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Managing marine harmful algal blooms in recreational settings: a review of international approaches to guide risk management practice in Aotearoa New Zealand

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Managing marine harmful algal blooms in recreational settings: a review of international approaches to guide risk management practice in Aotearoa New Zealand

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Executive summary

Microalgae (microscopic algae) are ubiquitous in marine environments and are an extremely important component of this ecosystem. However, under certain conditions, some species produce toxins and form harmful algal blooms (HABs) that can negatively impact human health. The routes of exposure in recreational settings are via ingestion of contaminated water, inhalation exposure to aerosolised toxins and skin irritation through direct contact.

In Aotearoa New Zealand there have been incidents of recreational exposure to microalgal blooms and toxins resulting in respiratory and skin irritation issues. The influence of climate change on the distribution and occurrence of HAB species is not yet fully understood, but several HAB taxa or types of HAB events are likely to become more prevalent and / or require further investigation.

There is no specific guideline to manage marine HAB risk in recreational settings for Aotearoa New Zealand, although there are guidelines for cyanobacteria in both recreational fresh water and drinking waters. Monitoring for marine HABs and toxins from a seafood safety perspective is comprehensive and the responsibility of the Ministry for Primary Industries; this includes monitoring toxic species in seawater and their associated toxins in shellfish. There are also some existing platforms that could be utilised for communication of HAB events if warnings for recreational users in coastal waters are implemented.

Internationally, there are examples of well-developed guidelines for managing marine HAB risks, including for the benthic dinoflagellate *Ostreopsis* cf. *ovata* in the Mediterranean Sea and the planktonic dinoflagellate *Karenia brevis*, as well as for benthic marine cyanobacteria in Florida and marine harmful algae and cyanobacteria in Australia. These guidelines either recommend measuring the causative species throughout the framework or they provide guidance on what to measure. For some of these frameworks, the association between HAB / toxin concentrations and human risk is well established, while for others, data gaps still exist.

Saxitoxin is the only marine HAB-associated toxin that has a World Health Organization recreational guideline value, and we were able to develop a cell concentration threshold for saxitoxin-producing marine microalgae in recreational waters for Aotearoa New Zealand. However, there is a lack of knowledge on appropriate indicators for the development of HAB events, and more information is required to build robust risk management frameworks.

Other knowledge gaps that could present barriers for developing recreational guidelines for marine environments include monitoring techniques for aerosolised toxins and toxins that irritate skin via contact, sampling approaches for benthic marine HABs and mat-forming cyanobacteria, and the ability to accurately quantify toxins in various matrices.

Despite the knowledge gaps identified in this report, the development of guidance material based on current knowledge would assist with responding to marine HAB events in Aotearoa New Zealand.

1. Introduction and scope of document

Microalgae (microscopic algae) are the foundation of all marine food webs. These tiny life forms are critical to support our marine ecosystems, fisheries and aquaculture, and they are a substantial carbon sink. However, some species can form harmful algal blooms (HABs) – the rapid growth and accumulation of microalgal biomass in aquatic ecosystems. Various types of microalgae can form HABs, but most causative species are cyanobacteria, dinoflagellates, diatoms or haptophytes. These blooms are considered harmful because of the production of toxic secondary metabolites; in addition, 'non-toxic' species can cause negative health impacts due to the high levels of cellular biomass (e.g. the formation of scums / foams, hypoxia / anoxia of waterbodies and the release of toxic compounds such as hydrogen sulphide from degrading blooms / mats). HAB events can range from small and short-lived (days to weeks) to extremely large; for example, large events can spread hundreds of kilometres along coastlines and persist for months to years, often reoccurring over multiple years. The frequency, duration and severity of HABs appears to be increasing in many locations worldwide (MacKenzie 2014; IPCC 2019; Dai et al. 2023), with climate change and other anthropogenic factors (e.g. nutrient loading) being implicated (Behrenfeld et al. 2006; Trainer et al. 2020).

HABs are naturally occurring phenomena, and they can develop rapidly in response to changes in ocean conditions due to the quick doubling times of microalgae (Irwin et al. 2015). HAB events are closely tied and thus controlled by physical, chemical and biological characteristics of the waterbody (Trainer et al. 2020). There is evidence that occurrences of HABs can be exacerbated by human activities such as increased nutrients and sediments entering waterways from terrestrial activities (e.g. agriculture fertilisers, road run-off, deforestation). El Niño periods are also associated with increased HABs (Phlips et al. 2020). Speculation about 'HAB-favourable' conditions combined with the accelerated progression of climate drivers have led to the hypothesis that HAB frequencies and distribution will increase in the future, but a conclusive link between climate drivers and HAB occurrence has not been demonstrated. Climate-induced changes are multi-faceted and complex and include optimal temperatures, thermal mixing of the water column, catchment biogeochemistry and grazing / competition interactions. It is therefore difficult to isolate single causative factors due to the multitude of overlapping or interacting drivers (Wells et al. 2020).

The toxins produced by some HAB species can accumulate in shellfish, crustaceans and / or finfish, which then become toxic to human and animal consumers, causing illness or even death in severe cases. The human health risks associated with seafood in Aotearoa New Zealand are well characterised, and our monitoring systems for seafood safety associated with HABs are world leading. The Ministry for Primary Industries (MPI) is responsible for implementing monitoring (water and / or seafood) for marine biotoxins related to seafood safety risk, and for issuing warnings or implementing closures of seafood harvesting areas (MPI 2022). However, human health can also be negatively impacted by recreational exposure to aerosolised or waterborne toxins, and dermatological contact with HABs.

HABs are a common occurrence in Aotearoa New Zealand's coastal waters and increased bloom events can be expected with warming seas, changing currents and other human-mediated impacts (Rhodes and Smith 2022). In addition, guidelines and information for the protection of public health in relation to HAB risks in recreational settings (e.g. bathing, ocean activities, aerosols) are currently limited in

Aotearoa New Zealand. Health New Zealand | Te Whatu Ora and the Ministry of Health (MoH) through The Institute of Environmental Science and Research (ESR), commissioned Cawthron Institute to review international and local material on recreational management of marine HABs (with a focus on bathing, water sports and aerosols, but not recreational gathering of aquatic foodstuffs). The aims of the review were to determine the feasibility of developing guidelines for Aotearoa New Zealand and to identify current knowledge gaps that might limit their development and implementation. This report provides an assessment of:

- HABs in Aotearoa New Zealand that could impact human health in recreational settings
- current water monitoring practices in Aotearoa New Zealand that could be adapted for or included in HAB monitoring for recreational purposes
- a summary of international guidance for managing marine HABs in recreational settings
- a case study on developing recreational risk management practices for saxitoxin-producing marine microalgae (a key marine biotoxin class in Aotearoa New Zealand)
- knowledge gaps that could present barriers for developing recreational guidelines for marine HABs in Aotearoa New Zealand.

2. Health impacts from marine HABs

Routes of toxin exposure from harmful algal blooms (HABs) to humans vary depending on the species involved, the toxin, and even the location; however, all fall into one of three exposure routes: (1) ingestion of contaminated seafood or water (oral exposure); (2) exposure to aerosolised HAB toxins (inhalation exposure); or (3) skin contact with a HAB (dermal exposure). This report focuses on these known routes of human exposure risk to HABs, excluding ingestion via contaminated seafood (i.e. fish or shellfish).

2.1 Exposure via ingestion of contaminated water

Marine HABs can create extremely high concentrations or biomass of microalgae, which cause water discolorations that often turn the seawater red (commonly known as a red tide; Kirkpatrick et al. 2004), green or brown. Blooms may also result in the formation of scums, foam or mucilage / slime, which may contain higher levels of toxins and represent an increased risk to human health. These types of blooms are less common in marine environments compared with freshwater systems. However, while rare, there is evidence that ingestion of marine waters contaminated with HABs can cause serious human health impacts. For example, in 2020, five surfers drowned after asphyxiation in a massive foam bank in Dutch coastal waters that was caused by the HAB species *Phaeocystis globosa* (Peperzak and van Wezel 2023). This was the first report of human fatalities caused by a HAB in the Netherlands, and the first globally due to a *Phaeocystis* bloom. Cyanobacterial blooms in sheltered marine ecosystems (e.g. fjords, inland seas) have been associated with animal illness / death, highlighting a potential risk to human health via recreational activities in these types of ecosystems (e.g. *Nodularia spumigena* blooms in the Baltic Sea).

2.2 Exposure via aerosolised toxins

Under certain environmental conditions (e.g. high wind, high HAB biomass, high turbulence), toxins generated from HABs or fragments of HAB cells may become airborne, and subsequent inhalation of the generated aerosols can induce adverse health effects in human bystanders (Lim et al. 2023). Reports of respiratory symptoms and general feelings of unwellness following water contact or inhalation of aerosols associated with marine HABs are common worldwide. Reoccurring blooms of HABs, such as *Karenia brevis* in the United States (Jackson et al. 2022) and *Ostreopsis* spp. in Europe (Berdalet et al. 2022), have been associated with respiratory, gastrointestinal, neurological and dermatological effects. However, data on the levels of toxins in sprays / aerosols and their associated impacts are lacking, meaning that guideline levels for human health risks cannot currently be developed (WHO 2021).

Additionally, when HABs collapse, they decompose. Nutrients and carbon dioxide are released, and under certain conditions, other gases such as methane and hydrogen sulphide are also emitted (Watson et al. 2015). These gaseous by-products can cause respiratory and neurological effects, as well as a raft of other symptoms; for example, exposure to hydrogen sulphide can cause nausea, eye and respiratory irritation, insomnia, fatigue, loss of appetite, headache, irritability, poor memory, dizziness, loss of smell and conjunctivitis (OSHA 2024).

2.3 Irritation via skin contact

Marine cyanobacteria are known to produce toxins that cause severe contact dermatitis (commonly known as swimmer's itch or seaweed dermatitis; WHO 2021). The most common reported incidents are caused by the benthic mat-forming cyanobacteria historically identified as *Lyngbya* spp. (the genus *Lyngbya* has since been taxonomically reclassified and some of the bloom-forming genera are now known as *Moorea, Okeania, Dapis* and others; Osborne 2021). Human illness from cyanotoxins has mainly been reported in tropical locations (e.g. Hawai'i and Florida in the United States, Okinawa in Japan and Queensland in Australia), but there seems to be increasing occurrences in more temperate regions, including Aotearoa New Zealand. Less commonly, marine dinoflagellates have also been associated with dermatitis outbreaks among swimmers and fishers, including skin lesions, rashes, swelling of the face, dry lips and redness of the eyes (e.g. *Vulcanodinium rugosum*; Moreira-González et al. 2021; Chomérat et al. 2022). More severe cases can occur when HAB biomass is trapped under clothing, swimwear or wetsuits, resulting in prolonged contact with skin.

3. HABs in Aotearoa New Zealand that could impact on human health in recreational settings

3.1 HAB species present in Aotearoa New Zealand

There are many microalgal species, including cyanobacteria, that can cause illnesses in humans, and in Aotearoa New Zealand, there have been incidents of recreational exposure to harmful algal blooms (HABs) and toxins with resultant respiratory and skin irritation issues. Microalgal species that occur in Aotearoa New Zealand, and which have either caused human health impacts in recreational settings or have the potential to do so, are described below and summarised in Table 1.

Heterocapsa – planktonic dinoflagellates

Heterocapsa is a common bloom-forming genus found worldwide. Blooms of some *Heterocapsa* species have been associated with shellfish mortality events and strains have demonstrated cytotoxicity in the laboratory (Kim et al. 2000; Zingone and Wyatt 2005; Hanifah et al. 2022). There are currently 29 species in the genus (Molinari Novoa 2022), and while they can be readily identified at the genus level, many, including the noxious *Heterocapsa illdefina*, may need further investigation to confirm species-level information. This process can be time consuming, as species-specific characteristics, such as body-scales, can only be visualised using transmission electron microscopy (Iwataki et al. 2004). In addition, molecular detection methods for *Heterocapsa* species are limited (Lee et al. 2019). In 2003, a nearshore red-tide bloom of the species *H. illdefina* caused skin irritations to swimmers in the Bay of Plenty (MacKenzie et al. 2004); however, the toxins involved, and the mode of action were not characterised.

Karenia – planktonic dinoflagellates

A large-scale bloom of a *Karenia* species occurred in 1993 in the Hauraki Gulf and resulted in the closure of all shellfish harvesting ventures throughout Aotearoa New Zealand. This sentinel event was the biggest recorded HAB toxin occurrence in Aotearoa New Zealand's history and resulted in the development of the New Zealand Marine Biotoxin Monitoring Programme. The bloom was associated with reports of respiratory distress by beachgoers at Orewa Beach (north of Auckland city), as well as 180 reported cases of human poisonings due to neurotoxic shellfish poisoning (NSP) and the death of pets fed contaminated shellfish scraps (Jasperse 1993; Hallegraeff et al. 2021). The dominant species, and the species thought responsible, was putatively identified as *Karenia* cf. *mikimotoi*, which is a common bloom-forming species in Aotearoa New Zealand that has been associated with fish mortality events (Smith et al. 2007).

Karenia brevisulcata, a novel HAB species, bloomed in the Wellington Region in 1998, killing marine biota throughout Wellington Harbour (Chang et al. 2001). More than 500 instances of human illnesses were also reported, including skin, throat and eye irritations, headaches, a sunburn sensation to the face, and occasionally severe respiratory effects (Rhodes and Smith 2022). The toxins involved have subsequently been identified as brevisulcatic acids and brevisulcenal toxins (Hamamoto et al. 2012; Holland et al. 2012; Suzuki et al. 2014).

Although the holotype species of the genus, *K. brevis*, has been the cause of marine issues internationally, it has not been detected to date in Aotearoa New Zealand, as it requires warmer temperatures than are currently experienced in the surrounding oceans. However, warming seas are likely to lead to *K. brevis* becoming a higher risk. The species produces brevetoxins, and when aerosolised (e.g. due to choppy seas), the cells and toxins can cause respiratory and skin irritations in humans. Brevetoxins can accumulate in seafood and cause illness in humans (Watkins et al. 2008), as well as marine mammals, birds and turtles (Landsberg et al. 2009). This species blooms regularly along the Florida coast of the Gulf of Mexico. *Karenia brevis* can be readily identified by light microscopy and there are species-specific molecular assays available (Haywood et al. 2007; Elleuch et al. 2020). Many species in the genus can now be determined using real-time polymerase chain reaction (PCR) assays, which target the large subunit ribosomal RNA gene of the species and will speed up identification (Smith et al. 2014; Elleuch et al. 2020) of new occurrences. Monitoring for this genus should be straightforward, even for novel species, provided that DNA sequencing data for species of interest are available to develop detection assays.

Ostreopsis – planktonic and benthic dinoflagellates

The genus *Ostreopsis* includes species that may produce palytoxin analogues, including ovatoxins, ostreocins or mascarenotoxin (Pavaux et al. 2020), which are intense vasoconstrictors. Palytoxin is considered one of the most poisonous non-protein substances known and, with no specific treatment or antidote, medical treatment is generally limited to supportive care (Wieringa et al. 2014). Respiratory illness due to inhalation of aerosols from *Ostreopsis* cf. *ovata* has been of particular concern in the Mediterranean Sea in recent years (Tartaglione et al. 2017). *Ostreopsis* cf. *ovata* (which produces ovatoxins) has also been detected in the northern waters of Aotearoa New Zealand (Chang et al. 2000; Rhodes 2011), although it has not yet been reported to form blooms. There is, however, a risk that it may become problematic with warming seas. Commonly reported symptoms from exposure to aerosolised *Ostreopsis* cells include skin irritations, respiratory symptoms, and even ocular (e.g. blurred vision) and neurological symptoms (e.g. dizziness and speech disturbance).

Ostreopsis cf. *siamensis* is a major bloom-forming benthic dinoflagellate that is present along the east coast of northern Aotearoa New Zealand, from eastern Bay of Plenty to the Bay of Islands (Shears and Ross 2009), mainly attaching to (and even smothering) macroalgae. However, it is rarely detected by current planktonic microalgal monitoring programmes. Despite producing palytoxin-like compounds, *O.* cf. *siamensis* has not been linked to respiratory illnesses in these northern coastal areas of Aotearoa New Zealand, but it remains a potential risk species.

A sampling approach that is currently being tested uses artificial substrates to target benthic and epiphytic HAB species to determine the risk of this genus (Fernández-Zabala et al. 2019; Tester et al. 2022). The approach requires revisiting the sampling site 24–48 hours later to retrieve the sample device, which adds to resourcing costs.

Pfiesteria and *Pseudopfiesteria* – planktonic and benthic dinoflagellates

Pseudopfiesteria shumwayae and the closely related *Pfiesteria piscicida* were first discovered in eastern estuaries in the United States. The two dinoflagellate species have been implicated in lesions on fish and people in contact with estuarine water during fish kill events. Neurological symptoms suffered by researchers working with the organism in the laboratory have been a major concern, and experimental work with this dinoflagellate in the United States is now carried out under strict containment conditions. *Pfiesteria* was headlined by the United States media as "the Cell from Hell" (Morris 1999) and aroused such public concern that it is described by the more cynical as "*Pfiesteria* hysteria" (Terlizzi 2006). The toxicity of the species has been the subject of considerable debate (Morris et al. 2006).

Pfiesteria shumwayae and *Pseudopfiesteria* have been detected throughout estuaries in Aotearoa New Zealand using molecular methods and microscopy techniques (Rhodes et al. 2002; Rhodes et al. 2006). *Pfiesteria* is also one of three marine HAB taxa included in the Australian Guidelines for Managing Risks in Recreational Waters (NHMRC 2008; see sections below). The presence of these dinoflagellates in Aotearoa New Zealand waters (Rhodes et al. 2006) is a concern, and current monitoring is non-existent since the cells exist predominantly as a benthic life stage. However, molecular tests are available (Bowers et al. 2000) for monitoring programmes, if needed.

Vulcanodinium – planktonic and benthic dinoflagellates

A producer of cyclic imines, *Vulcanodinium rugosum,* was first detected in Aotearoa New Zealand through the shellfish monitoring programme, which at that time relied on the mouse bioassay for toxicity assessments. It has only been detected from the far north, in particular Rangaunu Harbour (Rhodes et al. 2011). Further research determined *V. rugosum* was the producer of cyclic imines known as pinnatoxins and portimine. Cyclic imines are not currently regulated in shellfish, but there is growing awareness of this issue in the European Union (Arnich et al. 2020). Cyclic imines are fast acting neurotoxins and exhibit neuromuscular blocking activity (Hellyer et al. 2013). This effect may only follow consumption of large quantities of contaminated shellfish and not dermal contact, but it does raise concern as to the potential toxicity of these compounds to humans. No illnesses from the consumption of seafood contaminated with cyclic imines have been recorded in Aotearoa New Zealand to date (Rhodes et al. 2011; McNabb et al. 2012).

Internationally, a bloom of *V. rugosum* was the cause of acute dermal irritation for more than 60 people, mostly children, in Cienfuegos Bay (Cuba), with antibiotics and hospitalisations required for some individuals (Moreira-González et al. 2021). A *V. rugosum* HAB event in Senegal was associated with record values for portimine (pinnatoxins were also present) and occurred in an offshore environment affecting artisanal fishers. The fishers, using hand-deployed fishing nets, suffered from severe dermal irritation to their faces, mouths and limbs, which were covered in pimples and lesions. Further research is underway to elucidate causative compounds and mechanisms of toxicity, as well the genetic signature of the strains involved (Hess et al. 2022).

Vulcanodinium rugosum has both motile (planktonic) and non-motile (benthic) life stages and would therefore require a benthic sampling approach and phytoplankton monitoring to reliably ascertain risk.

Phaeocystis – planktonic haptophyte

Phaeocystis spp. are small bloom-forming microalgae (haptophytes) found worldwide. Blooms of *Phaeocystis* spp. can form thick foul-smelling foams or scums on coastal beaches, especially during high winds or high wave activity due to the production of large quantities of extracellular polysaccharides (Karlson et al. 2021). *Phaeocystis* spp., including *P. globosa*, occur in Aotearoa New Zealand (Rhodes et al. 2012), and *Phaeocystis* spp. have caused massive mucilage-producing nuisance blooms (Chang 1983) that have clogged nets in Tasman Bay / Te Tai-o-Aorere and reduced fish catch, with records of such blooms dating back to the 1860s (Bradstock and MacKenzie 1981).

Decaying blooms are also associated with the production of compounds that create a foul odour (e.g. dimethylsulfoniopropionate / dimethyl sulfide). As such, these blooms are usually considered a nuisance rather than a HAB event (Karlson et al. 2021), but as described above, a *P. globosa* bloom in the Netherlands was linked with the death of five surfers, highlighting the potential risk associated with these types of events (Peperzak and van Wezel 2023).

Mat-forming marine cyanobacteria

In marine systems, cyanobacteria can be found onshore, nearshore or offshore, attached to roots and rocks, floating, planktonic, or on the benthos forming benthic cyanobacterial mats (Berthold et al. 2021). Growth of benthic cyanobacterial mats have been prominent in tropical and sub-tropical regions, but proliferations are increasing with ongoing nutrient inputs and climate warming; for example, benthic cyanobacteria are now becoming dominant on ocean floors and reefs (Paul et al. 2005; Paerl and Paul 2012; Berthold et al. 2021). Benthic cyanobacterial mats can also be a nuisance due to toxins and unknown secondary compound production. They can cause acute dermatitis as well as eye and respiratory irritation in humans via aerosolised toxins (Osborne et al. 2001). The mats can emit noxious odours when blooming and decomposing, decreasing dissolved oxygen and leading to hypoxia and fish kills (Ford et al. 2018). Despite causing negative ecological effects and being detrimental to human health, little is known about the biological and chemical diversity of marine cyanobacterial mats (Sharp et al. 2009; Engene et al. 2011).

Large mats, historically identified as *Lyngbya* spp., were reported on Omana Beach near Auckland for several years around the turn of the 21st century. Two toxins (lyngbyatoxin-A and malyngamide-S) were identified from Omana Beach samples (Tricklebank and Hay 2007). *Lyngbya* has also been reported from Northland to Hawke's Bay, and it is predicted that these marine cyanobacterial blooms will become more prevalent in other estuaries around the country as sea temperatures warm (Rhodes and Smith 2022). A very large bloom of marine cyanobacteria from the genus *Okeania* was reported around Waiheke Island in the summers of 2022 and 2023, and several hundred tonnes of the cyanobacteria washed up on popular beaches (Biessy 2023). The mats testing positive for lyngbyatoxin-a, which was also detected in shellfish present in the estuaries (Biessy 2024 [forthcoming]).

Recreational water activities may be a significant route of exposure to marine cyanotoxins in Aotearoa New Zealand where water activities can happen daily over the warmer months. Occupational exposure may also occur through work directly in or on waterbodies affected by mats or scums. During the blooms of 2022 and 2023 on Waiheke Island, local residents reported being affected with mild to severe breathing issues for several months and stayed inside their homes to avoid contact with the fumes and potential aerosolised toxins (Waiheke Local Board, pers. comm.). Filamentous marine cyanobacteria species can dry on fishing nets and result in contact with fresh and dried material, causing severe skin reactions as well as breathing difficulties for workers in the fishing industry (Grauer and Arnold 1961; Osborne et al. 2001). Potential routes of recreational exposure to marine cyanotoxins include direct contact via exposed body parts and cell material trapped under clothing (i.e. bathing suits or wetsuits), accidental swallowing of contaminated water, and inhalation of aerosols (Chorus and Welker 2021).

Nodularia spumigena – planktonic cyanobacteria

Nodularia spumigena occurs in brackish waters and produces the toxin nodularin. It blooms regularly in Te Waihora / Lake Ellesmere, which is intermittently open to coastal waters (MacKenzie 2016). *Nodularia spumigena* is known to occur in other brackish lakes around Aotearoa New Zealand (Etheredge and Pridmore 1987), although the occurrence of nodularin has not been investigated (MfE and MoH 2009). While no human illnesses have been reported, there is long history of stock deaths around the Canterbury lakes that experience *N. spumigena* blooms (Connor 1977). The blooms can be present in very high concentrations and appear as a thick surface scum. Exposure to *N. spumigena* (and other cyanobacteria) can cause skin rashes, nausea, stomach cramps, and tingling and numbness around the mouth and fingertips (Stewart et al. 2006). Exposure to the toxin nodularin can promote liver tumours and, in sufficiently high doses, can result in liver failure.

Table 1. Microalgal species that have caused human health impacts in recreational settings.

Species	Illness or symptoms in recreational settings	Toxins or risk	Reported in NZ
Heterocapsa illdefina	Skin irritations	Unknown	Yes
Karenia brevisulcata	Respiratory and neurological	Brevisulcatic acids, brevisulcenals	Yes
Karenia* cf. *mikimotoi	Respiratory and neurological	Unknown	Yes
Karenia brevis	Respiratory and neurological	Brevetoxins	No
Mat-forming cyanobacteria, *Lyngbya*-like species	Skin lesions, acute dermal irritation, eyes and throat irritation	Lyngbyatoxin-a	Yes
Nodularia spumigena	In humans: skin rashes, nausea, stomach cramps, tingling and numbness around the mouth and fingertips, liver damage. Reports of fatal dog poisonings	Nodularins	Yes
Ostreopsis* cf. *ovata	Neurosensory and neurological; Respiratory; Dermal; Cardiac: Digestive; Systemic (fever); Locomotor (muscle and joint pain)	Isobaric palytoxin (or palytoxin-like toxins), ovatoxins, ostreocins and mascarenotoxins	Yes
Ostreopsis* cf. *siamensis	Neurosensory and neurological; Respiratory; Dermal; Cardiac: Digestive; Systemic (fever); Locomotor (muscle and joint pain)	Palytoxin-like toxins, ovatoxins	Yes
Pfiesteria piscicida	Respiratory, lesions, cognitive impairment*	Unknown	Yes
Pseudopfiesteria shumwayae	Respiratory, lesions, cognitive impairment*	Unknown	Yes
Vulcanodinium rugosum	Skin lesions, acute dermal irritation	Pinnatoxins, portimine-A	Yes
Phaeocystis globosa	Asphyxia	Formation of foam on the water surface or slime	Yes

* There is still debate as to the harmful effects of exposure to *Pfiesteria* and *Pseudopfiesteria*.

3.2 HABs that may increase with climate change

We recently reviewed the potential effects of climate change on marine HABs and the implications for public health in Aotearoa New Zealand (Rhodes and Smith 2022). The influence of climate change on HAB species distribution and occurrence is not yet fully understood, but several HAB taxa or types of HAB events were identified as likely to become more prevalent and / or require further investigation.

- **Species that can cause respiratory illnesses and skin / eye irritations:** *Ostreopsis* blooms occur regularly along the northeastern Aotearoa New Zealand coastline, and as the waters warm, a more toxic but uncommon species, *O.* cf. *ovata*, could become dominant. As *O.* cf. *ovata* is an epiphyte on macroalgae, its monitoring is problematic and thus it needs consideration. Other HAB taxa present in Aotearoa New Zealand, such as the dinoflagellates *Karenia* and *Heterocapsa* and the *Lyngbya*-like cyanobacteria species, have been associated with skin, eye and respiratory irritation.
- **Benthic marine HABs:** Although benthic monitoring is not currently carried out in Aotearoa New Zealand it is a research area that requires urgent attention, especially 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 process will require development of cheap and rapid sampling methods / technologies that are tailored towards benthic taxa. Linking these approaches to molecular techniques, such as quantitative polymerase chain reaction (qPCR) or high-throughput sequencing metabarcoding, would create robust monitoring tools.
- **Current HAB forming species (both planktonic and benthic) will increase in frequency:** For example, *Karenia* spp. already bloom throughout Aotearoa New Zealand and *Vulcanodinium* occurs in sub-tropical Northland. Species that favour our northern waters (both planktonic and benthic) are likely to increase their range and incidence of blooms events as waters warm.
- **Mat-forming cyanobacteria:** For example, it is likely that as coastal waters become warmer increased mats of the cyanobacteria (*Lyngbya*-like spp.), 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.

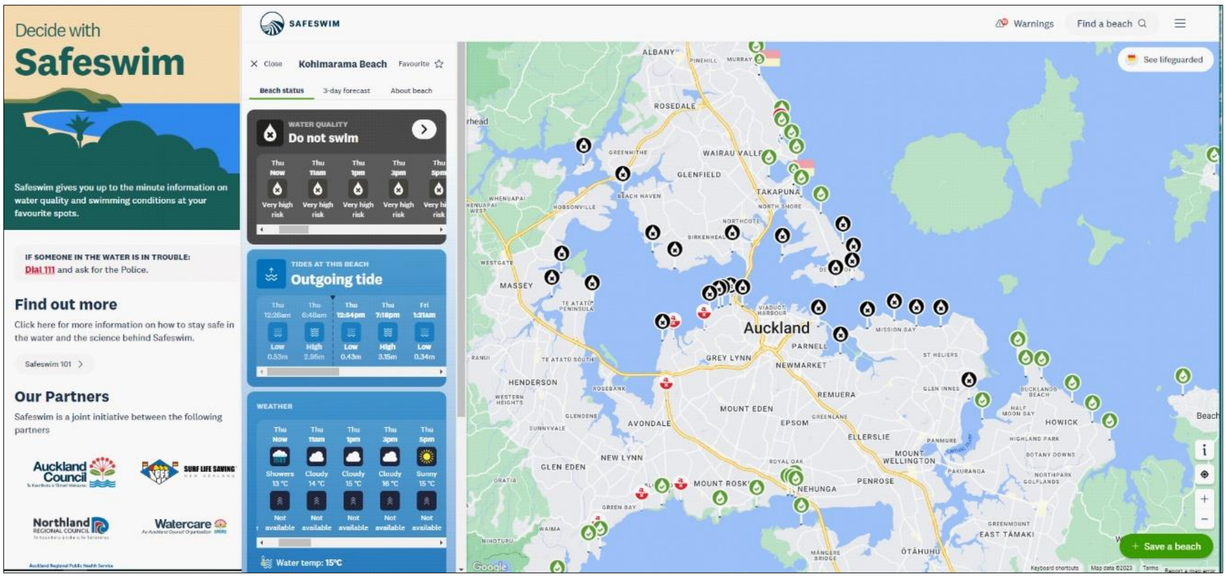
4. Current recreational water monitoring practices in Aotearoa New Zealand

There is a great deal of information available on harmful algal bloom (HAB) toxins that contaminate seafood and impact the economic state of the seafood industry in Aotearoa New Zealand (Hallegraeff et al. 2021). There is less information, however, on the risk from HABs to people using the extensive coastal areas of Aotearoa New Zealand for recreational activities. The coastline, with its many bays, harbours and fiords, stretches at least 15,000 km, with no location being more than 130 km from the sea (Walrond 2005).

In Aotearoa New Zealand there is no specific guideline for marine HAB risk in recreational settings, although there are the interim 'New Zealand guidelines for cyanobacteria in recreational fresh waters', which includes alert-level frameworks for both planktonic and benthic cyanobacteria (MfE and MoH 2009). The 'Guidelines for drinking-water quality management for New Zealand', also includes an 'alert-levels framework' for the management of cyanobacteria in water supplies (MoH 2020). Local public health officials are alerted to a risk of seafood contamination by marine HABs for a particular area if monitoring by MPI demonstrates that toxin levels are unsafe, or if potentially toxic HAB species exceed cell concentration thresholds. No alerts are provided for recreational risks such as aerosols or skin irritations. A review of the practices used for recreational gathering of seafood in Northland, Aotearoa New Zealand, whether to fulfil food needs or for enjoyment, was undertaken by Guy et al. (2021), but the report focused on biotoxin risk from shellfish consumption.

MPI relies on microalgal monitoring results to assess if there is a potential problem species and receives notification of biotoxin results from regular shellfish monitoring programmes. If there is a bloom of a microalgal species associated with a respiratory illness or other health issue, MPI will work with public health organisations and issue a public health warning (Piers Harrison, MPI, pers. comm.).

If a regulation regarding HAB risk to recreational users of the coastal domain is triggered, there are effective methods to communicate such risk. The website Safe Swim, which is hosted by Te Kaunihera o Tāmaki Makaurau | Auckland Council and Te Kaunihera ā rohe o Te Taitokerau | Northland Regional Council, provides information on beach hazards such as poor water quality (e.g. faecal contamination), jellyfish or sharks, or adverse swimming conditions (Auckland Council 2024; Figure 1). The website represents an ideal way to inform the public of HAB risk, although it has not yet been used for this purpose. Alerts can be posted from various appropriate sources, for example, Life Saving New Zealand. If HABs are included in a recreational guideline then, at least for Auckland and Northland, the Safe Swim website offers a suitable platform for alerts.



Decide with Safeswim

Safeswim gives you up to the minute information on water quality and swimming conditions at your favourite spots.

IF SOMEONE IN THE WATER IS IN TROUBLE:
Dial 111 and ask for the Police.

Find out more

Click here for more information on how to stay safe in the water and the science behind Safeswim.

Our Partners

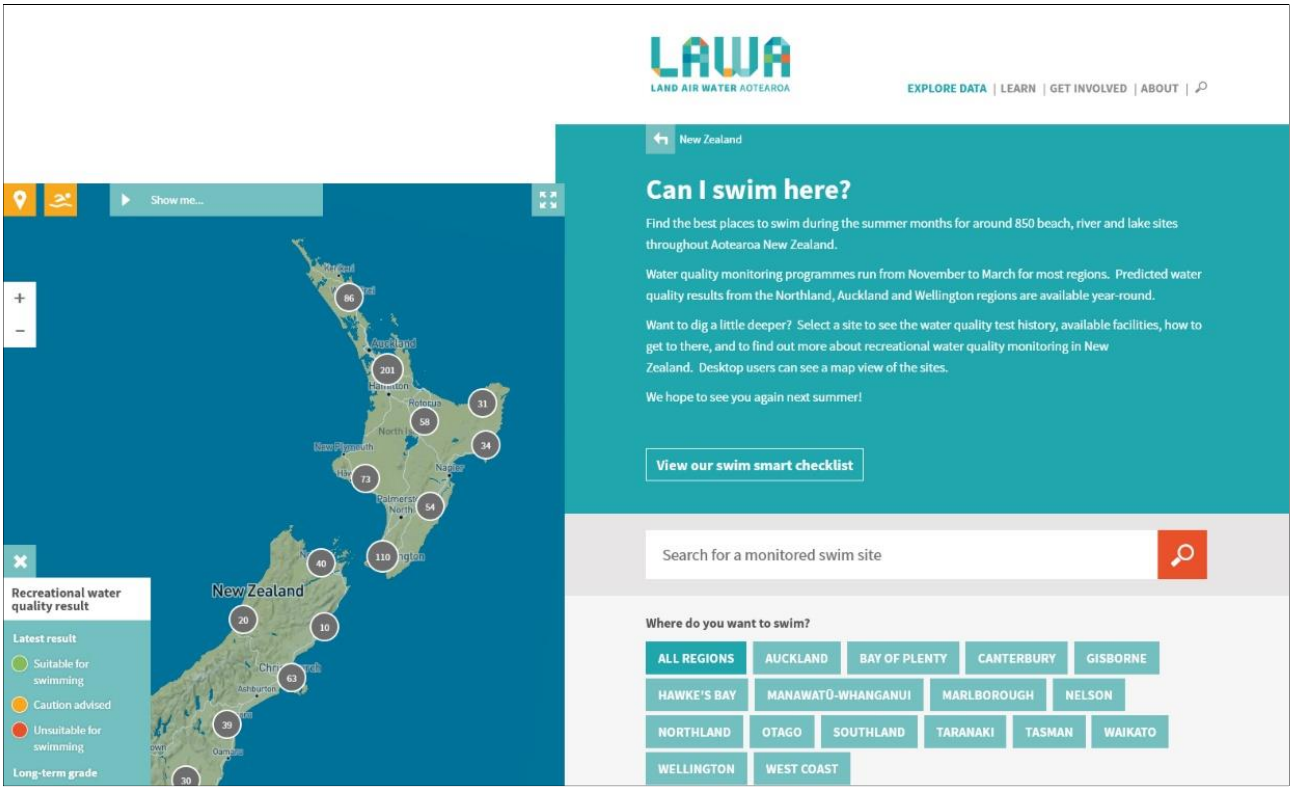
Safeswim is a joint initiative between the following partners

Figure 1. Left: Safe Swim website; Right: Advisory for Auckland City (accessed 28 September 2023).

The website LAWA (Land, Air, Water Aotearoa; www.lawa.org.nz; Figure 2) has been developed to allow beachgoers to check the health / risk status for recreational use. To quote the LAWA website:

> Initially a collaboration between New Zealand's 16 regional councils and unitary authorities, LAWA is now a partnership between the Te Uru Kahika – Regional and Unitary Councils Aotearoa, Cawthron Institute, the Ministry for the Environment, the Department of Conservation, Statistics New Zealand and has been supported by the Tindall Foundation and Massey University.

The website has a similar format to Safe Swim and can present results of samples taken by public health or regional council officials, therefore providing the same content as existing council sites. LAWA does contain some information that is specific to marine HABs, and most of the information relates to benthic and planktonic cyanobacteria in rivers and lakes, respectively. However, LAWA is potentially a good outlet for information on marine toxic algal blooms within the 'Can I swim here?' module.



Can I swim here?

Find the best places to swim during the summer months for around 850 beach, river and lake sites throughout Aotearoa New Zealand.

Water quality monitoring programmes run from November to March for most regions. Predicted water quality results from the Northland, Auckland and Wellington regions are available year-round.

Want to dig a little deeper? Select a site to see the water quality test history, available facilities, how to get to there, and to find out more about recreational water quality monitoring in New Zealand. Desktop users can see a map view of the sites.

We hope to see you again next summer!

Figure 2. LAWA 'Can I swim here?' website (accessed 7 November 2023).

5. International guidelines for managing marine HABs in recreational settings

Internationally, guideline values and alert-level frameworks for marine harmful algal blooms (HABs), including cyanobacteria, are limited. Moreover, data on the risk to human health associated with the occurrence of marine HABs during recreational activities are limited to a few species and geographic areas (WHO 2021).

The potential for HAB development in marine waters can be associated with environmental conditions, including elevated nutrient concentrations, particularly total nitrogen, warmer temperatures and water column stratification (Anderson et al. 2002). However, the environmental conditions that can be associated with excessive proliferation of certain HAB species can be species specific, and other biological factors such as competition and level of grazing pressure can also promote blooms (Davidson et al. 2014). These environmental factors can be used to trigger specific monitoring actions, such as initiation of or increased sampling efforts. The drivers of marine HABs are likely to be similar to those that cause freshwater HABs. The well-developed alert-level frameworks and associated indicator parameters for freshwater HABs may serve as a good starting point for the development of marine HAB alert levels.

The World Health Organization 'Guidelines on recreational water quality – coastal and fresh waters' (2021) are an update of the guidelines published in 2003. The more recent guidelines contain a section focused on toxic algae and cyanobacteria (chapter 5.2) and highlight the problem of marine cyanobacteria, such as the genus previously known as *Lyngbya* (now taxonomically reorganised into several genera, including *Moorea, Okeania, Dapis* and others). A brackish species that can bloom in brackish waters is also highlighted, namely *Nodularia spumigena*. Illnesses may result from contact with blooms, particularly if water is ingested. Severe contact dermatitis or lesions may also occur if bloom material is trapped under swimwear. The species that cause these effects are mat-forming and require a different monitoring approach to current water column monitoring practices. *Karenia* blooms are also noted in the WHO guidelines, as some species may cause skin irritation. More commonly, *Karenia* is known for causing respiratory issues and 'general malaise' which can result when sea spray containing cell fragments or toxins is inhaled. Such events have been reported as impacting on health services, and *Karenia* blooms have caused illness in Aotearoa New Zealand (Jasperse 1993; Chang et al. 2001; refer to Section 3).

Ostreopsis is another bloom-forming species in our waters, although, to date, it has not caused human health issues in Aotearoa New Zealand. In the Mediterranean Sea, *O.* cf. *ovata* has caused illnesses, and locally, this species has been reported in Northland waters (Rhodes 2011). Monitoring options are discussed within the guidelines, including methods for HAB toxin detection in sea spray, although more research and method development in this area is needed.

A joint technical guidance for the implementation of early warning systems for HABs was recently published by FAO et al. (2023). The document highlights that there is no 'one-size fits all' monitoring solution and regional responses and solutions should be the primary aim. Various new approaches for detecting blooms are highlighted, and the document also emphasises the need to identify HABs to the species level to avoid unnecessary closures. Benthic and planktonic species, including cyanobacteria, should be included, as well as reporting of HAB events from both brackish and marine environments. This reporting does require a reasonable level of expertise, whether microscopic or molecular approaches are implemented, including autonomous *in situ* technologies.

The FAO et al. (2023) guidelines stress the importance of collaboration between regulators (including scientists, policymakers, resource managers and monitoring agencies), the health sector and managers of water and food security. Stakeholders should include community members, recreational fishers and tourists. The impact on health support services in addition to beachgoers is highlighted in relation to *Ostreopsis* blooms in the Mediterranean Sea (FAO, IOC & IAEA 2023). Coordination between health, environment and scientific entities is seen as critical and is re-emphasised.

Prediction, magnitude of event, species and associated risk, and hotspots should all be addressed. In Aotearoa New Zealand, world-class monitoring programmes exist for the protection of consumers of seafood, and these programmes are the ideal way to move forward towards monitoring for recreational risk from HABs. Identifying the links between MPI and public health would be one way forward, with public health warnings being issued if a risk was assessed as being present.

As mentioned previously, in Aotearoa New Zealand, there are already excellent methods for communicating risk notifications and alerting public; however, an important advisory is that notices must be rescinded post bloom, both to avoid warning fatigue and the unnecessary restriction of recreational water sports activities. In the World Health Organization guidelines for safe recreational water environments, guideline values relevant for human health only exist for freshwater cyanobacteria toxins. One group of toxins, saxitoxins, are produced by both freshwater cyanobacteria and marine dinoflagellates (*Alexandrium* species, *Gymnodinium catenatum* and *Pyrodinium bahamense*), and this group has a guideline value of 30 µg/L of water. Internationally, guidelines do exist for marine HABs, but they are often specific to a single species and / or tailored towards a specific risk within a geographic region.

Below are three international examples of well-developed guidelines for marine HAB risks: the benthic dinoflagellate *Ostreopsis* cf. *ovata* in the Mediterranean Sea (Italy), the planktonic dinoflagellate *Karenia brevis* and benthic marine cyanobacteria in Florida (United States), and marine harmful algae and cyanobacteria in Australia.

5.1 Guidelines for the benthic dinoflagellate *Ostreopsis* cf. *ovata* in the Mediterranean Sea (Italy)

Ostreopsis cf. *ovata* is a benthic dinoflagellate that can produce palytoxin analogues, including ovatoxins. It has bloomed throughout the Mediterranean Sea and, in particular, along the Italian coasts since the early 1990s. Almost all Italian coastal regions are frequently affected by *O.* cf. *ovata* blooms (Funari et al. 2015). When blooms along coastal areas coincide with weather conditions favourable to the formation of onshore aerosols, *O.* cf. *ovata* can cause an influenza-like illness and respiratory symptoms in swimmers and coastal visitors. For example, in the summer of 2005, more than 200 people reported symptoms that were mainly linked to inhalation of marine aerosols, or more rarely to direct contact (Durando et al. 2007). Several other events associated with *Ostreopsis* blooms have occurred within the Mediterranean basin and more recently the French and Spanish Basque coasts (Berdalet et al. 2022; Paradis et al. 2024).

Following the 2005 outbreak in Genoa, the Italian Ministry of Health published the first guidelines for assessing and managing the human health risk associated with *O.* cf. *ovata* blooms along the coast in 2007. These guidelines were then updated in 2014 (Funari et al. 2014, 2015) by a panel of experts who referred to the increased knowledge disseminated in the scientific literature. The guidelines continue to be used by local authorities responsible for bathing water quality and management. The guidelines, which are for bathing water risk only, aim to protect the public from risk via ingestion of water, inhalation of aerosols and dermal exposure. Three phases of monitoring have been established – Routine, Alert, and Emergency, and information on the monitoring approaches and other details for each phase are provided (Table 1). Funari et al. (2015) explains, '*The aim of these guidelines is to prevent effects on human health associated with* Ostreopsis *cf.* ovata *blooms; therefore, the activities (…) should allow the early detection of presence of the marine algae and / or the onset of any health effects, in order to adopt the adequate preventive measures*.' The guidelines are supported by supplementary information on strategies, methods and protocols to carry out the activities (e.g. samples of different matrices, analyses, reporting to health authorities).

In regions with high risk – for example, those with multiple, reoccurring blooms – a multi-step surveillance system is suggested. This system involves increased communications with a wider range of stakeholders, including the general public and health care professionals, to create a cost-effective mechanism with more focus on prevention due to the limitations of monitoring activities (e.g. limited sampling locations, time lag between sampling and analysis).

Table 2. Guidelines to protect human health in bathing waters affected by *Ostreopsis* cf. *ovata* blooms. Source: Funari et al. (2015).

Phase of the monitoring plan (no. cells and environmental / meteorological conditions)	Level of health risk	Activities requested	Management measures
Routine: **(1) Density in the water column ≤ 10,000 cell/L regardless of meteorological conditions** **(2) Density in the water column 10,000–30,000 cell/L with a prolonged period (7–10 days) of sustained hydrodynamism and *T*« to optimal bloom *T****	Negligible	Monthly visual observations and / or routine monitoring	None
Alert: **(1) Density in the water column of 10,000–30,000 cell/L with prolonged period (7–10 days) of poor hydrodynamism and optimal bloom *T**** **(2) Density in the water column of 30,000–100,000 cell/L with meteorological conditions unfavourable to aerosol and spray formation**	Negligible Possible mild local and / or systemic signs or symptoms	• Intensification of monitoring • Assessment of the extension of the affected area • Health surveillance • Observation of effects on aquatic organisms • Chemical analysis of PLTXs in water and seafood • Information sent to health authorities	Information presented to the public aimed at preventing dangerous exposures
Emergency: **(1) Density in the water column > 30,000 cell/L and meteorological and hydrological conditions favourable to aerosol and spray formation** **(2) Density in the water column > 100,000 cell/L regardless of meteorological and hydrological conditions** **(3) Presence of dense material on the surface** **(4) Reports of human health effects that might be linked to a *O.* cf *ovata* bloom**	Contact: Possible local signs / symptoms Inhalation: Possible local signs / symptoms or respiratory and systemic effects Ingestion: Health surveillance; Possible local signs / symptoms due to contact; risk of systemic effects due to water ingestion	Beyond the activities of the alert phase • Health surveillance • Analysis of PLTXs in the aerosol • In case of a storm, cleaning of the shoreline	Information presented to the public to prevent dangerous exposures (posters, newsletters, signage, publications in national and regional portals; any order of ban by mayor)

* Temperature varies in the different regions.

The Italian guidelines also include sampling recommendations. Swimmers and children are considered to be at the highest risk during recreational activities, as they can ingest water containing a high number of *O.* cf. *ovata* cells, which would correspond to palytoxin concentrations that can cause severe systemic effects. Therefore, although *O.* cf. *ovata* is a benthic species, to reduce exposure to humans via oral and inhalation exposure, sampling of the water column is recommended.

> In order to protect human health by preventing oral and inhalation risky exposure, water is the matrix of interest to be sampled and analyzed. Benthic sampling is also suggested in shallow bathing waters, where direct contact with benthic material can be significant and/or its release into the overlying water column can lead to very high cell density. It is recommended to take a sample of the water column as much representative as possible, in one site of the bathing area where the risk of *Ostreopsis cf. ovata* proliferation is higher. Visible foam or floating materials should be collected separately, to further assess toxin content (Funari et al. 2015).

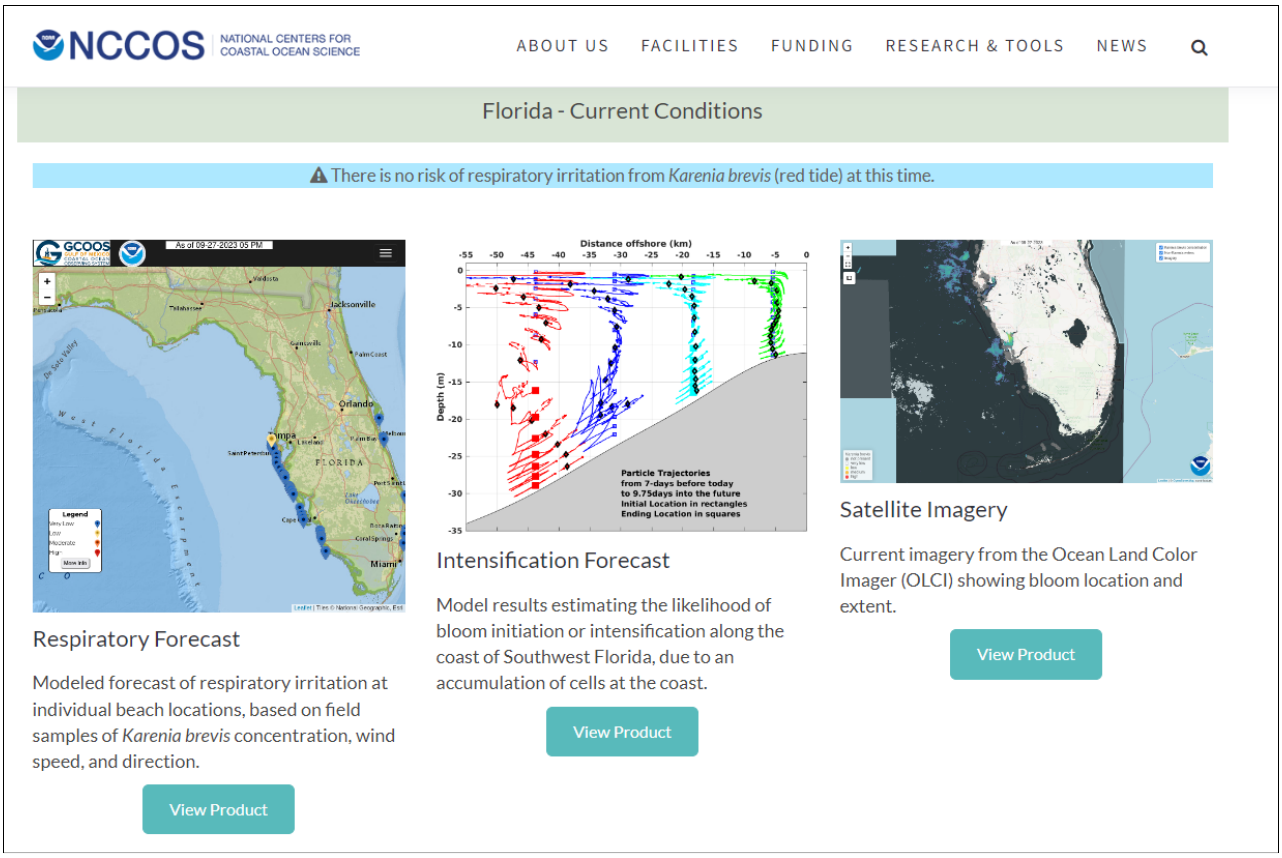
5.2 Guidelines for the planktonic dinoflagellate *Karenia brevis* and benthic marine cyanobacteria blooms in Florida (United States)

Blooms of the toxic planktonic dinoflagellate *Karenia brevis* have frequently occurred along the Florida Gulf since the 1940s. The coast has been monitored regularly since the mid-1990s following a severe event. *Karenia brevis* produces brevetoxins, which can cause harm to human health via several routes of exposure. Brevetoxins are neurotoxic and can accumulate in shellfish and cause neurotoxic shellfish poisoning. Brevetoxins can also become aerosolised when *K. brevis* cells are damaged in high turbulence water zones, especially nearshore, and transported onshore by winds (Stumpf et al. 2022). The aerosolised toxins cause respiratory irritation and pose a significant risk to beachgoers with chronic respiratory illnesses such as asthma. For susceptible populations, respiratory irritation may be long-lasting, while acute symptoms in healthy people usually subside as soon as they leave the exposure area (Fleming et al. 2005a; Fleming et al. 2005b). During *K. brevis* blooms, toxins have been measured at distances greater than 1.5 km from the shore (Kirkpatrick et al. 2011), and blooms have also associated with massive fish kill events, as well as marine mammal and turtle mortalities.

In the United States, *K. brevis* blooms occur mainly between August and December. Currently, Mote Marine Laboratory, the Florida Fish and Wildlife Conservation Commission's Fish and Wildlife Research Institute, and the National Oceanic and Atmospheric Administration (NOAA) provide status reports about Florida red tides to the public. For weekly reports, beachgoers can refer to https://myfwc.com/research/redtide/. Forecasts for Florida and Texas beaches can also be found at https://coastalscience.noaa.gov/science-areas/habs/hab-forecasts/gulf-of-mexico/ (Figure 3). A series of HAB forecasts are produced externally by NOAA partners and collaborators for different regions (e.g. Gulf of Maine, California, Pacific Northwest, as well as the Gulf of Mexico and Florida). These communications provide advanced warning of HAB events to local stakeholders and the public.

To cite the NOAA website:

> The Algal Bloom Monitoring System delivers near real-time products for use in locating, monitoring and quantifying algal blooms in coastal and lake regions of the US. This application delivers a suite of bloom detection products in the form of geographic based images.



Florida - Current Conditions

⚠ There is no risk of respiratory irritation from *Karenia brevis* (red tide) at this time.

Respiratory Forecast

Modeled forecast of respiratory irritation at individual beach locations, based on field samples of *Karenia brevis* concentration, wind speed, and direction.

Intensification Forecast

Model results estimating the likelihood of bloom initiation or intensification along the coast of Southwest Florida, due to an accumulation of cells at the coast.

Satellite Imagery

Current imagery from the Ocean Land Color Imager (OLCI) showing bloom location and extent.

Figure 3. National Centres for Coastal Ocean Science website highlighting the respiratory forecast for Florida beaches.

Swimming is considered safe for most people during a *K. brevis* bloom; however, some individuals may suffer skin irritation and burning eyes, and those with respiratory illness may also experience respiratory irritation while in the water. Aotearoa New Zealand's phytoplankton monitoring programmes could adequately detect such blooms, although currently monitoring sites are based on a risk to seafood safety and may not adequately cover risk via recreational activities. Advisories and warnings could be issued via the MPI, MoH, or city council websites.

In Florida, routine monitoring for *K. brevis* occurs year-round at sampling sites distributed along coastal areas of the entire state. Increased sampling efforts are triggered when cell concentrations increase. The association between *K. brevis* cells and the occurrence and intensity of respiratory irritation is well established, as the production of brevetoxins is stable and predictable (Kirkpatrick et al. 2004). Cell counts above 50,000–100,000 cells/L can cause slight to moderate respiratory irritation, and cell counts exceeding 1,000,000 cells/L are often associated with more severe irritation (Florida Fish and Wildlife Conservation Commission 2024; Table 3). Routine monitoring provides information for forecasts that help the public avoid respiratory exposure and informs resource managers to also take actions to protect public health (e.g. beach closures, warning signs). Monitoring results are also used by state agencies (e.g. Florida Department of Agriculture and Consumer Services) to determine closures of shellfish harvest areas. Shellfish harvesting is prohibited at cell concentrations over 5,000 cells/L. Satellite monitoring has also been used routinely since 1999, and if a suspected bloom is detected, it is confirmed by field sampling.

Table 3. *Karenia brevis* guidance levels used in Florida, United States (Florida Fish and Wildlife Conservation Commission 2024).

Description	*Karenia brevis* abundance	Possible effects
NOT PRESENT – BACKGROUND	Background levels of 1,000 cells or less	No effects anticipated
VERY LOW	> 1,000–10,000 cells/L	Possible respiratory irritation; shellfish harvesting closures when cell abundance equals or exceeds 5,000 cells/L
LOW	> 10,000–100,000 cells/L	Respiratory irritation; shellfish harvesting closures; possible fish kills; probable detection of chlorophyll by satellites at upper range of cell abundance
MEDIUM	> 100,000–1,000,000 cells/L	Respiratory irritation; shellfish harvesting closures; probable fish kills; detection of surface chlorophyll by satellites
HIGH	> 1,000,000 cells/L	As above, plus water discoloration

Following the recent Florida Blue-Green Algae State of the Science Symposium, new guidance was published on the monitoring of cyanobacterial blooms, including benthic marine cyanobacteria for Florida was published (Krimsky and Staugler 2023). To cite this document:

> Benthic cyanoHABs are often multi-generic and multi-specific, making identification complex and challenging. However, correct identification aids risk assessment and communication among managers and scientists. Identification of benthic cyanoHABs can be done using genetic and morphological techniques. Genetics can be used to initially aid in determining genera and species differences; once you know what to look for, morphology can be used to identify many of Florida's primary organisms. Marine benthic cyanobacterial blooms can contain toxins as well as other pathogenic microorganisms including bacteria, fungus, or planktonic microeukaryotes (i.e., the eukaryotic HAB species). Many of these secondary compounds constrained within the benthic mats are still unknown. Thus, accurate identification is important for safe and effective monitoring, mitigation, and public health response. The lifecycle of benthic cyanobacterial

> blooms follows a simple pathway, however, specific bloom dynamics are still unknown, specifically in regards to nutrient cycling and benthic cyanobacteria can continue to reproduce up until the point of decomposition. Consistent monitoring protocols are important because how and where sampling occurs can produce different information. For example, toxin analysis of a water column sample will yield significantly lower toxin concentrations than analysis of benthic mats or time-integrative SPATT (Solid Phase Adsorption Toxin Tracking) samples.

This document highlights the following five steps for the monitoring protocol of marine benthic cyanobacteria, acknowledging that sampling procedures can be habitat dependent:

- coverage and visual assessment of the bloom
- collection of bloom mat material for species and toxin identification
- cleaning of mat material to remove microfauna
- collection of water column samples
- deployment of Solid Phase Adsorption Toxin Tracking (SPATT) devices to detect *in situ* toxins through time.

Effective management of benthic cyanobacteria HABs will require a greater understanding of these blooms. A roadmap for response has been outlined, which starts with identifying what species are present, what toxins are being produced, and by which organisms. A robust spatio-temporal monitoring programme needs to be developed for each country or region to help determine the drivers of benthic cyanobacterial blooms. Consistent monitoring of the benthos is also important for accurately assessing the overall health of a system.

5.3 Guidelines for harmful algae and cyanobacteria in Australia

The Australian 'Guidelines for managing risks in recreational water' (NHMRC 2008) are non-mandatory standards designed to protect the health of humans from threats posed by the recreational use of coastal, estuarine and fresh waters, including both natural and artificial hazards. Although these guidelines were published in 2008 and are overdue for a review, they offer a reasonably comprehensive framework for managing marine HAB events in recreational waters.

The framework uses both waterbody grading and guideline values to manage risks. Waterbody grades provide the basic means to assess safety status over time using knowledge of the waterbody and coastal and catchment characteristics (e.g. nutrient inputs, concentration processes), combined with information on the history of algae and cyanobacteria blooms in the waterbody. The combination of these factors gives a low, moderate or high category, and alert-level values are used to help water managers determine when intervention is required.

Alert-level values have only been developed for four species – *Karenia brevis, Lyngbya majuscula, Pfiesteria* spp. and *Nodularia spumigena* – which presents a limitation of the guidelines (Table 4). The results of monitoring at the different alert levels trigger recommended actions, including monitoring rates and inspections, and notifications to appropriate health authorities (Table 5).

Table 4. Australian alert levels for marine harmful algal bloom species in recreational water.

Species	Green level Surveillance mode	Amber level Alert mode	Red level Action mode
Karenia brevis	≤ 1 cells/mL	> 1 – < 10 cells/mL	≥ 10 cells/mL
***Lyngbya majuscula* and / or *Pfiesteria* present in high numbers**	History but no current presence of organism	Present in low numbers	Present in high numbers*
***Nodularia spumigena*[a]**	Biovolume equivalent of > 0.04 to < 0.4 mm^3/L for the combined total of all cyanobacteria	Biovolume equivalent of ≥ 0.4 to < 4 mm^3/L for the combined total of all cyanobacteria where a known toxin producer is dominant in the total biovolume	Biovolume equivalent of ≥4 mm^3/L for the combined total of all cyanobacteria where a known toxin producer is dominant in the total biovolume

* For *Lyngbya majuscula* this involves the relatively widespread visible presence of dislodged algal filaments that are in the water and washed up onto the beach.

[a] From the guidelines for cyanobacteria and algae in fresh water.

Table 5. Australian recommended actions for each of the alert levels.

Alert level	Recommended actions
Surveillance mode (Green level)	• Regular monitoring • Weekly sampling and cell counts • Regular visual inspection of water surface for visible discoloration or scums
Alert mode (Amber level)	• Notify agencies as appropriate • Increase sampling frequency to twice weekly if warranted at representative locations to establish population growth and spatial variability in the waterbody* • Decide on requirement for toxicity assessment or toxin monitoring
Action mode (Red level)	• Continue monitoring as for amber level • Immediately notify health authorities for advice on health risk • Carry out toxicity assessment or toxin measurement of water if not already performed • Health authorities advise public of risk to health (i.e. authorities assess health risk by considering toxin monitoring data, sample type and variability)

* The recommendation to increase sampling frequency to twice weekly depends on the sensitivity and usage of the area; for example, whether there is a pressing need to issue advice on usage if the site is being heavily used for recreation. In most circumstances, weekly sampling provides adequate information to assess the rate of change of algal populations and judge the population growth rate and spatial variability.

State authorities in the Queensland Region have also developed species-specific guidance and response plans for reoccurring HAB events. Queensland has been subject to frequent *Moorea* (formerly classified as *Lyngbya majuscula*) blooms in the last decade. The Moreton Bay Regional Council published a harmful algal bloom response plan in 2018, which included monthly monitoring (i.e. visual inspections from boats, combined with shore-based inspections) and the three-level response plan shown in Table 6 (City of Moreton Bay Council 2024). The risk assessment for marine dermatotoxic cyanobacteria is not usually included in cyanobacteria guidelines, as the exposure patterns are different – that is, cutaneous contact with mats rather than unintentional ingestion of planktonic cells. Measures to protect site users include providing information about avoiding skin contact, such as removing bathing suits and showering after immersion to ensure removal of any filaments from the skin (Osborne et al. 2007).

Table 6. Three-level response plan to Moorea blooms in Moreton Bay, Australia.

Alert level	Detection	Response
1	Small to moderate bloom material at locations away from developed areas	No action required to remove material, but signs to inform the public of the presence of a potentially harmful algal bloom may be appropriate. Activate stakeholder communications
2	Large quantities of bloom material washing ashore or forming rafts adjacent to developed areas or areas of high public use	Activate or install signs immediately. Issue media release. Physically remove material from foreshores
3	Very large quantities of material washed ashore or beginning to form large rafts adjacent to developed areas or areas of high public use	Same response as for Level 2, but closure of beaches may also be required, particularly where large amounts of blooms are growing close to the water's edge

6. Protection of human health from saxitoxin-producing marine microalgae in recreational settings

Blooms of saxitoxin (STX)-producing microalgae occur in marine environments around Aotearoa New Zealand. The species capable of producing STXs that have been detected in Aotearoa New Zealand are *Gymnodinium catenatum, Alexandrium pacificum, A. minutum* and *A. ostenfeldii* – these species are common in temperate environments elsewhere in the world. Other significant STX-producing species that have not been detected in Aotearoa New Zealand to date include *A. catenella* (temperate species) and *Pyrodinium bahamense* (tropical species).

Blooms of these species are generally observed in the North Island of Aotearoa New Zealand (e.g. Northland, Bay of Plenty and the west coast of the North Island); however, the causative species appear to be extending their distributions, with the most common STX producer, *A. pacificum*, being detected in the top of the south for the first time in 2011. Blooms in the Marlborough Sounds, Tasman Bay / Te Tai-o-Aorere and Golden Bay / Mohua now regularly occur each year in late summer through to mid-winter. Elsewhere in the country, the seasonality and dynamics of *Alexandrium / Gymnodinium* blooms are less predictable (MacKenzie 2014). Additionally, climate change may alter the timing, duration and location of these blooms in the future (Rhodes and Smith 2022).

To date, human health protection related to these types of blooms has been focused on the consumption of shellfish, which as filter-feeders accumulate the toxins, rather than exposure through contact recreation. In this section, we explore the potential risk posed to recreational users by marine waterbodies that contain STX-producing microalgae and the feasibility for managing this risk. The steps involved in this process were:

- evaluating the suitability of the WHO guideline value for STXs in recreational waters (WHO 2020) for application to marine environments
- compiling a dataset of STX cell quotas, evaluating patterns in the data, and determining robust summary values
- developing a cell concentration threshold (or multiple thresholds) where access to waterbodies should be restricted to protect human health
- proposing risk management strategies that might be amenable to marine recreational settings.

6.1 The WHO guideline value for saxitoxins in recreational waters

In 2020, the WHO developed a guideline value for STXs in drinking water and recreational water environments (WHO 2020). STXs are produced by both freshwater cyanobacteria and marine dinoflagellates. The guideline value for STXs was developed alongside guideline values for other freshwater cyanotoxins, and therefore it was likely intended for the protection of human health in recreational freshwaters. However, we explored whether the approach used would also be fit-for-purpose for contact recreation of STXs in marine environments.

The WHO guideline value (GV) for STXs is based on a lowest-observed-adverse-effect level (LOAEL) for mild symptoms of 1.5 µg/kg body weight from a review of human paralytic shellfish poisoning (PSP) cases by the Food and Agriculture Organization of the United Nations (FAO 2004). Following this, the European Food Safety Authority (EFSA 2009) reviewed approximately 500 cases of human PSP and also identified a LOAEL for STXs of 1.5 µg/kg body weight when assuming an adult body weight of 60 kg (EFSA 2009). Because many individuals did not show symptoms at much higher estimated STX intakes, EFSA (2009) reasoned that the LOAEL must be near to the threshold for effects in sensitive individuals; therefore, an uncertainty factor of three was used 'to extrapolate from the LOAEL to a no observed adverse effect level (NOAEL)'. This established an acute reference dose (ARfD) for STXs of 0.5 µg/kg body weight. An uncertainty factor for intraspecies variation was not applied because the documented human cases included a wide spectrum of people (occupation, age and sex; WHO 2020).

The GV was derived from data related to poisoning events caused by mixtures of STXs, rather than solely STX itself, with total STXs expressed as STX concentration equivalents (not toxicity equivalents). This approach assumes that all STX congeners are similar in toxicity to the parent STX. The GV therefore applies to total STXs in a sample, not just the parent compound STX. This also requires that a similar evaluation is applied to the STX cell quotas used to develop cell concentration thresholds – the total STX concentration should be evaluated, and STX concentration equivalents should be used.

The WHO GV for STXs in recreational waters is based on the incidental ingestion of 250 mL of water by a child (15 kg body weight was used; WHO 2020). This is set to cover a worst-case scenario, and an adult would need to ingest a much higher volume of water for the equivalent dose (based on their higher body weight). Available studies indicate that adults ingest less water during contact recreation than children. This volume is likely appropriate (sufficiently conservative) for recreational settings in Aotearoa New Zealand coastal waters. In a review of water ingestion rates during aquatic recreational activities – including swimming (adult and child), surfing, rowing, canoeing / kayaking, boating and fishing – swimming and surfing were associated with the highest levels of accidental ingestion of water (Table 7). Rates of water ingestion associated with swimming were calculated at ingestion rate per hour, and excessive periods of swimming were required to exceed the ingestion rates used in the GV calculations (i.e. more than 7 hours). Surfing was the riskiest activity with a mean water ingestion rate of 171 mL/day and a 95th percentile of 665 mL/day, indicating a potential risk of exceeding GVs calculated using 250 mL/day. However, surfers are likely to be older and have greater body weights than the reference child values used for the GV (Sport Research Group 2005), and the greater rate of water ingestion is unlikely to result in a greater dose when expressed on a body weight basis.

Table 7. Summary of water ingestion rates during aquatic recreational activities. P95/P97.5 is the 95th or 97.5th percentile.

Activity	Water ingestion rate (mL)				Source
	Per hour		Per day		
	Mean	P95/P97.5	Mean	P95/P97.5	
Swimming – Adults	12.4	14			Dufour et al. (2017)
Swimming – Children	23.9	33			Dufour et al. (2017)
Surfing			171	665	Stone et al. (2008)
Rowing			3.9	11.8	Dorevitch et al. (2011)
Canoeing / kayaking			3.9	11.8	Dorevitch et al. (2011)
Boating (without capsize)			3.7	11.2	Dorevitch et al. (2011)
Fishing			3.6	10.8	Dorevitch et al. (2011)

The WHO recreational GV calculation for STXs (reproduced below) is based on a scenario of a child swimming and playing in water with a high-density bloom (section 8.1 of the WHO background document for STXs, page 18; WHO 2020). As described above, the calculation components used by the WHO appear to be appropriate for recreational activities undertaken in oceanic environments in Aotearoa New Zealand. Although surfers may potentially ingest far more than 250 mL/day of water, the surfer would need to have a body weight of less than 40 kg for the GV to be less protective for the activity.

$$\mathrm{GV_{rec}} = \frac{\mathrm{LOAEL} \times \mathrm{bw}}{\mathrm{UF} \times \mathrm{C}} = \frac{1.5 \times 15}{3 \times 0.25} = 30\ \mu\mathrm{g/L}$$

Where:

$\mathrm{GV_{rec}}$ = Recreational guideline value

LOAEL = lowest-observed-adverse-effect level using human data from paralytical shellfish poisoning reports (1.5 µg saxitoxin-equivalents/kg body weight; based on EFSA (2009)

bw = body weight (15 kg for a child)

UF = uncertainty factor (3, for use of a LOAEL rather than a NOAEL)

C = daily incidental water consumption (0.25 L for a child)

6.2 Review of saxitoxin cell quota data

The species of microalgae from marine environments that produce STXs in Aotearoa New Zealand are well established and include *Alexandrium pacificum, A. minutum, A. ostenfeldii* and *Gymnodinium catenatum*. Toxin cell quota (based on STX concentration equivalents) from these taxa were gathered from the scientific literature and unpublished data from Cawthron Institute (Selwood et al. 2018; Appendix 1). Datasets were limited to those where toxin analyses were presented in concentration per cell (Chang et al. 1997; MacKenzie and Berkett 1997). A confidential client report produced by Cawthron Institute contributed STX data for 16 strains of *Alexandrium* species and three strains of *G. catenatum* held in the Cawthron Institute Culture Collection of Microalgae. All data originated from cultured isolates (i.e. no environmental samples).

For the international data, STX cell quotas were collated from studies representing all known producers, including the two species that have not been detected in Aotearoa New Zealand to date: *A. catenella* (temperate species) and *Pyrodinium bahamense* (tropical species; Appendix 2). For species with large datasets (e.g. *A. pacificum, A. minutum*) only studies from the last 4 years (i.e. since 2020) were included. STX detection methodology has improved dramatically in recent years, and limiting the data insured that high quality STX quotas were included. Representative data from different geographic regions were used. For *G. catenatum* and *P. bahamense*, the datasets were smaller and we attempted to include all available data. Again, almost all the data came from cultured isolates, except for two field studies of *P. bahamense*.

The two datasets (Aotearoa New Zealand and international) were very similar (Table 8). Minimum quotas for both were less than 1 picogram (pg) per cell and maximum quotas were 232 pg/cell and 338 pg/cell, respectively. The international dataset overall was slightly higher for all values, but due to the similarities observed, the combined dataset was used for developing cell concentration thresholds.

Table 8. Summary of toxin quota data from marine planktonic microalgae identified in a literature review of data from Aotearoa New Zealand and international studies.

Dataset	n	Saxitoxin cell quota (pg/cell)				
		Minimum	Maximum	Median	Mean	95th percentile
Aotearoa New Zealand	24	0.04	232	4.4	21.5	94
International	40	0.18	338	4.6	24.3	127
Combined*	64	0.04	338	4.5	23.2	124

* A combination of the Aotearoa New Zealand and international data.
n = number of data points in dataset.

The combined data were grouped by genera: *Alexandrium* species, *G. catenatum* and *P. bahamense* (Table 9). For *Alexandrium* species, the dataset is robust with 50 data points, while *G. catenatum* and *P. bahamense* datasets had less than 10 data points each, meaning 95th percentile STX cell quotas could not be calculated due to insufficient data. *Alexandrium* species had the lowest quotas for all values, and *G. catenatum* had the highest quotas. Due to the acute effects of STXs on human health, a conservative summary statistic is most appropriate for the development of a cell concentration threshold. The lack of data means that the use of maximum cell quota values may be the best approach, although maximum values can be unreliable and the 95th percentile is likely to be a more robust estimate of a high cell quota.

Knowledge of STX-producing species distributions is biased towards sites that are monitored as part of Aotearoa New Zealand's Marine Biotoxin Monitoring Programme. Data in Table 9 represents cell concentration data for STX-producing species from the Marine Biotoxin Monitoring Programme and Cawthron's unpublished research, conducted since 2008. *Alexandrium* species are the most common taxa in our coastal waters, particularly *A. pacificum* (MacKenzie 2014; previously known taxonomically as *A. catenella*). Historically, this species was only recorded in the Northland Region but has since spread to the top of the south and now regularly blooms in the Marlborough Sounds. These blooms can reach extremely high cell concentrations of over 200,000 cells/L with visible seawater discoloration or a 'red tide' (Table 10). *Alexandrium minutum* occasionally blooms in the Bay of Plenty and the Marlborough Sounds and the highest cell concentration recorded is 52,000 cells/L (Table 10). *Alexandrium ostenfeldii* strains are known to range in toxicity from highly toxic to non-toxic. The cysts of this species are common in coastal sediments around Aotearoa New Zealand, but it is rarely observed as a motile cell in the water column (MacKenzie 2014) and only at low concentrations (Table 10).

Gymnodinium catenatum is less common although it does bloom sporadically, mainly along the west coast of the North Island. Extensive blooms have occurred historically, which expanded across almost the entire coastline of the North Island and into the Marlborough Sounds (MacKenzie 2014). However, due to the low cell concentrations observed around our coastline, *G. catenatum* presents little risk in recreational settings, with cell concentrations peaking at 6,600 cells/L (Table 10). *Pyrodinium bahamense* has never been detected in Aotearoa New Zealand and is currently only known from tropical regions.

Table 9. Summary of saxitoxin quota data for microalgal taxa identified using the combined data from Aotearoa New Zealand and international studies (bold values are those used for threshold calculations).

Microalgal taxa	n	Saxitoxin cell quota (pg/cell)				
		Minimum	Median	Mean	Maximum	95th Percentile
***Alexandrium* species**[a]	50	0.04	4.0	7.6	126	**15**
Gymnodinium catenatum[a]	8	1.65	55.1	100.2	**338**	NA [c]
Pyrodinium bahamense[b]	6	2.00	19.1	50.5	**147**	NA [c]

[a] A combination of the Aotearoa New Zealand and international data.

[b] Only international data were available. This species has not been detected in Aotearoa New Zealand.

[c] Not applicable, as insufficient data to calculate a 95th percentile.

n = number of data points in dataset.

Table 10. Summary of environmental data for saxitoxin-producing microalgal taxa from various sites in Aotearoa New Zealand. Data sourced from the New Zealand Marine Biotoxin Monitoring Programme managed by the Ministry for Primary Industries.

Microalgal taxa	Cell concentration (cells/L)			
	Minimum	Median	Mean	Maximum
Alexandrium minutum	100	200	751	52,000
Alexandrium ostenfeldii	100	100	227	3,300
Alexandrium pacificum	100	300	1,711	327,000
Gymnodinium catenatum	100	800	1,303	6,600

6.3 Risk management scenarios for saxitoxin-producing microalgae in marine recreational settings

Because routine monitoring for toxin-producing marine microalgae is not currently targeted towards recreational 'hot spots' around Aotearoa New Zealand, the development of an alert-level framework – similar to those in the 'New Zealand guidelines for cyanobacteria in recreational fresh waters' – may not be a useful outcome of the current exercise. The success of a multi-tier risk management framework relies on the collection and evaluation of regular data to guide risk management decision-making. Implementation and resourcing of the regular data collection can be a large undertaking, and responsible agencies would need to be highly engaged to ensure successful implementation.

The risk management approach most appropriate for a region might depend on the following regional factors: the frequency of STX-producing marine microalgal blooms, the types of microalgae observed, the likelihood of thresholds being exceeded, and the recreational activities that occur in the area. To assist with responding to bloom events, we developed cell concentration thresholds for STX-producing marine microalgae and advice on the actions to be undertaken when the thresholds are exceeded. A succinct summary table (Table 13) brings together the key information from this exercise.

Cell concentration threshold for saxitoxin-producing marine microalgae

A cell concentration threshold for STX-producing marine microalgae was calculated using the WHO GV for STXs in recreational waters and the 95th percentile STX cell quota for the combined dataset (studies from Aotearoa New Zealand and overseas). The resulting cell concentration threshold for STX-producing marine microalgae is 241,935 cells/L, which was rounded to 200,000 cells/L (Table 11).

Table 11. Calculation of cell concentration threshold for saxitoxin (STX)-producing marine microalgae based on World Health Organization (WHO) guideline value for STXs and STX cell quotas.

95th percentile STX quota value [a]	124 pg/cell
WHO recreational guideline value	30 µg/L
Cell concentration threshold [b]	241,935 cells/L
Adopted health-based threshold	200,000 cells/L of summed STX-producing microalgae

WHO = World Health Organization.

[a] STX quota data for all STX-producing microalgal genera from international and Aotearoa New Zealand studies.

[b] Cell concentration threshold = 95th percentile STX quota value ÷ recreational guideline value × 1,000,000

Compared with environmental monitoring data from Aotearoa New Zealand, the cell concentration threshold for STX-producing marine microalgae (200,000 cells/L) was at the upper end of the data range. The 200,000 cells/L threshold was higher than the median and mean cell concentrations for each environmental dataset (Table 10). For some datasets, the threshold was higher than the maximum cell concentrations observed, and health warnings would not have been triggered. For other datasets, the maximum cell concentrations observed were higher than the 200,000 cells/L threshold, and health warnings would have been triggered at certain times. These observations validate the usefulness of the health-based threshold for STX-producing marine microalgae since environmental cell concentrations do reach potentially health-adverse levels at certain times in certain locations. The assessment also suggests that the introduction of a cell concentration threshold for STX-producing marine microalgae would not overly restrict recreational access to oceanic environments (based on the cell concentration data available for this evaluation).

The microalgal taxa that should be included in risk evaluations for STX-producing marine microalgae are *G. catenatum*, *P. bahamense* and all species of *Alexandrium*. The sum of the cell concentrations from each STX-producing taxon should be used for recreational public health decision-making. While *P.*

bahamense has not yet been reported in Aotearoa New Zealand, STX-producing examples have been reported overseas. Other STX-producing microalgal species likely also exist, and therefore, this list may expand with time, and international literature should be regularly reviewed for new STX-producing microalgal taxa.

When the cell concentration threshold for STX-producing marine microalgae is exceeded, public health staff should warn the public of the existence of potential health risks and the need to restrict access for swimming and recreational activities. In some regions, local and regional councils could play a role in communicating the health risk to the public, as they often have the necessary relationships and communication networks / channels in place. This should be done (although not exclusively) via media releases, notifications through the communications channels of the region's responsible agencies, and by erecting signs at affected beaches and / or access points (e.g. jetties and boat ramps). In addition, local doctors should be encouraged to report any illnesses that may be linked to contact with water containing toxin-producing microalgae, as these are classed as a notifiable disease under the Health Act – Chemical poisoning arising from contamination of the environment.

If a regular monitoring programme is not in place, at least weekly sampling should be implemented to track the bloom and determine when the health risk has abated. Sampling might also be undertaken at additional sites to understand the extent and variability of the bloom. The health warning should not be lifted until two successive results from representative samples have been recorded. The sampling interval between these should be greater than 7 days.

Saxitoxin testing of water samples could be undertaken by responsible agencies to better understand the health risk (e.g. using liquid chromatography-mass spectrometry). If STX concentrations fall below the recreational GV (30 µg/L), then the health warning could be removed. However, continued STX testing should be undertaken while cell concentrations for STX-producing microalgae remained above or close to the threshold.

To ensure that there is cohesion in the messaging used to communicate information about recreational shellfish harvesting and recreational bathing activities, responsible agencies in the region should also coordinate with MPI.

In regions where thresholds are regularly being exceeded, responsible agencies might consider proactive communications informing the public about the risks associated with STX-producing harmful algal blooms (HABs) and how to stay safe. Past events have shown that communicating the risks associated with toxic freshwater cyanobacteria can lead to a more receptive audience when health warnings are issued.

Cell concentration thresholds for different genera of saxitoxin-producing marine microalgae

To account for scenarios where an algal bloom comprises a single STX-producing microalgal taxon, rather than a mixture of taxa, genera-specific cell concentration thresholds were calculated. The WHO GV for STXs in recreational waters was used in combination with the 95th percentile STX cell quota for *Alexandrium* and the maximum STX cell quota for *Gymnodinium* and *Pyrodinium* (since the datasets were insufficient to calculate robust 95th percentiles). While *Alexandrium* was a mixture of different species, *Gymnodinium* and *Pyrodinium* were composed of a single species – *G. catenatum* and *P. bahamense*. *Alexandrium* species are difficult to identify to species level, and other STX-producing *Alexandrium* species may become established in Aotearoa New Zealand's coastal waters (e.g. *A. catenella* is present in Australia but has not been detected in Aotearoa New Zealand); therefore, the use of a genus-level grouping is appropriate.

The calculated cell concentration threshold for *Alexandrium* spp. was 1,998,202 cells/L, for *G. catenatum* it was 88,803 cells/L, and for *P. bahamense* it was 203,985 cells/L (Table 12). The cell concentration thresholds for *Alexandrium* spp. and *P. bahamense* would serve no purpose, as they were higher than or equivalent to the cell concentration threshold derived for a mixture of STX-producing marine microalgae (see the previous section). Because STX cell quotas observed in *G. catenatum* were higher than those observed in other microalgal taxa, the genera-specific cell concentration threshold was lower. If *G. catenatum* is the primary STX-producing microalgae present in a bloom, a cell concentration threshold of 90,000 cells/L (rounded for usability) should be used for recreational public health decision-making.

Table 12. Calculation of taxa-specific cell concentration thresholds for saxitoxin (STX)-producing marine microalgae based on World Health Organization (WHO) guideline value for STXs and STX cell quotas.

	***Alexandrium* spp.**	***Gymnodinium catenatum***	***Pyrodinium bahamense***
95th percentile or maximum STX quota value [a]	15 pg/cell [b]	338 pg/cell [c]	147 pg/cell [c]
WHO recreational guideline value	30 µg/L	30 µg/L	30 µg/L
Cell concentration threshold [d]	1,998,202 cells/L	88,803 cells/L	203,985 cells/L
Adopted genera-specific health-based threshold	NA [e]	90,000 cells/L of *Gymnodinium catenatum*	NA [e]

WHO = World Health Organization.

[a] STX quota data for each taxa from international and Aotearoa New Zealand studies.

[b] The 95th percentile STX cell quota value was used.

[c] The maximum STX cell quota value was used.

[d] Cell concentration threshold = 95th percentile or maximum STX quota value ÷ recreational guideline value × 1,000,000

[e] Not applicable as the genera-specific threshold is higher or equivalent to the health-based threshold derived using the STX quota dataset from all genera (200,000 cells/L; see Scenario 1).

Compared with available environmental monitoring data from Aotearoa New Zealand (Table 10), the genera-specific threshold for *G. catenatum* (90,000 cells/L) was higher than the maximum cell concentrations observed. Health warnings would not have been triggered in this dataset. Risk management actions taken would be the same as outlined in the previous section for a mixture of STX-producing marine microalgae.

Table 13. Summary table of cell concentration thresholds for saxitoxin-producing marine microalgae and advice on the actions to be undertaken when the thresholds are exceeded.

Recreational activity / thresholds	Action
Situation 1: The cell concentration of total saxitoxin-producing marine microalgae is **≥ 200,000 cells/L**, or **Situation 2:** *Gymnodinium catenatum* is the dominant species and has a cell concentration **≥ 90,000 cells/L**, or **Situation 3:** Saxitoxin concentrations are **≥ 30 µg/L**	• Undertake sampling at least weekly • Notify the public of a potential risk to human health • To better understand the human health risk, water samples should be tested for saxitoxins

7. Knowledge gaps that present barriers for developing recreational guidelines for marine HABs in Aotearoa New Zealand

7.1 Supporting advice on HAB management for recreational settings

Establishing guidelines for recreational marine harmful algal blooms (HABs) in Aotearoa New Zealand will require the development of guidance material on managing specific marine HAB risks (covered in this report), but also supporting advice on how to implement a recreational marine HAB risk management programme in a region. This advice will need to include information on roles and responsibilities, the location and timing of monitoring, the development of regional protocols, and established methods for communication.

While the cyanobacterial guidelines for recreational fresh waters provide a good foundation on which to base further work, a better understanding on how end-users (council and public health staff) currently undertake recreational public health monitoring in marine environments would improve the development of this material. Integrating recreational marine HAB programmes within existing monitoring programmes (e.g. for microbial contamination at swimming beaches) would likely improve uptake and implementation. End-users operating in this space will also have valuable insights on how to go about selecting monitoring sites for marine recreation.

The development of template communications material for marine HABs in recreational settings will assist public health staff with issuing health warnings. Establishing appropriate messaging to communicate risks and developing the resources to support communications (e.g. images, sign templates) both take time, and these processes are not feasible when urgently responding to a HAB event that poses a risk to public health. The development of base / template material in advance will alleviate this pressure.

7.2 Monitoring for aerosolised and dermal toxins

Many types of marine HABs can produce toxins that are capable of aerosolisation, including planktonic and benthic HABs and mat-forming cyanobacteria. There is a need to quantify these toxins in spray and aerosols and define how these levels relate to symptoms or illness in humans; this work will contribute to the development of public health guidelines aimed at limiting human exposure to health-adverse levels of aerosolised toxins. The *Karenia brevis* framework described in Section 5.2 is a good example of a well-developed association between *K. brevis* cells and the intensity of respiratory irritation. These blooms have occurred regularly over decades and toxin production per cell is stable, enabling the establishment of robust cell thresholds. The monitoring programme and threshold levels are used to inform both public health and the closure of shellfish harvesting. However, for other types of blooms, this association has not been established.

Information on dermal toxins is also scarce and most of the toxins characterised are produced by cyanobacteria (e.g. lyngbyatoxins). Planktonic marine HABs have also been associated with acute dermal irritation and skin lesions (e.g. *Vulcanodinium, Heterocapsa*), but knowledge of the compounds responsible and cell concentrations associated with negative health effects in humans is lacking. However, the development of chemical detection methods (e.g. liquid chromatography coupled with mass spectrometry) for some of these toxins are possible and could be implemented as part of a monitoring programme or in response to a HAB event.

7.3 Sampling approaches for benthic marine HABs and mat-forming cyanobacteria

Sampling approaches for quantitively measuring marine HAB species in the water column (planktonic blooms) are well established internationally and are used in Aotearoa New Zealand as part of the Marine Biotoxin Monitoring Programme for seafood safety purposes. However, there is no standardised monitoring of benthic HAB species, and fit-for-purpose monitoring techniques are crucial to safely manage this risk to human health. In the scientific literature, artificial substrates have been used to target benthic species and are in the process of being validated internationally. The sampling sites need repeated visitations to deploy and retrieve the devices within 24–48 hours, which increases costs and turnaround times. Additionally, some HAB species have various life stages that comprise both planktonic and benthic stages. In Italy, the use of planktonic monitoring approaches has been employed for the benthic *Ostreopsis* spp. It has been established that the risk to human health occurs from cells that are distributed in the water column, as mats are easily resuspended by water hydrodynamics. Standardised monitoring for benthic mat-forming cyanobacteria is even less well established, and the visual assessments and coverage estimates used (Table 6) will likely have high rates of associated variability or uncertainty.

7.4 Quantification of toxins in different matrices

Development of accurate and sensitive methods for analysis of marine HAB toxins, including standardised reference materials for their quantification, is important for establishing associations been cell concentrations and toxins, as well as for use in routine monitoring. Instrumental analyses using liquid chromatography-mass spectrometry have been developed for many of the marine biotoxins, particularly those that cause seafood safety issues. However, these methods will also need to be validated for the wide range of matrices or sample types that are likely to be sampled as part of a recreational monitoring programme or in response to a bloom event. This might include seawater samples, aerosols and bloom material (mats, scum, slime, etc.), which will all have differing impacts on the efficiency and sensitivity of the analytical method. Rapid screening methods such as immunoassays, receptor-binding assays and cell bioassays are also important and can establish toxicity as well as toxin quantification. The detection of toxin genes using molecular methods is not possible for marine HABs (except for saxitoxins (STXs); Murray et al. 2011) because the gene biosynthesis pathways have not been characterised, as is the case with toxin-producing freshwater cyanobacteria.

7.5 Developing multi-tier risk management frameworks

As described in Section 6.1, the development of multi-tier risk management frameworks (like those included in the cyanobacteria guidelines for recreational fresh waters and drinking waters) requires the implementation of regular monitoring that guides risk management decision-making. This approach has resourcing implications, and the implementation of effective monitoring programmes should be end-user driven to serve the needs of their region. The development of multi-tier risk management frameworks also requires robust knowledge on the risk (e.g. the potency of the toxin, how it acts, the levels expected in the causative species, the likely exposure rates) and indicators for the risk (an attribute that can be easily monitored to track the likelihood of the hazard occurring and to deviate monitoring actions, e.g. chlorophyll, total cell concentrations / biovolumes, nutrient concentrations, temperature).

In the case of STX-producing marine microalgae, sufficient knowledge on the risk was available to provide cell and STX concentration 'action-level' thresholds that could guide decisions on when to issue health warnings for an area. However, there was insufficient knowledge on robust environmental parameters that could be used as indicators for the development of STX-producing HABs. This was also reflected in the review of international guidance material (Section 5) where alert-level frameworks that have been developed in other countries either measure the causative species throughout the framework (e.g. guidance levels for *K. brevis* blooms in Florida; Table 3) or provide limited guidance on what to measure (e.g. the three-level response plan to Moorea blooms; Table 6).

In the case of other HAB-related hazards, the knowledge deficits are greater. For example, with regard to lyngbyatoxin-producing marine cyanobacteria mats, there is a lack of knowledge on multiple aspects of the risk:

- How potent are lyngbyatoxins?
- How do lyngbyatoxins act?
- What lyngbyatoxin levels are expected in marine cyanobacteria mats?
- What are the likely exposure rates when dealing with mat material?

Without this information, it is not possible to develop thresholds where health-adverse effects are not expected. But deficits also exist around the ecology of lyngbyatoxin-producing HABs, e.g. When would we expect to see blooms? – and the chemical ecology, e.g. Does the toxin remain contained in the mats? – both of which guide monitoring practice, i.e. When and what should we monitor?

This report captures current knowledge on the potential HAB risks in Aotearoa New Zealand and the associated effects of continued climate change. Improving the understanding of recreational marine HAB problems identified across Aotearoa New Zealand will also help prioritise the investment of effort needed to produce the required knowledge for robust risk management frameworks.

8. Conclusions

Marine harmful algal blooms (HABs) regularly occur in Aotearoa New Zealand, and climate change and other human impacts will likely drive an increased occurrence of HAB events, which will in turn impact on human health. In both Aotearoa New Zealand and internationally, public health monitoring of HABs in recreational settings is less established than monitoring that focuses on seafood safety risks. However, there are some examples of well-established guidelines or frameworks for marine HABs in the international literature. In most cases, these are focused on a specific species in a specific location that causes reoccurring HAB events over a long period.

Saxitoxin (STX) is the only marine HAB-associated toxin that has a WHO recreational guideline value (GV), and we were able to develop cell concentration thresholds for STX-producing marine microalgae in recreational waters. However, the development of a multi-tier risk management framework for STX-producing marine microalgae is currently not possible due to a lack of knowledge on indicators for the development of these HABs. Knowledge gaps for other marine HABs were wider and will restrict the development of robust science-based risk management frameworks for these potential hazards.

Other knowledge gaps that could present barriers for developing recreational guidelines were also identified, with the most urgent being monitoring techniques for aerosolised and dermal toxins, sampling approaches for benthic marine HABs and mat-forming cyanobacteria, and the ability to accurately quantify toxins in the matrices likely to be encountered when responding to recreational marine HABs.

Despite the knowledge gaps identified in this report, the development of guidance material based on current knowledge would assist council and public health staff in responding to marine HAB events; this material is also required for communicating with the public about the risks posed by marine HABs.

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10. Appendices

Appendix 1. Saxitoxin cell quotas collated from studies in Aotearoa New Zealand

Microalgal Taxa	Strain	Total STXs (pg/cell)	Source	Reference
Alexandrium minutum	CAWD11	4.43	Culture	Selwood et al. (2018)
A. minutum	CAWD11	3.20	Culture	Mackenzie and Berkett (1997)
A. minutum	CAWD12	2.61	Culture	MacKenzie and Berkett (1997)
A. minutum	Croisilles 1	2.17	Culture	MacKenzie and Berkett (1997)
A. minutum	AMABOPO06	8.19	Culture	Chang et al. (1997)
A. minutum	AMABOPO14	4.27	Culture	Chang et al. (1997)
A. ostenfeldii	CAWD135	1.03	Culture	Selwood et al. (2018)
A. ostenfeldii	CAWD136	0.57	Culture	Selwood et al. (2018)
A. pacificum	CAWD234	13.93	Culture	Selwood et al. (2018)
A. pacificum	CAWD46	26.45	Culture	Selwood et al. (2018)
A. pacificum	CAWD262	11.60	Culture	Selwood et al. (2018)
A. pacificum	CAWD49	15.90	Culture	Selwood et al. (2018)
A. pacificum	CAWD47	13.13	Culture	Selwood et al. (2018)
A. pacificum	CAWD235	9.93	Culture	Selwood et al. (2018)
A. pacificum	Manukau Harbour	6.99	Culture	Selwood et al. (2018)
A. pacificum	CAWD45	1.96	Culture	Selwood et al. (2018)
A. pacificum	CAWD50	2.61	Culture	Selwood et al. (2018)
A. pacificum	CAWD44	1.23	Culture	Selwood et al. (2018)
A. pacificum	CAWD260	0.29	Culture	Selwood et al. (2018)
A. pacificum	CAWD121	0.04	Culture	Selwood et al. (2018)
A. pacificum	CAWD261	0.06	Culture	Selwood et al. (2018)
Gymnodinium catenatum	CAWD102	100.71	Culture	Selwood et al. (2018)
G. catenatum	CAWD126	53.01	Culture	Selwood et al. (2018)
G. catenatum	CAWD101	231.57	Culture	Selwood et al. (2018)

Appendix 2. Saxitoxin cell quotas collated from international studies

Microalgal Taxa	Strain	Total STXs (pg/cell)	Country	Source	Reference
A. australiense	Various	0.80	Australia	Culture	Ruvindy et al. (2023)
A. catenella	Various	126.10	Australia / US	Culture	Ruvindy et al. (2023)
A. catenella	AT.TR/F	9.86	Tasmania, Australia	Culture	Seger et al. (2020); Turnbull et al. (2020)
A. minutum	RCC4871	8.50	France	Culture	Caruana et al. (2020)
A. minutum	17-037	0.18	Turkey	Culture	Selwood et al. (2018)
A. minutum	AM89BM	3.90	France	Culture	Castrec et al. (2021)
A. minutum	Da1257	0.23	France	Culture	Castrec et al. (2021)
A. minutum	RCC3167	0.63	France	Culture	Geffroy et al. (2021)
A. minutum	CH940x	1.07	Ireland	Culture	Geffroy et al. (2021)
A. minutum	RCC4871	6.62	France	Culture	Geffroy et al. (2021)
A. minutum	RCC4872	1.32	France	Culture	Geffroy et al. (2021)
A. minutum	RCC4890	1.43	France	Culture	Geffroy et al. (2021)
A. minutum	RCC7037	6.99	France	Culture	Geffroy et al. (2021)
A. minutum	RCC7038	1.58	France	Culture	Geffroy et al. (2021)
A. minutum	RCC7039	3.20	France	Culture	Geffroy et al. (2021)
A. minutum	RCC3327	1.99	France	Culture	Geffroy et al. (2021)
A. pacificum	TFB_C/18	4.07	New South Wales	Culture	Barua et al. (2020)
A. pacificum	TFB_G/18	4.28	New South Wales	Culture	Barua et al. (2020)
A. pacificum	IFR-ACA-15	13.90	France	Culture	Caruana et al. (2020)
A. pacificum	Various	9.60	Australia / NZ / Korea / Japan / Singapore	Culture	Ruvindy et al. (2023)
A. pacificum	G6-7	8.46	Spain	Culture	Geffroy et al. (2021)
A. pacificum	IFR-ACA-15	11.03	France	Culture	Geffroy et al. (2021)
A. pacificum	B9-1	2.02	France	Culture	Geffroy et al. (2021)
A. pacificum	C11-4	5.88	France	Culture	Geffroy et al. (2021)
A. pacificum	F5-4	0.63	France	Culture	Geffroy et al. (2021)
A. pacificum	G2-1	4.78	France	Culture	Geffroy et al. (2021)
A. pacificum	H8-4	4.04	France	Culture	Geffroy et al. (2021)
A. pacificum	C2-4	6.62	France	Culture	Geffroy et al. (2021)
A. pacificum	IFR-ACA-17	1.58	France	Culture	Geffroy et al. (2021)
Gymnodinium catenatum	TOPO5	1.65	Mexico	Culture	Band-Schmidt et al. (2014)
G. catenatum	52L	57.25	Mexico	Culture	Band-Schmidt et al. (2014)
G. catenatum	Not reported	337.83	Japan	Culture	Oh et al. (2010)
G. catenatum	Y3F24	15.07	China	Culture	Park et al. (2004)

Microalgal Taxa	Strain	Total STXs (pg/cell)	Country	Source	Reference
G. catenatum	SW1	4.49	China	Culture	Park et al. (2004)
Pyrodinium bahamense	Field	6.50	Mexico	Environmental	Núñez-Vázquez et al. (2022)
P. bahamense	Not reported	2.00	Red Sea	Culture	Banguera-Hinestroza et al. (2016)
P. bahamense	Various	147.07	Philippines	Culture	Usup et al. (1994)
P. bahamense	PBC-MZ-061593	109.57	Philippines	Culture	Gedaria et al. (2007)
P. bahamense	Field	31.69	Malaysia	Environmental	Al-Has et al. (2023)
P. bahamense	CC-UHABS-040(M)	6.06	Malaysia	Culture	Al-Has et al. (2023)

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