The value of monitoring in efficiently and adaptively managing biotoxin contamination in marine fisheries

Christopher M. Free[1,2]*, Stephanie K. Moore[3], Vera L. Trainer[4]

[1] Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, CA, 93106, USA
[2] Marine Science Institute, University of California, Santa Barbara, Santa Barbara, CA, 93106, USA
[3] Conservation Biology Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, WA, 98112, USA
[4] Environmental and Fisheries Science Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, WA, 98112, USA

*** Corresponding author:** Bren School of Environmental Science and Management, University of California, Santa Barbara, 2400 Bren Hall, Santa Barbara, CA 93106-5131; 610-999-4732; cfree14@gmail.com

Abstract (251 words)

Harmful algal blooms (HABs) can produce biotoxins that accumulate in seafood species targeted by commercial, recreational, and subsistence fisheries and pose an increasing risk to public health as well as fisher livelihoods, recreational opportunities, and food security. Designing biotoxin monitoring and management programs that protect public health with minimal impacts to the fishing communities that underpin coastal livelihoods and food systems is critically important, especially in regions with worsening HABs due to climate change. This study reviews the history of domoic acid monitoring and management in the highly lucrative U.S. West Coast Dungeness crab fishery and highlights three changes made to these programs that efficiently and adaptively manage mounting HAB risk: (1) expanded spatial-temporal frequency of monitoring; (2) delineation of clear management zones; and (3) authorization of evisceration orders as a strategy to mitigate economic impacts. Simulation models grounded in historical data were used to measure the value of monitoring information in facilitating efficient domoic acid management. Power analysis confirmed that surveys sampling 6 crabs (the current protocol) have high power to correctly diagnose contamination levels and recommend appropriate management actions. Across a range of contamination scenarios, increasing the spatial-temporal frequency of monitoring allowed management to respond more quickly to changing toxin levels and to protect public health with the least impact on fishing opportunities. These results highlight the powerful yet underutilized role of simulation testing and power analysis in designing efficient biotoxin monitoring programs, demonstrating the credibility of these programs to stakeholders, and justifying their expense to policymakers.

Keywords (6 maximum): harmful algal blooms; *Pseudo-nitzschia*; domoic acid; amnesic shellfish poisoning; Dungeness crab; *Metacarcinus magister*

Highlights (3-5 bullet points, 85 characters each)

- Efficient biotoxin management protects public health at least cost to fishers
- Evisceration orders offer flexibility during extended contamination events
- Clearly delineated management zones promote predictable management
- High frequency monitoring (spatially/temporally) enables efficient management
- Simulation testing and power analysis can guide survey design and establish credibility

1. Introduction

Harmful algal blooms (HABs) represent an increasingly significant threat to fisheries and aquaculture globally. In some, but not all, regions (Hallegraeff et al., 2021), they are increasing in size, frequency, and duration due in part to the combined effects of eutrophication and climate change (Glibert, 2020; Hallegraeff, 2010, 1993; Van Dolah, 2000) and these trends are expected to persist or worsen with continued climate change ("high confidence" in (IPCC, 2019)). Many HABs are harmful because they produce toxins that accumulate in species harvested by fisheries and aquaculture and can cause human illness or mortality when consumed in high doses (Grattan et al., 2016). As a result, toxin levels in vulnerable seafood species are closely monitored and elevated levels often trigger the closure of fisheries and aquaculture operations, which can undermine their economic, nutritional, and sociocultural value (Bauer et al., 2010; Ritzman et al., 2018; Trainer et al., 2020a). Designing biotoxin monitoring and management programs that effectively protect public health with minimal impacts to fishing and aquaculture operations is critical to maintaining the viability of coastal communities in a changing ocean.

On the North American West Coast, diatoms in the *Pseudo-nitzschia* genus can produce the neurotoxin domoic acid, which can cause amnesic shellfish poisoning (ASP) when shellfish containing elevated levels of the toxin are consumed by humans. The symptoms of ASP range from gastrointestinal issues (e.g., stomach pain, vomiting, diarrhea, etc.) to neurological issues (e.g., headaches, dizziness, confusion, memory loss, seizures, etc.) to, in rare cases, death (Teitelbaum et al., 1990). The first cases of ASP and its linkage to *Pseudo-nitzschia* and domoic acid were documented in eastern Canada in 1987 (Bates et al., 1989; Perl et al., 1990; Wright et al., 1989) and domoic acid contamination has been monitored in several commercially and recreationally harvested seafood species on the U.S. West Coast since 1991 (CA-OST, 2016a). Domoic acid commonly enters the food web through filter feeders such as mussels, clams, and anchovies and is then transferred to predators such as crabs, lobsters, and fish (Lefebvre et al., 2002). Bivalves and crustaceans generally exhibit the highest risk of contamination, are monitored the most frequently, and receive the greatest regulatory oversight in their fisheries and farming operations.

HABs of *Pseudo-nitzschia* are significantly increasing in the U.S. (Hallegraeff et al., 2021). In 2015, a marine heatwave known as "the blob" caused a *Pseudo-nitzschia* bloom of unprecedented size and duration (McCabe et al., 2016; McKibben et al., 2017). The bloom spanned from southern California to Alaska (McCabe et al., 2016) and resulted in expansive and prolonged closures of commercial and recreational fisheries (Ekstrom et al., 2020). The Dungeness crab fishery, among the most lucrative fisheries on the U.S. West Coast (hereafter West Coast), was hit especially hard (Fisher et al., 2021; McCabe et al., 2016; Moore et al., 2019). The California season was delayed by 6 months in some regions and was declared a federal fisheries disaster with over $25 million in relief aid distributed to impacted fishers, dealers, and processors (Bonham, 2018; Holland and Leonard, 2020). In addition to financial losses, the individuals living and working in West Coast fishing communities reported losses to emotional well-being and sense of place (S. K. Moore et al., 2020; Ritzman et al., 2018). Many individuals expressed mistrust in the handling of the closures surrounding the event and skepticism about the severity of the health risk (Ekstrom et al., 2020). Ekstrom et al. (2020) and Ritzman et al. (2018) suggest that this mistrust stemmed from the appearance of arbitrary and inconsistent management across states. For example, the commercial Dungeness crab fishery in northern California remained closed months after southern Oregon had opened, leading fishers to believe that agencies were using political boundaries rather than physical ones to implement closures (Ritzman et al., 2018). In addition, the commercial Dungeness crab fishery was closed in some parts of California while the recreational fishery remained open with an advisory to remove contaminated viscera, leading to confusion around the public health risk of domoic acid (Ekstrom et al., 2020). This highlights a dual need to demonstrate the credibility of the science supporting toxin monitoring and management and to standardize best practices across fisheries and management boundaries.

The monitoring and management of domoic acid in the West Coast Dungeness crab fishery (**Fig. 1; Tables S1, S2**) is based on design principles common to most biotoxin monitoring and management programs (Langlois and Morton, 2018; Park et al., 1999). First, a level of contamination that triggers management action is specified. The action level for Dungeness crab is 20 ppm domoic acid in the meat or 30 ppm in the viscera (guts) based on the analysis of data from the 1987 ASP outbreak (Toyofuku, 2006; US-FDA, 2019; Wekell et al., 2004). Second, criteria for determining when to take or cease management actions based on this action level is defined. In all three West Coast states, a fishing area will open if each of six crabs collected from the area test below the action level. If one or more of the collected crabs test above the action level, management action is taken and is only ceased when two successive surveys, conducted at least 7 days apart, test clean (each of six crabs below the action level). Third, the spatial-temporal frequency of monitoring and size and arrangement of the associated management zones is determined. Decisions related to this third principle are arguably the most critical to determining the ability of management to efficiently respond to changes in toxin contamination and all three states have employed different approaches to this critical dimension of biotoxin monitoring. Finally, management actions for responding to high levels of toxin contamination are identified. When the 2015 HAB event hit, the only management action available to West Coast states was to employ area closures.

After the surprise of the 2015 HAB event and its devastating impact on coastal communities, all three states made modifications to their biotoxin monitoring and management plans (**Fig. 1**). In Nov 2017, Oregon passed legislation to allow the use of “evisceration orders” as an alternative to full fishery closures (ODA, 2017). Evisceration orders require the removal of crab viscera, which harbor the greatest domoic acid contamination (Wekell et al., 1994), in the event that the viscera tests above the action level but the meat tests below the action level. Although eviscerated crabs often receive lower market prices (Hackett et al., 2003), this option presents the fishing industry with some flexibility during extended closures. Oregon also more than doubled its number of biotoxin monitoring sites for Dungeness crab, presumably increasing the efficiency with which management can react to changes in contamination, and delineated clear management boundaries, facilitating rapid and objective decision-making for managers and increasing predictability for fishers (ODA, 2017). In Oct 2020, California delineated domoic acid management boundaries and adopted rules to require sampling at sites that were previously sampled voluntarily, though consistently (CDFW, 2020a). In Oct 2021, it legalized evisceration orders as a management option (McGuire, 2021). In Feb 2021, Washington adopted an emergency rule temporarily allowing evisceration orders (WDFW, 2021) and is currently considering legislation to grant long-term authority for issuing evisceration orders and to fund expanded testing of crab harvested in the Puget Sound (Chapman and Pollet, 2021). Although intuitively beneficial, these expansions come with increased costs. Understanding the benefits of these expansions is therefore necessary to justify increased spending on biotoxin monitoring and to increase stakeholder trust in the effectiveness of these measures.

Simulation testing and power analysis are powerful tools for quantitatively measuring the ability of monitoring programs to track ecosystem dynamics and to accurately and effectively inform management (Field et al., 2007; Legg and Nagy, 2006). Simulation testing leverages ‘operating models’ that attempt to replicate the dynamics of a system as a platform for comparing alternative monitoring and management programs with predefined performance metrics. Power analyses are a class of simulation methods used to determine the minimum sample size required to detect an effect of a given size, or the corollary, the minimum size of an effect that can be determined by a given sample size. Simulation testing and power analysis are commonly used to evaluate the performance of wildlife monitoring surveys for fish (Parker et al., 2016), birds (Thomas, 1996), mammals (Kendall et al., 1992), reptiles (Sewell et al., 2012), and amphibians (Barata et al., 2017), but only a few studies have used these approaches to evaluate biotoxin monitoring programs. For example, (Solow et al., 2014) used power analysis to optimize the number and arrangement of monitoring sites for resting cysts of the harmful alga *Alexandrium catenella* in the Gulf of Maine, and (Fontana et al., 2020) applied a similar approach for biotoxin contamination in bivalve aquaculture in Brazil. Wider utilization of tailored simulation testing in the design of biotoxin monitoring programs – whether for benthic resting cysts, pelagic algal blooms, or contamination in wild, farmed, or sentinel (i.e., placed by humans for monitoring) species – could assist in establishing scientific foundations for defining program attributes (e.g., sample sizes, site arrangement, etc.) and finding cost-effective solutions that protect public health while limiting impacts on fishers. In turn, this could serve to justify the costs of monitoring and build stakeholder trust.

This study used a two-pronged approach to evaluate the value of biotoxin monitoring in facilitating efficient and adaptive management that protects public health with the least impact on fishing communities. First, a review of historical domoic acid monitoring and management programs in the West Coast Dungeness crab fishery is used to identify design principles that have promoted efficient and adaptive management. Second, a simulation model and power analysis based on this system is used to quantitatively measure the benefits of expanded monitoring for jointly achieving public health and fisheries objectives. Although focused on the West Coast Dungeness crab fishery and domoic acid contamination, this study reveals principles relevant to the design of monitoring and management programs for other regions, species, and biotoxins. It also highlights the powerful but underutilized role of simulation testing and power analysis in anticipating and comparing the performance of alternative biotoxin monitoring programs and management strategies.

2. Methods

2.1 Historical review

2.1.1 Monitoring history

Domoic acid testing results from state-run biotoxin monitoring programs were provided by the California Department of Public Health (CDPH), Oregon Department of Agriculture (ODA), and Washington Department of Health (WDOH). The records were variable in temporal coverage but all spanned 2015 to 2021 (**Fig. 2B**). The test results primarily described domoic acid contamination in Dungeness crab (*Metacarcinus magister*), razor clam (*Siliqua patula*), and California mussel (*Mytilus californianus*) but included results for 39 other species. The data were formatted by: (1) harmonizing common names, scientific names, and other categorical attributes (e.g., tissue type, tissue source) across states and years; (2) harmonizing location names and georeferencing all locations; and (3) grouping Dungeness crab results into surveys, which were defined as samples of crab viscera collected from a given location on the same day.

2.1.2 Management history

Fishery closures and other management actions pertaining to the West Coast Dungeness crab fishery (**Fig. 2A**) were reconstructed by extracting information from news releases posted on various agency websites (**Table S3**). The following information was extracted from each news release: (1) the date of the action; (2) the type of action (i.e., close/open or enact/lift); (3) the category of action (i.e., fishery delay/closure or evisceration order); (4) the reason for the action (5) the latitudinal extent of the action; and (6) the fisheries (i.e., commercial, recreational, tribal) affected by the action. Reasons for management actions include elevated levels of domoic acid, poor quality determined by low meat recovery, and increased risk of marine life entanglement in fishing gear (or a combination of these reasons). In a few cases, fishery openings were missing for earlier closures (and vice versa), and missing actions were filled using information from the other sources or through targeted internet searches. The datasets derived from each source were merged to create as detailed a spatial-temporal history of fishery closures and other management actions as possible.

2.1.3. Indicators of potential mid-season contamination risk

Several indicators of historical HAB risk were examined to assess potential contamination risk during past Dungeness crab fishing seasons. Consortia of federal, state, and tribal agencies, universities, and other research organizations monitor *Pseudo-nitzschia* densities and particulate domoic acid concentrations at piers and beaches coastwide (**Fig. 3A**). These data are collected and collated by the HABMAP partnership in California (Kudela et al., 2015), the Oregon Department of Fish and Wildlife (ODFW) in Oregon (the MOCHA project; (McKibben et al., 2015)), and the ORHAB partnership in Washington (Trainer and Suddleson, 2005). The California data were accessed through the SCCOOS ERDDAP server and the Oregon and Washington data were provided by ODFW and ORHAB. The data were analyzed by calculating the maximum weekly density of *Pseudo-nitzschia* and particulate domoic acid at sampling sites on harmonized weekly time steps. Domoic acid contamination in other monitored fishery species (**Fig. 2C**) was examined as another indicator of potential Dungeness crab contamination risk.

2.2 Simulation testing

2.2.1 Parameterization using historical data

The first step in simulation testing and power analysis is to leverage historical data to parameterize models that mimic conditions likely to be confronted in the real world. The domoic acid testing results described above were used to characterize the range of contamination profiles encountered by West Coast Dungeness crab biotoxin monitoring and management programs in the past. Log-normal distributions were fit to the 741 domoic acid surveys with a minimum of 6 samples of crab viscera from 2014 to 2021 using the *fitdistrplus* package (Delignette-Muller and Dutang, 2015) in R (R Core Team, 2021). Log-normal distributions were used because contamination results are continuous, greater than zero (i.e., the detection limit is >1 ppm), and are generally right-skewed. The centrality and variability of the contamination profiles were described using the median and coefficient of variation (CV) of the distributions, respectively. These values were used instead of the explicit centrality (μ) and variability (σ) parameters of the log-normal distribution because of their ease of interpretation and familiarity to readers. These distributions are central to the power analysis described below and the range of centrality and variability values and example distributions are illustrated in **Fig. 4**.

2.2.2 Power analysis of monitoring survey sample size

A simple simulation model was used to measure the power of monitoring surveys sampling six crabs (the current protocol in all three states) to accurately diagnose contamination across a range of contamination profiles. This range was delineated using a generalized envelope surrounding the centrality and variability combinations observed in historical surveys (**Fig. 4**). Scenarios within this envelope were defined using pairs of median domoic acid levels in 5 ppm intervals and coefficients of variability in 0.25 intervals (**Fig. 5A**). A thousand monitoring surveys (iterations) were simulated for each pair of centrality and variability parameters; a survey represents random draws of six crabs from the contamination distribution defined by the selected centrality and variability parameters. Both the true and estimated contamination profiles were defined as 'clean' when <1 in 6 crabs (<16.6% of crabs) had viscera contaminated at or above the 30-ppm domoic acid action level and 'contaminated' when ≥1 in 6 crabs (≥16.6% of crabs) had viscera at or above the action level. Performance was measured as the percentage of surveys that (1) correctly diagnosed the results as clean or contaminated and thus recommended the appropriate management action (power of the test), (2) incorrectly diagnosed the results as clean when they were actually contaminated (Type II error) and thus riskily opened the fishery; and (3) incorrectly diagnosed the results as contaminated when they were actually clean (Type I error) and thus unnecessarily closed the fishery (**Table S4**).

2.2.3 Simulation testing the spatial and temporal frequency of monitoring

A separate simulation model was developed to measure the ability for monitoring programs of different spatial-temporal sampling designs to efficiently track and respond to changing Dungeness crab contamination rates under a range of potential contamination scenarios. Ideally, the operating model would be based on a statistical model (e.g., a spatio-temporal autoregressive model) fit to historical observations to most realistically capture and represent likely contamination dynamics. However, the lack of historical mid-season sampling in California and Washington and lack of extreme contamination events in Oregon during the 2015 to 2021 time period examined here (**Figs. 2B, S1**) precludes this best practice as an option. Instead, an array of plausible toxin contamination scenarios, informed by but not fitted to data, were developed for testing monitoring strategies of various designs.

The spatial and temporal domain of the model was based on Oregon's Dungeness crab fishery to ground hypothetical simulations in a real-world context. This served the dual purpose of providing general insights into the relationship between monitoring and fishery/public health outcomes and specific insights into the value of Oregon's recent investments in expanding the spatial-temporal extent of its domoic acid monitoring program. Thus, the model represents a coastline spanning 4 degrees of latitude (42-46°N) and simulates toxin dynamics in 0.1° latitudinal bands. It runs for 263 days representing Oregon's Dec 1-Aug 14 (256 days) commercial ocean Dungeness crab fishing season plus 1 week (7 days) of pre-season testing.

Six toxin contamination scenarios were designed based on historical contamination events. The scenarios are defined by their size and intensity (small, medium, or large events) and whether they include mid-season contamination risk. The small, medium, and large contamination scenarios represent events of increasing size, intensity, and duration and are modeled after the historical contamination events labeled in **Fig. S1**. In all six scenarios, early-season risk increases in intensity along a south-to-north gradient such that the northern portion of the contamination event is more intense and prolonged than the southern portion. In the scenarios with mid-season contamination risk, additional mid-season contamination events were modeled after mid-season events that have been detected in Oregon (**Fig. S1**). The mid-season contamination event is smaller, less intense, and less prolonged than the early-season event; however, the size, intensity, and duration of the simulated hotspot increases across the small, medium, and large contamination scenarios.

A hundred iterations of each contamination scenario were constructed by randomly drawing key characteristics for the simulated early and mid-season contamination events (e.g., their intensity, duration, latitudinal span) from the ranges of plausible values listed in **Table S5**. Early season contamination events were defined by their peak intensity, latitudinal span, and southern and northern duration. Mid-season contamination events were defined by their peak intensity, latitudinal span, duration, and the day and latitude of their peak intensity. intensity represents the proportion of crabs contaminated above the 30-ppm action level. Early season contamination events were constructed in two steps. First, the initial (day 1) contamination profile was constructed by linearly scaling the randomly selected peak intensity at the northern limit to zero at the randomly selected southern limit. Second, the remainder of the contamination event was constructed by linearly dissipating the initial contamination profile to zero by the days randomly selected for the northern and southern limits of the event. Mid-season contamination events were also constructed in two steps. First, an ellipse with the randomly selected centroid (day and latitude of peak intensity), width (peak duration), and height (peak latitudinal span) was specified. Second, contamination intensity was linearly scaled from zero at the ellipse's edge to the randomly selected peak intensity at the ellipse's center. See **Fig. 6A** for an illustration of these procedures for simulating toxin contamination.

The performance of monitoring programs differing in spatial and temporal resolution was tested. The spatial resolution of monitoring was tested by varying the number of sampling sites (2-12 sites) evenly spaced along the coast. Each monitoring site was assumed to correspond to its own management zone (i.e., similar to Oregon but different from California and Washington; **Fig. 1**). The temporal resolution of monitoring was tested by varying the frequency with which mid-season "follow up" testing is conducted after a zone tests clean. Seven scenarios were evaluated: one where follow up testing was not conducted (i.e., no sampling after a zone tested clean) and six scenarios where follow up testing occurred at regular intervals (i.e., sampling occurs every 1-6 weeks after a zone tested clean). The simulated monitoring programs followed all other standard monitoring protocols: (1) a zone opened if the pre-season test was clean (<1 of 6 samples tested at or above the 30-ppm action level); and (2) a zone was closed when a test was contaminated (≥1 in 6 crabs tested at or above the action level) and only re-opened after two consecutive clean tests conducted at least a week apart. For simplicity, it was assumed that monitoring occurred on perfect one-week intervals and perfectly diagnosed contamination rates. Introducing stochasticity into these two assumptions would increase variability in performance but the average impact would likely remain unchanged. Thus, this analysis focused on the variability generated by contamination events of differing characteristics. See **Fig. 6B** for an illustration of these procedures for simulating toxin monitoring.

The management performance facilitated by different monitoring programs was measured and compared using two performance measures: (1) lost fishing opportunity, measured as the percent of the fishing season closed unnecessarily (Type 1 error; i.e., the fishery was closed but crabs were clean) and (2) undetected public health risk, measured as the percent of the fishing season opened riskily (Type II error; i.e., the fishery was open but crabs were contaminated) (**Table S4**). To calculate both metrics, the fishing season was conceptualized in terms of "latitude-days", which integrate fishing opportunities across space (where fishing can occur) and time (when fishing can occur). Thus, the two metrics represent the proportion of latitude-days closed unnecessarily (light red areas in **Fig. 6C**) or opened riskily (light blue areas in **Fig. 6C**), respectively. See **Fig. 6C** for an illustration of these procedures.

3. Results

3.1 Historical review

3.1.1 Washington

Of the three states, Washington experienced the lowest domoic acid contamination and least expansive closures during the 2015-16 commercial Dungeness crab fishing season because of the 2015 HAB event (**Fig. 2AB**). However, Washington was the only state to conduct mid-season sampling during the 2014-15 season (May 2015), initiated in response to elevated domoic acid levels in razor clam samples (**Fig. 2C**) (Wilson, 2018), and ultimately closed its fishery for much of the remaining season. Washington experienced coastwide closures again during the 2016-17 and 2020-21 seasons, though the 2016-17 closures were to wait for northern Oregon to open following domoic acid delays (Reed, 2016) in accordance with the Tri-State Agreement that coordinates management actions across the West Coast Dungeness crab fishery (PSMFC, 2018). Washington's domoic acid monitoring and management has remained largely unchanged (**Fig. 1**), with the exception of adopting an emergency rule temporarily allowing evisceration orders in Feb 2021 (WDFW, 2021), which were used in the southern portion of the state from Feb-Apr 2021 (#5 in **Fig. 2A**). The state legislature is currently considering an amendment (HB 1508) to extend the Washington Department of Fish and Wildlife (WDFW) long-term authority to issue evisceration orders (Chapman and Pollet, 2021). Washington's regular monitoring program is sparser than Oregon and California with only two sites regularly monitored coastwide (**Fig. 2B**) and the lowest number of samples per landings and latitude (**Fig. S2**). However, Washington adjusts its crab sampling requirements in response to test results from razor clams, sentinel mussels, and to ORHAB *Pseudo-nitzschia* and particulate domoic acid data. This policy aims to efficiently use lab resources and has proved responsive to risk in the past (see 2014-15 example above). State and tribal fisheries are subject to the same domoic acid management protocols.

3.1.2 Oregon

Oregon experienced high domoic acid contamination and coastwide closures of the commercial Dungeness crab fishery during both the 2015-16 and 2016-17 seasons (**Fig. 2**). In response to these closures, Oregon instituted the most dramatic overhaul of their domoic acid monitoring and management system. In 2017, Oregon became the first state to pass a rule allowing evisceration orders (ODA, 2017) and used them during the 2017-18 and 2018-19 seasons. The state also increased regular monitoring sites from 5 to 12 locations and established clear management zones around these sites before the 2017-18 season (ODA, 2017) (**Fig. 1**). These management zones were designed in collaboration with the commercial fishing industry and were delineated using easily recognizable natural landmarks to facilitate compliance and enforcement (ODFW, 2017). This reduced the average zone size from 0.85° latitude to 0.35° latitude (**Table S6**) and significantly increased the number of samples per landings and latitude (**Fig. S2**). As a result of this investment, contamination was well characterized in the southern three zones (J/K/L) during the 2017-18 and 2018-19 seasons, which were least sampled during the monitoring regime of earlier seasons (**Fig. 2B**). This enabled more surgical closures (**Fig. 2A**) than would have been possible under the 5-zone monitoring and management regime; the 12-zone system led to closures in only K and L whereas the 5-zone system would have prompted closures in J, K, and L. Finally, unlike Washington and California, which halt pre-season sampling after a single clean test and only restart in response to indicators of elevated risk, Oregon has regularly sampled at monthly intervals over the last six seasons (**Fig. 2B**). This has enabled the detection of high mid-season domoic acid contamination and the subsequent enactment of mid-season closures or evisceration orders (**Fig. 2A**). However, monthly sampling has not been universal among seasons and zones. It has been most common in the southern region of the state (**Fig. 2B**) in response to high and enduring contamination in razor clams (**Fig. 2C)** (A. Manderson, pers. comm.).

3.1.3 California

California was hit especially hard by the massive 2015 HAB event, experiencing considerably higher domoic acid levels in Dungeness crab (#2 in **Fig. 2B**) and considerably longer fishery closures during the 2015-16 season than Oregon and Washington (#2 in **Fig. 2A**). Elevated levels of domoic acid and extended closures of the commercial Dungeness crab fishery occurred again during the 2016-17 and 2018-19 seasons. Despite this history of domoic acid contamination and closures, California has been slower to adjust its monitoring and management regime. The state established management zones for the first time before the 2020-21 season (**Fig. 1**) and passed legislative amendments allowing for the capture and sale of contaminated crabs under evisceration orders before the 2021-22 season (McGuire, 2021). The management zones were designed to be consistent with the management zones used to mitigate whale entanglement risk (CDFW, 2020b) and were delineated using easily recognizable natural landmarks to facilitate compliance and enforcement (Juhasz, 2020). California samples at more pre-season test sites than Oregon or Washington (**Figs. 1, 2B, S2**) but halts sampling at a given site after a single clean pre-season test (**Fig. 2B**). Furthermore, California has never initiated mid-season sampling in response to other indicators of domoic acid risk (e.g., elevated contamination in other species or elevated *Pseudo-nitzschia* or domoic acid concentrations in water samples). Thus, unlike Oregon and Washington, it has never recorded or responded to mid-season domoic acid risk (**Fig. 2AB**). Although it is possible that domoic acid risk remained low after each season opener, it is difficult to know without mid- and late-season testing.

3.1.4 Indicators of potential mid-season contamination risk

Indicators of historical HAB and domoic acid risk highlight the potential for mid- to late-season domoic acid contamination in the West Coast Dungeness crab fishery. *Pseudo-nitzschia* densities generally peak in early spring (Feb-Apr) with the concentration of particulate domoic acid peaking a few weeks later (May-Jun) (**Fig. 3**). This indicates potential risk for contamination of Dungeness crab both in the middle and towards the end of the commercial fishing season. Indeed, mid-season Dungeness crab contamination has been observed in both Oregon and Washington, where some mid-season testing has occurred (#1, #3, and #4 in **Fig. 2B**). Contamination in other species, including razor clam, rock crab, sardines, and anchovies, has also been observed during the commercial Dungeness crab fishing season (stars in **Fig. 2C**), highlighting the potential risk of contamination in Dungeness crab at those times.

3.2 Simulation testing

3.2.1 Number of sampled crabs

The current protocol of sampling six crabs per survey has high power to correctly diagnose the safety of opening the Dungeness crab fishery across a wide range of possible contamination profiles (**Fig. 5B**). Across all 146 evaluated contamination profiles, the six crab sampling program was, on average, 89% effective at recommending the correct decision about whether to open or close the fishery. On average, the six crab sampling program risked closing the fishery unnecessarily in 7% of contamination scenarios and opening the fishery riskily in 4% of contamination scenarios. The six crab sampling program is most vulnerable to recommending incorrect management actions when the median contamination is low but the variability in contamination is high. However, these situations have been, historically, relatively rare (**Fig. 5A**).

3.2.2 Spatial and temporal frequency of monitoring

In the scenarios with only early-season contamination risk, all monitoring programs except the 2-site monitoring program were generally able to protect public health with low incidences of lost fishing opportunity due to unnecessary closures. The 2-site monitoring program failed to detect, on average, 78%, 6%, and 7% of public health risk in the small, medium, and large contamination scenarios, respectively (**Fig. 7A**). In comparison, the 4-site to 12-site monitoring programs failed to detect, on average, less than 3% of public health risk, with relatively low incidences of unnecessary closures (less than 3.5% across contamination scenarios on average) (**Fig. 7A**). In general, increasing the spatial resolution of monitoring programs increased the proportion of public health risk captured by management, although the rank order of monitoring programs and magnitude of the benefits varied by contamination scenario (**Fig. 7A**). The 12-site monitoring program provided the greatest benefits to public health in the small and medium contamination scenarios and the third greatest benefits to public health in the large contamination scenario. Importantly, it achieved these benefits with small additional unnecessary losses in fishing opportunities relative to the coarser monitoring programs. These results indicate that, on average, Oregon's transition from 5 to 12 monitoring sites detected an additional 1.4%, 2.7%, and 0.1% of public health risk in the small, medium, and large contamination scenarios, respectively, with little impact on fishing opportunities (**Fig. 7A**). Performance fails to perfectly scale with increasing spatial resolution as an artifact of the circumstantial alignment between the monitoring zones and the limited variability in the parameterization of the simulated contamination scenarios. A different approach to parameterizing the contamination scenarios would result in a different rank order in monitoring performance, but with benefits generally increasing with more sites.

In the scenarios with both early- and mid-season contamination risk, increasing the temporal resolution of follow up monitoring dramatically reduced the frequency of undetected public health risk, but slightly increased the frequency of unnecessary fishery closures (**Fig. 7B**). The incremental benefits to public health outcomes were considerably larger than the incremental losses to fishery outcomes. For example, in the large contamination and 12-site monitoring program scenario (**Fig. 7B**), transitioning from no follow up sampling to weekly follow up sampling resulted in a reduction in the proportion of undetected public health risk by 16% (from 19% to 3% on average) and increase in the proportion of unnecessary fishery closures of only 2% (3% to 5% on average). The tradeoff between increased public health outcomes but diminished fishery outcomes weakened with decreasing contamination intensity. For example, in the small contamination and 12-site monitoring program scenario (**Fig. 7B**), transitioning from no follow up sampling to weekly follow up sampling resulted in a reduction in the proportion of undetected public health risk by 34% (47% to 13% on average) and increase in the proportion of unnecessary fishery closures of only 1% (1% to 2% on average). In general, the 4-12 site monitoring programs performed similarly to each other while the 2-site monitoring program performed considerably worse (**Fig. 7B**). Across scenarios, Oregon's transition from 5 to 12 monitoring sites and from no follow up monitoring to monthly follow up monitoring prevented, on average, an additional 11% of public health risk from going undetected (range: 8% in large to 14% in small event scenario) while closing, on average, only 1% of the fishing season unnecessarily (range: 0.6% in small to 1.2% in large event scenario). These benefits came more from the expansion in temporal monitoring than the expansion in spatial monitoring.

4. Discussion

After the massive 2015 HAB and subsequent closures of the lucrative commercial Dungeness crab fishery, West Coast states increased the efficiency of Dungeness crab domoic acid monitoring and management by: (1) expanding the spatial-temporal frequency of monitoring; (2) delineating clear management zones; and (3) legalizing evisceration orders as a potential mitigation option. These actions have already served to protect public health while limiting impacts on fishing communities. In Oregon, expanded spatial sampling allowed monitoring to closely track contamination in an emerging domoic acid hotspot (Trainer et al., 2020b) and management to surgically respond to elevated contamination with targeted closures and evisceration orders (#3, #4 in **Fig. 2AB**). In Oregon and California, the delineation of clear management zones (already in place in Washington) provided states with a roadmap for action during periods of changing contamination risk and increased the consistency, predictability, and transparency of management for fishers. In all three states, the development of legislation and infrastructure to allow evisceration orders as a mitigation option added flexibility to a management system in which fishery delays and closures were previously the only options.

Evisceration orders can reduce the burden of HABs by allowing fishing to continue when domoic acid exceeds action levels in the viscera but not the meat, but they can also introduce new costs and equity challenges. For example, the California State Senate recently passed legislation (SB 80) authorizing evisceration orders as a management option (McGuire, 2021). The California Departments of Public Health (CDPH) and Fish and Wildlife (CDFW) estimated that the new inspection, tracking, and enforcement procedures required by the bill will require $1.3 million in upfront costs and more than $500,000 in ongoing seasonal costs (Portantino, 2021). Furthermore, not all seafood buyers and processors have the capacity for or interest in eviscerating crab, which could limit which fishing communities or vessels are able to land and sell crab during an evisceration order (Humberstone, pers. comm.). Larger vessels are often more supportive of evisceration orders than smaller vessels, because unlike smaller vessels, their profits depend more on quantity than on price (Jardine, pers. comm.). Despite these challenges, a vast majority of industry, non-profit, and management organizations endorsed SB 80 and support the consideration of evisceration orders as a management option (Wood, 2021).

Historical synthesis and simulation testing provide useful tools for demonstrating and communicating the credibility of biotoxin monitoring programs and for earning stakeholder trust. For example, this study directly addresses three issues that have contributed to stakeholder mistrust in West Coast Dungeness crab domoic acid monitoring programs (Ekstrom et al., 2020). First, it illustrates that the extended closures in northern California relative to southern Oregon during the 2015-16 season (#2 in **Fig. 2A**) were due to actual differences in toxin contamination, as determined by the existing five-site monitoring system, and not to differences in management procedures across political boundaries (#2 in **Figs. 2B; Fig. S1**). Second, it reveals that sampling six crabs has high power to accurately diagnose contamination in an area. Finally, it shows that investments in expanded biotoxin monitoring limit unnecessary closures to the fishery. These results could be used to gain stakeholder trust by demonstrating the credibility of state biotoxin monitoring programs. This is especially important given that monitoring frequently depends on commercial fishing operators for the collection of samples and increasing monitoring will likely depend on strengthened stakeholder trust and participation.

Simulation testing (including power analysis) is a powerful tool for designing efficient biotoxin monitoring programs and can provide either strategic or tactical management advice. Tactical advice concerning the absolute number of samples, number and arrangement of monitoring sites, and frequency of follow up monitoring required for optimized management requires a detailed understanding of a system and can require large amounts of data to parameterize realistic operating models (e.g., (Fontana et al., 2020; Solow et al., 2014)). Strategic advice concerning the relative benefits of increasing or decreasing the resolution of different dimensions of monitoring programs can be provided with a coarser understanding of a system and simpler operating models. For example, the power analysis used here leverages a detailed understanding of the range of contamination profiles that monitoring programs are likely to encounter to provide tactical advice regarding the number of crabs needed to accurately diagnose contamination rates and recommend appropriate management actions. On the other hand, the simulation testing of the spatial-temporal resolution of monitoring programs used here relies on a more limited understanding of spatial-temporal contamination dynamics due to poor sampling coverage over the full fishing season and can only provide strategic advice regarding the value of a few monitoring sites versus many monitoring sites. Without a more complete understanding of spatial-temporal contamination dynamics, it cannot provide exact advice regarding the optimal number or arrangement of monitoring sites or frequency of follow-up testing. Thus, it may be advantageous to “over monitor” during the initial years of a monitoring program to develop a thorough and holistic understanding of the system, then use the acquired knowledge to pare back to a more efficient monitoring program through simulation testing.

Simulation testing confirmed the role of expanded monitoring linked with clearly delineated management zones in promoting efficient fisheries and public health outcomes. Under a range of potential contamination scenarios, expanded spatial resolution of monitoring promoted efficient closures that protected public health while also limiting impacts to fisheries resulting from unnecessary closures. Furthermore, expanded temporal resolution of monitoring was essential to identifying and responding to mid-season contamination risk and resulted in efficient closures when paired with a high resolution constellation of monitoring sites. Although mid- to late-season monitoring has been relatively rare, several indicators of mid-season HAB risk highlight the potential of undetected mid-season contamination risk in Dungeness crab: *Pseudo-nitzschia* and particulate domoic acid densities peak in the spring and mid-season contamination has been observed in Dungeness crab in Oregon and Washington and in California for other species. The risk of mid-season contamination and importance of mid-season monitoring is only likely to increase as a result of climate change, which is increasing the frequency, duration, intensity, and unpredictable seeding of HABs in the region (Anderson et al., 2021; McCabe et al., 2016; McKibben et al., 2017; Trainer et al., 2020b).

Regular biotoxin monitoring throughout the fishing season will likely trigger more frequent mid-season management actions. However, if mid-season monitoring finds contamination above the action level, then such actions are both mandated under federal law (US-FDA, 2019) and necessary for protecting public health (Toyofuku, 2006). This study shows that high frequency spatial-temporal monitoring can limit the extent of mid-season management actions. In Oregon, for example, monthly monitoring has triggered mid-season management (both closures and evisceration orders), but continued monitoring has been relatively quick (8, 14, 17, 42 days) to lift restrictions (#3, #4 in **Fig. 2AB**). However, even efficient mid-season management restrictions could strain the West Coast Dungeness crab fishery and those who depend on it, especially if they occur in rapid succession with other management restrictions. For example, mid-season restrictions due to domoic acid could further constrain already shortened fishing seasons resulting from low meat quality and high risk for marine life entanglements in crab fishing gear (CDFW, 2020b). Furthermore, mid-season restrictions could disproportionately impact smaller vessels, which rely more heavily on the late season fishery than larger vessels (Liu, unpublished data) and can be disproportionately impacted by area closures (Jardine et al., 2020). Nevertheless, bad press from a public health outbreak could have even larger negative impacts on consumer perceptions of and demand for crab (Mao and Jardine, 2020). Thus, protecting public health is also crucial to maintaining a viable fishery, especially as the threat of HABs and toxin contamination increases under climate change (Anderson et al., 2021; McCabe et al., 2016; McKibben et al., 2017; Trainer et al., 2020b).

Increasing the frequency of monitoring would increase costs, capacity demands, and coordination requirements, all of which already challenge current biotoxin management (CA-OST, 2016b). At a minimum, demands for both donated (volunteer) and paid (state employees) time for the collection and processing of samples would increase. Furthermore, additional sample loads could compete with testing for other toxins and species at approved laboratories, creating a backlog and potentially increasing wait times between sample collection and results. Increased wait times could lead to more recalls of contaminated product if mid-season testing triggers a management action, with negative impacts on fishers and processors. In anticipation of such challenges, Washington is currently considering increased funding for additional testing to support evisceration orders (Chapman and Pollet, 2021). Management strategy evaluations that include key components of the social system could help to identify and evaluate trade-offs associated with expanded monitoring.

Simulation testing could be used to optimize biotoxin monitoring programs for other fisheries, potentially generating efficiencies by identifying where there is an over investment of effort (e.g., spatial-temporal frequency of monitoring and the number of samples could be reduced without compromising management goals). For example, razor clam depurate domoic acid extremely slowly compared to other shellfish (Dusek Jennings et al., 2020; Schultz et al., 2008; Wekell et al., 1994), so high contamination levels are unlikely to fall below the federal action level over a single week or even two or more weeks; in some cases entire clamming seasons have remained closed (Dyson and Huppert, 2010). Scenarios could be explored where razor clam sampling becomes less frequent when contamination levels are high to explore potentially deprioritizing the processing of less information-rich samples. However, any such reduction in monitoring effort of razor clams would need to be carefully weighed against the benefits they provide as a risk indicator for contamination of Dungeness crab that is also relatively easy to acquire from coastal beaches (i.e., typically highly abundant and does not require a vessel or specialized fishing gear), and also the social, cultural, and economic services they provide to coastal communities, especially in Washington and Oregon (Crosman et al., 2019; Dyson and Huppert, 2010; Ritzman et al., 2018).

Strengthened stakeholder partnerships may also significantly lower costs associated with expanded biotoxin monitoring of West Coast Dungeness crab (Lomonico et al., 2021). This could partially be achieved by partnering more tightly with the phytoplankton monitoring programs run by ORHAB (Washington), ODFW (Oregon), and HABMAP (California) (Kudela et al., 2015; McKibben et al., 2015; Trainer and Suddleson, 2005). These programs “set the stage” for understanding the potential for crab contamination before, during, and after the commercial fishing season. These phytoplankton data (**Fig. 3**) were invaluable for determining the potential risk for contamination of Dungeness crab both in the middle and towards the end of the commercial Dungeness crab fishing season, when biotoxin monitoring in crab has historically been less frequent than during pre-season testing. This monitoring could be used to trigger additional testing in crab when *Pseudo-nitzschia* abundance or particulate domoic acid exceed proven threshold levels (Trainer and Suddleson, 2005).

In a similar manner, knowledge of where HABs develop (e.g., local hotspots for *Pseudo-nitzschia* initiation, such as the Juan de Fuca eddy and a site at the Oregon/California border; (Trainer et al., 2020b, 2002)) and information about their advection are critical to optimizing monitoring programs, especially when resources for sustaining extensive sampling are limited. An understanding of seasonal HAB abundance at these initiation sites could improve the accuracy of forecasts and reduce the need for extensive coastal monitoring of water and shellfish. Indeed, remote sampling using automated underwater vehicles is currently being implemented for offshore sampling at initiation sites (Varanasi et al., 2021). These offshore data could provide greater confidence in estimating HAB arrival at beaches and an advanced warning of crab contamination.

A centralized repository of biotoxin sampling data across all levels of the food web in the California Current Large Marine Ecosystem would accelerate understanding of contamination dynamics and ability to forecast and efficiently manage biotoxin risk. Currently, monitoring is conducted by a widely distributed network of management agencies (federal, regional, state, and tribal), industry members, universities, non-profits, and other scientific institutions. These monitoring programs track *Pseudo-nitzschia* cell densities and particulate domoic acid concentrations in the water column, domoic acid contamination in wild and farmed species, and incidents of domoic acid poisoning in seabirds and marine mammals. Although much of this data is collated into monthly HAB Bulletins in California (HABMAP[1]) and Oregon and Washington (Pacific Northwest HAB Bulletin[2]), there is a need to bridge these regional silos, to include data and partners from Mexico and Canada where monitoring and managing HAB risks is also a priority (García-Mendoza et al., 2009; Lewitus et al., 2012; McKenzie et al., 2020; Sierra-Beltrán et al., 1998), and to make this data easily accessible in a web-based repository. Such a comprehensive database would present a platform for catalyzing rapid progress in understanding the trophic transfer of domoic acid in food webs, forecasting contamination risk in seafood species, and promoting efficient biotoxin management.

Efficient monitoring and management can limit unnecessary biotoxin closures, but necessary closures will remain a reality and may increase in a changing ocean (e.g., (Trainer et al., 2020b)). As such, additional measures may be required to increase the resilience of fishing communities to HABs, especially communities that have strong dependence on the Dungeness crab fishery for their livelihoods (Moore et al., 2019). The most effective adaptive strategies for reducing and recovering income loss during the 2015 HAB event were fishing for alternate species or in alternate locations, advertising more widely, and taking side jobs (K. M. Moore et al., 2020; S. K. Moore et al., 2020). Individuals also adopted a range of short-term coping strategies such as taking out loans, borrowing money from family, friends, and employers, and applying for social services (S. K. Moore et al., 2020). However, when asked about adaptive or coping actions taken in response to the 2015 HAB event, the most common response among impacted individuals was “none” (S. K. Moore et al., 2020). Indeed, the vast majority (71%) of Dungeness crab fishers in California stopped fishing entirely during the 2015-16 closures (Fisher et al., 2021). It is unclear why so few fishers and surveyed individuals undertook any adaptive and coping actions to deal with the 2015 HAB event, but it may indicate a lack of resources and strategies available to fishing communities (S. K. Moore et al., 2020). If increasing the resilience of fishing communities to HABs is a policy goal, then government actions that strengthen and streamline access to effective adaptive strategies may be needed. Federal and state agencies have already made concerted efforts to improve communication between agencies and with stakeholders, enhance forecasting capacity, provide fast and equitable disaster relief funding, and support scientific research and coordination across jurisdictions (Ekstrom et al., 2020). Continued advancement of these priorities would complement efficient monitoring and management in limiting the impacts of HABs on fishing communities.

5. Conclusion

This study provides a synthetic portrait of biotoxin monitoring and management in the U.S. West Coast’s most lucrative commercial fishery and illustrates how states have changed their monitoring and management programs in response to mounting HAB risk. This provides an instructive template for other regions threatened by increasing risk of contamination in marine seafood. Specifically, it highlights the value of (1) designing the spatial-temporal frequency of monitoring to reflect the spatial-temporal dynamics of contamination processes; (2) delineating

---

[1] CA HAB Bulletin: https://sccoos.org/california-hab-bulletin/

[2] Pacific Northwest HAB Bulletin: https://depts.washington.edu/orhab/pnw-hab-bulletin/

clear management zones to provide a roadmap for action during periods of changing contamination risk and to increase the consistency, predictability, and transparency of management for fishers; (3) exploring the efficacy of alternative management actions -- such as evisceration orders -- that allow fishers, processors, and distributors to continue operations during extended contamination events; (4) coordinating streamlined data sharing to improve understanding of contamination dynamics; and (5) using simulation testing and power analysis to design efficient biotoxin monitoring programs, demonstrate the credibility of these programs to stakeholders, and justify their expense to policymakers. Together, these actions can advance the design of biotoxin monitoring and management programs that reduce public health risk with the least impacts to fishing communities in a 21st century ocean.

Acknowledgements

We are grateful to Tracie Barry (WDOH), Alex Manderson (ODA), Christina Grant (CDPH), Duy Truong (CDPH), Vanessa Zubkousky (CDPH), and Matthew Hunter (ODFW) for providing data from state-run biotoxin monitoring programs and to the many other scientists, fishermen, and farmers involved in collecting and processing this data. We thank ORHAB and its member partners for providing *Pseudo-nitzschia* abundance and particulate domoic acid data along the Washington coast. The Olympic Region Harmful Algal Bloom (ORHAB) partnership has been funded since 2006 through a surcharge to Washington State shellfish and seaweed licenses as authorized by RCW 77.21.555. We are grateful to Camila Vargas Poulsen and Juan Silva for help assembling the management action data. We thank Sunny Jardine (UW), Jameal Samhouri (NOAA), Jenn Humberstone (TNC), Lyall Bellquist (TNC), Christy Juhasz (CDFW), Joe Schumacher (Quinault Indian Nation), Beckye Stanton (OEHHA), Shannon Murphy (OEHHA), Dan Ayres (WDFW), Jerry Borchert (WDOH), and the data providers listed above for discussions and feedback on early drafts of the paper. This research was funded by TNC California.

References

Anderson, D.M., Fensin, E., Gobler, C.J., Hoeglund, A.E., Hubbard, K.A., Kulis, D.M., Landsberg, J.H., Lefebvre, K.A., Provoost, P., Richlen, M.L., Smith, J.L., Solow, A.R., Trainer, V.L., 2021. Marine harmful algal blooms (HABs) in the United States: History, current status and future trends. Harmful Algae 102, 101975. https://doi.org/10.1016/j.hal.2021.101975

Barata, I.M., Griffiths, R.A., Ridout, M.S., 2017. The power of monitoring: optimizing survey designs to detect occupancy changes in a rare amphibian population. Sci. Rep. 7, 16491. https://doi.org/10.1038/s41598-017-16534-8

Bates, S.S., Bird, C.J., Freitas, A.S.W. de, Foxall, R., Gilgan, M., Hanic, L.A., Johnson, G.R., McCulloch, A.W., Odense, P., Pocklington, R., Quilliam, M.A., Sim, P.G., Smith, J.C., Rao, D.V.S., Todd, E.C.D., Walter, J.A., Wright, J.L.C., 1989. Pennate Diatom Nitzschia pungens as the Primary Source of Domoic Acid, a Toxin in Shellfish from Eastern Prince Edward Island, Canada. Can. J. Fish. Aquat. Sci. 46, 1203–1215. https://doi.org/10.1139/f89-156

Bauer, M., Hoagland, P., Leschine, T.M., Blount, B.G., Pomeroy, C.M., Lampl, L.L., Scherer, C.W., Ayres, D.L., Tester, P.A., Sengco, M.R., Sellner, K.G., Schumacker, J., 2010. The importance of human dimensions research in managing harmful algal blooms. Front. Ecol. Environ. 8, 75–83. https://doi.org/10.1890/070181

Bonham, C., 2018. Letter from Charlton Bonham (CDFW) to Randy Fisher (PSMFC) on July 19, 2018.

CA-OST, 2016a. Frequently Asked Questions: Harmful Algal Blooms and California Fisheries. California Ocean Science Trust (CA-OST), Oakland, CA.

CA-OST, 2016b. Framing the Scientific Opportunities on Harmful Algal Blooms and California Fisheries: Scientific Insights, Recommendations and Guidance for California. California Ocean Science Trust (CA-OST), Oakland, CA.

CDFW, 2020a. Update on Biotoxin Management in the California Commercial Dungeness Crab Fishery.

CDFW, 2020b. Risk Assessment Mitigation Program: Commercial Dungeness Crab Fishery, California Code of Regulations, Title 14.

Chapman, M., Pollet, G., 2021. HB 1508: Concerning the sanitary control of shellfish.

Crosman, K., Petrou, E., Rudd, M., Tillotson, M., 2019. Clam hunger and the changing ocean: characterizing social and ecological risks to the Quinault razor clam fishery using participatory modeling. Ecol. Soc. 24. https://doi.org/10.5751/ES-10928-240216

Delignette-Muller, M.L., Dutang, C., 2015. **fitdistrplus** : An *R* Package for Fitting Distributions. J. Stat. Softw. 64. https://doi.org/10.18637/jss.v064.i04

Dusek Jennings, E., Parker, M.S., Simenstad, C.A., 2020. Domoic acid depuration by intertidal bivalves fed on toxin-producing Pseudo-nitzschia multiseries. Toxicon X 6, 100027. https://doi.org/10.1016/j.toxcx.2020.100027

Dyson, K., Huppert, D.D., 2010. Regional economic impacts of razor clam beach closures due to harmful algal blooms (HABs) on the Pacific coast of Washington. Harmful Algae 9, 264–271. https://doi.org/10.1016/j.hal.2009.11.003

Ekstrom, J.A., Moore, S.K., Klinger, T., 2020. Examining harmful algal blooms through a disaster risk management lens: A case study of the 2015 U.S. West Coast domoic acid event. Harmful Algae 94, 101740. https://doi.org/10.1016/j.hal.2020.101740

Field, S.A., O’connor, P.J., Tyre, A.J., Possingham, H.P., 2007. Making monitoring meaningful. Austral Ecol. 32, 485–491. https://doi.org/10.1111/j.1442-9993.2007.01715.x

Fisher, M.C., Moore, S.K., Jardine, S.L., Watson, J.R., Samhouri, J.F., 2021. Climate shock effects and mediation in fisheries. Proc. Natl. Acad. Sci. 118. https://doi.org/10.1073/pnas.2014379117

Fontana, I., Delphino, M.K.V.C., Sesterhenn, P.M., Bertotto, D., Gonçalves, V.S.P., Ferreira, F., 2020. A sampling plan for phycotoxins surveillance in bivalve mollusc farms along the Santa Catarina coast, Brazil. Aquaculture 518, 734732. https://doi.org/10.1016/j.aquaculture.2019.734732

García-Mendoza, E., Rivas, D., Olivos-Ortiz, A., Almazán-Becerril, A., Castañeda-Vega, C., Peña-Manjarrez, J.L., 2009. A toxic Pseudo-nitzschia bloom in Todos Santos Bay, northwestern Baja California, Mexico. Harmful Algae 8, 493–503. https://doi.org/10.1016/j.hal.2008.10.002

Glibert, P.M., 2020. Harmful algae at the complex nexus of eutrophication and climate change. Harmful Algae 91, 101583. https://doi.org/10.1016/j.hal.2019.03.001

Grattan, L.M., Holobaugh, S., Morris, J.G., 2016. Harmful algal blooms and public health. Harmful Algae, Harmful Algal Blooms and Public Health 57, 2–8. https://doi.org/10.1016/j.hal.2016.05.003

Hackett, S.C., Krachey, M.J., Dewees, C.M., 2003. An economic overview of Dungeness crab (Cancer magister) processing in California 44, 8.

Hallegraeff, G.M., 2010. Ocean climate change, phytoplankton community responses, and harmful algal blooms: A formidable predictive challenge. J. Phycol. 46, 220–235. https://doi.org/10.1111/j.1529-8817.2010.00815.x

Hallegraeff, G.M., 1993. A review of harmful algal blooms and their apparent global increase. Phycologia 32, 79–99. https://doi.org/10.2216/i0031-8884-32-2-79.1

Hallegraeff, G.M., Anderson, D.M., Belin, C., Bottein, M.-Y.D., Bresnan, E., Chinain, M., Enevoldsen, H., Iwataki, M., Karlson, B., McKenzie, C.H., Sunesen, I., Pitcher, G.C., Provoost, P., Richardson, A., Schweibold, L., Tester, P.A., Trainer, V.L., Yñiguez, A.T., Zingone, A., 2021. Perceived global increase in algal blooms is attributable to intensified monitoring and emerging bloom impacts. Commun. Earth Environ. 2, 117. https://doi.org/10.1038/s43247-021-00178-8

Holland, D.S., Leonard, J., 2020. Is a delay a disaster? economic impacts of the delay of the california dungeness crab fishery due to a harmful algal bloom. Harmful Algae 98, 101904. https://doi.org/10.1016/j.hal.2020.101904

IPCC, 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Jardine, S.L., Fisher, M.C., Moore, S.K., Samhouri, J.F., 2020. Inequality in the Economic Impacts from Climate Shocks in Fisheries: The Case of Harmful Algal Blooms. Ecol. Econ. 176, 106691. https://doi.org/10.1016/j.ecolecon.2020.106691

Juhasz, C., 2020. 2020 CDFW Updates to Dungeness Crab Task Force.

Kendall, K.C., Metzgar, L.H., Patterson, D.A., Steele, B.M., 1992. Power of Sign Surveys to Monitor Population Trends. Ecol. Appl. 2, 422–430. https://doi.org/10.2307/1941877

Kudela, R.M., Bickel, A., Carter, M.L., Howard, M.D.A., Rosenfeld, L., 2015. Chapter 5 - The Monitoring of Harmful Algal Blooms through Ocean Observing: The Development of the California Harmful Algal Bloom Monitoring and Alert Program, in: Liu, Y., Kerkering, H., Weisberg, R.H. (Eds.), Coastal Ocean Observing Systems. Academic Press, Boston, pp. 58–75. https://doi.org/10.1016/B978-0-12-802022-7.00005-5

Langlois, G.W., Morton, S.L., 2018. Marine Biotoxin and Harmful Algae Monitoring and Management, in: Harmful Algal Blooms. John Wiley & Sons, Ltd, pp. 377–418. https://doi.org/10.1002/9781118994672.ch10

Lefebvre, K.A., Bargu, S., Kieckhefer, T., Silver, M.W., 2002. From sanddabs to blue whales: the pervasiveness of domoic acid. Toxicon 40, 971–977. https://doi.org/10.1016/S0041-0101(02)00093-4

Legg, C.J., Nagy, L., 2006. Why most conservation monitoring is, but need not be, a waste of time. J. Environ. Manage. 78, 194–199. https://doi.org/10.1016/j.jenvman.2005.04.016

Lewitus, A.J., Horner, R.A., Caron, D.A., Garcia-Mendoza, E., Hickey, B.M., Hunter, M., Huppert, D.D., Kudela, R.M., Langlois, G.W., Largier, J.L., Lessard, E.J., RaLonde, R., Jack Rensel, J.E., Strutton, P.G., Trainer, V.L., Tweddle, J.F., 2012. Harmful algal blooms along the North American west coast region: History, trends, causes, and impacts. Harmful Algae 19, 133–159. https://doi.org/10.1016/j.hal.2012.06.009

Lomonico, S., Gleason, M.G., Wilson, J.R., Bradley, D., Kauer, K., Bell, R.J., Dempsey, T., 2021. Opportunities for fishery partnerships to advance climate-ready fisheries science and management. Mar. Policy 123, 104252. https://doi.org/10.1016/j.marpol.2020.104252

Mao, J., Jardine, S.L., 2020. Market Impacts of a Toxic Algae Event: The Case of California Dungeness Crab. Mar. Resour. Econ. 35, 1–20. https://doi.org/10.1086/707643

McCabe, R.M., Hickey, B.M., Kudela, R.M., Lefebvre, K.A., Adams, N.G., Bill, B.D., Gulland, F.M.D., Thomson, R.E., Cochlan, W.P., Trainer, V.L., 2016. An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. Geophys. Res. Lett. 43, 10,366-10,376. https://doi.org/10.1002/2016GL070023

McGuire, M., 2021. SB-80 Commercial fishing: inspection: crab traps.

McKenzie, C.H., Bates, S.S., Martin, J.L., Haigh, N., Howland, K.L., Lewis, N.I., Locke, A., Peña, A., Poulin, M., Rochon, A., Rourke, W.A., Scarratt, M.G., Starr, M., Wells, T., 2020. Three decades of Canadian marine harmful algal events: Phytoplankton and phycotoxins of concern to human and ecosystem health. Harmful Algae 101852. https://doi.org/10.1016/j.hal.2020.101852

McKibben, S.M., Peterson, W., Wood, A.M., Trainer, V.L., Hunter, M., White, A.E., 2017. Climatic regulation of the neurotoxin domoic acid. Proc. Natl. Acad. Sci. 114, 239–244. https://doi.org/10.1073/pnas.1606798114

McKibben, S.M., Watkins-Brandt, K.S., Wood, A.M., Hunter, M., Forster, Z., Hopkins, A., Du, X., Eberhart, B.-T., Peterson, W.T., White, A.E., 2015. Monitoring Oregon Coastal Harmful Algae: Observations and implications of a harmful algal bloom-monitoring project. Harmful Algae 50, 32–44. https://doi.org/10.1016/j.hal.2015.10.004

Moore, K.M., Allison, E.H., Dreyer, S.J., Ekstrom, J.A., Jardine, S.L., Klinger, T., Moore, S.K., Norman, K.C., 2020. Harmful Algal Blooms: Identifying Effective Adaptive Actions Used in Fishery-Dependent Communities in Response to a Protracted Event. Front. Mar. Sci. 6, 803. https://doi.org/10.3389/fmars.2019.00803

Moore, S.K., Cline, M.R., Blair, K., Klinger, T., Varney, A., Norman, K., 2019. An index of fisheries closures due to harmful algal blooms and a framework for identifying vulnerable fishing communities on the U.S. West Coast. Mar. Policy 110, 103543. https://doi.org/10.1016/j.marpol.2019.103543

Moore, S.K., Dreyer, S.J., Ekstrom, J.A., Moore, K., Norman, K., Klinger, T., Allison, E.H., Jardine, S.L., 2020. Harmful algal blooms and coastal communities: Socioeconomic impacts and actions taken to cope with the 2015 U.S. West Coast domoic acid event. Harmful Algae 96, 101799. https://doi.org/10.1016/j.hal.2020.101799

ODA, 2017. Oregon Administrative Rules - Chapter 603: Department of Agriculture - Division 25: Food Establishment Standards and Standards for Retail Food Service Activities - Rule 603-025-0410: Requirements for Dungeness Crab.

ODFW, 2017. Dungeness Crab Fishery Newsletter.

Park, D.L., Guzman-Perez, S.E., Lopez-Garcia, R., 1999. Aquatic Biotoxins: Design and Implementation of Seafood Safety Monitoring Programs, in: Ware, G.W. (Ed.), Reviews of Environmental Contamination and Toxicology: Continuation of Residue Reviews, Reviews of Environmental Contamination and Toxicology. Springer, New York, NY, pp. 157–200. https://doi.org/10.1007/978-1-4757-6427-7_2

Parker, D., Winker, H., Bernard, A., Götz, A., 2016. Evaluating long-term monitoring of temperate reef fishes: A simulation testing framework to compare methods. Ecol. Model. 333, 1–10. https://doi.org/10.1016/j.ecolmodel.2016.04.006

Perl, T.M., Bédard, L., Kosatsky, T., Hockin, J.C., Todd, E.C.D., Remis, R.S., 1990. An outbreak of toxic encephalopathy caused by eating mussels contaminated with domoic acid. N. Engl. J. Med. 322, 1775–1780. https://doi.org/10.1056/NEJM199006213222504

Portantino, A., 2021. SB 80 (McGuire) - Commercial fishing: inspection: crab traps. Sacramento, CA.

PSMFC, 2018. Revised Pre-Season Testing Protocol for the Tri-State Coastal Dungeness Crab Commercial Fishery.

R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Reed, H., 2016. Letter to Coastal Dungeness Crab Fishers.

Ritzman, J., Brodbeck, A., Brostrom, S., McGrew, S., Dreyer, S., Klinger, T., Moore, S.K., 2018. Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 U.S. West Coast harmful algal bloom. Harmful Algae 80, 35–45. https://doi.org/10.1016/j.hal.2018.09.002

Schultz, I.R., Skillman, A., Woodruff, D., 2008. Domoic acid excretion in dungeness crabs, razor clams and mussels. Mar. Environ. Res., Pollutant Responses in Marine Organisms (PRIMO 14 66, 21–23. https://doi.org/10.1016/j.marenvres.2008.02.012

Sewell, D., Guillera-Arroita, G., Griffiths, R.A., Beebee, T.J.C., 2012. When Is a Species Declining? Optimizing Survey Effort to Detect Population Changes in Reptiles. PLOS ONE 7, e43387. https://doi.org/10.1371/journal.pone.0043387

Sierra-Beltrán, A.P., Cruz, A., Núñez, E., Del Villar, L.M., Cerecero, J., Ochoa, J.L., 1998. An overview of the marine food poisoning in Mexico. Toxicon 36, 1493–1502. https://doi.org/10.1016/S0041-0101(98)00139-1

Solow, A., Beet, A., Keafer, B., Anderson, D., 2014. Testing for simple structure in a spatial time series with an application to the distribution of Alexandrium resting cysts in the Gulf of Maine. Mar. Ecol. Prog. Ser. 501, 291–296. https://doi.org/10.3354/meps10705

Teitelbaum, J.S., Zatorre, R.J., Carpenter, S., Gendron, D., Evans, A.C., Gjedde, A., Cashman, N.R., 1990. Neurologic Sequelae of Domoic Acid Intoxication Due to the Ingestion of Contaminated Mussels. N. Engl. J. Med. 322, 1781–1787. https://doi.org/10.1056/NEJM199006213222505

Thomas, L., 1996. Monitoring Long-Term Population Change: Why are there so Many Analysis Methods? Ecology 77, 49–58. https://doi.org/10.2307/2265653

Toyofuku, H., 2006. Joint FAO/WHO/IOC activities to provide scientific advice on marine biotoxins (research report). Mar. Pollut. Bull. 52, 1735–1745. https://doi.org/10.1016/j.marpolbul.2006.07.007

Trainer, V., Suddleson, M., 2005. Monitoring Approaches for Early Warning of Domoic Acid Events in Washington State. Oceanography 18, 228–237. https://doi.org/10.5670/oceanog.2005.56

Trainer, V.L., Davidson, K., Wakita, K., Berdalet, E., Suddleson, M., Myre, G., 2020a. GlobalHAB: Evaluating, reducing and mitigating the cost of Harmful Algal Blooms: A Compendium of case studies. PICES Press 28, 30–32.

Trainer, V.L., Hickey, B.M., Horner, R.A., 2002. Biological and physical dynamics of domoic acid production off the Washington coast. Limnol. Oceanogr. 47, 1438–1446. https://doi.org/10.4319/lo.2002.47.5.1438

Trainer, V.L., Kudela, R.M., Hunter, M.V., Adams, N.G., McCabe, R.M., 2020b. Climate Extreme Seeds a New Domoic Acid Hotspot on the US West Coast. Front. Clim. 2, 571836. https://doi.org/10.3389/fclim.2020.571836

US-FDA, 2019. Fish and Fishery Products Hazards and Controls Guidance: Fourth Edition – August 2019.

Van Dolah, F.M., 2000. Marine algal toxins: origins, health effects, and their increased occurrence. Environ. Health Perspect. 108, 133–141. https://doi.org/10.1289/ehp.00108s1133

Varanasi, U., Trainer, V.L., Schumacker, E.J., 2021. Taking the Long View for Oceans and Human Health Connection through Community Driven Science. Int. J. Environ. Res. Public. Health 18, 2662. https://doi.org/10.3390/ijerph18052662

WDFW, 2021. WSR 21-05-027 Amends rules for coastal commercial crab fishery.

Wekell, J.C., Gauglitz, E.J., Barnett, H.J., Hatfield, C.L., Eklund, M., 1994. The occurrence of domoic acid in razor clams (Siliqua patula), Dungeness crab (Cancer magister), and anchovies (Engraulis mordax). J. Shellfish Res. 13, 587–593.

Wekell, J.C., Hurst, J., Lefebvre, K., 2004. The origin of the regulatory limits for PSP and ASP toxins in shellfish. J. Shellfish Res. 23, 927–930.

Wilson, K., 2018. Marine toxin closes Washington crab season. The Astorian.

Wood, J., 2021. SB 80 (McGuire) – As Amended April 20, 2021. Sacramento, CA.

Wright, J.L.C., Boyd, R.K., Freitas, A.S.W. de, Falk, M., Foxall, R.A., Jamieson, W.D., Laycock, M.V., McCulloch, A.W., McInnes, A.G., Odense, P., Pathak, V.P., Quilliam, M.A., Ragan, M.A., Sim, P.G., Thibault, P., Walter, J.A., Gilgan, M., Richard, D.J.A., Dewar, D., 1989. Identification of domoic acid, a neuroexcitatory amino acid, in toxic mussels from eastern Prince Edward Island. Can. J. Chem. 67, 481–490. https://doi.org/10.1139/v89-075

Tables & Figures

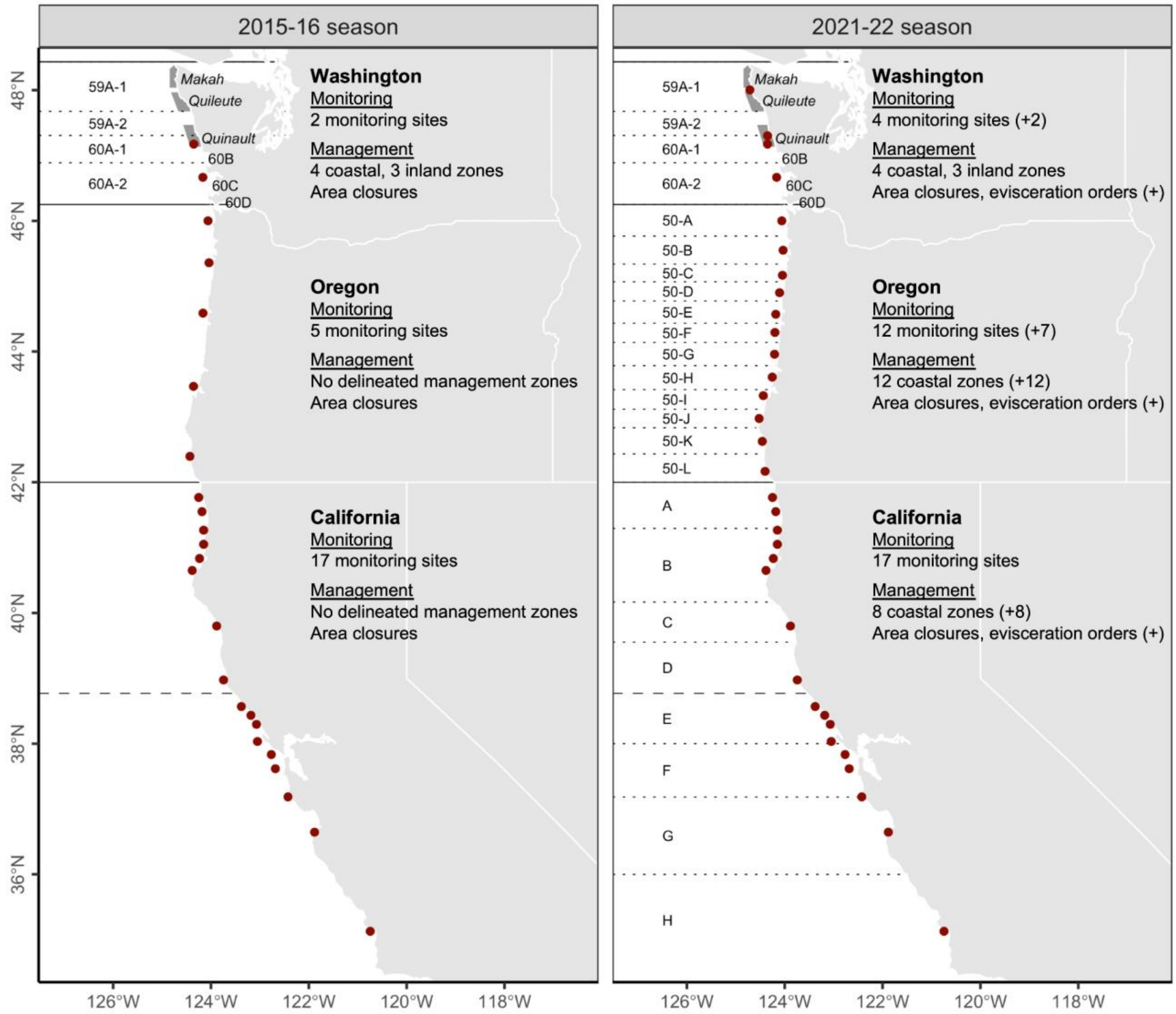


Figure 1. Dungeness crab domoic acid monitoring sites, management zones, and action options along the U.S. West Coast before the 2015-16 and 2021-22 seasons. Since the 2015-16 season, state agencies have added 9 monitoring sites and delineated 20 monitoring zones along the coast. Solid black lines indicate state borders, dotted lines indicate biotoxin management zones, and the dashed line indicates the boundary between the Northern and Central California management regions. In Washington, zones 60B, 60C, and 60D are the semi-enclosed coastal bays of Grays Harbor, Willapa Bay, and the Columbia River, respectively. At-sea shaded polygons and italic text indicate Special Management Areas (SMAs) that are co-managed by state and treaty tribe managers. Plus (+) signs indicate the addition of monitoring sites, management zones, or action options since the 2015-16 seasons.

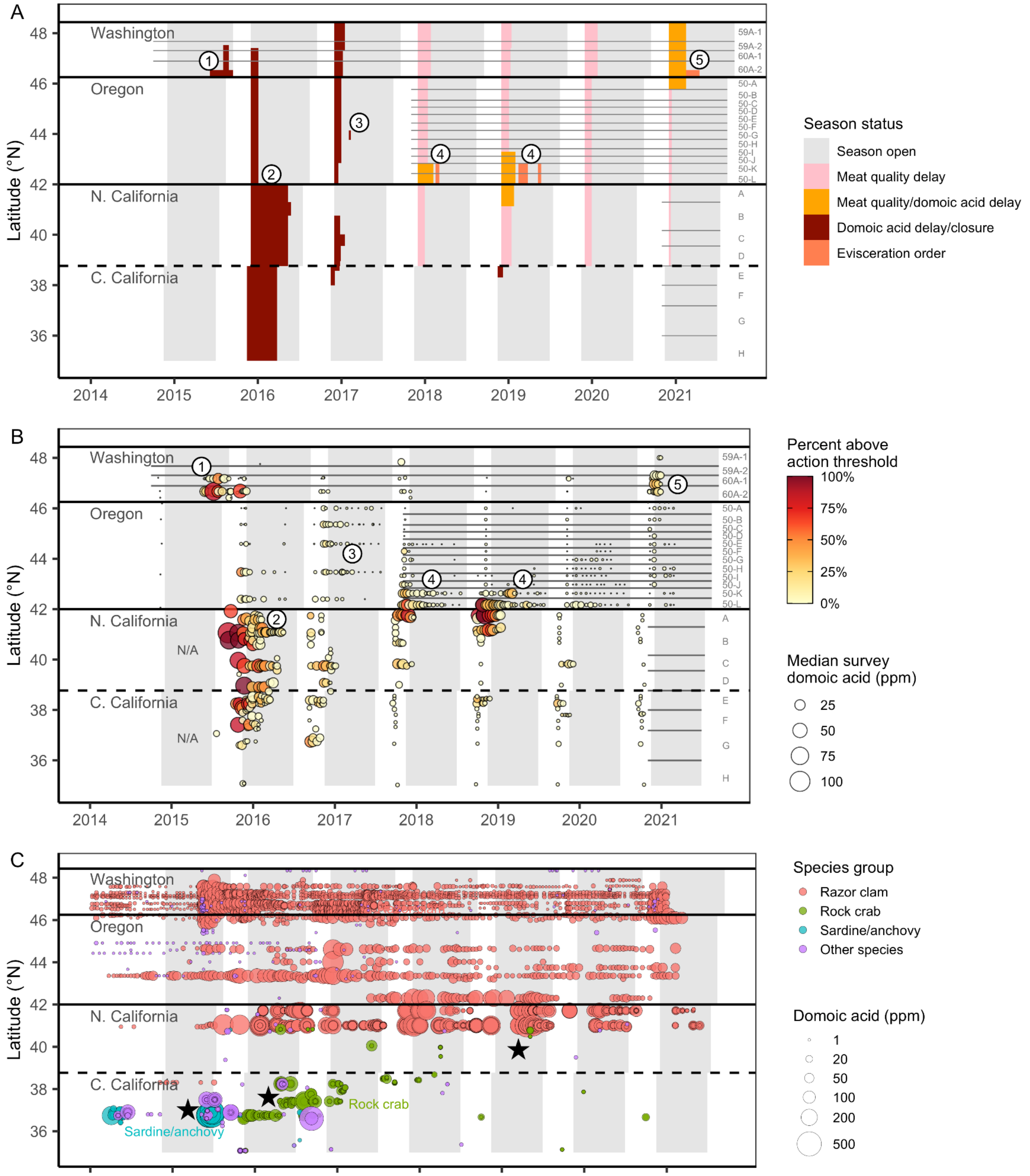


Figure 2. History of **(A)** U.S West Coast Dungeness crab fishery closures and domoic acid monitoring in **(B)** the Dungeness crab fishery and **(C)** other wild capture fisheries from 2014-2021. In **(B)** monitoring surveys (circles) are defined as a group of six or more individual samples of crab viscera collected at the same location on the same day. Note: California conducted testing before the 2014-15 season but was unable to share these results. In **(A)** and **(B)**, the labeled points highlight the following notable events: **(1)** late season monitoring and closures in Washington, triggered by elevated domoic acid in razor clams; **(2)** extended

contamination and closures in California relative to southern Oregon; mid-season **(3)** closure and **(4)** evisceration orders triggered by mid-season monitoring in Oregon; and **(5)** Washington's first evisceration order following early-season contamination. In **(C)**, points represent individual samples; black stars mark mid-season periods during which Dungeness crab biotoxin monitoring ceased despite elevated domoic acid levels in other monitored species. In all panels, solid black lines indicate state borders and the dashed line indicates the border between the Northern and Central California management zones. In **(A)** and **(B)**, gray lines indicate the biotoxin management zones established in Washington several decades ago, in Oregon before the 2017-18 season, and in California before the 2020-21 season. In **(B)** and **(C)**, gray shading indicates the commercial Dungeness crab fishing season in each region.

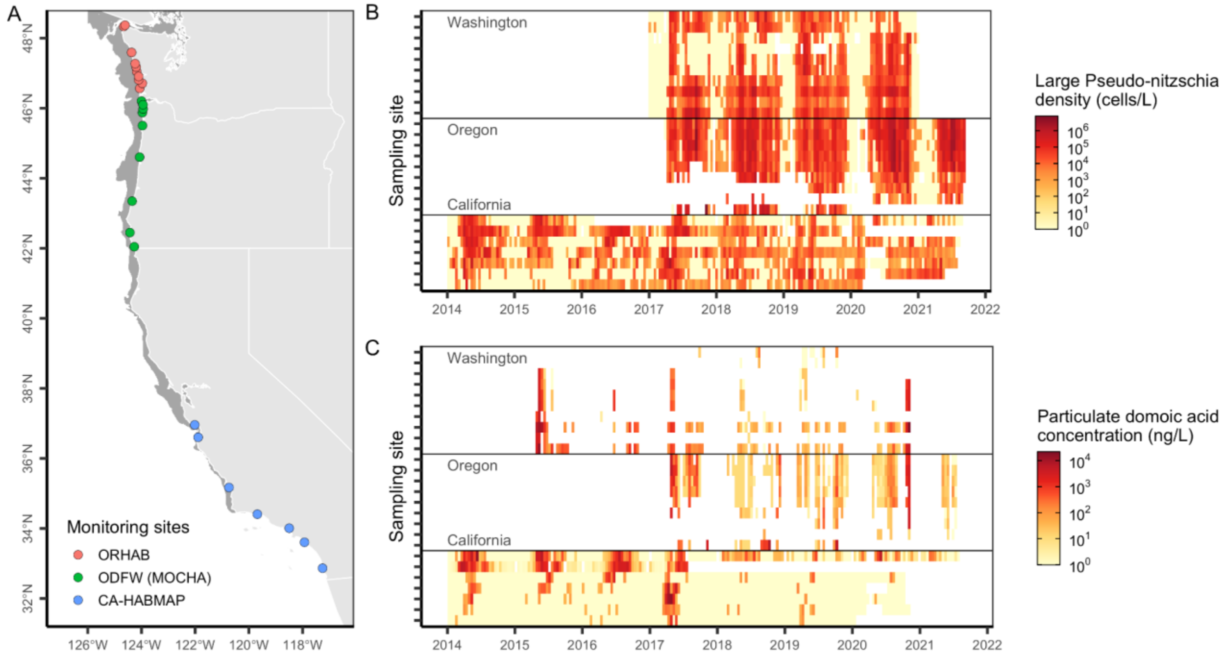


Figure 3. Historical indicators of potential mid-season domoic acid risk in the commercial California Dungeness crab fishery. Panel **(A)** shows the location of *Pseudo-nitzschia* and particulate domoic acid monitoring at selected piers and beaches along the West Coast. Gray shading indicates Dungeness crab fishing grounds (i.e., water <100 fathoms deep north of Point Conception). Panels **(B)** and **(C)** show historical *Pseudo-nitzschia* (large cells, >3 µm valve width, often *Pseudo-nitzschia seriata*) and particulate domoic acid densities at selected piers and beaches. Colors indicate maximum densities in 2-week intervals. Sites are ordered from north to south and lines indicate state boundaries. In all plots, only sites with both *Pseudo-nitzschia* and domoic acid observations for ≥5 2-week intervals are shown.

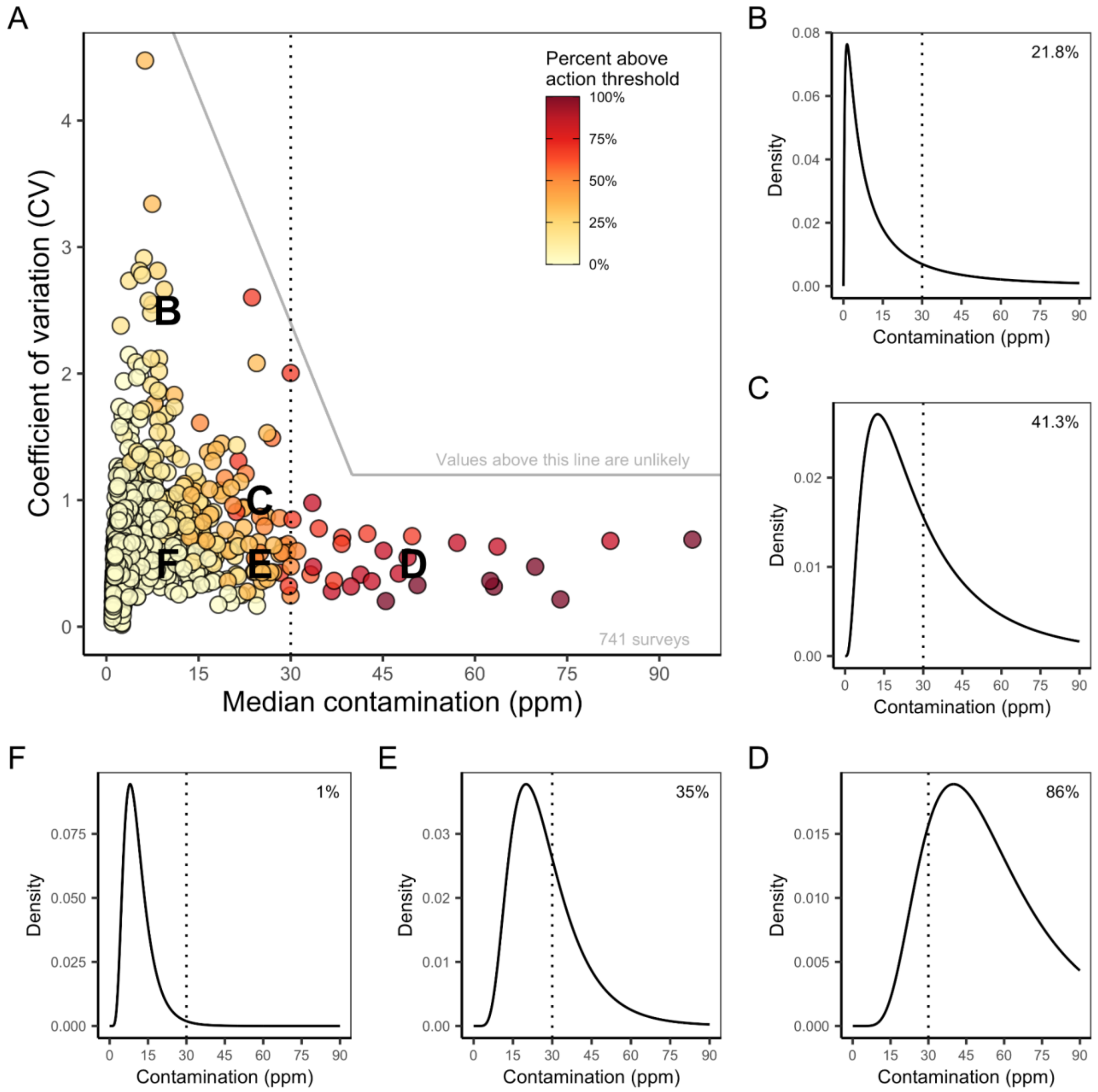


Figure 4. Distributions of domoic acid contamination in sampled Dungeness crab viscera in 741 biotoxin surveys (≥ 6 samples of crab viscera per survey) conducted on the U.S. West Coast from 2014-2021. In **(A)**, each point represents the scale (median) and shape (CV) of a log-normal distribution fit to the results of each survey. Points are colored based on the observed percentage of samples testing above the 30-ppm action level (vertical dotted line, in all panels). The solid gray lines delineate unlikely contamination distributions based on historical monitoring; values above these lines are not considered in the power analysis (**Fig. 5**). The letters indicate the scale and shape of the five example domoic acid contamination distributions illustrated in **B-F**. In **B-F**, percentages indicate the percent of crab viscera samples testing at or above the 30-ppm action level.

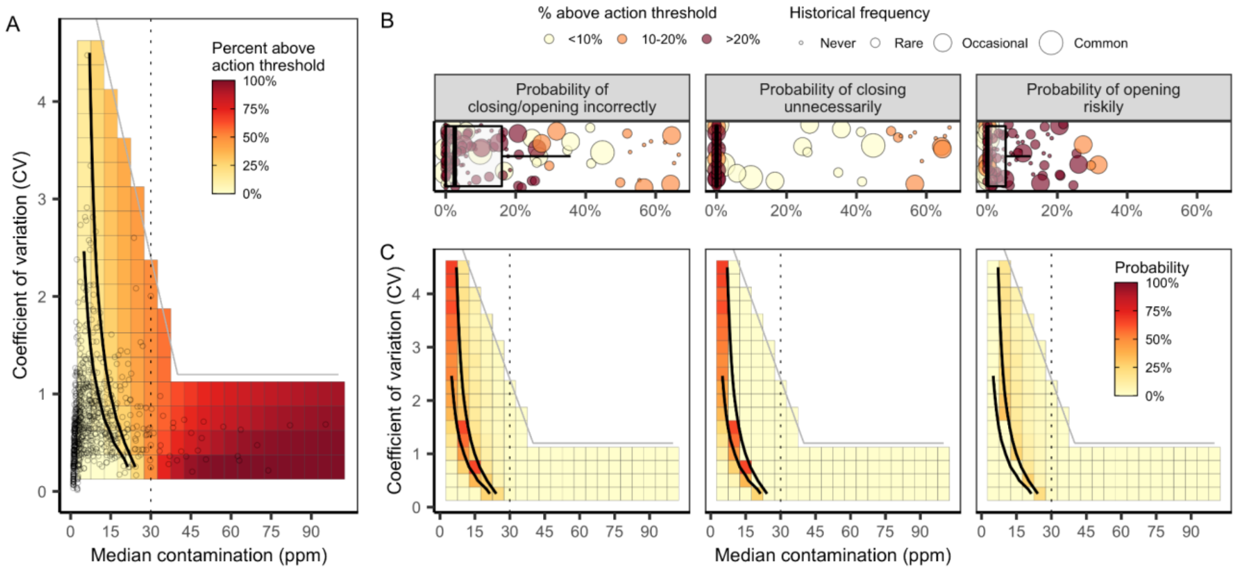


Figure 5. The **(A)** 146 contamination profiles evaluated in the power analysis and the **(B)** overall and **(C)** profile-specific power for domoic acid monitoring sampling 6 crabs to correctly diagnose contamination rates and recommend appropriate management actions when tested on these contamination profiles. In **(A)**, each cell represents a pair of centrality-variability parameters evaluated in the power analysis. White cells above the gray line were not evaluated because they represent unlikely contamination profiles based on historical observations (gray points; see **Fig. 4** for additional information). Black contours separate contamination profiles that are well below (<10% above action level), close to (10-20% above action level), and well above (>20% of crabs above action level) the 1 in 6 crab management action trigger. In **(B)**, points represent the median performance of 1,000 simulated surveys when sampling each contamination profile. Boxplots illustrate the distribution of these performances; the solid line indicates the median, the box indicates the interquartile range (IQR; 25th and 75th percentiles), the whiskers indicate 1.5 times the IQR, and the points beyond the whiskers indicate outliers. In **(C)**, cell color indicates performance when tested on individual profiles. Unnecessary closures occur when a survey deems that management action is necessary when it is not and risky openings occur when a survey deems that management action is not necessary when it is (**Table S4**).

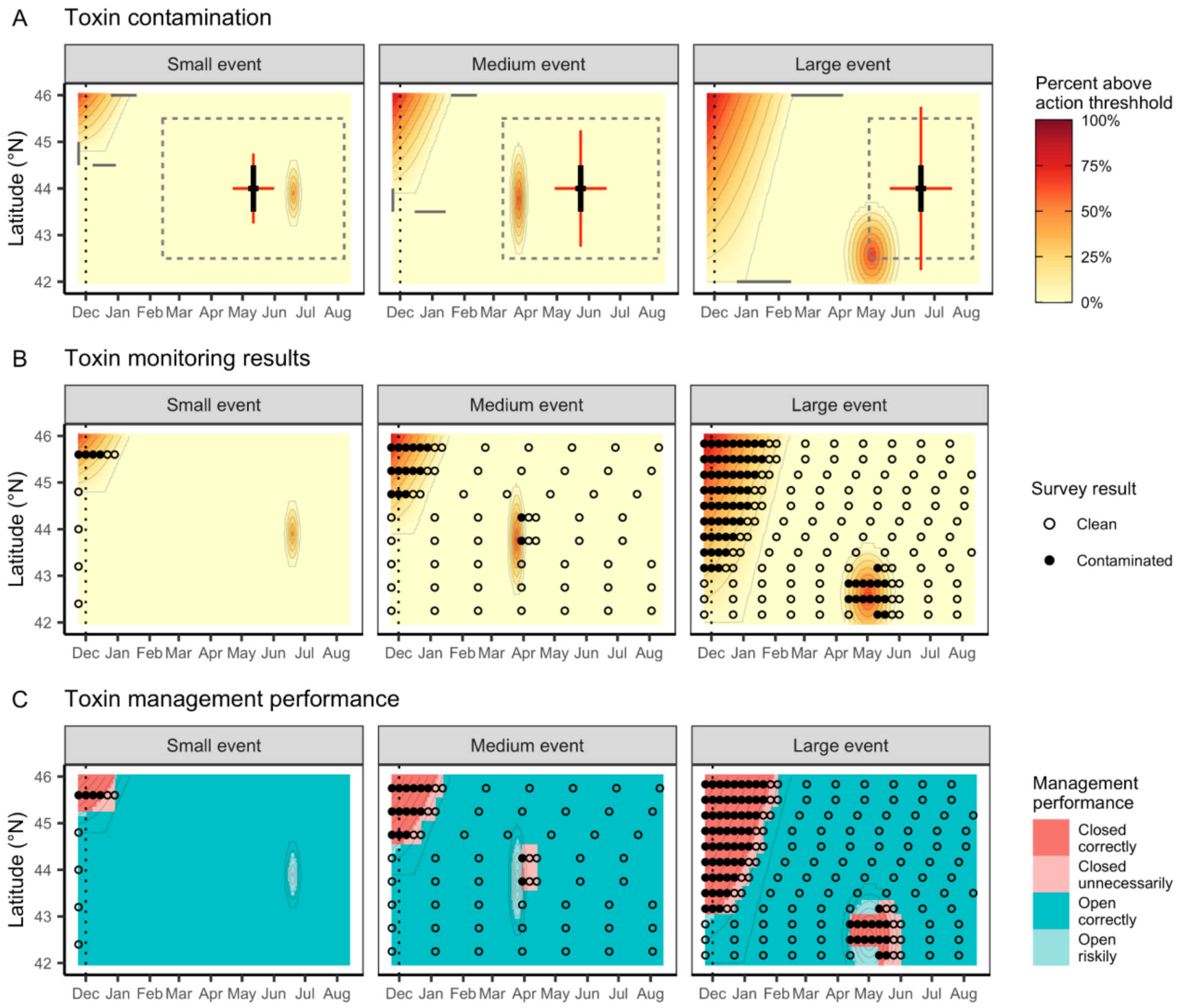


Figure 6. An illustration of the procedure for testing the performance of monitoring programs with varying spatial-temporal resolutions using simulated contamination events. **Panel A** illustrates the methods for simulating early and mid-season contamination events of small, medium, and large magnitude. Early season contamination linearly increases along a south-to-north gradient with initial contamination levels drawn from the ranges listed in **Table S5**. Colors and contours indicate the intensity of the contamination event. The latitudinal height of the contamination event is drawn from the range illustrated by the solid vertical lines on the y-axis. Durations of contamination at the southern and northern extents of the event are drawn from the ranges illustrated by the solid horizontal lines. Mid-season contamination linearly increases then decreases within an elliptical contamination event with a peak contamination level drawn from the ranges listed in **Table S5**. The center of the ellipse is randomly drawn from the ranges illustrated by the gray dotted box. The height and duration of the contamination event are randomly drawn from ranges illustrated by the reference crosses. The black cross indicates the smallest possible event and the red cross indicates the largest possible event. **Panel B** illustrates the results of monitoring programs applied to the simulated contamination events and **Panel C** illustrates management outcomes resulting from the specified monitoring program. Monitoring program performance was evaluated in terms of the program's ability to minimize both unnecessary fishery closures ("closed unnecessarily") and undetected public health risk ("open riskily"). In all panels, the vertical dotted line indicates the start of the season.

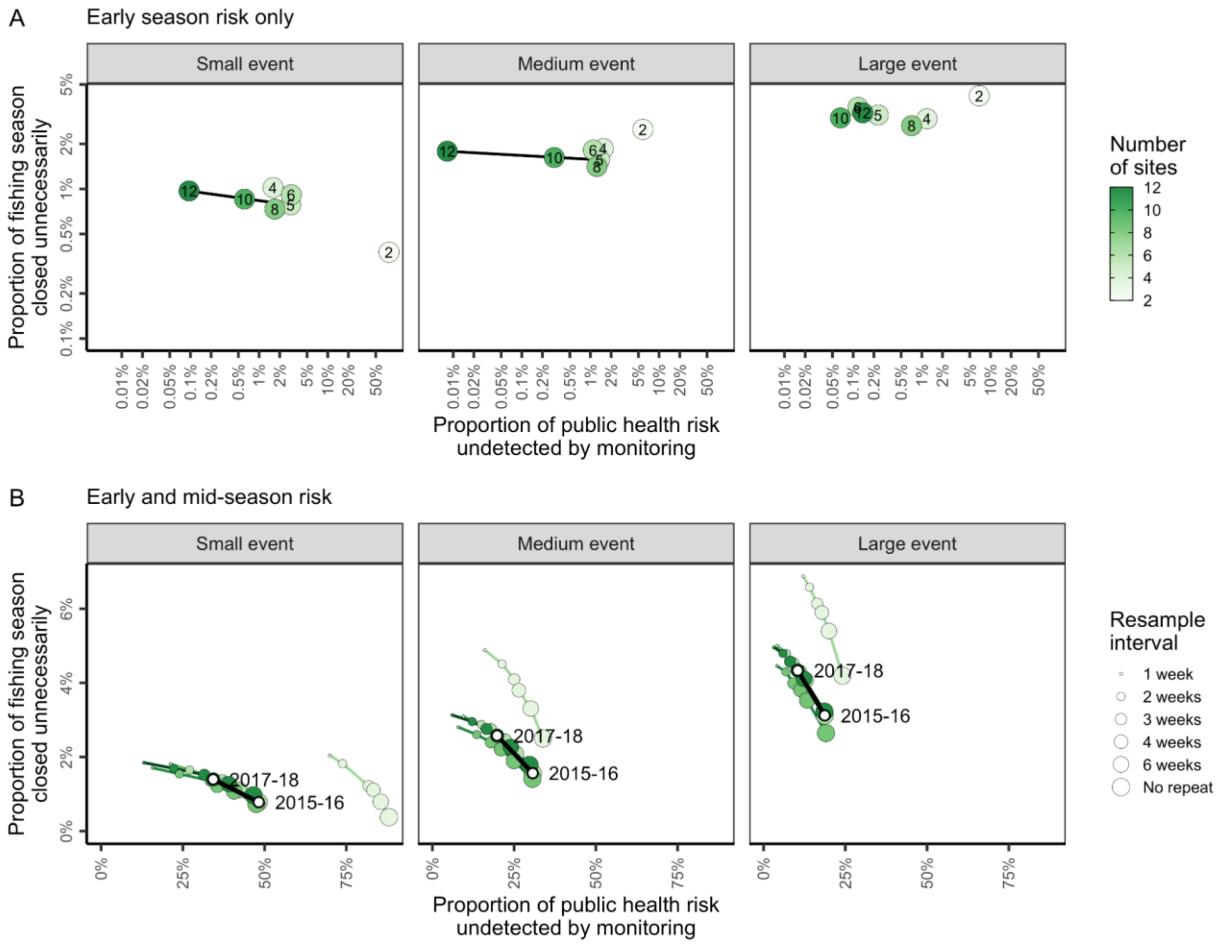
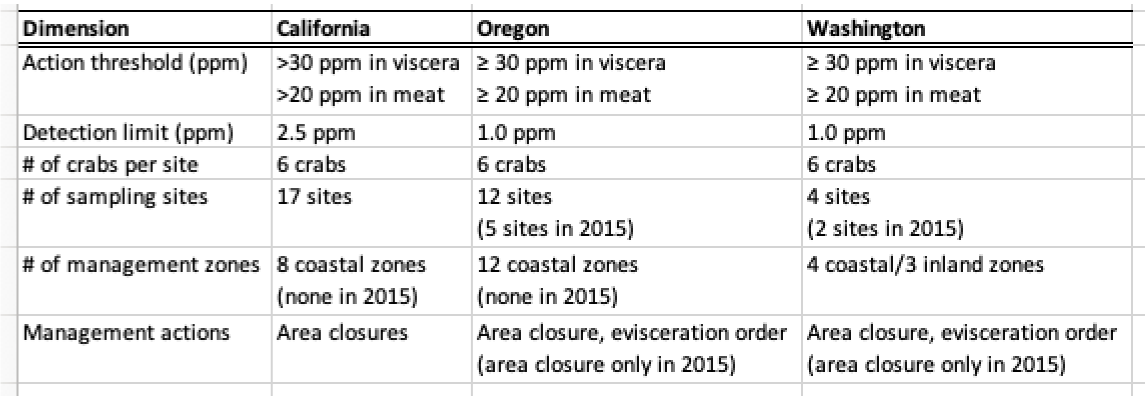


Figure 7. The simulated performance of various domoic acid monitoring programs when tested in scenarios with **(A)** only early season contamination risk and **(B)** both early and mid-season contamination risk. Points indicate the average performance of a monitoring program across 100 iterations of each contamination scenario. Point color indicates the number of monitoring sites in the monitoring program and point size indicates the frequency of follow up testing in the monitoring program. The origin indicates optimal performance (no unnecessary closures to the fishery and no undetected public health risk) and points closest to the origin represent the most efficient monitoring programs. The black lines indicate the average changes in efficiency incurred when increasing monitoring from 5 to 12 sites, as Oregon did before the 2017-18 season, when applied to this particular suite of contamination events. In **(A)**, axes are log-scaled to visually stretch the difference between quantitatively similar results. In **(B)**, only the 2, 5, 8, and 12 monitoring site results are plotted to preserve clarity.

Supplemental Tables and Figures

Supplemental Tables

Table S1. Dungeness crab domoic acid contamination monitoring and management program design[1] in California, Oregon, and Washington before the 2020-21 and 2015-16 seasons (2015-16 season values are provided in parentheses if different from the 2020-21 season).



Dimension	**California**	**Oregon**	**Washington**
Action threshold (ppm)	>30 ppm in viscera >20 ppm in meat	≥ 30 ppm in viscera ≥ 20 ppm in meat	≥ 30 ppm in viscera ≥ 20 ppm in meat
Detection limit (ppm)	2.5 ppm	1.0 ppm	1.0 ppm
# of crabs per site	6 crabs	6 crabs	6 crabs
# of sampling sites	17 sites	12 sites (5 sites in 2015)	4 sites (2 sites in 2015)
# of management zones	8 coastal zones (none in 2015)	12 coastal zones (none in 2015)	4 coastal/3 inland zones
Management actions	Area closures	Area closure, evisceration order (area closure only in 2015)	Area closure, evisceration order (area closure only in 2015)

[1] See **Table S2** for more information on the management of commercial and recreational Dungeness crab fisheries in California, Oregon, and Washington.

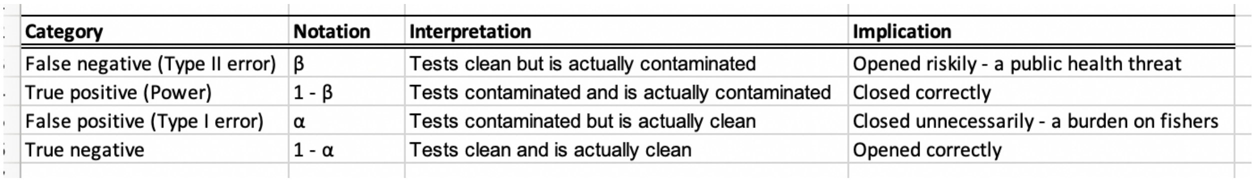
Table S2. "3S" management (sex-size-season) of commercial and recreational Dungeness crab fishing in California, Oregon, and Washington.

State	Open	Close	Min. size (in)	Daily bag limit	Season notes
Commercial					
Washington	Dec 1	Sep 15	6.25"	Males only	Summer season = July 1-Sep 1 = 2,500 lb trip limit, potential offshore closures, more testing
Oregon (bay)	Sep 1	Dec 31	6.25"	Males only	No weekends or holidays, not in December if adjacent ocean area is closed
Oregon (ocean)	Dec 1	Aug 14	6.25"	Males only	
California (northern)	Dec 1	Jul 15	6.25"	Males only	
California (central)	Nov 15	Jun 30	6.25"	Males only	
Recreational					
Washington	Year round	----	6.25"	5 males	
Oregon (bay)	Year round	----	5.75"	12 males	
Oregon (ocean)	Dec 1	Oct 15	5.75"	12 males	
California (northern)	Early Nov	Jul 30	5.75"	10 males/females	First Saturday in November
California (central)	Early Nov	Jun 30	5.75"	10 males/females	First Saturday in November

Table S3. Sources of news releases describing closures, advisories, and other management actions related to biotoxin contamination on the U.S. West Coast.

State	**Type**	**Years**	**Link**
PSMFC	Dungeness crab	2004-present	http://www.psmfc.org/crab/
WA	Dungeness Crab	2009-present	https://wdfw.wa.gov/fishing/commercial/crab/coastal/letters-notices
OR	ODFW news releases	2010-present	https://www.dfw.state.or.us/news/2021/index.asp
OR	ODA news releases	2016-present	https://odanews.wpengine.com/tag/shellfish/
CA	CDFW news releases	2015-present	https://cdfwmarine.wordpress.com/2020/
CA	CDPH shellfish advisories	2014-present	https://www.cdph.ca.gov/Programs/OPA/Pages/Shellfish-Advisories.aspx

Table S4. A guide to interpreting the results of the power analysis.

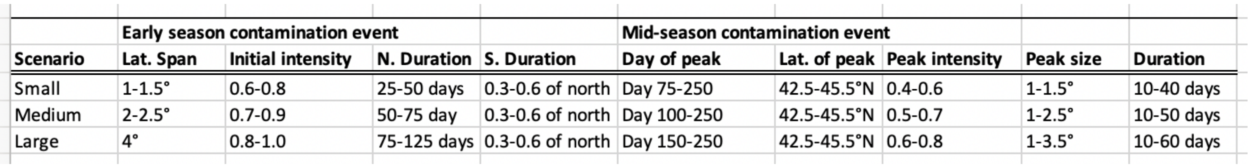


Category	Notation	Interpretation	Implication
False negative (Type II error)	β	Tests clean but is actually contaminated	Opened riskily - a public health threat
True positive (Power)	1 - β	Tests contaminated and is actually contaminated	Closed correctly
False positive (Type I error)	α	Tests contaminated but is actually clean	Closed unnecessarily - a burden on fishers
True negative	1 - α	Tests clean and is actually clean	Opened correctly

[1] Negative test = clean test; Positive test = contaminated test

[2] Clean = <1 in 6 crabs above the action level; Contaminated = ≥1 in 6 crabs above the action level

Table S5. Range of plausible values for the key characteristics used to construct the simulated early- and mid-season contamination events.*



	Early season contamination event				Mid-season contamination event				
Scenario	**Lat. Span**	**Initial intensity**	**N. Duration**	**S. Duration**	**Day of peak**	**Lat. of peak**	**Peak intensity**	**Peak size**	**Duration**
Small	1-1.5°	0.6-0.8	25-50 days	0.3-0.6 of north	Day 75-250	42.5-45.5°N	0.4-0.6	1-1.5°	10-40 days
Medium	2-2.5°	0.7-0.9	50-75 day	0.3-0.6 of north	Day 100-250	42.5-45.5°N	0.5-0.7	1-2.5°	10-50 days
Large	4°	0.8-1.0	75-125 days	0.3-0.6 of north	Day 150-250	42.5-45.5°N	0.6-0.8	1-3.5°	10-60 days

* Lat = latitudinal/latitude; N = northern; S= southern; intensity = proportion of crabs contaminated above the 30-ppm action level; southern duration = a proportion of the northern duration

Table S6. Latitudinal density of domoic acid monitoring sites for Dungeness crab by state.

State	Lat. range	Lat. height	2015-16 site density	2020-21 site density
Washington	46.25° - 48.43°N	2.18°	2 sites, 1 per 1.09°N	4 sites, 1 per 0.55°N
Oregon	42.00° - 46.25°N	4.25°	5 sites, 1 per 0.85°N	12 sites, 1 per 0.35°N
California	35.00° - 42.00°N	7.00°	17 sites, 1 per 0.41°N	17 sites, 1 per 0.41°N

Supplemental Figures

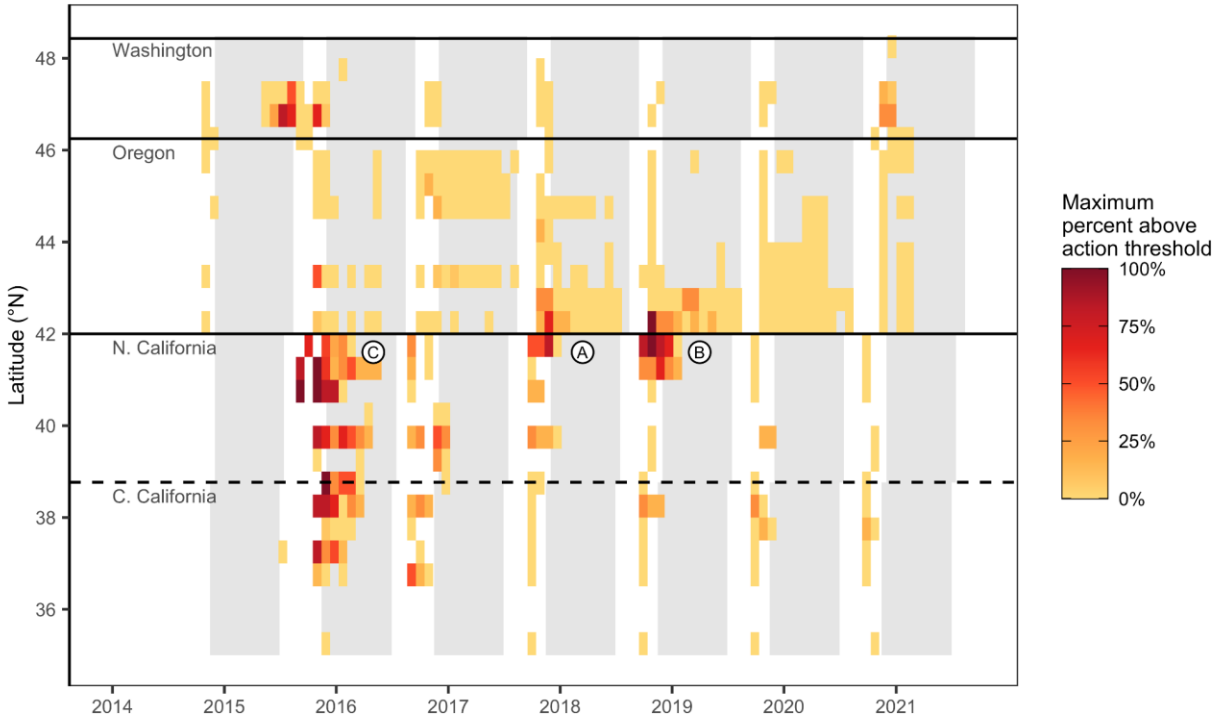


Figure S1. The maximum proportion of crabs contaminated above the 30-ppm action level in surveys falling with 0.5° latitude and 4 week intervals along the West Coast from 2014-2021. The (A) small, (B) medium, and (C) large contamination scenarios are modeled after the labeled historical contamination events.

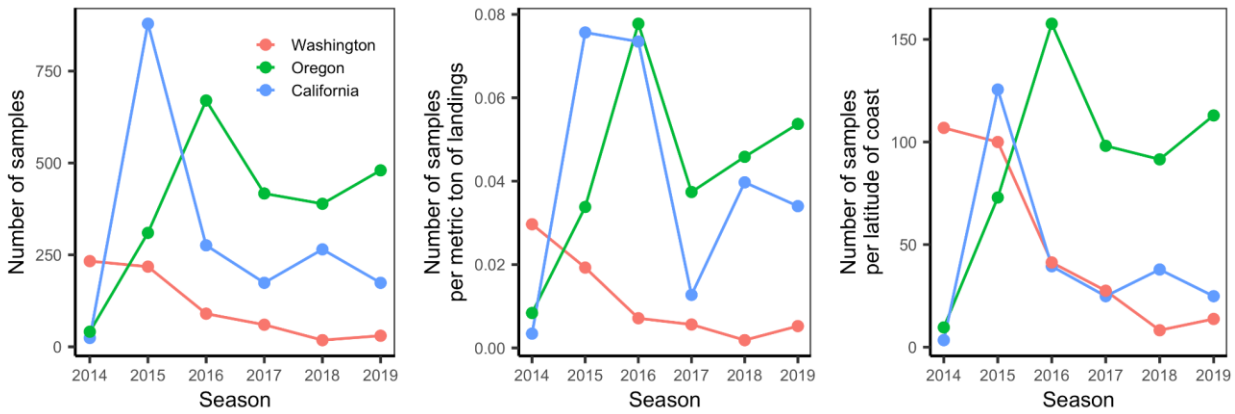


Figure S2. Number and density of Dungeness crab domoic acid samples by state and season. The season labels on the x-axis indicate the years during which seasons begin (e.g., 2014 indicates the 2014-15 commercial fishing season).