxic.

Domoic acid causes amnesic shellfish poisoning (ASP; Table 3), and during a major outbreak in Canada in 1987, consumption of contaminated blue mussels, resulted in 150 cases with symptoms that included memory loss, and three deaths were recorded. Histopathological follow-up revealed extensive neurotoxic injury in the amygdala and hippocampus, with neuronal death and astrocyte reactivity noted in the amygdala, hippocampus, olfactory cortex and thalamus (Subba Rao et al. 1988; Bates et al. 1989; Quilliam & Wright 1989; Carpenter 1990; Petroff et al. 2021).

Along the Northwest coast of the United States, recent increases in *Pseudo-nitzschia* blooms have been linked to warm periods such as El Niño, positive phases of the Pacific Decadal Oscillation, or record-setting marine heatwaves (Trainer et al. 2020). This has impacted DA concentrations in seafood collected along the Oregon coastline. In Aotearoa New Zealand, *Pseudo-nitzschia* blooms already occur around the coastline. Monitoring practices have ensured that ASP has been well managed, with DA having been monitored in shellfish since 1993 (Hay et al. 2000).

The Aotearoa New Zealand shellfish industry conducts biotoxin screening of their shellfish products prior to release for sale to ensure access to overseas markets. In contrast, for non-commercial harvest areas, seawater samples are analysed to determine the concentrations of *Pseudo-nitzschia* cells. Blooms of *Pseudo-nitzschia* are regularly reported. The monitoring results provide risk assessments for the shellfish industry and regulators (Rhodes et al. 2013; Hallegraeff et al. 2021b; Nishimura 2022) and help public health officials determine whether to post warnings of potential toxins in seafood for non-commercial harvesters. A recent report to the MPI advised on the appropriate cell concentrations for harvest closures (Nishimura et al. 2022).

Nishimura et al. (2021a) noted that despite intensive monitoring of shellfish in Aotearoa New Zealand since 1993 only one critically high DA concentration has been recorded in the digestive glands of scallops in 1994 following the collapse of a *Ps. australis* bloom in Bream Bay, Northland (Rhodes et al. 1996). More recently, a DA concentration above the regulatory level was reported in queen scallops' flesh collected from deep water off the coast of Otago, Aotearoa New Zealand in December 2020. These flesh products were not distributed to the market due to the toxin screening prior to release (Nishimura et al. 2021a). It should be noted that neither cooking nor freezing reduces the toxin content of contaminated seafood, although the process of canning may lead to some detoxification of the shellfish (Vieites et al. 1999).

Interestingly, another toxic species, *Ps. silvae*, was recently recorded in Japan (Funaki et al. 2022). It has the potential to be widely distributed from temperate to subtropical regions and as it can grow in coastal waters of up to 30 °C, it is another species to monitor for as the oceans warm.

No human illnesses due to DA poisoning have occurred by consumption of shellfish harvested in Aotearoa New Zealand to date. If cases were to occur, there is no antidote. The only treatment for severe cases is the use of life support systems until the toxin passes from the victim's system. Although the current regulatory limits have protected people from the acute effects associated with ASP, DA is an increasingly significant public health concern, particularly for coastal dwelling populations. There is some evidence of health effects following repeated exposures to toxin levels below the current safety guidelines (Petroff et al. 2021). The only human study dedicated to understanding the health effects of DA is the Communities Advancing the Studies of Tribal Nations Across the Lifespan (CoASTAL) cohort, based in the Northwest Pacific region, USA (Tracy et al. 2016). A study of adults associated with this cohort showed an association with low-level DA exposure and decreased verbal memory recall (Stuchal et al. 2020) and the authors hypothesized that this effect was an attenuated form of ASP in adults. In Washington State, USA, new guidance suggests limiting consumption of razor clams to 15 per month, particularly for pregnant women, nursing mothers, children, the elderly and people with compromised renal function (Petroff et al. 2021; https://wdfw.wa.gov/fishing/basics/domoic-acid/levels).

*As* Pseudo-nitzschia *blooms are already common throughout Aotearoa New Zealand, the most likely adverse effects from climate change would be through the input of trace metals into coastal waters where increased rainfall could result in more toxic blooms (refer to Section 1.1.2; Rhodes et al. 2006). There is a possibility that* Pseudo-nitzschia *HABs could increase in number or increase their geographic range during El Niño conditions or if marine heatwaves occur.*

Table 3. Amnesic shellfish poisoning symptoms*.

- Nausea, vomiting, diarrhoea, abdominal cramps (within 24 h)
- Dizziness, headache, disorientation (within 48 h)
- Short term memory loss (may be permanent)
- Motor weakness,
- Seizures, cardiac arrhythmias
- Profuse respiratory secretions, coma, possible death

Note: There is no known antidote; effects of chronic exposure to low levels of DA are of concern.

*https://doh.wa.gov/community-and-environment/shellfish/recreational-shellfish/illnesses/biotoxins/amnesic-shellfish-poisoning; Grant et al. 2010.

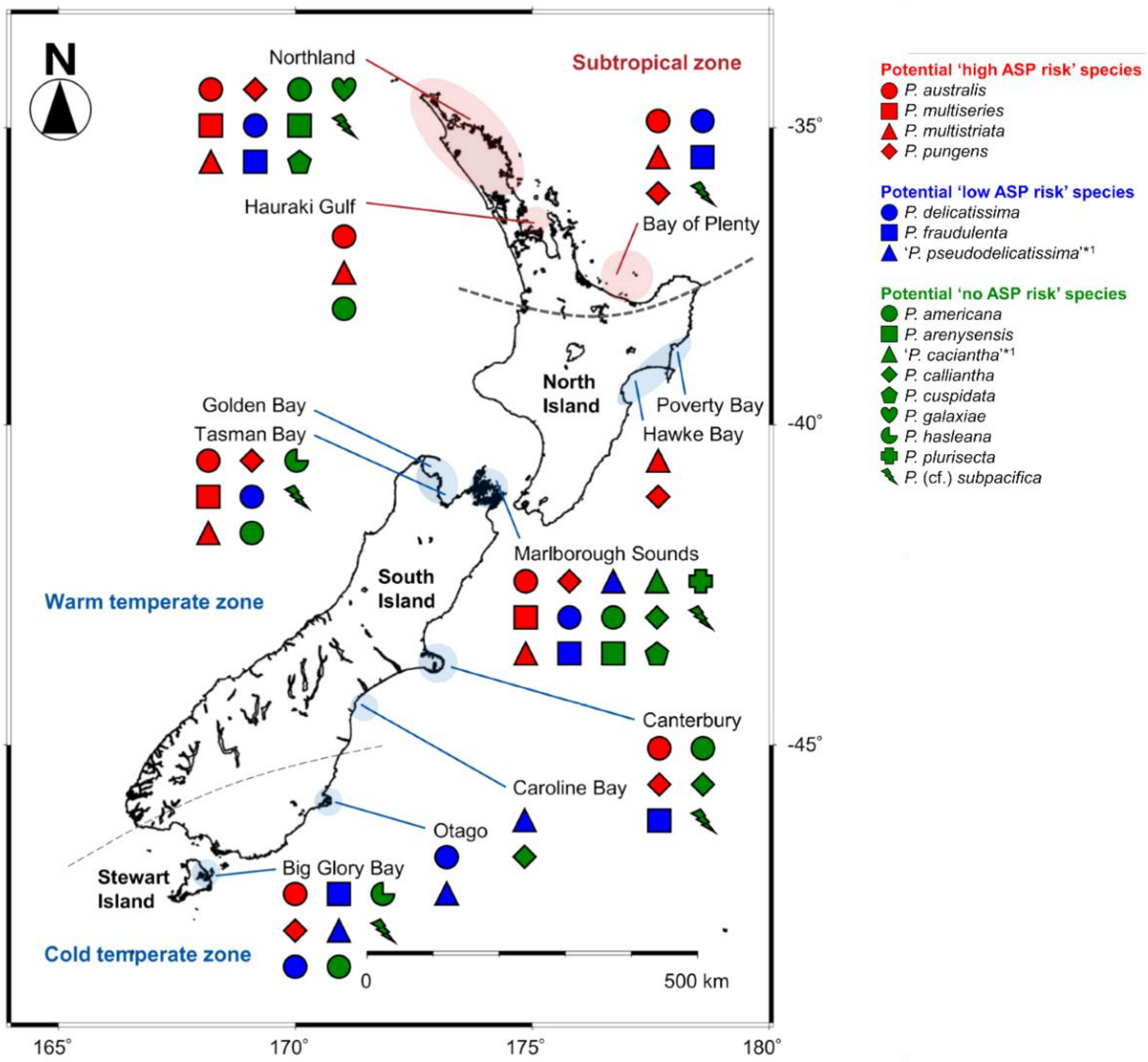


Figure 3. Distribution map of 16 *Pseudo-nitzschia* species in Aotearoa New Zealand coastal waters between 1993 and 2020. Red, blue, and green fonts indicate potential 'high, low, and no ASP risk' species; red, blue, and green shadings indicate sampling sites. *[1] Species identification should be treated as tentative (from Nishimura et al. 2021a).

## 3.2. *Azadinium*, *Amphidoma* and azaspiracid shellfish poisoning

Azaspiracid shellfish poisoning is an illness caused by toxin-producing species in the family Amphidomataceae. The illness is characterised by symptoms of nausea, vomiting and diarrhoea. The condition is not fatal, and recovery is usually within three days of exposure.

The first recorded incident occurred in the Netherlands in 1995 when diners became ill after consuming blue mussels (*Mytilus edulis*). The mussels were cultured in Ireland and the Irish shellfish aquaculture industry, with a value of > US$65M per year, suffered economic losses from closed markets until the issue was resolved (Satake et al. 1998; Twiner et al. 2008; Rhodes & Munday 2016). A new biotoxin management plan and monitoring regime was implemented. The toxins responsible were identified as azaspiracids (AZAs), although the planktonic microalga responsible for their production, *Azadinium spinosum*, was not identified until more than a decade later (Tillmann et al. 2009).

No AZA poisonings have occurred in Aotearoa New Zealand, but trace levels of AZA-1 and AZA-2 have been detected in shellfish by liquid chromatography with tandem mass spectrometry (LC-MS/MS; McNabb et al. 2005). The causative organisms do occur, particularly in temperate regions, but are difficult to identify by microscopy. To this end, molecular assays have been developed. This has led to the discovery of *A. poporum, A. dalianense, A. spinosum* and *Amphidoma languida* in Aotearoa New Zealand coastal waters (Smith et al. 2016; Balci et al. 2021).

*It is not known whether temperature fluctuations will lead to changes in the geographic spread of* Azadinium *and* Amphidoma. *It is possible that if blooms occurred or if toxin production per cell increased, there could be associated human illnesses. Monitoring of both AZAs in shellfish and the causative organisms in water samples will continue.*

## 3.3. *Vulcanodinium rugosum* and the cyclic imines, the pinnatoxins

The pinnatoxins (PnTX) are cyclic imine toxins produced by the dinoflagellate species *Vulcanodinium rugosum* (Rhodes et al. 2011a). The cyclic imines are regarded as emerging toxins in the European Union and a new toxin class, Spiroimine Shellfish Poisoning (SSP), has been proposed for them (Guéret & Brimble 2010), although no illnesses from shellfish consumption have been reported to date. Additionally, a bloom of *V. rugosum* was linked to acute dermatitis cases at two recreational beaches in Cienfuegos Bay, Cuba. The predominant toxins in the bloom were portimine, PnTX-E and PnTX-F. Sixty people who had prolonged contact with the dinoflagellate bloom suffered acute dermal irritation. Most patients (79.2%) were children and had to be treated with antibiotics; some required more than five days of hospitalisation (Moreira-González et al. 2021).

Pinnatoxins E, F and G were first characterised from razor clams and Pacific oysters from South Australia in 2007 (Selwood et al. 2010; Rhodes et al. 2011b). A year later, PnTX-E and -F were detected retrospectively in Pacific oysters collected and archived between 1994 and 2007 from Northland, Aotearoa New Zealand (McNabb et al. 2008; Selwood et al. 2010; Rhodes et al. 2011a,c). The toxins had caused the death of mice during regulatory biotoxin testing, and this led to precautionary harvesting closures for shellfish in both South Australia and Aotearoa New Zealand, although no illnesses were recorded.

*Vulcanodinium rugosum* mainly occurs in a non-motile form which divides asexually, and mats of this form were found around the edges of Rangaunu Harbour, Northland (Rhodes et al. 2011a; Mackenzie 2011). On rare occasions, the motile form would be taken up by oysters growing on racks in the harbour.

Different geographic strains of the species produce different pinnatoxin profiles and PnTX-E, -F (Aotearoa New Zealand strains) and -G (South Australian strains) are all highly toxic when given as intraperitoneal injections during mouse bioassays. Pinnatoxin-E is much less toxic by oral administration (of more relevance to human health), but PnTX-F has a median lethal dose that is still highly toxic by both gavage and voluntary intake by mice (Munday et al. 2012). This raises the concern that although there have been no toxic effects noted in humans to date in Aotearoa New Zealand, particularly in Northland where *V. rugosum* blooms are detected (McNabb et al. 2012), a high concentration of the toxin in consumed shellfish could result in extremely unpleasant adverse effects (Munday et al. 2012). The highest level of PnTX-F so far recorded in Aotearoa New Zealand Pacific oysters is 160 mg/kg. An acute oral toxicity study of PnTX-G calculated an oral $LD_{50}$ for PnTx-G of 208 µg $kg^{-1}$ and estimated a provisional NOEL of 120 µg $kg^{-1}$ (Sosa et al. 2020). It is possible that at least PnTX-G will be regulated in Europe in the foreseeable future.

Research carried out at the University of Otago demonstrated neuromuscular blocking activity in rat hemidiaphragm preparations, and that PnTX-E, -F and -G target nicotinic receptors (Hellyer et al. 2011, 2013, 2015). An observed decline in respiration rates in mice leading to death by asphyxia is consistent with inhibition of neuromuscular transmission (Munday et al. 2012).

Vulcanodinium rugosum *is typically sub-tropical, and it is likely that the geographic range will spread further south with warming coastal waters. It may be fortuitous that concentrations of the toxin in shellfish have not been sufficient to cause illness in Aotearoa New Zealand, or in fact globally. Despite this, the French agency responsible for food safety (ANSES) has recommended that pinnatoxins be considered within the French shellfish biotoxin monitoring programme (Arnich et al.*

*2020). A risk profile of cyclic imines in shellfish is currently in preparation (Harwood et al. 2022).*

## 3.4. *Dinophysis* and *Prorocentrum* species, the cause of diarrhetic shellfish poisoning

Blooms of the temperate planktonic dinoflagellate species *Dinophysis acuminata* and *D. acuta* have been documented throughout Aotearoa New Zealand, with *D. acuminata* occurring most years in an important green-lipped mussel growing area, Port Underwood, in the Marlborough Sounds (MacKenzie et al., 2005; MacKenzie, 2019). The cellular toxin content of the bloom-forming *D. acuminata* is low and the toxin profile is dominated by pectenotoxin-2 and dinophysistoxin-1 (DTX-1; MacKenzie, 2019).

Suspected historical cases of diarrhetic shellfish poisoning (DSP; Table 4) have been reported in Aotearoa New Zealand (MacKenzie et al. 2002) and these were from non-commercial shellfish prior to the use of liquid chromatography mass spectrometry in the risk management programme. They are anecdotal reports and the risk of exposure to the diarrhetic shellfish toxins (DSTs) of concern, okadaic acid (OA) and DTX-1, is considered small in Aotearoa New Zealand (Boundy et al. 2020). As reported by Boundy et al., of those Aotearoa New Zealand shellfish samples analysed during the decade between 2009–2019, only 4.2% contained DSTs with only 0.4% of samples over the current maximum permissible level of 0.16 mg OA mg/kg and a maximum concentration of 1.4 mg/kg. The absence of outbreaks supports the conclusion that the existing regulatory limit is fit for purpose.

*Prorocentrum lima* is a ubiquitous and predominantly benthic dinoflagellate which has rarely been reported in phytoplankton monitoring, and then only following storms that have disturbed the mats which had grown on benthic substrates. It is not considered of concern in terms of human illness, although strains of *P. lima* produce OA and DTX-1 in Japan. Interestingly those isolated from temperate shallow coastal waters (from clades 1e and 1i) produced both toxins whereas those that produced just OA or OA and extremely low DTX-1 were from sub-tropical shallow waters (Nishimura et al. 2020).

In Aotearoa New Zealand waters strains of the *P. lima* complex occur from sub-tropical to temperate zones. Nishimura et al. (2021b) noted that different strains may produce OA or both OA and DTX-1 and that whereas another toxic *Prorocentrum* species, *P.* aff. *foraminosum,* has strains that produce OA others do not, although all strains tested produce DTX-1. No other *Prorocentrum* species reported so far in Aotearoa New Zealand waters produce diarrhetic toxins.

Globally, OA-group toxins have been known to cause DSP since the late 1970s, although no deaths have been reported (Munday 2014). It has been suggested that OA-group toxins could be associated with gastrointestinal tract cancers (Cordier et al. 2000) but this view is considered controversial. In a case of human intoxication from shellfish containing acyl derivatives of DTX-1, only free DTX-1 was observed in the faeces, suggesting that hydrolysis of OA-group esters can occur within the human gastrointestinal tract (García et al. 2005). Based on the available evidence, the European Food Safety Authority panel concluded that the mechanism by which OA induces diarrhoea in humans includes submucosal fluid accumulation in the intestine wall, with the fluid then crossing the epithelial barrier eventually being secreted into the intestinal lumen (EFSA 2008).

*Although DSP is considered of concern globally, it is unclear whether climate change will have a major impact on bloom development or human health in Aotearoa New Zealand. Mats of* P. lima *have already been recorded in Northland and blooms of* Dinophysis *have occurred throughout temperate Aotearoa New Zealand without any confirmed DSP cases. Continued monitoring for the dinoflagellates in seawater and for OA and DTX-1 in shellfish flesh will minimise the risk of DSP outbreaks in Aotearoa New Zealand.*

Table 4. Diarrhetic shellfish poisoning symptoms*.

| |
|---|
| • Diarrhoea (most common symptom), nausea, vomiting, and abdominal pain<br>• Reversal of hot and cold sensations (as for ciguatera poisoning)<br>Note: Symptoms generally resolve within 2-3 days. |

*https://doh.wa.gov/community-and-environment/shellfish/recreational-shellfish/illnesses/biotoxins/diarrhetic-shellfish-poisoning.

## 3.5. *Ostreopsis* species: producers of palytoxins

The benthic HAB genus *Ostreopsis* is another toxic dinoflagellate, species of which may produce palytoxin-like compounds. Palytoxin is an intense vasoconstrictor and is considered one of the most poisonous non-protein substances known, second only to maitotoxin (MTX) in terms of toxicity in mice (MTX-1 is produced by *Gambierdiscus australes*, refer section 4). Palytoxin is a polyhydroxylated and partially unsaturated compound with a long carbon chain. It was first recorded in Hawaii in a species of zoanthid, *Palythoa toxica*, a reef-dwelling organism related to corals and resembling a cluster of miniature anemones. There is no specific treatment or antidote for palytoxin poisoning with medical treatment limited generally to supportive care.

Six of the eleven recognised species of *Ostreopsis* are toxic. A serious issue is respiratory illness due to inhalation of aerosols, and this has been of particular concern in the Mediterranean Sea in recent years (Table 5). The key species of concern in that region has been *O. ovata*, a producer of ovatoxins (Amzil et al. 2012; Tartaglione et al. 2017). Exposure to aerosols of the palytoxin analogue ovatoxin-a have resulted mainly in respiratory illness. *Ostreopsis ovata* has been recorded in Aotearoa New Zealand, although in low concentrations (Chang 2000) and palytoxin has not caused health issues in Aotearoa New Zealand to date.

*Ostreopsis* cf. *siamensis* (also referred to as *Ostreopsis* sp. 9), was first observed in Northland in 1995 (Chang 1996; Rhodes et al. 2000). It has become a major bloom former in the Hauraki Coast in recent years and has been recorded in low numbers as far south as the cool temperate coastal waters of Wellington (records from Aotearoa New Zealand's National Marine Biotoxin monitoring programme). Even visible blooms are not always detected in water samples as *Ostreopsis* usually occurs as mats attached to shallow reefs and macroalgae (Shears & Ross 2009).

A palytoxin-like compound produced by Aotearoa New Zealand strains of *Ostreopsis* cf. *siamensis* (toxic as determined by intraperitoneal injection of mice; Rhodes et al. 2000) is distinguishable from palytoxin and ostreocin D by liquid chromatography-mass spectroscopy; it has yet to be fully characterised (Munday 2008, 2011). The toxin has been detected in shellfish gut contents both in the wild and in laboratory feeding studies, although concentrations have been low (Briggs et al. 1998; Pearce et al. 2001; Rhodes et al. 2002, 2008, 2009). Crabs may take up palytoxin-like compounds, for example through feeding on shellfish contaminated with *Ostreopsis* (Yasumoto 1986; Rhodes et al. 2009). To this end, New Zealand's Ministry of Primary Industries and Ministry of Health have issued advisories that crabs for export or local consumption should be gutted before cooking and flesh removal. Kina (sea urchins; *Evechinus chloroticus*) are particularly vulnerable to *O.* cf. *siamensis* blooms in Aotearoa New Zealand and mass mortalities have occurred (Shears & Ross 2009). Consumption of dead kina is unlikely, and it is unknown whether this could pose a health risk.

Many incidents of poisoning through the handling of soft corals which carry the dinoflagellate (for example, those held in aquaria), have been reported globally and some incidents have resulted in the development of serious symptoms (Hoffmann et al. 2008; Pelin et al. 2016).

*No incidents of human illness have been associated with* Ostreopsis *species in Australasia, but future respiratory illnesses cannot be ruled out for New Zealand as blooms of* O. ovata *may develop with warming sea temperatures. Both* O.*cf* siamensis *and* O. ovata *are likely to extend their range southwards.*

Table 5. Palytoxin poisoning symptoms*.

| |
|---|
| • Skin symptoms: rash (hives), itching, numbness, dermatitis<br>• Flu-like symptoms[#] such as coughing, fever, chills, sore throat, headache, muscle aches, chest pain<br>• Respiratory symptoms[#]: wheezing, tight chest, shortness of breath, runny nose, fluid in the lungs<br>• Gastrointestinal symptoms: abdominal cramps, nausea, vomiting, diarrhoea<br>• Ocular symptoms[#], conjunctivitis, photophobia, blurred vision, corneal ulceration<br>• Neurological symptoms: fatigue, dizziness, speech disturbance, bitter metallic taste, tremors, tingling or numbness of extremities<br>• Muscle symptoms: pain, weakness, cramps, spasms<br>• Cardiac effects: irregular, slow, fast hear rate, cardiac muscle damage, low or high blood Pressure<br><br>Note: In severe cases muscle breakdown, kidney failure, coma, and death from cardiac or respiratory failure. |

*https://www.sahealth.sa.gov.au/wps/wcm/connect/public+content/sa+health+internet/conditions/poisons/palytoxin+poisoning+marine+aquarium+safety; #: includes ovatoxin-a symptoms.

# 4. CIGUATERA POISONING EXPECTED WITH RANGE EXPANSIONS DUE TO CLIMATE CHANGE

## 4.1. The dinoflagellate *Gambierdiscus*: the cause of ciguatera poisoning throughout the Pacific region

Ciguatera poisoning (CP) is the most common non-microbial food-borne illness globally and is caused mainly by the consumption of fish contaminated with *Gambierdiscus* toxins, the ciguatoxins (CTXs) and possibly maitotoxins (MTXs) (Munday et al. 2017; Murray et al. 2018, 2020a, 2021). Any predatory fish can be carriers of CTXs, which do not affect the appearance or taste of the fish, so consumers will be unaware that the toxin is present. Freezing or cooking the fish once it has been contaminated will not degrade the toxin or prevent CP. Some gastropods and bivalve molluscs have also been reported as being contaminated (Roué et al. 2018).

The severity of the symptoms of CP will depend on previous exposures to CTXs so consumers of the same meal may exhibit different levels of distress. While acute symptoms can include severe neurotoxicity (indicative of central and peripheral nervous system injury; Table 6), chronic CP is also of concern. It may lead to anxiety, impairment of spatial reference memory and decision-making behaviour in test animals (Wang 2016). In humans, triggers of CP symptoms have been noted, for example, there may be sensitisation to non-toxic fish. Avoidance of alcohol, caffeine, fish sauces and nuts for six months following CP is advised as they may cause symptoms to recur. Strenuous physical activity should be avoided, and men are advised to use a barrier protection while having sexual activity for six months to avoid passing on the toxins. As CTX has also been identified in breast milk, it is possible that affected mothers could pass this disease to their nursing children (https://www.rph.org.nz/public-health-topics/illness-and-disease/ciguatera-fish-poisoning/ciguatera-fish-poisoning-factsheet.pdf; https://rarediseases.org/rare-diseases/ciguatera-fish-poisoning).

The CTXs from the Pacific region are produced by *G. polynesiensis* (Rhodes et al. 2017a, b), although more Pacific CTX producers may be found in the future. In fact, *G. polynesiensis* and *G. australes* (which produces MTX-1) occur throughout the south-west Pacific region, including the Kingdom of Tonga, the Cook Islands and Rangitāhua Kermadec Islands (Smith et al. 2017; Rhodes & Smith 2018). The toxin is cumulative and poisoning symptoms, which usually start between 1 and 48 hours after consumption of toxic fish, may differ for people eating the same meal depending on their previous CP history. Deaths from CP have been recorded.

Socioeconomic impacts from CP are also apparent and a study in the Rarotonga (southern Cook Islands) demonstrated that CP halved the per-capita fresh fish consumption and consequently, the consumption of alternative proteins (e.g., imported meat) has increased between 1989 to 2006 (Rongo & van Woesik 2012). The economic consequences of this decline in consumption of locally caught fish amounted to approximately NZD $750,000 per year and costs associated with dietary shifts amounted to NZD $1 million per year. These changes may have long-term health-related consequences, and alter the social, cultural, and traditional characteristics of a subsistence fishing lifestyle (Rongo & van Woesik 2012).

*Gambierdiscus* has only been reported once (as a single cell) in the northern waters of New Zealand (Chang 1996). It is, however, common in Rangitāhua Kermadec Islands, an Aotearoa New Zealand territory 1000 km to the north-east of New Zealand. The CTX-producing species, *G. polynesiensis,* has been isolated from samples from Rangitāhua Kermadec Islands (Rhodes et al. 2017a).

The closely related genus *Fukuyoa* has been found regularly during sampling carried out around Northland, particularly in the Bay of Islands (Rhodes & Smith 2018). Although *F. paulensis* (previously known as *Gambierdiscus yasumotoi*) is non-toxic, it is found in similar habitats to toxic *Gambierdiscus* species*. Fukuyoa* has been isolated most often from coralline macroalgae, but both *Fukuyoa* and *Gambierdiscus* can live epiphytically on a variety of macroalgae, eel grasses and coral substrates.

Interestingly, *Gambierdiscus* blooms have been recorded in more temperate regions of south-eastern Australia in recent years, indicating the ability to adapt to cooler waters. This compounds the likelihood of it eventually blooming in Aotearoa New Zealand waters. In Australia, CP cases have been mainly linked to eating CTX-contaminated Spanish mackerel, although tropical reef fish have been implicated in Queensland intoxication events. More than a thousand CP cases have been reported in Australia over the last four decades, including two fatalities, but since the reporting rate is thought to be extremely low, this perhaps represents only 10% of actual cases (Farrell et al. 2016; Friedman et al. 2008).

No cases of CP from locally caught and consumed fish have been reported in Aotearoa New Zealand, but as dinoflagellates related to *G. polynesiensis* do occur in Aotearoa New Zealand's far north, it is feasible that CTX producers will establish in the warming coastal waters and that local cases of CP may occur in the future.

*An analysis of a database of reported fish poisonings in the South Pacific showed a strong correlation between the annual incidence of CP and local warming of sea surface temperatures compared to a decade ago, including a link to El Niño conditions. Ongoing monitoring for* Gambierdiscus *in Northland coastal waters is critical to support the implementation of risk management measures for CP, if this algae becomes established.*

Table 6. Ciguatera poisoning symptoms *.

- Tingling and numbness in extremities and around lips, tongue, mouth, and throat, itchiness
- Nausea, vomiting, diarrhoea and/or abdominal cramps
- Dizziness or light headedness; fatigue and lethargy; headache
- Burning sensation or pain on contact with cold water; reversed temperature sensation
- Joint and muscle pains with muscular weakness
- Difficulty breathing in severe cases

Note: No known antidote. Chronic cases may occur.

*Regional Public Health, Hutt Valley District Health Board: https://www.rph.org.nz/public-health-topics/illness-and-disease/ciguatera-fish-poisoning/ciguatera-fish-poisoning-factsheet.pdf.

# 5. PACIFIC KAI MOANA – IMPORTED SEAFOOD

There is uncertainty as to how warming seas will impact CP cases, although an increase is to be expected (Llewellyn 2010; Kohli et al. 2015). CP is widely under-reported, and fatalities do occur. There is no reliable treatment or antidote; folk remedies based on the local floras are used in many Pacific Islands, and intravenous mannitol has been suggested as a possible treatment, although the efficacy of this substance has been disputed. Currently, treatment is largely supportive and symptom-driven, as a proven antidote has not yet been developed (Rhodes et al. 2020).

All CP cases reported in Aotearoa New Zealand to date have resulted from either (i) the consumption of contaminated reef fish by tourists who have returned to Aotearoa New Zealand from the Pacific Islands and then become ill, or (ii) from the consumption of reef fish imported from the Pacific Islands into Aotearoa New Zealand. Several cases of CP, linked to moray eel (*Muraenidae* sp.) brought back from Samoa and the Kingdom of Tonga have been reported (Armstrong et al. 2016; Waqanivavalagi et al. 2019).

Certainly, importing fish to Aotearoa New Zealand from the Pacific region has its risks. For example, in 2020 five people in the Canterbury Health District became ill (one was hospitalised) following the consumption of fish purchased as Fiji Kawakawa (camouflage grouper; Figure 4) and imported from Fiji. As noted by Murray et al. 2020b, meal remnants were analysed and contained CTXs, but other fish tested from the same consignment were negative, emphasising the importance of analysing the actual meal remnants (Murray et al. 2021).


Figure 4. Recall notice for a batch of fish, some of which caused ciguatera poisoning, Christchurch, Aotearoa New Zealand, 2020.

# 6. CONCLUSIONS

HABs are a common occurrence in Aotearoa New Zealand's coastal waters with El Niño conditions leading to increased events in northern waters. Microalgae are ubiquitous and nearly all the toxic genera described globally that can impact human health have been detected in Aotearoa New Zealand's sub-tropical and temperate coastal waters. It is likely that more toxic species from these genera will be recorded in the future through use of molecular tools that can detect cells at very low concentration. Increased bloom events can be expected with warming seas and changing currents. Sub-tropical species are expected to extend their range southwards, particularly following introduction events, for example, as attached to biofouling on ships' hulls, in ships' ballast water, or on rafting macroalgal mats, particularly with changes in the direction of major currents.

Due to the regular monitoring of toxins in shellfish for human consumption and the water column for microalgal producers, serious illnesses in Aotearoa New Zealand have mostly been avoided. In recent years, serious PSP illnesses have only occurred when public health advisories were ignored. Microalgal monitoring, which underpins risk management decisions, is currently focused on species present in the water column. New methods are needed to ensure that the arrival of epiphytic and benthic species or increases in uncommon species already in our waters are detected, particularly those species causing CP.

## 6.1. Knowledge gaps

- Temperature increases in our coastal waters are already underway. Future climate scenarios and associated changes in HAB distribution and abundance need to be modelled so that management actions can be informed. For example, the use of satellite-derived seawater temperature data, forecasted increases in seawater temperature and experimentally obtained temperature-growth relationships, could be used to project future distribution maps for species of concern. Some research is underway, but the list of species being investigated needs to be widened. Associated changes in the direction of currents due to temperature changes may facilitate the spread of sub-tropical HABs to more southern areas and should be considered when monitoring programmes are reviewed.
- Species that can cause respiratory illnesses and skin/eye irritations are understudied. For example, it is likely that as coastal waters become warmer increased mats of the cyanobacterium *Lyngbya*, including toxic strains, may spread to more southern waters or increase in frequency. Very little research has been carried out on any marine cyanobacteria and it is an area to focus on in the future.

- Knowledge on the impact of chronic exposure to HAB biotoxins on human health is lacking (e.g., domoic acid (DA), ciguatoxins). The common bloom-forming diatom *Pseudo-nitzschia* can produce DA (the cause of ASP) and studies focused on the functional effects of these toxins are needed, especially when considering the new evidence of human health consequences from chronic, low-level exposure.
- Regular monitoring of toxic epiphytic and benthic dinoflagellates is not currently undertaken except as part of on-going research projects. This should be considered if *Gambierdiscus* species become established in mainland northern Aotearoa New Zealand and the risk of CP increases. Current approaches to benthic/epiphytic monitoring are time-consuming so new methods, including field deployable methods, need to be explored or developed.
- The diatom *Pseudo-nitzschia* is well monitored in the water column but is most toxic when blooms collapse, and cells fall to the sea floor where toxins may be taken up by benthic marine animals such as scallops and kina. The diatom cells would also be picked up with better benthic monitoring approaches.
- Open ocean farming practices are now underway, but there is a lack of knowledge of open and deep water HABs in Aotearoa New Zealand, and how warming seas may impact them.
- The influence of climate change on microalgal species composition and community structure is not yet fully understood. In laboratory trials, increases in biotoxin production can be achieved by supplementing with certain trace metals *in vitro*, but this may be at the expense of cell growth. Conversely, optimisation of cell numbers in batch cultures can be at the expense of toxin production per cell. This highlights the potential for environmental impacts on HABs due to increased trace metal inputs into coastal waters with more heavy rainfall events predicted.
- Knowledge of the impacts of biologically essential trace elements on microalgal growth and biotoxin production includes the need to understand the role of trace metals in organic ligand complexes in shellfish and finfish and how this may impact on human illness.
- Information of the symptoms of biotoxin poisoning following consumption of toxin-contaminated seafood needs to be more widely disseminated. Illnesses such as CP, which appears to be increasing in Aotearoa New Zealand (although currently from imported seafood), requires actual meal samples to determine whether biotoxins are involved. Only then can the symptoms observed be directly linked to a biotoxin.

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