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Multi-trophic paralytic shellfish toxin risk and management across seafood sectors in Tasmania

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ABSTRACT

Multi-trophic biotoxin risk management is critically important to regions that suffer from extensive blooms of paralytic shellfish toxin (PST) producing algae. In Australia, Tasmania's east and south-east coasts are hotspots for PST activity due to recurrent blooms of *Alexandrium catenella* and *Gymnodinium catenatum* occurring in differing geographic regions and seasonal patterns. Toxins have been measured above bivalve regulatory levels in filter feeders, predatory crustaceans and herbivorous grazers at maximum levels of 340, 13.6 and 3.0 mg STX.2HCl equiv. kg^{-1} respectively, affecting commercial and recreational fisheries with a combined annual value of USD 103M. Toxin accumulation and depuration rates are highest in bivalve shellfish, followed by lobster and then abalone. Managing PST risk across these multiple seafood species in an area of recurrent bloom activity is challenging. Currently a siloed approach is taken, with diverse strategies for each species that reflect the harmful algal bloom dynamics and varied fishing activities. This review of Tasmanian data and the following stakeholder consultation identified benefits to adopting an integrated approach to risk management across all seafood species. Benefits included cost efficiencies (USD 54,100 per annum), improved data sharing for real-time awareness, streamlined communication and improved cross-sector collaboration.

1. Introduction

Paralytic shellfish poisoning (PSP) is caused by the consumption of seafood contaminated with paralytic shellfish toxins (PST), produced by specific species of dinoflagellates (EFSA, 2009). These toxins prevent the movement of sodium ions through sodium gated channels, affecting nerve conduction and preventing muscle contractions. Symptoms range from tingling of lips and extremities, nausea, vomiting, dizziness and headache, through to numbness of limbs, paralysis and in extreme cases respiratory paralysis leading to death (Chung et al., 2006; EFSA, 2009; Gessner and Middaugh, 1995; Van Dolah, 2000). As a result, many countries implement regulatory limits for bivalve shellfish production of 0.8 mg STX.2HCl equiv kg^{-1}, which has been found to be protective of illness (Toyofuku, 2006). Several studies highlight the potential for non-bivalve species to accumulate PST (Dean et al., 2020; Deeds et al., 2008; Garcia et al., 2015; Lopes et al., 2013; Silva et al., 2013, 2018), and there is increasing awareness of the need to manage PSP risk across these species (Costa et al., 2017; Silva et al., 2013, 2015).

Recurrent blooms of the PST producing dinoflagellates *Gymnodinium catenatum* and *Alexandrium catenella* occur on the Tasmanian south and east coasts (Condie et al., 2019; Dorantes-Aranda et al., 2018; Hallegraeff et al., 1995, 2021; Turnbull et al., 2021, 2017; Fig. 1). These two toxic dinoflagellates generally occur at different locations and at different times of the year, however both produce PST that may accumulate in seafood. No illnesses have been recorded in connection with consumption of commercially produced seafood, however several cases of PSP have been associated with recreational consumption of bivalve molluscs (Edwards et al., 2018; Turnbull et al., 2013).

A range of seafood species that are commercially and recreationally important to Tasmania are known to (or may potentially) accumulate PST (Campbell et al., 2013; Hallegraeff et al., 2017; Madigan et al., 2018a; Malhi et al., 2014; McLeod et al., 2017, 2018; Seger et al., 2020; Seger and Turnbull, 2023; Turnbull et al., 2021, 2015, 2020a). These species cover multiple trophic levels such as the filter feeding bivalve molluscs: Pacific Oyster (*Magallana gigas,* Thunberg 1793), Blue Mussel (*Mytilus galloprovincialis,* Lamark 1819), Native Oyster (*Ostrea angasi,* Sowerby 1871), clams (*Venerupis* spp.) and Commercial Scallop (*Pectin fumatus,* Reeve 1852); grazing gastropods and echinoderms: Blacklip Abalone (*Haliotis rubra rubra,* Leach 1814), Greenlip Abalone (*Haliotis laevigata*, Donovan 1808), Periwinkles (*Lunella undulata,* Lightfoot

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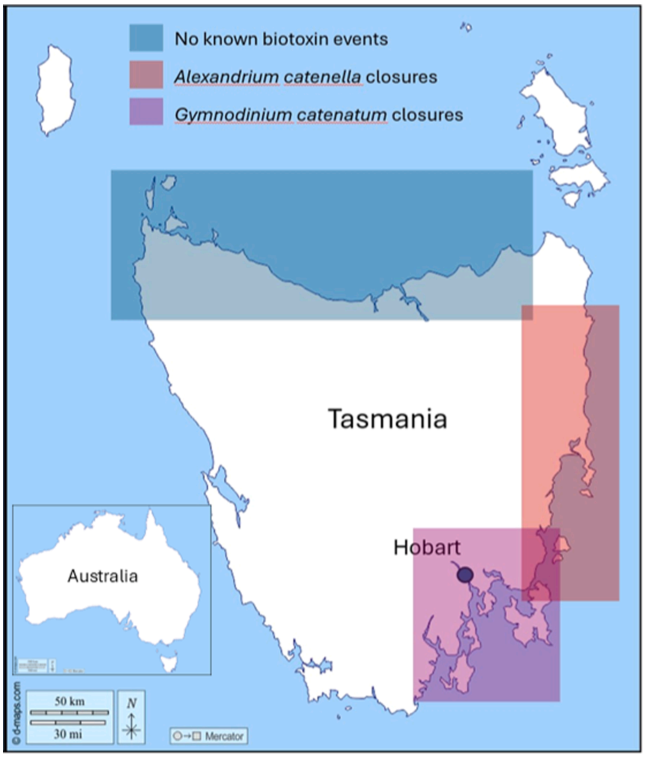

Fig. 1. Map of Tasmania showing areas that have experienced fisheries closures due to toxic blooms of *Alexandrium catenalla* and/or *Gymnodinium catenatum*. Data to December 2023.

1786), Longspined Sea Urchin (*Centrostephanus rodgersii,* Agassiz 1863) and Shortspined Sea Urchin (*Heliocidaris erythrogramma,* Valenciennes 1846); and the predator/omnivore crustacean: Southern Rock Lobster (*Jasus edwardsii,* Hutton 1875). The combined value of the commercial harvest of these species to the Tasmanian economy was USD 99.6 million[1] (Table 1) in the 2020–21 financial year. Whilst the value of recreational harvest is difficult to define, many of these seafoods are key target species for the Tasmanian recreational fishery, with an estimated value of food-safe harvests for these species of USD 3.5 million ($2020–21, Rust et al., 2023).

In Australia the Food Standards Code only lists maximum levels for marine biotoxins in bivalve molluscs (FSANZ, 2023). However, risk management strategies are in place for all the above listed species (Table 1) as there is a general requirement for the production of safe food and several importing countries have marine biotoxin standards that apply to all seafood species. The strategies in place for each fishery vary in accordance with legislation, risk (seasonality of fishing and of blooms, toxin accumulation and depuration rates and maximum levels attained), fisheries harvest and management regimes, and the size and value of the fishery. The non-bivalve species only consider PST, as the other toxin groups (amnesic, diarrhetic and neurotoxic shellfish toxins) are considered low risk in Tasmania (McCoubrey and Turnbull, 2021).

Biotoxin risk management in all species is based on the tissues consumed that may accumulate PST. Bivalves and periwinkles are consumed whole thus the whole animal is tested. For lobster, only the hepatopancreas is tested as this is the only organ that accumulates PST (Madigan et al., 2018a; Turnbull et al., 2021, 2020a, 2018). Previous work has demonstrated that consumers do eat this tissue at levels that might cause harm (Madigan et al., 2018b; McLeod et al., 2018). In abalone, both the viscera and foot tissue are monitored as toxins have exceeded bivalve regulatory levels in both tissues and the main trade is for live species (McLeod et al., 2017; Seger et al., 2020; unpublished field data). Canning is an option to reduce toxicity through removal of the viscera and epipodium tissues, and export requirements vary accordingly for live and processed product (DAFF, 2021). In urchins, only the roe is consumed and therefore this is the tissue that is monitored.

Currently the biotoxin risk management activities covering seafood sectors in Tasmania are defined in separate species-specific Management Plans (Table 1), managed by different entities (the Tasmanian Government, Tasmanian Abalone Council Limited, Tasmanian Scallop Fishermen's Association, Tasmanian Rock Lobster Fishermen's Association and individual periwinkle, urchin and abalone aquaculture businesses). Adding to the complexity, requirements from domestic and export regulators also vary, with three State government entities (Tasmanian Department of Health and Natural Resource and Environment Tasmanian Marine Resources and Biosecurity Branches) and one Commonwealth government entity (Department of Fisheries and Forestry Export Branch) having competent authority in different parts of the supply chain under three different legislative tools (DAFF, 2020; DoH, 2003; NRET, 2015).

Data sharing between seafood sectors occurs in a highly bespoke, and in some cases ad hoc, manner. There is no easy-to-access system that collates and displays all biotoxin related data to provide a State-wide situational awareness; and there is no formalised data storage to allow for the present and historic costs of regulatory monitoring to be leveraged by industry, the recreational sector (public good) and research institutions.

Intuitively, many stakeholders understand that integrating risk management across the fisheries would help save costs, enable data sharing for improved situational awareness and risk assessment, as well as assist in the development of the technical expertise that is needed to operate in the field. However, separate programs have been run for over a decade, indicating that hurdles to integration exist.

This review of the relative biotoxin risk and associated risk management strategies across multiple seafood sectors in Tasmania considered the available fisheries and PST data alongside the various risk management plans to compare the seasonality of fishing and high risk biotoxin periods; the geographic coverage of sampling sites across all species; and sampling frequencies in relation to biotoxin accumulation rates. We presented the data to stakeholders to establish industry and competent authority priorities for an integrated biotoxin management approach; understand the scale and distribution of resources required for effective integrated management; and identify benefits and costs to key stakeholders.

This is the first published study examining field rates of marine biotoxin accumulation and risk management across such a broad range of commercial and recreational fisheries from multiple trophic levels (bivalves, gastropods and crustaceans). We consider other risk management models internationally in proposing one integrated option for the main affected seafood sectors in Tasmania to provide a foundation for operational change.

2. Seafood sectors in Tasmania managing PST risk

Fisheries data of catch rates around Tasmania, seasonal closures for fisheries management, and fishing zones were compiled from State fisheries data and reports from the previous 10 years. The data was used to identify high-catch zones and fishing seasons for comparison with high risk biotoxin zones and seasons.

The three species of major commercial significance at risk of PST accumulation are aquaculture bivalves (predominantly Pacific Oysters) and wild harvest Southern Rock Lobster and Blacklip Abalone, harvesting 3604; 1050; and 885 tonne per annum respectively with gross revenue from landings of USD 25.5 M; 27.6 M; and 38.4 M respectively (Table 1; Department of Natural Resources and Environment Tasmania

[1] Current conversion rate from AUD to USD is highly variable. We used a ratio of 0.6284 (Google 28/1/2025).

Table 1
Fishery information and risk management of seafood (potentially) accumulating marine biotoxins in Tasmania. Fisheries information from Department of Natural Resources and Environment Tasmania, biotoxin monitoring costs from Rust et al. (2023).

Species	Production (tonnes annually, USD value, 2020–2021)	Fishery information	Biotoxin management plan	Biotoxin management costs USD '000 (low bloom year)	Risk management strategy	Responsible organisation
Commercial bivalves excluding scallops (oysters, mussels, clams)	3604, 25.5M	North, east and south coasts, mostly aquaculture with minimal wild harvest	ShellMAP Biotoxin Management Plan (ShellMAP, 2019)	631.7	Weekly toxin testing in high-risk areas, fortnightly elsewhere	Tasmanian Government – Shellfish Market Access Program
Commercial Southern Rock Lobster	1050, 27.6M	Quota managed, statewide, wild capture using pots	Rock Lobster Biotoxin Monitoring Decision Making Protocol (NRET, 2023)	37.7	Fortnightly sentinel mussel monitoring on east coast May to Dec, escalating to lobster hepatopancreas monitoring	Tasmanian Government - Wild Fisheries
Commercial Abalone	885, 38.4M	Quota managed, statewide, wild capture dive fishery	Abalone Biotoxin Management Plan 2023	–	Testing of viscera and foot tissues when notified of blooms by other monitoring programs	Tasmanian Abalone Council
Commercial Scallops	3,495, 1.1M	Seasonal openings for wild harvest using dredges on north and east coasts	Scallop Biotoxin Management Plan (SFAT, 2022)	8.8	Batch testing of harvests, based on pre-season surveys and aquaculture bivalve results	Scallop Fishermen's Association of Tasmania
Aquaculture Abalone	3.9M	On-shore aquaculture, east and south-east coasts	Export requirement for testing during blooms	3.1	Annual testing	Businesses
Commercial Periwinkles	56, 1.0M	Catch capped statewide, wild capture dive fishery	No formal program in place	–	Monthly testing of harvest in abalone closed zones	Businesses
Commercial Urchins	669, 2.2M	Uncapped (introduced) and capped (native) statewide wild capture dive fisheries, main take from the east coast. Introduced fishery government subsidised as pest control	Export requirement for monthly testing in each zone of harvest affected by blooms	15.1	Monthly testing of harvest in abalone closed zones	Businesses
Recreational fisheries	Unknown	Statewide, variety of species, some size limitations, no-take zones and seasonal closures	No formal program	–	Reliant on commercial results	Tasmanian Government - Health

(NRET) data). Smaller commercial fisheries for scallops, periwinkles, urchins and aquaculture abalone (all <USD3.5 M each) are also required to manage PST risk, with the recreational fishing sector notified when PST levels become concerning for human health.

Bivalve aquaculture occurs mainly on the east and south-east coasts of Tasmania (Fig. 2A), with year-round production when conditions allow.

The highest lobster catch volumes occur in the south and south-west (Fig. 2B; NRET, 2025). Relatively low catch weights of commercial lobster come from the east coast. The fishery is generally open from April to September, following which the fishery is closed for fisheries management reasons (e.g. moult season, presence of berried females, catch constraint and resource sharing between recreational and commercial sectors).

Commercial wild-caught abalone zones on the east coast of Tasmania have been closed for several years to enable stock rebuilding. The highest catches of abalone are in the south and south-west of the State (Fig. 2C; MacAllister and Mundy, 2023). Abalone blocks open in January and remain open until catch caps are caught.

Commercial scallop harvest occurs in an opportunistic fashion, with fishing areas on the north and east coast determined by seasonal stock surveys (Fig. 2D; NRET, 2025). Harvest occurs from July until the total allowable catch is taken.

The Periwinkle and urchin fisheries are low catch weight dive fisheries focused on the east coast of Tasmania, but eligible for statewide harvest (Fig. 2E&F; NRET, 2025). The native urchin species (*H. erythrogramma*) season opens in September and closes when the catch cap is reached. The majority of the catch is caught between July and February when roe is at best quality (Seger and Turnbull, 2023). The introduced species (*C. centrostephanus*) remains open year-round, with catches targeted from January to July.

In Tasmania, 27 % (n = 95,500) of the population engages in recreational fishing (Twiname et al. 2024), 17,555 of these have recreational lobster licences and 11,452 have recreational abalone licences (Tracey et al. 2024). The east coast (including the south-east) accounts for 77 % and 74 % of the recreational lobster and abalone catch respectively. Recreational lobster fishing runs from November to May on the east coast, whilst the recreational abalone fishing is year-round. Scallops can be caught recreationally between March and July, however other bivalves can be taken at any time.

3. PST risk across seafood sectors

Historic PST data held by the competent authority, research and fishery sectors, publications and risk assessments for each commercial fishery were reviewed to determine PST geographic range and seasonality, rates of PST uptake and depuration across species during bloom initiation and decline (calculated by fitting linear models to the log PST data where a minimum of four successive data points where available), maximum levels of PST recorded, and seasons of risk across the major seafood species impacted. PST concentrations that were reported in mg STX equiv kg^{-1} were converted to mg STX.2HCl equiv kg^{-1} (Turnbull et al., 2020b).

3.1. PST risk seasons, maximum levels and overlap with fishing seasons

The locations of the two PST producing phytoplankton blooming recurrently in Tasmania are depicted in Fig. 1 (ShellMAP, 1987–2022). *Alexandrium catenella* is predominantly seen on the mid east coast (Moulting Bay to Boomer Bay) from April to December, peaking in late

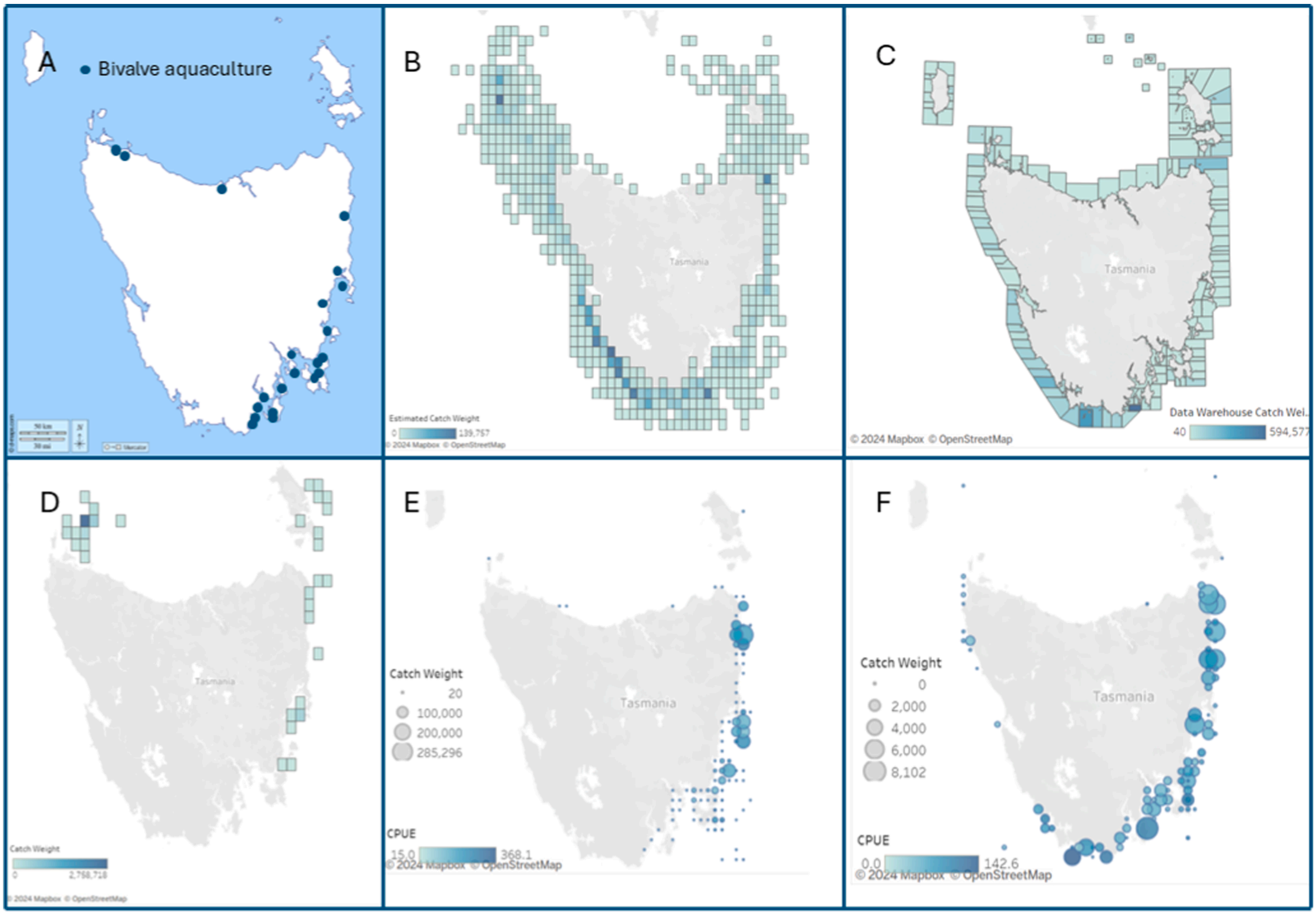

Fig. 2. Commercial zones and indicators of catch weights of fisheries sectors in Tasmania affected by PST. A) Bivalve aquaculture sites; B) Southern Rock Lobster catch weight; C) Blacklip Abalone catch weight; D) Scallop catch weight; E) Sea urchin catch weights; F) Periwinkle catch weights. Darker zones/larger circles indicate higher catch volumes.

winter/early spring. In contrast, *G. catenatum* is predominantly found in the south-east (ShellMAP, 1987–2022), and more likely to bloom in the first half of the year from January to August.

3.1.1. Bivalves

A significant portion of bivalve production occurs in bloom zones (Figs. 1 and 2) with year-round production when conditions allow. The 2012–2022 ShellMAP biotoxin dataset depicts the same seasonality for PST levels in bivalve shellfish as found for the toxic algae species, although toxins have been detected year around in some growing areas (Table 2; ShellMAP, 2012–2022). Shellfish from the east coast of Tasmania associated *A. catenella* can accumulate exceptionally high levels of PST, with the maximum detection of 173.6 mg STX.2HCl equiv kg^{-1}. Levels of PST in bivalves associated with *G. catenatum* on the south-east coast are highest in March to June, with a maximum level in this dataset of 22.1 mg STX.2HCl equiv kg^{-1} detected in Port Esperance. Prior 2012, the maximum level of toxin at this site was 235 mg STX.2HCl equiv kg^{-1} (McCoubrey and Turnbull, 2021). Blue mussels in particular accumulated toxins to an order of magnitude above the non-bivalve species, reaching a maximum level of 340 mg STX.2HCl equiv kg^{-1} (ShellMAP, 1987-2011).

Scallop PST testing occurs only during periods of active fishing and is therefore more sporadic due to the opportunist nature of the fishery. If fishing is occurring on the mid-east coast, it overlaps directly with the high-risk period for *A. catenella.* High levels of PST have been detected on occasion, with a maximum level of detection of 27.0 mg STX.2HCl equiv kg^{-1} (Table 3). As the wild fishery relocates activity during toxin events, this likely does not represent maximum levels attained.

3.1.2. Non-bivalves

For the non-bivalve species, lobster (hepatopancreas only) and abalone accumulated significant levels of PST (Table 3), with lobster hepatopancreas reporting a maximum level of 13.6 mg STX.2HCl equiv kg^{-1}. Paralytic shellfish toxins in lobster have only been detected on the east coast of Tasmania (no known toxic blooms have occurred in other harvest areas during fishing periods, so no testing has occurred outside the east coast). The seasonality of toxin detection is July to January, following the seasonality of *A. catenella* (Turnbull et al., 2021). Maximum PST levels in lobster occur during October to November, usually during non-fishing periods which may limit risk to recreational consumers.

Abalone PST levels are more complex as toxin retention appears to vary according to the toxic algal species and abalone tissue. In Tasmania, PST from abalone on the south-east coast were shown to accumulate to highest levels in the viscera (maximum 3.02 mg STX.2HCl equiv kg^{-1}) and follow *G. catenatum* seasonal patterns (McLeod et al., 2017). However, abalone from the east coast associated with *A. catenella* blooms have shown highest PST levels in foot tissues, which have retained toxin levels above 0.8 mg STX.2HCl equiv kg^{-1} several years after exposure to a toxic bloom (Fig. 3; unpublished industry data; Seger et al., 2022).

Only low levels of PST accumulation have been recorded in Periwinkles and urchins from the Tasmanian coast, below 0.15 mg STX.2HCl equiv kg^{-1} (Seger and Turnbull, 2023, IMAS unpublished data).

Table 2
Maximum PST concentrations recorded in Tasmanian oyster aquaculture zones on the east and south-east coasts of Tasmania (listed north to south) between 2012–2022 inclusive (ShellMAP data). Colours blue (<0.1 mg), yellow (0.1-<0.4 mg), light orange (0.4-<0.6 mg), orange (0.6-<0.8 mg) and brown (≥0.8 mg) indicate the maximum mg STX.2HCl equiv kg^{-1} levels.

Growing Area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Moulting Bay Z5						0.5	1.5	6.8			0.6		East Coast
Moulting Bay Z6							2.7	10.2	1.4	3.2	0.7		East Coast
Great Swanport				0.2	1.5	1.5	1.5	1.5	16.1	3.2			East Coast
Great Oyster Bay			0.4	1.7	3.8	7.4	1.6	29.8	18.6	2.5	1.6	0.5	East Coast
Little Swanport			0.2	1.5	1.5	1.5	1.5		16.1	3.2			East Coast
Spring Bay	0.4	0.5		0.5	0.5	0.2	1.4	12.4	79.4	173.6	54.6	4.6	East Coast
Boomer Bay	0.5			0.5	0.5			0.5	4.0	27.3	2.7		East Coast
Dunalley Bay						0.8	1.1	0.9		0.4			South East
Garfish Bay					0.4	0.5	0.6	0.6					South East
Pitt Water													South East
Island Inlet						0.3	1.2	1.1					South East
Pipe Clay Lagoon					1.1	1.3	1.2	2.0	1.1	1.1			South East
Great Bay		0.1		0.6	0.6	0.5	0.5	0.2				0.5	South Coast/Channel
Fleurtys Point			0.1	0.6	0.6	0.7	0.1						South Coast/Channel
Gardners Bay	1.6	2.2	0.4	12.4	10.9	1.6	2.0	1.0	0.5	0.2		0.4	South Coast/Channel
Port Esperance	0.4	2.6	4.1	22.1	14.5	3.2	1.1	0.2	0.3	0.3	0.4	0.6	South Coast/Channel
Little Taylors Bay		0.3		1.0	1.1	0.9							South Coast/Channel
Hastings Bay	0.4	0.1	0.9	2.5	1.0	0.5						0.7	South Coast/Channel
Cloudy Bay Lagoon					0.5	0.5							South Coast/Channel
Recherche Bay													South Coast/Channel

3.2. *PST accumulation and depuration rates across species*

When looking at field accumulation and depuration rates we have focused on the time frames that are most relevant to food risk management, i.e. the beginning and end of blooms when toxin levels in seafood are in the range of 0.1–1.5 mg STX.2HCl equiv kg^{-1}. For statistical accuracy, we calculated field accumulation rates from time series with a minimum of four consecutive samples. Our field accumulation and depuration rates for bivalves are influenced by bloom characteristics (e.g. the initial low cell numbers, the rate of increase in toxic cells, intracellular toxin quota, and the proportion toxic cells in relation to the total algal community/biomass, prior history of exposure and bivalve feeding characteristics (reviewed in Bricelj and Shumway 1998)). Similarly, accumulation and depuration rates in non-bivalve species in the field will be impacted by factors such as the toxin exposure route, toxicity of prey species, the proportion of prey that is toxic and feeding activity.

3.2.1. *Tasmanian bivalves*

A significant amount of monitoring data are available in the ShellMAP (2012-2022) database (over 5500 sampling events combined). However, in the early dataset as toxin concentrations became high and growing areas were closed, sampling frequency sometimes declined as the competent authority conserved funds (sampling policy has since changed to continue sampling during toxin events). This means there were only 14 occasions where four consecutive weekly samples were taken at the beginning of a bloom event, and 15 during the depuration phase. These data were used to calculate field rates of accumulation and depuration of PST for Blue Mussels and Pacific Oysters (Table 3). The highest observed accumulation and depuration rates where 0.10 day^{-1} in oysters from Pipe Clay Lagoon in May 2022 and 0.11 day^{-1} in oysters from Port Esperance in April 2018 respectively. The data shows several occasions during *A. catenella* blooms when PST levels increased from not detected one week to over the regulatory level the next week, supporting the supposition that accumulation rates could occasionally be higher than the figures included in Table 3. The average depuration rates found in Tasmanian for oysters and mussels (converted to average daily decay rates of 2.3 % and 11.7 % respectively) are consistent with those for fast detoxifiers reviewed in Bricelj and Shumway (1998), but lower than those found in experimental systems that immediately remove all toxic cells and aim to maximise depuration (e.g. compare experimentally determined rates from Lassus et al. 2005; Lassus et al. 2007; Xie et al. 2013 to depuration rates obtained in the present work for a field setting).

Accumulation and depuration rates for PST in Tasmanian scallops could not be calculated due to the movement of fishing activity away from zones where PST is present.

3.2.2. *Tasmanian non-bivalves*

Average field uptake and depuration rates in the lobster were slower, but of the same order of magnitude, when compared to those determined for bivalves (Table 3). Higher uptake rates have been measured in experimental systems for lobster fed to excess on highly contaminated prey (0.06 day^{-1}, Turnbull et al., 2020). The average field abalone uptake and depuration rates for PST were an order of magnitude lower, with field data indicating retention of PST in abalone above regulatory levels for up to two years between algal blooms (Fig. 3) in currently non-commercially active areas.

These comparative PST kinetics between the species are demonstrated in the PST field data collected at Maria Island between 2015 and 2023 (Fig. 3).

Table 3
Toxin kinetics for key seafood species in Tasmania and alignment to algal bloom risk. Toxin measured in all edible tissues unless otherwise stated. Data from risk monitoring databases unless otherwise specified. Uptake and depuration rates calculated by fitting linear models to the log PST data when a minimum of four successive data points where available.

Commercial Species (number samples in database)	Toxin uptake rate in Tasmania (day^{-1}; n = number of rates measured)	Toxin depuration rate in Tasmania (day^{-1}; n = number of rates measured)	Maximum toxin level recorded (mg STX.2HCl equiv kg^{-1})	High risk zones and seasons	Alignment with fisheries seasons
Blue Mussels (n > 1500)	0.036±0.014 (n = 7)[a,b,c]	0.010±0.06 (n = 11)[a,b,c]	340.0[d]	East coast: Apr-Dec South-east: Jan-Aug	Harvest year round when able, east coast only.
Pacific Oysters (n > 4000)	0.056±0.024 (n = 7)[a]	0.054±0.027 (n = 4)[a]	54.0[a]	East coast: Apr-Dec South-east: Jan-Aug	Harvest year round when able.
Southern Rock Lobster (n = 512)	0.011–0.024[b] (hepatopancreas; n = 2)	0.031±0.007[b] (hepatopancreas; n = 3)	13.6[b] (hepatopancreas)	East coast: July-Jan	Fishery closed Oct/Nov-March[e] (highest biotoxin risk).
Blacklip Abalone (n = 1024)	0.009±0.008[c] (viscera; n = 3) 0.003±0.001 (foot; n = 3)	0.006±0.002[c] (viscera; n = 4) 0.003±0.001 (foot; n = 4)	3.02[c] (viscera)	Lower D'Entrecasteaux Channel	Fishery opens in January[f] (*G.catenatum* high risk season north of peak fished area). No fishing in high-risk east coast.
Scallops (n = 148)	Not determined	Not determined	27.0[a]	East coast	Opportunistic harvest on east coast from July[e] (during high-risk biotoxin period).
Periwinkles (n = 27)	Not determined	Not determined	0.015	Not determined	Harvest year around, peak period August to November[e], matching east coast high risk season.
Urchins (n = 231)	Not determined	Not determined	0.15	No risk identified[g]	*C. rodgersii* catch on east coast peaks December to July[e] (some overlap with high-risk biotoxin period. *H. erythrogramma* catch on east and south-east peaks August to January[e], during high-risk biotoxin period.

[a] ShellMAP (2012–2022).
[b] Turnbull et al. (2021).
[c] McLeod et al. (2017).
[d] ShellMAP (1987-2011).
[e] NRET (2025).
[f] MacAllister and Mundy (2023).
[g] Seger and Turnbull (2023).

3.2.3. PST analogues

Cultures of *A. catenella* and *G. catenatum* isolated from Tasmanian waters contain distinct PST profiles. *Alexandrium catenella* produces a high percentage of the highly toxic gonyautoxins (GTX) 1–4 and significant proportions of the lesser toxic C 1&2, as well as small amounts of neosaxitoxin (Neo) and GTX 5 (Seger et al. 2020). In contrast, *G. catenatum* produces analogues with a lower toxin equivalency: mostly C1–4, smaller amounts of decarbomoyl (dc) GTX and dcSTX, and minor amounts of GTX 2&3, GTX5, and GTX6 (reviewed in Hallegraeff et al. 2012).

It follows that oysters and mussels that have accumulated PST from *A. catenella* blooms contain a high percentage toxicity of GTX1–4, and C1&2 (e.g. Dorantes-Aranda et al., 2017, Turnbull et al. 2020), whereas those that have accumulated PST from *G. catenatum* contain high proportions of dcSTX, dcGTX, C toxins and occasionally deoxydecarbamoyl-saxitoxin (doSTX), e.g. Turnbull et al. (2018), McLeod et al. (2017). The greater percentage of highly toxic analogues in bivalves contaminated with *A. catenella* toxins contributes to the rapid accumulation of total PST sometimes seen in the field associated with this species.

Both field and experimental work has shown that lobster accumulate and depurate the various PST analogues at different rates (Section 3.2). Paralytic shellfish toxin profiles in lobster hepatopancreas from the Tasmanian east coast during an *A. catenella* bloom in 2019 were initially >70 % C1&2, with smaller proportions of STX, GTX1&4, and C3&4 (reported as % toxicity in Turnbull et al. 2021). The proportion of C1–4 toxins decreased during toxin accumulation and depuration, whilst the proportion of GTX2&3 increased. The proportion of STX decreased during accumulation, then increased during depuration, whilst the proportion of GTX 1&4 did the reverse. Lobster experimentally fed mussels contaminated with PST from an *A. catenella* bloom contained similar profiles (Madigan et al., 2018a; Turnbull et al. 2020a).

In contrast, abalone PST profiles from an *A. catenella* feeding experiment were greater than 70 % STX, with the viscera containing close to 100 % STX, the foot tissue including small proportions of dcSTX and the epipodium containing smaller proportions of dcSTX and Neo (Seger et al. 2020). Field work from a *G. catenatum* bloom in the D'Entrecasteaux Channel shows abalone accumulate doSTX, dcSTX and STX in the foot, and doSTX, dcSTX, dcGTX2,3 and C toxins in the viscera.

4. Current PST risk management strategies in Tasmania

A variety of risk management strategies have emerged in Tasmania, (described in Table 1), based on regulatory and market access requirements, the two different PST producing algae that commonly bloom with differing toxin profiles, cell densities, geographic and seasonal patterns (Condie et al., 2019; Dorantes-Aranda et al., 2018; Hallegraeff et al., 1995, 2021; Turnbull et al., 2021, 2017), speed of PST accumulation in the tissue consumed, seasonality of risk in comparison to fishing activity, and value of the industry.

The year around commercial harvest of blue mussels and oysters from high risk biotoxin zones places these species at very high risk of toxin accumulation (ShellMAP data). In response, the oyster and mussel aquaculture industries undertake weekly biotoxin testing all year in areas where PST risk has been identified (Tables 2 and 3, ShellMAP, 2019), co-funded by the Tasmanian Government. The rapid PST uptake rates associated with *A. catenella* have seen toxicity rise from 'not detected' to 'over the regulatory level' within a week (ShellMAP, 2012–2022) and result in an average of 6.6 annual closures (289 days) across these zones. This is likely due to both the high toxin content per cell (Seger et al., 2020) and the large proportion of high-toxicity analogues. Weekly samples consist of one dozen pooled shellfish meats from each site. Bivalve risk management also includes monthly phytoplankton analysis. Trigger levels for closure pending bivalve testing for

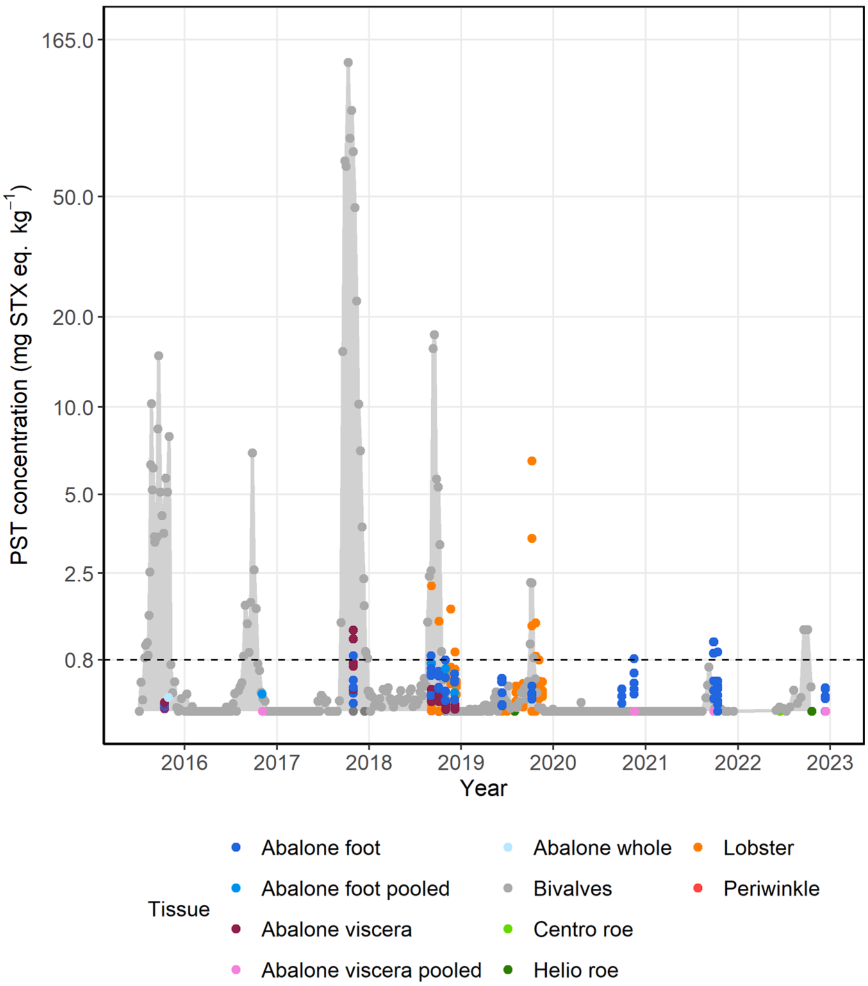

Fig. 3. Paralytic shellfish toxin concentration across multiple seafood species at Maria Island, Tasmania, 2015–2023. The bivalve regulatory level (0.8 mg STX.2HCl equiv kg^{-1} is indicated by the dashed line.

A. catenella are 500 cell l^{-1}, whereas those for *G. catenatum* are 5000 cells l^{-1}, reflecting the toxin content per cell.

The scallop fishery is seasonal and varies geographically depending on the productivity of scallop beds. Pre-season surveys for fishing area selection are also used to assess biotoxin risk prior to commercial harvest (SFAT, 2022). When scalloping occurs on the east coast of Tasmania, it directly overlaps with the high risk biotoxin season (Tables 2 and 3). The industry uses information from ShellMAP oyster and mussel PST monitoring as an early warning system and conducts monthly end-product testing of harvest (funded by industry, one dozen pooled meats) when fishing in this area. If toxins are identified, this industry has the potential to move to a different fishing area, thus avoiding risk.

In contrast, the commercial lobster fishing season on the east coast of Tasmania has less overlap with the key risk season for PST (Tables 2 and 3), and no lobster fishing occurs in the high-risk zones in the upper D'Entrecasteaux Channel. This, along with the slower uptake rate and lower level of accumulation, reduces the biotoxin risk for this fishery in comparison to bivalves. The lobster industry PST monitoring (funded by industry) is focused on the east coast of Tasmania where *A. catenella* blooms may occur between April and December. The program monitors toxins in mussel sentinels during this period to indicate risk, moving to monitor lobster hepatopancreas (5 individuals per sample event) if fishing is occurring when a bloom is identified (NRET, 2023). Low risk gaps in the lobster monitoring program are January to April on the east coast and year-round in the south-east of the State (in the lower D'Entrecasteaux Channel).

Commercial wild-caught abalone are currently not taken from the high-risk zones of the east coast due to fishery recovery reasons, and only low catch is taken from the high-risk zones on the south coast (Table 2 and 3). Abalone are slow to accumulate toxins, and very slow to depurate. Field data demonstrates that they do not necessarily accumulate toxins over the regulatory levels during bloom periods and may retain PST well after bloom activity has passed (Seger et al., 2022). Thus, whilst the abalone monitoring (funded by industry; 5 individuals per sample event) is triggered from information reported from the bivalve aquaculture and lobster monitoring programs, zone closures and testing also occurs independently of these programs and can continue well after blooms have passed, depending on levels detected in abalone flesh and viscera.

Urchin and Periwinkle risk management is based on known risk in other fisheries worldwide, and risk is yet to be positively corroborated in Tasmania (Seger and Turnbull, 2023). Minimal monthly monitoring (funded by businesses) occurs only in areas where abalone are known to have accumulated toxins given that these species are also grazers and exposed to the same source of toxin.

Recreational risk management is based on public health notices released when any commercial fishery exceeds the bivalve regulatory level. These are publicised on local media outlets, social media and notices at public boat ramps and jetties in affected areas.

4.1. Advantages and disadvantages of current PST risk management

Separate workshops conducted with industry and recreational representatives respectively, identified many common issues for biotoxin management in the State. Strengths identified in the current systems were focused on the comprehensive nature of bivalve aquaculture monitoring that underpins each risk assessment, the communication to key representative personnel, and the expertise available in Tasmania. The recreational workshop recognised as strengths the fact that the commercial sector was sharing a significant volume of biotoxin data, recreational fishers were engaged and that recreational closures were generally not mandated.

Weaknesses identified included high costs and ‘inequitable’ distribution of costs, spatial coverage of risk management, data ownership, legislative backing, potential confusion over recreational risk management, lack of expertise in some sectors, and multiple contact points for export authorities complicating communication. For the recreational sector, knowledge of recreational activities associated with high-risk species, the level of adherence to public health notices and the understanding held by recreational fishers of biotoxin risks were seen as an issue.

These weaknesses were seen to expose the State to threats from siloed risk management (hindering data sharing), loss of market access, recreational illnesses, and reputational loss.

5. Designing an integrated program

The design of an integrated approach to biotoxin management in Tasmania required careful consideration of the biotoxin dynamics over several trophic levels from filter feeders (bivalve molluscs) to keystone predators (lobster). We focused on the three largest fisheries with well-defined PST risk management programs (aquaculture bivalves, lobster and abalone) to build a baseline monitoring program that could benefit all stakeholders.

5.1. Over-arching objectives

Stakeholders agreed that the key principles for an integrated program were a) to maintain flexibility in the system such that each fishery can retain the existing risk management strategies matched to their risk profile and fishing activities; b) bring all plans together in one management plan clearly outlining roles, responsibilities, and protocols (including communication); and c) address public health, market access and business viability.

The three high-value commercial sectors impacted by marine biotoxins in Tasmania are Pacific Oyster, Rock Lobster and Abalone. A monitoring program was proposed that integrated all three sectors into a single baseline monitoring program using bivalves only during harvest periods, escalating to also test for PST in lobster and abalone when toxins were identified.

5.2. Sample sites and seasons

Current biotoxin monitoring sites for each species were mapped (Fig. 4), noting that abalone does not currently maintain permanent (independent) monitoring sites. A gap analysis of monitoring was

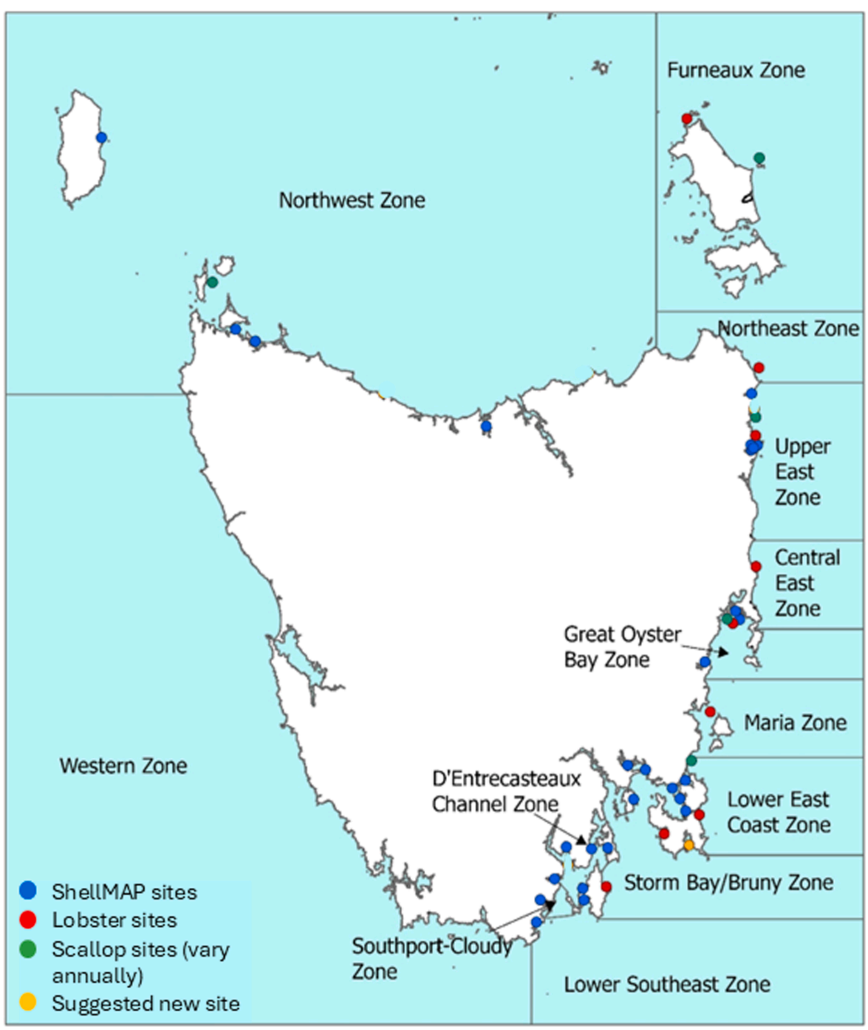

Fig. 4. Current monitoring sites for Tasmanian biotoxin risk management programs across all seafood species. Zones indicate current lobster risk management zones.

undertaken to determine both the overlap in sampling effort and any geographical/temporal areas that could be strengthened. In most cases the estuarine and near coastal bivalve monitoring sites around the State complemented the coastal lobster monitoring sites. A single duplicated site was identified at Great Oyster Bay. The current lobster program does not monitor its sites in the low-risk season (January to April) on the east coast but there are nine active bivalve sites in this area during this period. Similarly, 5 bivalve sites in the lower D'Entrecasteaux Channel cover other low risk zones for abalone and lobster that would otherwise be unmonitored. One new site was suggested on the eastern side of the Storm Bay/Bruny zone to improve the coverage of PST monitoring for lobster and abalone caught from this area.

5.3. Determining sampling frequencies and sentinel species

Traditional vectors (filter feeders) are able to accumulate PST to much higher levels in comparison to non-traditional vectors (grazers and predators), but the latter have consistently been shown to be a risk that also requires management (reviewed in Costa et al., 2017; Deeds et al., 2008; Shumway, 1995). The challenge in monitoring such a diverse range of species is to maintain a strategy that addresses the differing toxin accumulation and depuration dynamics. Costa et al. (2017) discussed this challenge, stating the need to adapt sampling frequency to the toxicokinetics of uptake and depuration, particularly when including consideration of the inherent costs associated with sampling and analysis.

Our work shows that bivalves are the faster accumulators of toxins, followed by carnivorous lobster, then the herbivorous grazing abalone. The work conducted in Tasmania appears unique in that it provides the only published studies of rates of toxin accumulation in non-traditional vectors from the field (McLeod et al., 2017; Turnbull et al., 2021).

The maximum Tasmanian field accumulation rate for PST in bivalves of 0.10 day^{-1} would result in shellfish increasing from 0.1 (the analytical level of reporting) to 0.8 mg STX.2HCl equiv kg^{-1} in 9 days, whereas the time for a similar increase in toxins using the average bivalve accumulation rate of 0.056 day^{-1} would be 16 days. This underpins the need for high frequency (weekly) monitoring in areas known to be affected by PST blooms (Table 2). For lobster, the maximum field accumulation rate measured of 0.024 day^{-1} would mean 38 days to increase from 0.1 to 0.8 mg STX.2HCl equiv kg^{-1}, although experimental rates have been considerably higher, with lobster accumulating toxins over the bivalve regulatory limit within 4 days of consuming highly toxic mussels (Turnbull et al., 2021). Nonetheless, the frequency required for appropriate risk management of lobster is lower than that required for bivalves, and two to three weeks has proven adequate in the past. This underpins the ability to use bivalves as a sentinel species for toxin accumulation in lobster (Turnbull, 2021), i.e. providing a safe margin to switch from bivalve monitoring to lobster monitoring. Similarly, abalone with an uptake rate of an order of magnitude lower also have a longer lead up to accumulate PST above regulatory/guideline levels, however consideration needs to be made for the potential for abalone to already contain remnant toxins from past events. Where no recent history of toxin monitoring in abalone exists, bivalve results may not be indicative of PST in abalone.

Costa et al. (2017) have produced a schematic describing toxicokinetics of uptake and depuration across trophic levels, based on current data available. We have adapted their figure demonstrating the various toxin kinetics to include herbivorous grazers (Fig. 5). This figure demonstrates that sampling frequencies for filter-feeders should be higher than those for predators and grazers, but also, after toxic phytoplankton leave the water column, sampling will need to continue for a longer period in the herbivorous grazers that retain toxins for longer periods. The longer retention of toxin found in abalone does not negate the use of bivalves as a sentinel species in a regular monitoring program for abalone. It does however mean that areas without a monitoring history cannot be assumed free of toxins in abalone simply through the results of bivalve testing, as toxins may still be present in abalone from a past bloom (Fig. 5).

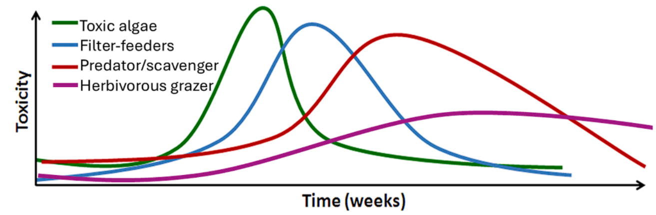

Fig. 5. Schematic representation of toxin dynamics (accumulation/elimination) in filter-feeding, predator and herbivorous grazer organisms after harmful algal blooms. Adapted from Costa et al. (2017).

5.4. Combining into one integrated system of monitoring

On the basis of the information above, we proposed a baseline bivalve sentinel monitoring system across all identified sites at a weekly/fortnightly frequency depending on the site and season (based on Table 2). For non-aquaculture sites, the sentinel species was mussels as successfully used in the current lobster monitoring program. If toxins in the bivalve shellfish of any zone exceeds the regulatory level then the bivalve zone is closed, and if fishing activity is occurring in the adjacent lobster/abalone fisheries, PST monitoring shifts to the target species (Fig. 6). Should either lobster or abalone exceed the bivalve regulatory level, then this fishery is closed for harvest re-opening only when PST concentrations return below the regulatory level.

6. Models of management

6.1. International programs

Several management models covering biotoxin risk are available internationally that cover multiple jurisdictions, partners and/or seafood species. Examples that appear relevant for Tasmania include the Alaskan Harmful Algal Bloom Program (AHAB; Harley et al., 2020); the Pacific northwest (ORHAB; Kourantidou et al., 2022; Weir et al., 2022); the Irish Shellfish Monitoring Program (FSAI, 2022; Klemm et al., 2022); the Scottish Harmful Algal Bloom, Biotoxin Monitoring and Risk Assessment (FSS, 2024) and the South African Biotoxin Monitoring Program (DFFE, 2024). Some of these programs include bivalves and gastropods and/or crustacea. Some programs are focused on recreational or cultural harvest, whilst others focus on commercial sectors (Table 4).

The AHAB network started in 2017 to provide state-wide awareness, monitoring and response to marine biotoxins in Alaska, allowing communities to manage their biotoxin risks across a broad range of bivalve species (AHAB, 2025). The monitoring efforts of multiple groups are shared through the AHAB data portal. The network consists of tribal governments and communities, government departments, seafood businesses and research institutes. Similarly, the ORHAB partnership coordinates monitoring and data sharing between researchers, marine resource managers, tribal communities and federal and state agencies in Washington State. Both networks involve both scientists and community members in data collection and analysis, but do not make collective decisions on harvest closures, leaving that to the local member groups.

The South African Aquacultured Marine Fish Food Safety Programme includes biotoxin management across a wide range of aquaculture species of bivalve shellfish, abalone, echinoderms and crustacea (DFFE, 2024). Biotoxin monitoring in all species is mandatory during harvesting periods. South Africa is divided into high and low risk zones (west and east of Cape Point respectively). The default sampling frequency for all non-filter feeders in the west is weekly, and fortnightly in the east, although filter-feeders may be used as sentinel species,

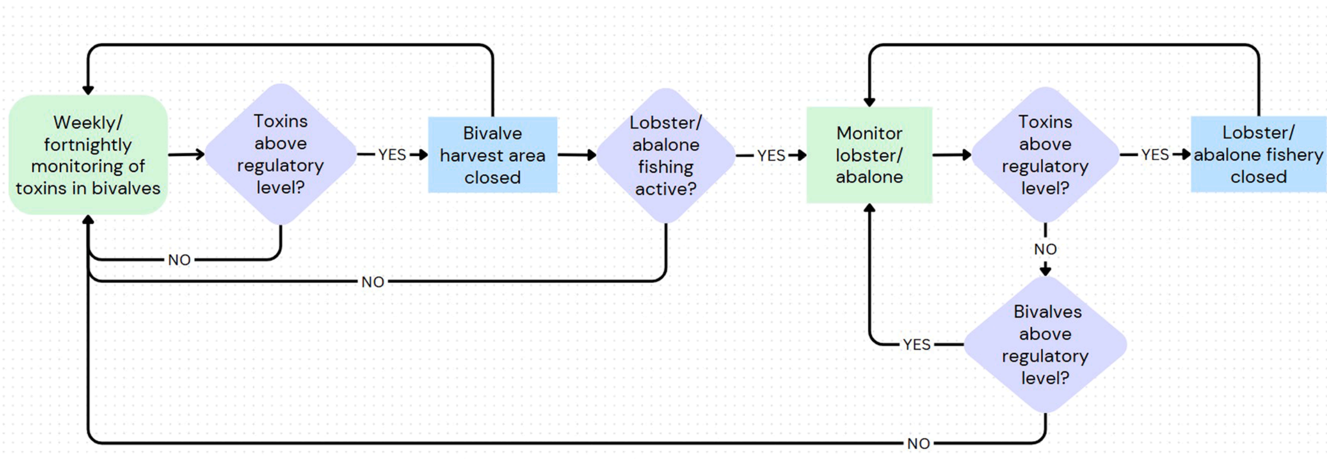

Fig. 6. Summary of the proposed integrated biotoxin risk management process for regular monitoring of aquaculture bivalves and wild caught lobster and abalone in Tasmania. Closed harvest zones are re-opened based on biotoxin monitoring results of each species following bloom termination.

Table 4
Selected biotoxin risk management programs covering multiple stakeholder groups and seafood species.

Name	Commerical/ recreational/ indigenous	Functional group	Roles	Partners	Reference
Alaskan Harmful Algal Bloom Program	Indigenous/ recreational/ commercial	Bivalve shellfish	Monitoring and promoting research	Indigenous groups	Harley et al. (2020) AHAB (2025)
ORHAB, Pacific North-west	Indigenous/ recreational/ commercial	Bivalve shellfish, crabs	Monitoring and promoting research	Government and Indigenous groups	Kourantidou et al. (2022); Weir et al. (2022)
Irish Shellfish Monitoring Program	Commercial	Bivalve shellfish, gastropods	Monitoring and control	Government, commercial fishers, and researchers	FSAI (2022); Klemm et al. (2022)
South African Aquacultured Marine Fish Food Safety Programme	Commercial Aquaculture only	Bivalve shellfish, abalone, echinoderm and crustaceans	Monitoring and control	Government and industry	DFFE (2024)

monitored at a twice weekly frequency. The Department of Forestry Fisheries and the Environment is the competent authority responsible for monitoring and controlling aquaculture production.

The Irish risk management model (FSAI, 2022) has a management structure designed for multiple commercial and government stakeholders, monitoring commercial bivalve and gastropod species around the Irish coast. The Sea-Fisheries Protection Authority is the competent authority managing official controls and administering the Irish Shellfish Monitoring Program for Biotoxins (FSAI, 2022). The program is overseen by a Molluscan Shellfish Safety Committee (MSSC) consisting of growers, producers, competent authorities (food authority, public health, Environmental Protection Agency (EPA) and fisheries management), researchers, and analytical laboratories. The MSSC provides a forum to discuss risk management, consumer protection and economic development. Assessments of public health risk are provided as required by an assisting 'management cell'.

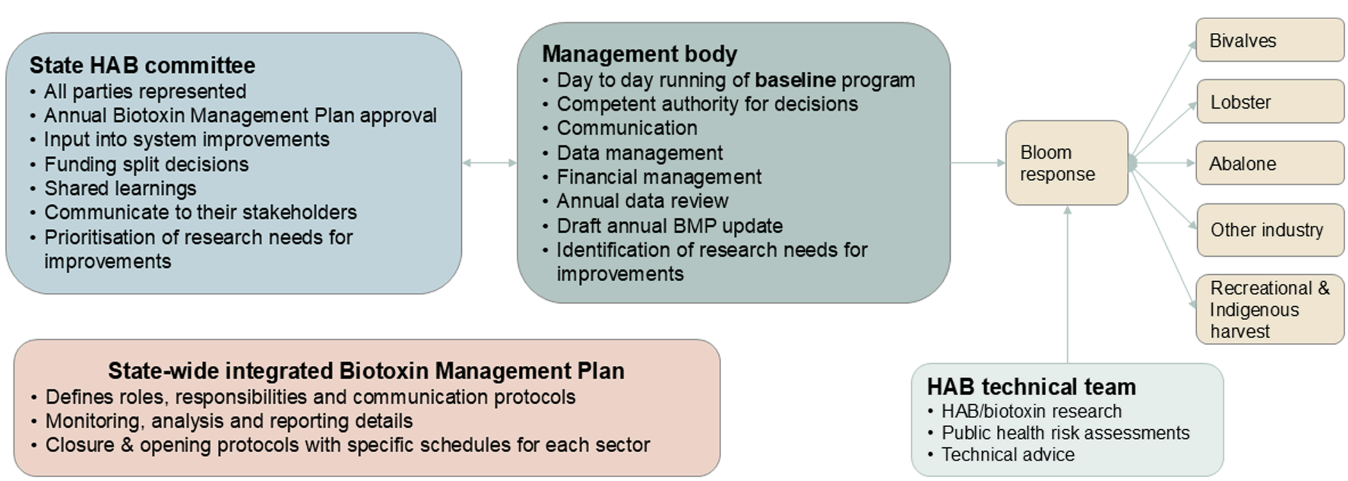

Fig. 7. The proposed management structure and roles of an integrated biotoxin risk management program for commercial and recreational seafood harvest in Tasmania.

6.2. Option for Tasmania

The Irish risk management model (FSAI, 2022) is closely matched to Tasmanian requirements. Moving to a similar model would involve a transition from a variety of independent programs (funded and run by industry and government) to a unified program managed by one organisation with multiple funders. A proposed structure, based on the Irish model, is presented in Fig. 7. If implemented, the Tasmanian program will be the first reported program covering commercial and recreational harvest of bivalves, gastropods and crustaceans. As such, benefits will be realised by the whole Tasmanian community.

7. Benefits of integration

7.1. Non-financial

Through working with stakeholders, many opportunities were identified to strengthen risk management in the State through integrating systems. These provided benefits including consolidating legislative backing, cost efficiencies, opportunities for improved cross-sector collaboration in the future to include other seafood sectors such as aquaculture finfish (currently monitoring for ichthyotoxic algae), assuring trading partners that all species have comprehensive risk management run by technical experts, and improving communication.

7.2. Financial

The financial benefit of integration to sectors was determined by identifying shared monitoring events (monitoring sites and monitoring periods that were of direct value to multiple fisheries), starting with determining the total cost for a combined Rock Lobster-Abalone integrated programme. This was estimated using a cost of USD 361.41 (2020–21) per monitoring event (average per event sampling and testing for east coast sentinel lines based on the Rock Lobster Monitoring Program), and assumed that the sites and sample frequencies identified in Sections 5.2 and 5.3 would be acceptable to the competent authorities; both industries continue current fishing operations (seasons, locations etc.); and the abalone industry would regain access to the east coast fishing zones that are currently closed for fisheries management reasons. The value of the data maintained by the competent authority managing food risk in the oyster industry was assessed using the reduction in annual sampling required from the combined Rock Lobster-Abalone programme following access to the oyster data.

The potential net benefit of integration to each sector in a 'typical' year of biotoxin activity (Table 5) was determined by analysing sampling sites with shared value across the three sectors, considering site locations and sample frequencies, as described in Section 5.2.

Table 5 shows the net benefit of shared monitoring for each of the three sectors (Rust et al., 2023). The value of the shared testing (USD 53, 850 in savings per annum) is apportioned equally among all three sectors ('Shared component baseline monitoring') and added to the remaining sector-specific baseline monitoring costs ('Baseline monitoring excluding shared component') for each sector. This determines the total cost of testing under the integrated system ('Total cost for each sector'). The current cost paid by each sector in a 'typical' year is then deducted ('Less current cost for each sector') to determine the additional costs (positive) or savings (negative) for each sector under the combined system ('Variance in baseline monitoring costs'). In the integrated proposal, the monitoring costs for the lobster industry would remain the same, whilst monitoring costs for abalone would increase, and those for the bivalve industry would decrease.

Table 5
Net benefits of the proposed integrated system for each participating industry (Rust et al., 2023). The bottom line shows the extra costs (black) or savings (bold) for each sector in a year of 'typical' biotoxin activity.

Costs (USD '000)	Abalone	Lobster	Bivalve aquaculture
Baseline monitoring excluding shared component	24.6	24.6	441.5
Shared component baseline monitoring	18.0	18.0	18.0
Total cost for each sector	42.6	42.6	459.5
Less current cost for each sector	0.0	42.3	495.4
Variance in baseline monitoring costs	42.6	0.3	**(35.9)**

Information currently gleaned from biotoxin monitoring is either shared between the industries that collect this data and other industries that benefit from it (at no cost) or else it is not shared at all. As a result, some industries perceive they are subsidising other sectors' programs. The proposed integrated baseline monitoring program aims to reduce these inefficiencies by recognising that a comprehensive sentinel and bivalve sampling program could monitor biotoxin levels for multiple species simultaneously and help to ensure a range of industries are able to continue to meet their market access requirements. By "sharing" only the costs of sampling sites that are of value to multiple fisheries for baseline monitoring, we have tried to make the cost distribution more equitable. The proposed management structure (Fig. 7) provides a forum for discussions on cost distribution between sectors should equity of costs become an issue during implementation (e.g. should biotoxin risk in each geographical area change significantly requiring a changed sample frequency, fishing areas change, sampling costs increase in remote areas only monitored by wild fisheries, or monitoring requirements change due to market access stipulations).

7.3. Possible extension to other fisheries and the recreational sector

The baseline monitoring program proposed will provide benefit to smaller scale (scallops, urchins, aquaculture abalone and periwinkles) and recreational fisheries. Once a management structure is in place, opportunity exists for these sectors to "buy-in" to the program. The value to each fishery will need to be determined on a case-by-case assessment and will be dependent on the proximity of monitoring sites relative to fishery/aquaculture areas. It is likely to vary annually in the case of the opportunistic wild fisheries (scallops, urchins and periwinkles).

The recreational sector currently receives broad public health warnings in relation to biotoxin risk based off the commercial sectors monitoring results. The baseline monitoring system proposed above could be extended further to provide monitoring capacity for the recreational sector, targeting high take areas and seasons for each PST-risk species. From an economic standpoint this should be provided up to a level that is commensurate with the total willingness to pay for such a service among Tasmanian recreational fishers. Detailed engagement with the recreational sector would be needed to determine service-level expectations (e.g., better targeted and time-limited no-fish area declarations, improved communications, monitoring for a broader range of species, etc.) and the necessary administrative mechanisms that are needed to implement this (e.g., a general recreational fishing licence or registration for Tasmania).

8. Conclusions

Managing PST risk across multiple seafood species in an area of recurrent bloom activity is challenging. Even though the current approach in Tasmania is effective in preventing illness and enabling market access, an integrated approach could reap benefits such as improved cost efficiencies, data sharing for real-time awareness, streamlined communication and improved cross-sector collaboration to respond to emerging seafood safety incidents. Under the current siloed risk management scenario, a management model was needed to allow stakeholders to envisage how integrated risk management could work. The integrated approach described here for Tasmanian waters presents key advantages over the current siloed biotoxin management plans for individual species.

The advantages of sharing of harmful algal bloom information and the formation of volunteer multi-sector programs across multiple organisations have been reported in the past (Harley et al., 2020; Kourantidou et al., 2022; McIntyre et al., 2013) and the success of shared commercial programs such as the Irish and Scottish Shellfish Monitoring Programs (FSAI, 2022; FSS, 2024) are indicative of the benefits cross-sectorial management can bring. Given the rise in knowledge of toxin accumulation in non-bivalve species and increasing regulation in this space (Costa et al., 2017) this type of program will likely become more common.

Working with all stakeholders, we have demonstrated financial and non-financial benefits for integrated risk management across multi-trophic seafood sectors in Tasmania to provide a foundation for operational change. Implementing an integrated approach will begin with the three major commercial sectors (oysters, lobster and abalone) then look to include scallops, periwinkles and urchins (if necessary), followed by additional stakeholders with over-lapping interests, such as recreational fishers and the salmon industry.

Understanding rates of toxin accumulation in various seafood vectors in Tasmania has informed the sampling frequency of the proposed field monitoring program to manage risk. As risk management programs for non-traditional vectors develop here and elsewhere, a better understanding of rates of accumulation across a broad range of species will be needed.

The program design is based on a systematic analysis of data and offers flexibility for each fishery, balancing the need to protect public health and market access with the requirement for minimal effective sampling in this costly area. Stakeholders expressed the key principles needed from such a system (flexible risk management based on science, clear management plan and protocols, and the need to address public health, market access and business viability), as well as the desire to improve communications, enable real-time data display to promote early awareness of bloom activity and data sharing to support research, and to build the expertise of risk managers.

Activities to integrate risk management across all seafood species in Tasmania are continuing and current work is focusing on implementing a suitable model of management, including funding mechanisms and communication protocols.

CRediT authorship contribution statement

Alison Turnbull: Writing – original draft, Visualization, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Steven Rust:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Deborah Bermudes:** Writing – review & editing, Methodology, Investigation. **Andreas Seger:** Writing – review & editing, Visualization, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Alison Turnbull reports financial support was provided by Tasmania Department of Natural Resources and Environment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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