PLOS CLIMATE

RESEARCH ARTICLE

Exploring the human dimensions of harmful algal blooms through a well-being framework to increase resilience in a changing world

Stephanie K. Moore[1]*, **Maggie Broadwater**[2], **Curtis Cha**[3], **Quay Dortch**[4], **Chris J. Harvey**[1], **Karma C. Norman**[1], **Justin Pearce**[5], **Carrie Pomeroy**[6], **Jameal F. Samhouri**[1]

1 Conservation Biology Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, Washington, United States of America, **2** Competitive Research Program, National Centers for Coastal Ocean Science, National Ocean Service, National Oceanic and Atmospheric Administration, Charleston, South Carolina, United States of America, **3** Nicholas School of the Environment, Duke University, Durham, North Carolina, United States of America, **4** CSS, Under Contract to National Centers for Coastal Ocean Science, National Ocean Service, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, United States of America, **5** Domestic Fisheries Division, Office of Sustainable Fisheries, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, United States of America, **6** Institute of Marine Sciences Coastal Science and Policy Program, University of California Santa Cruz, Santa Cruz, California, United States of America

* stephanie.moore@noaa.gov

Citation: Moore SK, Broadwater M, Cha C, Dortch Q, Harvey CJ, Norman KC, et al. (2024) Exploring the human dimensions of harmful algal blooms through a well-being framework to increase resilience in a changing world. PLOS Clim 3(5): e0000411. https://doi.org/10.1371/journal.pclm.0000411

Editor: Nicola Caroline James, South African Institute for Aquatic Biodiversity, SOUTH AFRICA

Received: December 11, 2023

Accepted: April 2, 2024

Published: May 6, 2024

Data Availability Statement: All indicator data identified from the literature review are provided as supporting information.

Funding: The authors received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Abstract

Climate change is expected to alter harmful algal bloom (HAB) dynamics in marine and freshwater systems around the world, with some regions already experiencing significant increases in HAB events. There has been considerable investment of effort to identify, characterize, track, and predict the direction and magnitude of HAB response to climate variability and change. In comparison, far less effort has been devoted to understanding how human communities respond to HABs in a changing world. Harmful algal blooms alter social-ecological interactions and can have negative consequences for human well-being. This is especially true for fishing communities because their resource-based economies operate at the interface of the natural environment and society. Identifying the components of human well-being that are most affected by HABs can advance ecosystem assessment and inform choices about climate-ready management strategies in and across complex systems. This study uses a framework for considering human well-being in management contexts to explore the effects of HABs of *Pseudo-nitzschia* spp. on US West Coast fishing communities. We find that HABs, and the management strategies to address them, affect almost every domain of human well-being; however, less than half of these effects meet the criteria to be considered by federal disaster response and recovery programs that provide relief to impacted communities. Moreover, much of the data used to measure the effects of HABs that are eligible for consideration by these programs are not consistently collected, which could lead to inequitable access to disaster relief. Our analysis provides a starting point for communities to develop a suite of high-quality indicators of human well-being to

evaluate HAB impacts, assess the effectiveness of management actions and the equity of management outcomes, and track adaptation to system dynamics and external pressures.

Introduction

Marine and aquatic ecosystems provide people with a wide range of ecosystem services, including the provision of food, opportunities for tourism and recreation, and a sense of place and cultural identity [1]. Harmful algal blooms (HABs) disrupt the flow of these services, largely through the production of biotoxins that disrupt food systems, constrain fisheries operations and profitability, restrict access to clean drinking water, and prevent people from interacting with coastal settings [2, 3]. This can give rise to a multitude of consequences for human well-being [4–7]. Human communities may respond to HAB events through a range of institutional mechanisms and motivations (e.g., public health, fisheries management, lake access), creating interactions and feedback loops among ecological and human subsystems that also have implications for ecosystem services and human well-being [8–10]. Our understanding of the human dimensions of HABs is beginning to deepen; however, for most social-ecological systems, it is mostly patched together from a small number of uncoordinated research efforts that tend to focus narrowly on the economic and health impacts. This fragmented approach complicates efforts to track the effects of HABs (and policies to address them) on human well-being over time [11], overlooks less tangible but important components of well-being (e.g., culture and identity, social relationships), and inhibits the development of place-based management strategies to increase resilience to future HABs [6].

Human well-being can be conceptualized as a state of being with others and the environment when human needs are met and individuals and communities can pursue their goals and enjoy a good quality of life [12]. This conceptualization decomposes well-being into four major constituents–*Connections*, *Conditions*, *Capabilities*, and *Cross-cutting domains*–and provides a structured framework for considering well-being in management contexts (Fig 1A; ibid). When coupled with carefully selected indicators (Fig 1B), this 4Cs framework offers a way to measure and track changes in well-being in response to environmental perturbations and management interventions [13]. The 4Cs framework grew from an effort to assess the full social-ecological system, not just the biophysical components, in the National Oceanic and Atmospheric Administration's (NOAA) Integrated Ecosystem Assessment (IEA) of the California Current Large Marine Ecosystem (CCLME). It has since been used to examine linkages between ecosystem services and human well-being in Alaska and Hawaii [14, 15] and to explore issues of sustainability and equity in fisheries management in Alaska [16], demonstrating its broad utility in a range of management contexts. Consideration of HABs through the 4Cs framework may provide the necessary structure for compiling and examining the effects of HABs across a comprehensive suite of human well-being components.

The well-being of fishing communities is closely tied to the fishery resources that they depend on to meet social and economic needs [e.g., 17, 18]. As such, fishing communities are particularly vulnerable to HABs that reduce access to key fisheries and associated benefits to human well-being. This can occur when fished or cultured stocks are reduced by HAB-related fish and shellfish mortality events, or when HAB toxins contaminate fish and shellfish, making them unsafe for human consumption and triggering harvest closures [e.g., 19–22]. In the latter case, fishery resources are temporarily unavailable to harvesters and consumers until the HAB toxins in fish and shellfish fall to acceptable levels. Identifying the pathways by which HAB

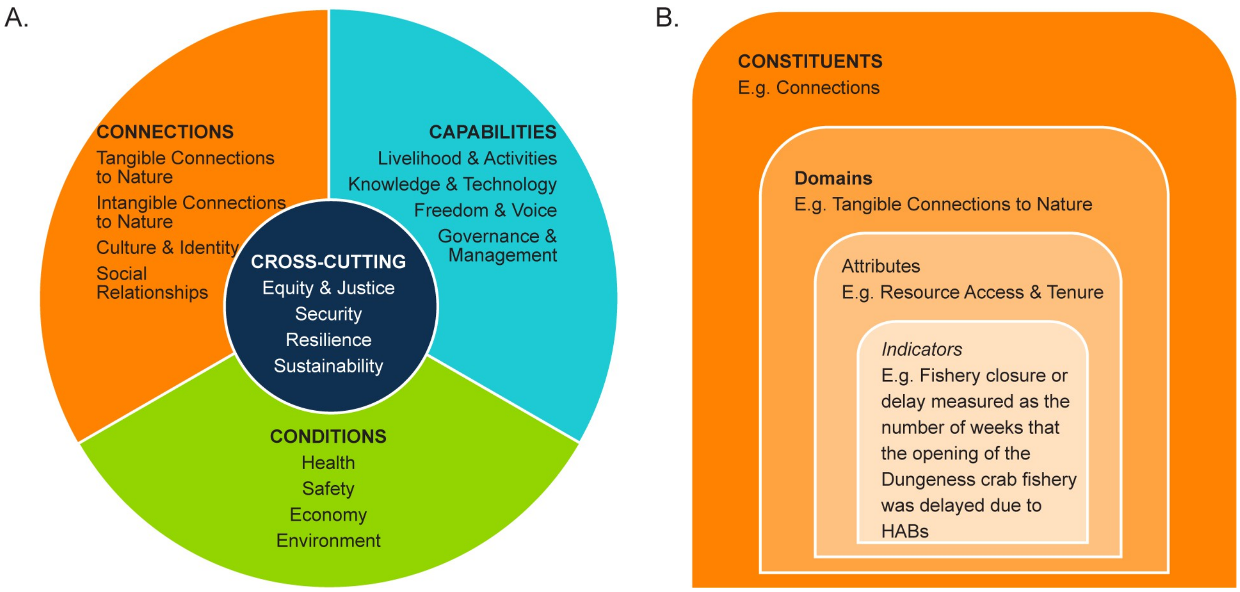

Fig 1. The 4Cs framework of human well-being. (A) The 4Cs conceptual framework of human well-being defined by Breslow et al [12] decomposes well-being into four main constituents. Each "C" represents one of these constituents. *Connections* refer to being with others and the environment, *Conditions* refer to circumstances where human needs are met, *Capabilities* refer to factors enabling individuals and communities to act meaningfully to pursue their goals, and *Cross-cutting domains* refer to sustaining our collective satisfactory quality of life now and into the future. (B) The nested categories of the 4Cs framework composed of constituents, domains, attributes, and indicators. An example categorization of an indicator of fishery closures or delays is shown. Adapted from Breslow et al. [12].

https://doi.org/10.1371/journal.pclm.0000411.g001

events reverberate through fishing communities to affect individuals directly and indirectly involved in fisheries, and the human contexts within which they occur, is essential for characterizing the full range of HAB effects on human well-being.

Climate change is expected to alter the dynamics of HABs in marine systems around the world [23–26], and some, but not all, regions are already experiencing significant increasing trends in HAB impacts [27]. One such region is the US West Coast where HAB events caused by diatoms in the genus *Pseudo-nitzschia* have worsened since 1990 [27, 28]. Several species of *Pseudo-nitzschia* produce the toxin domoic acid, which can accumulate in shellfish and finfish species that are harvested for commercial, recreational, and subsistence use. Increases in the toxicity, geographic scope, and duration of these toxic blooms have been associated with anomalously warm ocean conditions and have resulted in widespread and prolonged closures of fisheries for Pacific razor clam (*Siliqua patula*), rock crab (*Cancer productus*), and Dungeness crab (*Metacarcinus magister*) [29–31]. As waters continue to warm along the US West Coast, *Pseudo-nitzschia* blooms may continue to worsen with the potential for more frequent extreme HAB events with associated severe impacts to fishing communities.

In the US, financial relief to aid recovery efforts may be made available to fishing communities severely impacted by HAB events pending the determination of a Fishery Resource Disaster (FRD) or a Harmful Algal Bloom or Hypoxia Event of National Significance (HHENS). Fishery Resource Disasters are determined under the authority of the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006 (MSA; Pub. L. 109–479) as amended by the Fishery Resource Disasters Improvement Act included in the Consolidated Appropriations Act of 2023 (Pub. L. 117–328). A FRD is determined when there is an unexpected large decrease in fish stock biomass or other change that results in significant loss of revenue or negative subsistence impacts and is due to an allowable cause. Harmful algal blooms are just one possible allowable cause of a FRD, and of the 82 FRD determinations for the period 1990–2020, HABs were implicated in 7 [32]. Harmful Algal Bloom or Hypoxia Event of National Significance are determined under the authorization of the Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2017 (HABHRCA; Pub. L. 115–423) when a HAB (or hypoxia) event has had or will likely have a significant detrimental environmental, economic, subsistence use, or public health impact on an affected State. Harmful Algal Bloom or Hypoxia Event of National Significance was added to the 2017 reauthorization and amendment of HABHRCA and aligns HAB management more closely with disaster preparedness and response practices [33, 34]. While HHENS is not specific to fishing communities, it may provide them with an alternative path for requesting financial relief in the event of a severe HAB. This remains to be seen, however, as there have not been any HHENS determinations to date.

It is not yet clear if or how FRD and HHENS determinations may overlap or interact, or the extent to which human well-being is considered in the criteria (and indicators) used to determine whether a FRD and/or HHENS has occurred. Without guidance on how to implement HHENS in fishing communities, including a framework for identifying potential indicators for evaluating HAB impacts, it may be difficult to effectively target relief and to identify gaps and unmet needs. This paper uses the 4Cs framework to identify and compile the human well-being effects of HABs in fishing communities by focusing on toxic blooms of *Pseudo-nitzschia* on the US West Coast. We conduct a meta-analysis of indicators of human well-being extracted from the literature, identify those that meet the criteria described in the relevant statutes for consideration in FRD and HHENS determinations, and assess the extent to which they are being monitored. Finally, we identify data considerations that may lead to inequitable access to disaster relief and explore how FRDs and HHENS may interact.

Methods

Site description and history: *Pseudo-nitzschia* spp. blooms and their management on the US West Coast

Blooms of *Pseudo-nitzschia* spp. have been a frequent problem on the US West Coast since they were first documented in 1991 [35, 36]; the toxicity of blooms varies with the species and environmental conditions. Monitoring and management strategies implemented in response to their emergence limit harvest of contaminated shellfish and are protective against human illness, although 25 (unconfirmed) human illnesses are thought to be associated with the 1991 event [35]. Two important fisheries that are impacted by toxic *Pseudo-nitzschia* spp. blooms are the lucrative commercial Dungeness crab fishery and the popular razor clam fishery. The Dungeness crab fishery is one of the most economically valuable commercial fisheries on the US West Coast with total ex-vessel revenues averaging over $200 million annually between 2014 and 2018 [37]. The fishery accounts for a large fraction of the commercial fisheries annual ex-vessel revenue (i.e., 41% in Washington, 58% in Oregon, and 25% in California in 2021) [38], and many fishery participants and communities have come to rely on that revenue [5]. The Dungeness crab fishery also supports a popular recreational sector that plays an important role in local economies [39]. This extensive engagement and dependence on Dungeness crab makes US West Coast fishing communities highly vulnerable to any shock or perturbation to the fishery [20, 40].

The recreational razor clam fishery can attract as many as 30,000 participants in a single day in Washington and Oregon, with as many as 1,000 people per mile of beach digging for clams (D. Ayres, personal comm.). Northern California also has an active recreational razor clam fishery. Many fishery participants travel to coastal beaches from inland urban areas, and their expenditures generate significant tourism-related revenue that local businesses have come to rely on during the winter months when the fishery is open [41]. Razor clams are also of great social and cultural significance to coastal residents [5] and are considered a cultural keystone species for the Quinault Indian Nation on the Washington coast [42].

The largest and most toxic HAB of *Pseudo-nitzschia* spp. on record occurred in 2015 and resulted in geographically widespread and prolonged closures of the Dungeness crab and razor clam fisheries [29, 43]. The opening of the commercial Dungeness crab fishery was delayed up to five months in California and one month in Washington and Oregon. This resulted in FRD determinations for the 2015–16 season of the California commercial Dungeness crab and rock crab fisheries as well as the Quileute commercial Dungeness crab fishery, prompting the Secretary of Commerce to allocate >$26 million of congressional appropriations for fishery disasters to mitigate the impacts of those FRDs [32]. Harvest closures for razor clam implemented in May 2015 continued at one Washington beach until June 2016 [29], and fairly persistent closures have since plagued southern Oregon and northern California beaches [30, 44]. The 2015 HAB was linked to the 2014–16 Northeast Pacific Marine Heatwave [29, 31], and has been called a "dress rehearsal" for climate change [45].

Monitoring and management of domoic acid in the US West Coast Dungeness crab fishery were reconsidered in the wake of the 2015 HAB [34, 46, 47]. One of the most transformative modifications is the introduction of "evisceration orders." Domoic acid accumulates in the viscera (guts) of crab. As a management measure, evisceration orders allow for the capture and sale of crab when domoic acid in the viscera tests above the regulatory limit but the meat is safe (the regulatory limits for human consumption are 30 ppm in the viscera or 20 ppm in the meat), provided the viscera are removed and destroyed by a licensed and approved processor prior to or after cooking. Oregon was the first US West Coast state to pass legislation enabling the use of evisceration orders in November 2017, followed by California in October 2021 [46]. Washington temporarily adopted a rule allowing evisceration in February 2021 [46], and is currently considering legislation to grant long-term authority for issuing evisceration orders. Evisceration orders are a more flexible alternative to fishery closures and enable fishers and seafood handlers to continue working with local catch. However, the Dungeness crab fishery has a history of reactive management, demonstrated by a cycle of crises and responses that do not always lead to economically and socially optimal outcomes [48, 49]. Moreover, there are trade-offs with evisceration that are not yet fully appreciated. For example, eviscerated crab can receive lower market prices (S. Jardine and A. Abken, pers. comm.), and evisceration may not be accessible to some crab fishermen and handlers, with social and economic implications for fishery participants, communities, and consumers (C. Pomeroy, pers. obs.). A comprehensive history of the Dungeness crab fishery and its management is provided elsewhere [46, 50, 51].

Meta-analysis of HAB effects on human well-being

We conducted a meta-analysis of published literature to determine the effects of toxic *Pseudo-nitzschia* spp. blooms on human well-being in US West Coast fishing communities. A literature review was performed in Web of Science (https://www.webofknowledge.com/) on September 6, 2022, using the query ("harmful alga*" OR "toxic alga*" OR Pseudo-nitzschia OR "domoic acid" OR "amnesic shellfish poisoning" OR ASP OR "Dungeness crab" OR "razor clam") AND (Washington OR Oregon OR California OR "United States West Coast" OR "U. S. West Coast") AND (human OR communit* OR people OR soci* OR cultural OR economic OR health OR well-being OR wellbeing OR welfare) in the topic field, yielding a total of 409 results. The terms "Dungeness crab" and "razor clam" were included in the query because of the importance of these HAB-sensitive fisheries to many US West Coast communities. This

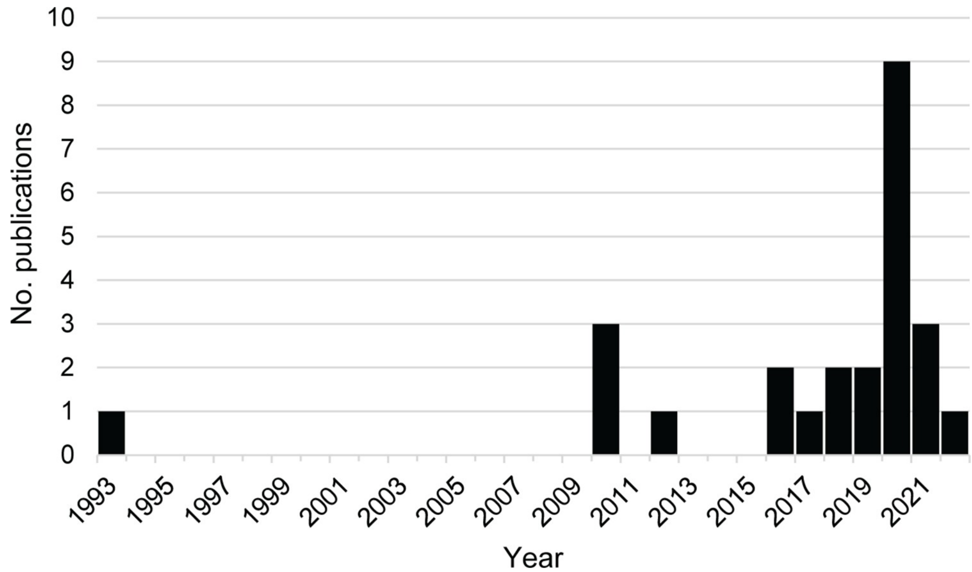

Fig 2. Number of publications included in the meta-analysis by year. Number of publications included in the meta-analysis of HAB effects on human well-being in US West Coast fishing communities shown by the year that they were published.

https://doi.org/10.1371/journal.pclm.0000411.g002

enabled us to identify publications by authors who may not have classified their work on these fisheries as a HAB study for further review.

From this list, titles and abstracts were reviewed for suitability, leading to selection of 30 publications for additional screening. Criteria for exclusion included (1) reports of domoic acid levels in seafood if the data were not linked to fisheries closures or human illness; (2) reports of domoic acid effects at a cellular level if the implications for physical health were stated; (3) reports of domoic acid levels in marine wildlife or the health effects of domoic acid on marine wildlife if they were not linked to disruptions to ecosystem services (e.g., subsistence fisheries, aesthetic experiences); and (4) descriptions of environmental conditions that support blooms, bloom dynamics, and the biology of *Pseudo-nitzschia* spp. or the prediction of toxic *Pseudo-nitzschia* spp. blooms. One publication was not considered because it was cost prohibitive to obtain. After inspecting the full texts, a total of 25 publications were selected for our meta-analyses. The vast majority of publications were published after 2015 with many works focusing on the effects of the massive 2015 HAB (Fig 2).

From these publications, indicators of HAB effects on human well-being were identified and categorized to the 4Cs framework. The 4Cs framework consists of a nested structure of four categories beginning with the four major constituents of human well-being as defined by Breslow et al. [12]. Each "C" in the 4Cs framework represents one of these constituents. *Connections* refer to being with others and the environment, *Conditions* refer to circumstances where human needs are met, *Capabilities* refer to factors enabling individuals and communities to act meaningfully to pursue their goals, and *Cross-cutting domains* refer to sustaining our collective satisfactory quality of life now and into the future (ibid.). The *Cross-cutting domains* are so named because they directly affect well-being and they arise from variabilities and interactions among all constituents. Domains in this category include *Equity & Justice* and *Resilience*. Within each constituent of human well-being are domains that represent thematic clusters of attributes identified for their validity and relevance to the social, ecological, and management context of the CCLME [12]. Indicators of well-being were categorized to the relevant attribute (or domain for *Cross-cutting domains*) of the 4Cs framework. Although indicators can reflect multiple components of human well-being, we restrict our categorization to a single attribute or domain that best reflects the context provided by authors in the publications from which they were extracted. This includes categorization of indicators to *Cross-cutting domains*.

FRD and HHENS determinations

Of the indicators extracted from the literature review, we identified those that meet the criteria described in the relevant statutes for consideration in the determination of a FRD or HHENS. It is important to note that the indicators we identify were not necessarily used in the evaluation of FRD or HHENS requests, rather they were determined to meet the criteria for consideration in a FRD or HHENS determination should a request be made and data were available to measure them. As such, this was a hypothetical exercise to examine federal disaster response and recovery programs that provide relief to impacted fishing communities through a human well-being lens. Fishery Resource Disaster indicators were identified using the new considerations introduced in the Fishery Resource Disasters Improvement Act. Of note, the indicators identified here may or may not have been eligible for consideration in FRD determinations in the past under the old program. Eligible information may include (1) fishery characteristics (e.g., size and value, number of participants, whether jobs are full- or part-time); (2) percent decline in landings, economic impact, revenues, or net revenues by sector etc.; (3) number of participants involved by sector etc.; (4) length of time the resource (or access to it) is restricted; and (5) documented decline in the resource. This information may be used to determine whether a FRD occurred.

The following requirements must be met in order for the Secretary of Commerce to make a positive FRD determination (1) the cause for the FRD must be an allowable cause under the MSA; and (2) there must be an economic or subsistence impact stemming from the FRD that supports a determination of a FRD under MSA section 312(a). Under the Fishery Resource Disasters Improvement Act, if a FRD from an allowable cause has occurred, NOAA assesses the loss of 12-month revenue compared to the average annual revenue over the most recent five-year period for which no disaster has occurred. Revenue losses greater than 80% may result in a positive FRD determination, losses between 35 and 80% are further evaluated to determine the severity of economic impacts based on other factors such as whether fishers have permits and gear to temporarily transition to another fishery to offset losses, whether alternate employment opportunities in the community are available and economic dependence on the affected fishery, and losses less than 35% are generally not eligible for a determination. In considering subsistence fisheries, the severity of negative impacts to the fishing community are also evaluated.

Harmful Algal Bloom or Hypoxia Event of National Significance indicators were selected based on the statutory considerations described in the in HABHRCA (Pub. L. 115–423). These include information on (1) the toxicity of the HAB; (2) its potential to spread; (3) the economic impact; (4) its size compared to the past five occurrences; and (5) the geographic scope of the HAB. In making a HHENS determination, this information is considered by the Under Secretary of Commerce for Oceans and Atmosphere for marine or coastal HABs, or the Administrator of the Environment Protection Authority for freshwater HABs. Economic impacts to many sectors (e.g., tourism and recreation, real estate, public health, monitoring and response) may be considered in HHENS determinations, extending far beyond those that are eligible for consideration in FRD determinations.

Indicators were deemed ineligible for consideration in FRD or HHENS determinations if they did not fully meet the criteria set out in the relevant statutes. For example, an indicator that measures the length of delays or closures of the Dungeness crab fishery due to the combined effects of HABs, low meat recovery (based on "quality testing"), and increased risk of marine life entanglement is ineligible for determining if a HHENS occurred because the indicator includes components that are not directly related to HABs. Further, only indicators that can directly be considered in determinations were deemed eligible. For example, job losses in a fishery are related to revenue losses, but are not typically included in FRD analyses. Similarly, the timing of harvest closures can affect revenues, but also is not directly considered in FRD analysis.

Data considerations

Indicators of HAB effects on human well-being identified from the meta-analysis were evaluated against a subset of screening criteria based on the data considerations described in Breslow et al. [13]. These include the availability of data in each state and for the relevant time period (typically five years prior to the event), whether the data are regularly collected or were generated from one-time or limited duration efforts, and whether the entity responsible for data collection is a government agency or an academic or other institution. This last criterion is relevant because different entities differ in their missions, structures, and functions, with implications for the scale, scope, timing, and duration of data collection (and, more broadly, research) efforts. While different, these efforts can be complementary and mutually informing, and ultimately enhance the validity and utility of data collected and its application. These data considerations were used to determine the temporal and spatial coverage as well as the availability and reliability (i.e., can the data collection effort be counted on to provide needed/valid/useful information) of data for measuring the effects of HABs on human well-being.

Results

Categorization of indicators to the 4Cs framework

From the 25 publications that comprised our meta-analysis, we identified 109 indicators of HAB effects on human well-being in US West Coast fishing communities. The indicators were categorized to 26 attributes of the 4Cs framework, representing 15 of the 16 domains and all four constituents of human well-being (S1 Table). These results show that HABs of *Pseudo-nitzschia* spp. affect nearly all components of human well-being in US West Coast fishing communities in measurable ways. Some of the 109 indicators were the same or similar to one another. That is, they were calculated using the same data or data type and appeared in multiple publications. These indicators were given the same name, but they were usually calculated over different temporal/spatial scales and in some cases were categorized to different attributes of the 4Cs framework depending on how they were used in the publication from which they were extracted. As such, we include all indicators identified from the meta-analysis and do not filter indicators to include only those that are unique. A summary of indicators categorized to each constituent and domain of the 4Cs framework is provided below. A more detailed description of the indicators is provided in the S1 Text.

Conditions constituent

Almost half of the total number of indicators identified were categorized to the *Conditions* constituent (48%) which refers to circumstances where human needs are met. This is expected as this constituent includes the tangible qualities of environment, economy, safety, and human health that are commonly measured in well-being assessments [12]. Domains within this constituent of the 4Cs framework are *Environment*, *Economy*, *Health*, and *Safety*. Nearly all of the

19 indicators categorized to the *Environment* domain report on the concentrations of domoic acid in shellfish and finfish tissues [29, 30, 35, 42, 46, 52–56]. Most of the 18 indicators categorized to the *Economy* domain report on lost revenue, income, and employment due to harvest closures from HABs [4, 5, 37, 41, 42, 57]. Other indicators in the *Economy* domain report on price impacts to Dungeness crab [58] and financial distress [4, 5]. The 15 indicators categorized to the *Health* domain focus on human exposure to domoic acid [52–55, 59] and its consequences for physical health [35, 54, 55, 59], and the negative effects of HAB occurrences on emotional and mental health [4, 5]. No indicators were categorized to the *Safety* domain.

The *Safety* domain, which includes disaster preparedness, physical safety at home and work, and peace and security, was the only domain in the 4Cs framework that did not receive any indicators. With respect to disaster preparedness, this is because many of the indicators identified in this study were designed to monitor HABs or identify a FRD or HHENS, rather than prepare for them. As such, these indicators were more appropriately categorized to other domains, such as the *Environment* (e.g., shellfish toxicity), *Tangible Connections* (e.g., lost fishing opportunity), and the *Economy* (e.g., lost revenues). Also, in the context of this study, "safety" refers to seafood safety and human health, and these indicators were more appropriately categorized to the *Environment* (e.g., shellfish toxicity) and *Health* (e.g., human illnesses attributable to HAB toxins) domains.

Connections constituent

Eighteen percent of indicators were categorized to the *Connections* constituent, which refers to being with others and the environment [12]. Domains within this constituent include *Tangible* and *Intangible Connections to Nature*, *Culture & Identity*, and *Social Relationships*. All of the indicators categorized to the *Tangible Connections to Nature* domain report on direct avenues and outcomes of access to fishery resources [34–36, 42, 46, 49, 57, 60–62]. The only indicator categorized to the *Intangible Connections to Nature* domain related to the sense of spirituality and connectedness from harvesting and eating clams [42]. Indicators categorized to the *Social Relationships* domain reported on family and community events [4, 42], the aging fisheries workforce [5], and on levels of trust in information sources about ocean conditions or seafood safety and availability [34]. Indicators categorized to the *Culture & Identity* domain reported on the importance of multigenerational families clamming together [42], the inability to practice community traditions related to shellfish harvest and consumption due to HABs of *Pseudo-nitzschia* [5], and the loss of identity from being unable to practice community traditions related to shellfish harvest and consumption as a result of HABs of *Pseudo-nitzschia* [5, 42].

Capabilities constituent

Fifteen percent of indicators were categorized to the *Capabilities* constituent, which refers to factors enabling individuals and communities to act meaningfully to pursue their goals [12]. Domains within this constituent include *Livelihood & Activities*, *Knowledge & Technology*, *Freedom & Voice*, and *Governance & Management*. Indicators categorized to the *Livelihood & Activities* domain reported on subsistence harvests of Dungeness crab and razor clams, the importance of subsistence harvests for personal or "home use", and the loss of subsistence harvests due to HABs [4, 42]. All of the indicators categorized to the *Knowledge & Technology* domain related to education and information. These indicators covered topics ranging from perceived health risks of domoic acid to press coverage on HABs and its adequacy, perceived knowledge of HABs, and intergenerational knowledge transfer [5, 34, 42, 58, 63]. Indicators categorized to the *Freedom & Voice* domain were specific to the Quinault Indian Nation, reporting on the sense of efficacy and pride that comes from earning income and providing food by razor clamming, and on the importance of ongoing comanagement of razor clams [42]. Indicators categorized to the *Governance & Management* domain were related to resource management, spanning a wide range of issues from biotoxin monitoring to evisceration orders to comanagement concerns and perceptions around government communication, transparency, and distribution of financial assistance [5, 34, 42, 46].

Cross-cutting domains

The remaining 19% of indicators were categorized to the *Cross-cutting domains* of *Equity & Justice*, *Security*, *Resilience*, and *Sustainability*. These domains, which comprise their own constituent, refer to a state of caring for oneself, other people, and living things, and sustaining our collective satisfactory quality of life now and into the future [12]. Indicators categorized to the *Equity & Justice* domain focused on the distribution of revenue to, and levels of participation by, different components of the Dungeness crab fleet [49]. Indicators categorized to the *Security* domain reported on the dependence of communities on the Dungeness crab fishery [20, 36, 57] or the harvest of razor clams [42], the timing of harvest closures in relation to important fishing periods [42], and income diversification that can buffer the effects of HABs [5]. Indicators categorized to the *Resilience* domain reported patterns of fishery participation in response to HABs [20], spatial shifts in Dungeness crab fishing activity in response to HABs [49], and whether individuals took coping or adaptive actions in response to HABs and outcomes associated with those actions [4, 5, 57]. There was also an indicator focused on communities rather than individuals, describing social vulnerability, a measure of socioeconomic and demographic factors that affect a (place-based) community's ability to withstand impacts from multiple stressors [36]. Indicators categorized to the *Sustainability* domain reported on the perceived adequacy of coping and adaptive actions taken by individuals in response to HABs [4], and the risk of whale entanglements in Dungeness crab fishing gear [60, 61], which can be amplified by HAB-related delays to the start of the Dungeness crab fishing season.

Temporal and spatial scope of indicator data

The spatial and temporal coverage of data used to measure indicators across the US West Coast states were evaluated. Coverage was evaluated based on how the indicators were reported in the publications from which they were extracted; however, we recognize that for some indicators data coverage may be greater than what was presented (e.g., shellfish toxicity data measured by state agencies). Spatial coverage was greatest in Washington followed by California and Oregon (90, 72, and 44 indicators, respectively; Fig 3A). This in part reflects the sizable effort to understand the well-being effects of HABs on razor clam harvests in Washington (including effects that are specific to tribal communities) and the 2015–16 California Dungeness crab and rock crab FRD. Nevertheless, the relative proportion of indicators across constituents of the 4Cs framework was fairly consistent in all three states, such that no one state had a larger/lesser proportion of indicators in any one constituent compared to the other states. In contrast, both the temporal coverage of indicators and the relative proportion of indicators across constituents was not consistent over time (Fig 3B). Considerably more indicators were reported from 2014 through 2017, spanning the period immediately before to shortly after the 2015 HAB event. Temporal coverage was greatest for indicators categorized to the *Conditions* and *Connections* constituent of the 4Cs framework and included measures of fishery landings, shellfish toxicity, harvest closures, and human illness, whereas indicators categorized to the *Cross-cutting domains* and *Capabilities* constituent did not appear until 2007 and 2013, respectively.

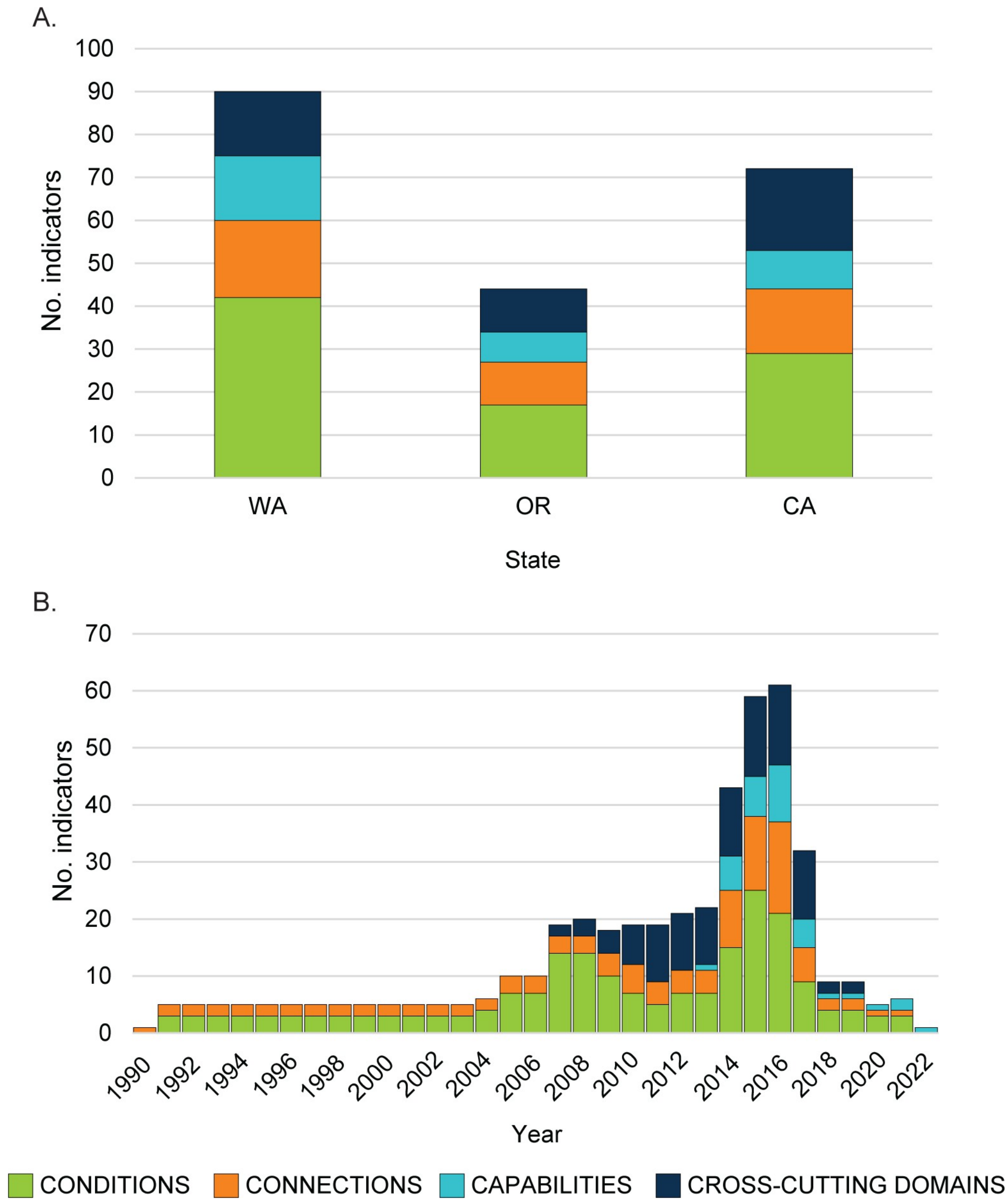

Fig 3. Number of indicators of HAB effects on human well-being measured across space and time. Stacked bar chart of the number of indicators reported in (A) Washington, Oregon, and California, and (B) across years from 1990 through 2022 by constituent of the 4Cs framework for human well-being.

https://doi.org/10.1371/journal.pclm.0000411.g003

Indicators with the most coverage were usually reported using data collected and monitored on an ongoing basis by government agencies (Fig 4). This was true across all four constituents of the 4Cs framework. This is not surprising as the largely consistent funding to government agencies supports such sustained monitoring programs. Indicators reported using data that were collected once only or over a limited time period were usually measured or generated by non-government (typically academic) researchers. Further, data collected by academic researchers were usually obtained by interviewing, surveying and/or observing community members, providing a combination of "objective-material" data (e.g., demographics; physical, financial and technological capitals) and subjective-perceptual data (e.g., knowledge,

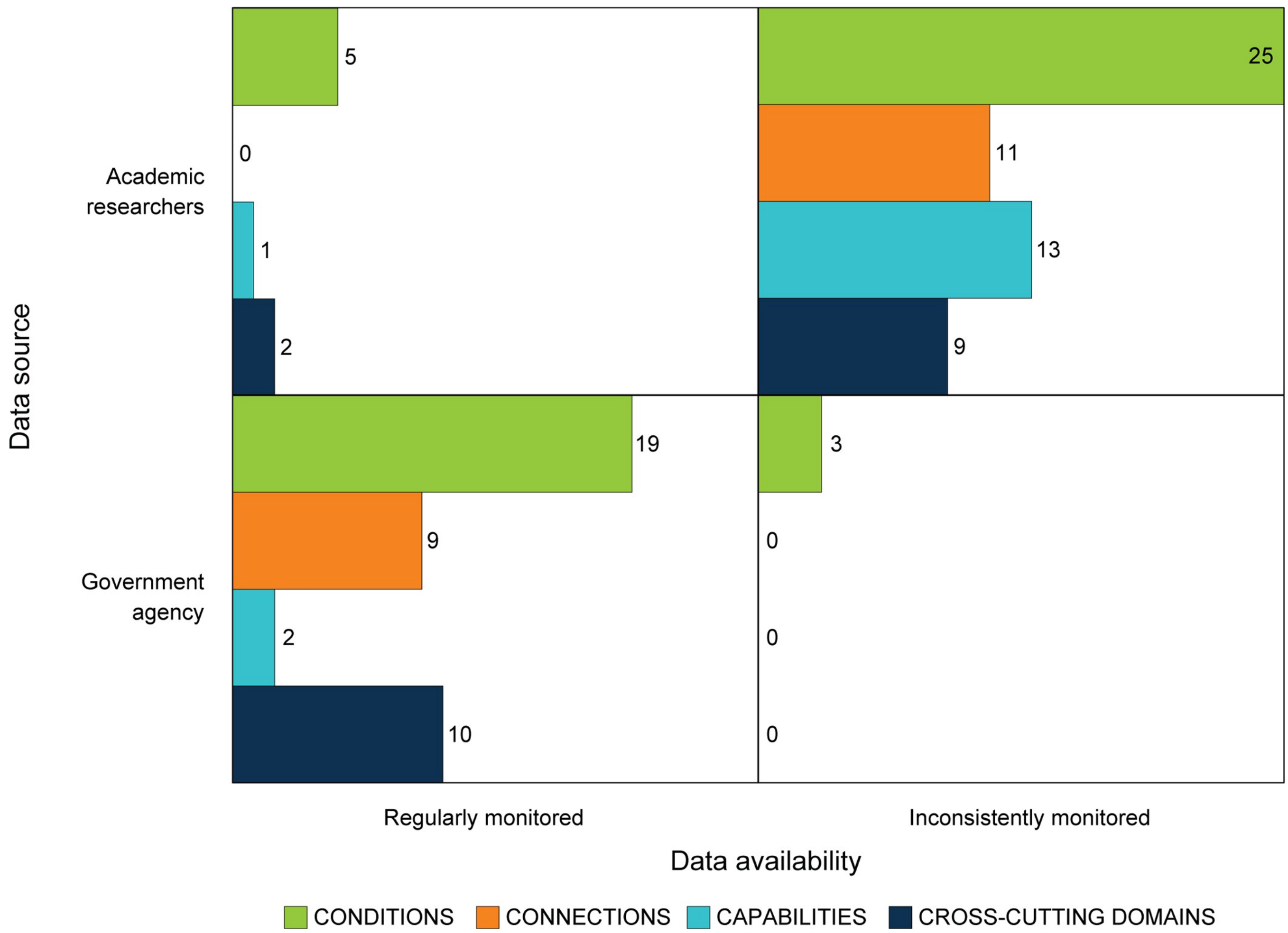

Fig 4. Number of indicators of HAB effects on human well-being by data source and availability. Number of indicators of HAB effects on human well-being within each constituent of the 4Cs framework by data source (academic researchers vs government agency) and data availability (regularly monitored vs inconsistently monitored). The number of indicators in each data source-availability category are also shown.

https://doi.org/10.1371/journal.pclm.0000411.g004

experience, perceptions, opinions [see 17]. By contrast, data collected by government agencies were usually based on "objective-material" measures (e.g., fishery landings, ex-vessel value) collected for regulatory purposes. The rich subjective data used to measure some of the less tangible impacts of HABs on human well-being are less consistently collected and less available compared to the objective data collected or otherwise available to government agencies.

FRD and HHENS indicators

Of the 109 indicators of human well-being effects of HABs in US West Coast fishing communities, over half (i.e., 56%) did not meet criteria for consideration in the determination of a FRD or HHENS (Fig 5). Fishery Resource Disaster determinations could consider 14% of the indicators whereas HHENS could consider almost three times as many indicators (39%). Nine percent of indicators could be considered in both FRD and HHENS determinations. Both FRD and HHENS indicators focus primarily on the *Conditions* and *Connections* constituents of the 4Cs framework. Indicators from the *Capabilities* constituent and the *Cross-cutting domains* of *Equity & Justice*, *Security*, *Resilience*, and *Sustainability* are largely

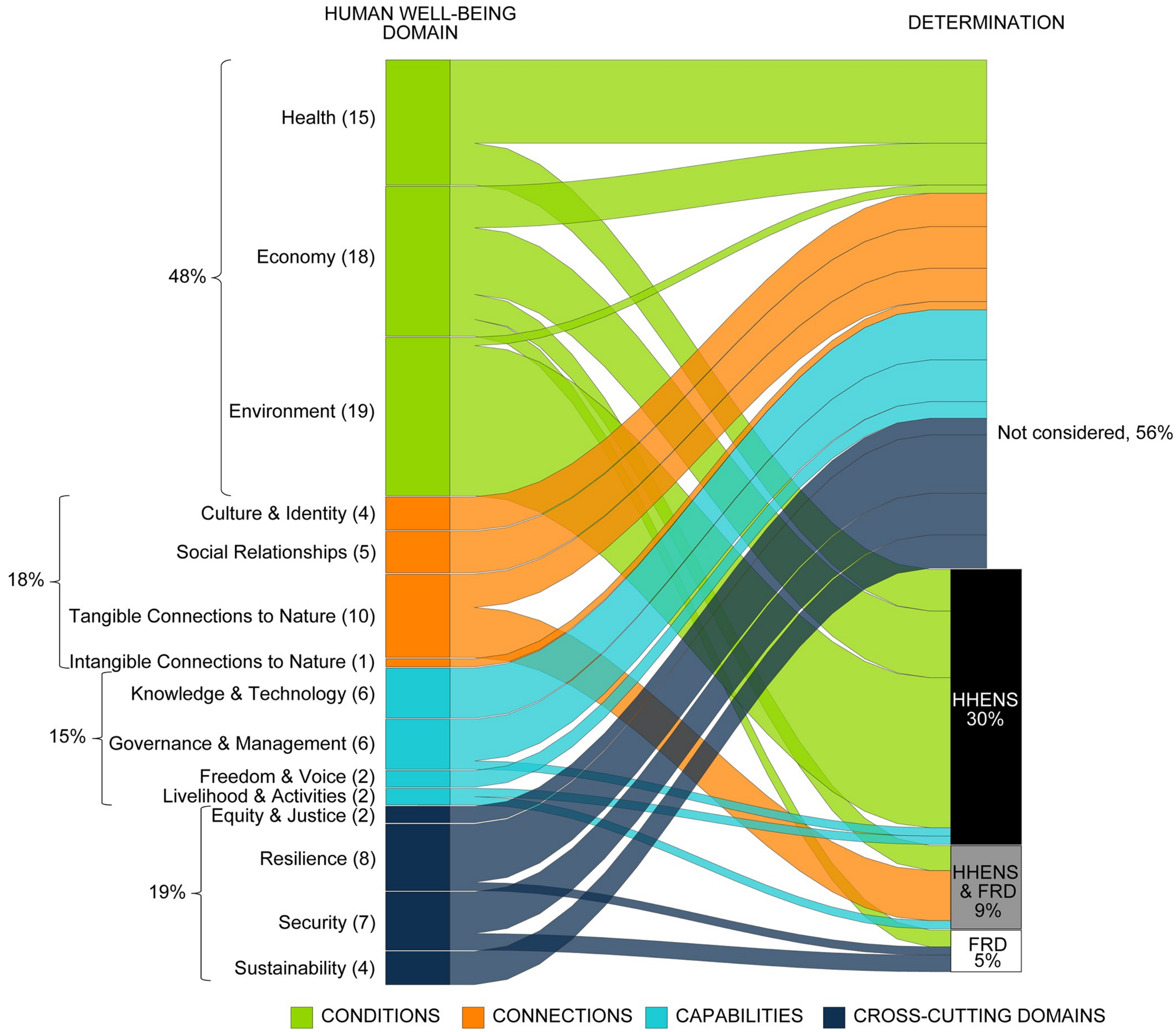

Fig 5. Proportion of indicators of HAB effects on human well-being categorized to each constituent of the 4Cs framework that could/could not be considered in FRD and/or HHENS determinations. Alluvial diagram showing the proportion of indicators of HAB effects on human well-being in each domain of the 4Cs framework that could/could not be considered in FRD and/or HHENS determinations. The number of indicators in each domain is indicated in parentheses. The colors of the lines represent the constituent of human well-being from the 4Cs framework to which the indicator was categorized.

https://doi.org/10.1371/journal.pclm.0000411.g005

underrepresented in FRD and HHENS determinations; no indicators from the *Cross-cutting* constituent could be considered in a HHENS determination. Indicators not considered in either FRD or HHENS determinations include social, emotional, and behavioral impacts (e.g., feelings of stress or sadness, impacts to family or community events, coping or adaptive actions), community social vulnerability, and sub-acute health impacts of HAB exposures.

Fishery Resource Disaster indicators were mostly focused on the economic impacts of a curtailed fishery on the fishing industry (i.e., fishing and receiving/processing operations) and subsistence losses. The remaining few FRD indicators describe socio-economic characteristics of fishing communities (e.g., Dungeness crab dependence) that can help to determine the

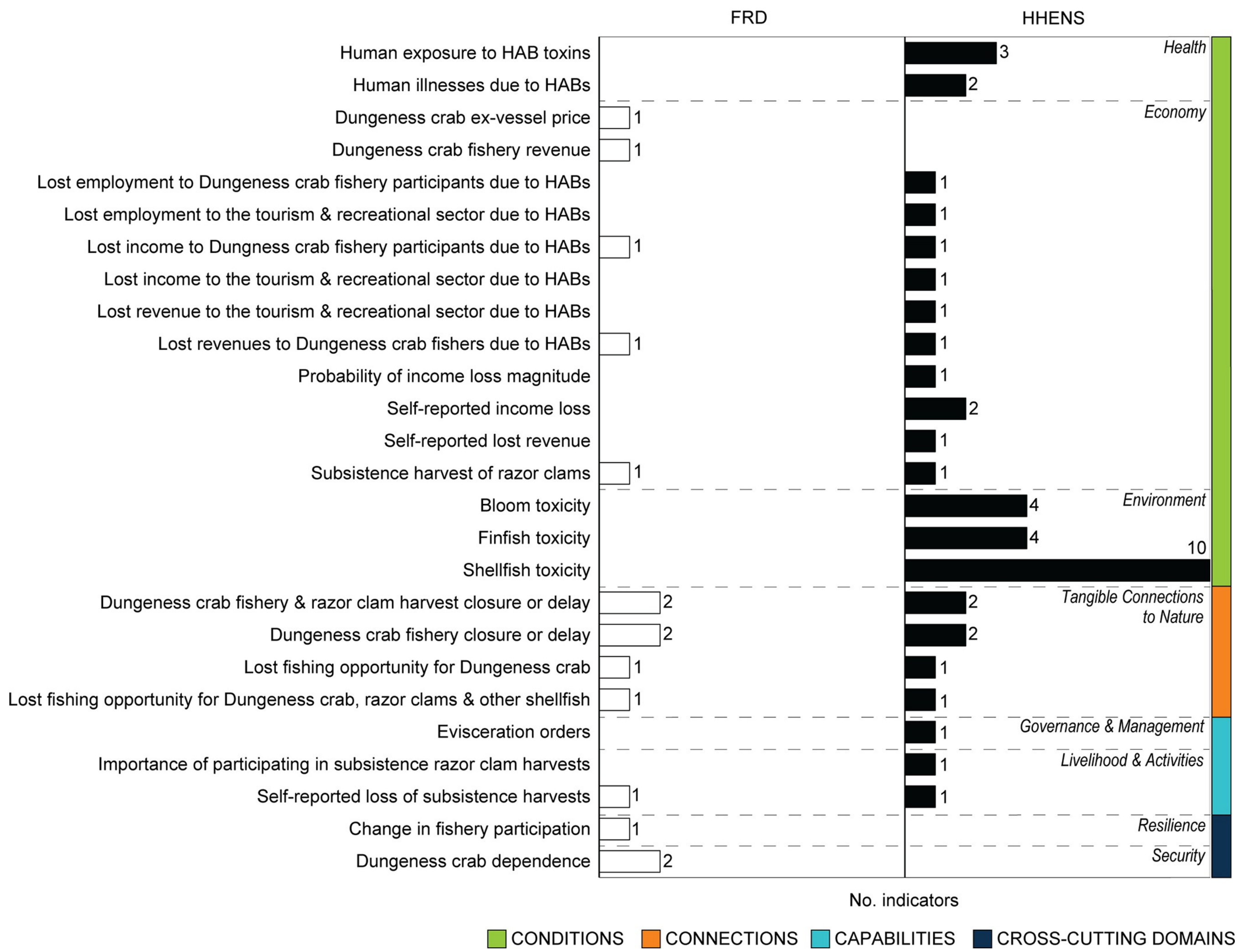

Fig 6. Indicators of HAB effects on human well-being that can be considered in FRD and HHENS determinations. Indicators of HAB effects on human well-being that can be considered in FRD (white bars) and HHENS (black bars) determinations. The background shading represents the constituent of human well-being from the 4Cs framework to which the indicator was categorized.

https://doi.org/10.1371/journal.pclm.0000411.g006

severity of impacts to fishing communities. Harmful Algal Bloom or Hypoxia Event of National Significance indicators spanned a wider range of domains of human well-being compared to FRD indicators, and included aspects of the environment, human health, and resource management (Fig 6). All of the FRD indicators except for one (i.e., Change in fishery participation) were reported using regularly monitored data, whereas almost one third of HHENS indicators were reported using data that were collected once-only or over a limited time period by academic researchers (not shown). Therefore, while HHENS determinations consider a wider range of human well-being indicators compared to FRD, a higher proportion of them are measured using data that are less consistently available.

The partially overlapping criteria and associated indicators that can be considered in FRD and HHENS determinations creates the potential for them to interact. The sectors impacted by a severe HAB will likely determine which path is most appropriate for communities to request relief, but the availability of data to evaluate impacts and support requests may also play a role. If commercial, recreational, and/or subsistence fisheries are impacted, then requesting a FRD determination under the Fishery Resource Disasters Improvement Act will likely be the most appropriate path given its focus on revenue and subsistence losses to fishers, charter fishing operators, subsistence users, fish processors, and related fishery infrastructure or businesses. Impacts to other sectors, such as tourism, recreation, real estate, public health, monitoring, and response, will be best mitigated through the HHENS process given the wider range of human well-being effects it can consider. States may, however, include fishery impacts in HHENS requests, or request both a FRD and HHENS determination to mitigate impacts to fisheries and other sectors, respectively.

State and federally mandated monitoring and reporting of fisheries landings and revenues means that data are usually readily available to evaluate FRD requests. It is less clear who is responsible for monitoring and reporting data to evaluate HHENS requests, particularly data that are not collected for regulatory purposes. Of note, the appropriate federal official has the discretion to declare a FRD or HHENS on their own. Additionally, if a disaster declaration has been made under another statutory authority, the Secretary of Commerce may determine a FRD has occurred without being bound to the revenue loss thresholds described above. Therefore, it is possible that the requirement for data to evaluate HAB impacts may be overridden if these data are not readily available or would be overly burdensome to collect.

Discussion

Toxic blooms of *Pseudo-nitzschia* spp. affect almost every aspect of human well-being in US West Coast fishing communities. To date, most impacts stem from HAB toxins curtailing two "keystone fisheries", Dungeness crab and razor clam. These fisheries are economically and culturally significant and feature notable participation from community members who rely on them. This study demonstrates the utility of the 4Cs framework for compiling and assessing the wide range of well-being effects of HABs, and for identifying indicators that can be used to measure them.

Developing a suite of high-quality indicators is an important step in decision support. Evaluation of indicators is a key part of decision-support frameworks such as IEA [64]. An IEA provides a coupled social-ecological systems lens on the classic adaptive management loop [65, 66], and includes the identification of management goals, development and application of indicators to evaluate status relative to those goals, risk assessment and scenario analysis to identify opportunities to increase alignment with the goals, and implementation followed by monitoring of new actions to achieve those goals. Indicators are thus a central means of linking goals to measurable variables, and then tracking those variables as proxies for progress toward goals such as the well-being outcomes that are represented by the 4Cs framework and that underpin the objectives of mitigation tools like FRD and HHENS determinations. In the context of HABs, indicators that can provide decision support include those used for assessing the effectiveness of management actions and the equity of management outcomes, and tracking adaptation to system dynamics and external pressures.

While past CCLME IEA efforts have focused on indicators of biophysical risk factors that can trigger HABs and on some human well-being impacts, such as HAB toxin levels in target species and durations of fishery closures [e.g., 44], a more comprehensive suite of indicators that represents the complexity and richness of human well-being considerations and connections to potential management actions has not been identified until now. Even this improvement, however, demonstrates that the *Conditions* constituent has received disproportionate attention compared to the *Connections*, *Capabilities*, and *Cross-cutting* constituents (Figs 3–5). This crosswalk thus serves as both a prospectus for future efforts to track HAB impacts on human well-being—building on indicators identified here, especially those that are regularly monitored—and a gap analysis that directs attention to areas where more consideration is needed to fully describe these impacts. We encourage future work to identify and evaluate how 4Cs indicators have been developed and tracked in other regions in relation to HABs and associated management responses mitigation tools, such as FRD or HHENS determinations.

Moreover, on the US West Coast, there are emerging opportunities to assess the human well-being outcomes of HAB management actions beyond FRD and HHENS determinations, such as the use of evisceration orders. While it is clearly the intent of these actions to promote well-being by keeping fisheries from being shuttered, the full well-being consequences for fishers and coastal communities more broadly have not yet been evaluated. It is possible that impacts of evisceration orders on domains of well-being, such as *Health* and *Security*, will be heterogeneous across communities, depending on whether consideration is given to harvesters, processors, consumers, business-owners, or a cross-section of community members. These areas are ripe for future research inquiry.

Over half of the human well-being indicators of the effects of HABs in US West Coast fishing communities identified in this study were measured using data that are not regularly monitored (Fig 5). This finding is consistent with the sentiment that largely uncoordinated and inconsistent (or even non-existent) reporting mechanisms challenge efforts to establish baselines and determine if policies and management strategies designed to prevent, control, or mitigate HABs are successful [11]. An exception to this is the Centers for Disease Control and Prevention One Health Harmful Algal Bloom System that collects information to better understand HABs and help prevent human and animal illnesses caused by HABs; however, reporting is voluntary and may not be comprehensive. In the context of this study, insufficient baseline information for assessing the impacts of severe HABs may make it harder to determine whether a FRD or HHENS has occurred. Lack of information may be particularly problematic for HHENS because almost a third of HHENS indicators identified in this study were measured using data that were less consistently monitored whereas all but one of the FRD indicators were measured using regularly monitored data. HHENS determinations may therefore be undercut by the lack of monitoring of well-being impacts in some states, putting more pressure on states to collect data. This strain could be made all the more acute when states are actively responding to severe HAB events. Inequities arising from data justice issues may also arise if some states/communities have more resources than others for monitoring to support HHENS requests.

A spike in data collection efforts by academic researchers to determine the well-being effects of HABs in US West Coast fishing communities occurred in response to the particularly severe 2015 event, but data collection efforts dropped considerably soon after the event (Fig 4B). This pattern is not surprising as academia is not structured for conducting long-term monitoring. Data that are consistently monitored are typically collected by government agencies to enforce government regulations (i.e., for regulatory purposes). This begs the question, might it also be the government's responsibility to collect, or to promote/support the collection of, data to enact government policies?

The diversity of HABs and their physical characteristics, as well as the diversity of human contexts, are cited as the primary challenges to the development of coordinated and consistent reporting mechanisms for the well-being effects of HABs [11]. Human exposures to HAB toxins occur in a variety of different ways, such as consuming contaminated seafood, drinking or contacting contaminated water, or inhaling contaminated aerosols [67]. These mechanisms of exposure, and the management actions taken to reduce them, give rise to a wide range of impacts via multiple pathways that depend in part upon how HAB-affected resources are used and/or valued in different locations by different groups of people. Accordingly, this diversity of impacts points to a need for contextually relevant indicators that are still amenable to nation-wide comparisons. While some indicators may be relevant for some places, the most apt baseline requires a more specific regional or even local context. This may make implementing HHENS challenging at first, but there may be lessons learned from the implementation of prior policies, such as the Coastal Zone Management Act of 1972 (CZMA; Pub. L. 92–583).

The CZMA created infrastructure that facilitates access to federal support for states and territories to focus their coastal management efforts on state and local needs while still adhering to national guidelines [68]. Participating states and territories have leveraged federal CZMA funds, for example, to support research and development of locally informed and socially and culturally appropriate strategies to minimize risk to socially vulnerable communities in the US Virgin Islands [69]. This model lays the foundation for the development of monitoring programs that are tailored to the needs of local municipalities but also amenable to the creation of national standards.

In the absence of any new infrastructure investments to implement HHENS, other programs may provide opportunities for monitoring some of the well-being indicators needed to track the effects of HABs and HAB management actions. For example, the nascent National Harmful Algal Bloom Observing Network (NHABON) leverages the U.S. Integrated Ocean Observing System network of regional associations to tailor monitoring to the unique set of HAB problems faced in each region [70, 71]. The primary goal of NHABON, however, is to support HAB early warning and forecasts by detecting HAB organisms and their toxins. Therefore, while NHABON will advance the collection of data to support some of the well-being indicators needed to track HAB impacts and recovery efforts, significant data gaps would remain unless the program was expanded to include the collection of socioeconomic data.

Given funding and other constraints that limit monitoring capacities, states may need to prioritize monitoring efforts, requiring the consideration of trade-offs among indicators. Our approach of pairing monitoring and indicators with pathways for accessing relief may offer guidance in prioritizing investments to implement policy (e.g., target indicators that are used in HHENS determinations). Even within this application, however, we acknowledge that such indicators still may neglect some aspects of well-being, in particular, attributes of the cross-cutting domains. This neglect could ultimately prevent vulnerable communities from being identified initially or at all. To avoid such an outcome, the separation of well-being components offered by the 4Cs framework requires an additional concomitant step of disaggregating data by social variables [12, 13]. Expanding on indicator screening and development for marine ecosystem-based management [72], human well-being indicators identified through the 4Cs framework will necessarily be aimed at environmental conditions with equity and justice in mind from the outset [e.g., 16].

Any process for selecting and prioritizing indicators is most likely to meet the needs of stakeholders if it is conducted on a regionally or case-specific basis [73]. These processes will be further ameliorated by the participatory identification of new indicators developed in collaboration with the people most affected by HABs. Participatory and collaborative processes allow for the development of indicator suites specific to the location and salient social and cultural realities within the affected communities [13, 74–76]. The base of knowledge at the national level is not always sufficient or suited to identifying indicators at the local level, despite the need for cross-regional, national comparisons [e.g., 15]. Therefore, our approach aids in identifying a tension between the need for scalable, readily measured indicators, available nationally, and indicators that are meaningful to the communities subject to well-being assessments.

Both FRD and HHENS determinations, the scope of which are dictated by statute, largely overlook indicators from the *Cross-cutting* constituent that includes the domains of *Equity &*

Justice, *Security*, *Resilience*, and *Sustainability*. Indicators from this constituent include measures of sensitivity and adaptive capacity of communities impacted by HABs and the distributional effects of HABs that disproportionately impact particular populations or communities. While these *Cross-cutting* indicators may seem, in some cases, more difficult to identify or develop than those within other categories, they are important to interpreting many of the other indicators. For example, measures of well-being associated with governance and management, from within the *Capabilities* constituent, are linked directly to *Cross-cutting* indicators of equity and justice, as equity in access to governance channels is often at the root of satisfaction measures of governance. Moreover, these *Cross-cutting* indicators are distinct from the others in that they often capture aspects of well-being that are fundamentally associated with community well-being generally, and the maintenance of the domains within the other three constituents [12].

Efforts to promote equity and increase resilience of underserved communities to future HABs may be hampered by the inability to consider *Cross-cutting* indicators in FRD and HHENS determinations or lack of data to identify these communities. For example, communities with high social vulnerability, such as high rates of unemployment and poverty, may have heightened sensitivity to HAB impacts such that an event that falls short of qualifying for relief still has devastating impacts on well-being. Communities still recovering from the effects of a previous environmental shock (or series of shocks) may similarly have heightened sensitivity to HAB impacts. The laws available for providing relief currently ignore these cross-cutting aspects of well-being (largely). As such, they may inadvertently perpetuate existing inequities by systematically denying funds to assist vulnerable populations and/or communities in their recovery efforts.

While HABs are only one possible type of disaster that FRDs are designed to address, a FRD determination has been the only pathway used to date to access relief to mitigate the well-being effects of HABs in US fishing communities. Because HHENS can consider a wider range of well-being indicators compared to FRD, including those related to non-fishing related sectors, it may fill an unmet need to provide fishing communities and coastal communities more broadly with relief to mitigate HAB impacts. The sectors impacted by severe HAB events, as well as the availability of data to measure indicators used in determinations of a FRD or HHENS, will likely determine which pathway eligible entities pursue for requesting relief. The FRD and HHENS programs may, however, interact due to the partially overlapping criteria and associated indicators used in determinations. Further, the two pathways are not mutually exclusive, creating the potential for eligible entities to receive both positive FRD and HHENS determinations for the same HAB event. In this case, requesting entities may need to harmonize spend plans to ensure equitable access to relief by all eligible impacted sectors.

As new types of HABs emerge in new regions, other types of disaster relief outside of FRD may be employed to mitigate HAB impacts which could create more potential for interaction with HHENS. For example, in 2022, a Federal Emergency Management Agency (FEMA) disaster declaration was made when an influx of the genus *Sargassum*, a floating brown macroalgae, interfered with the desalination plant that is the primary source of water for St. Croix in the United States Virgin Islands [77]. The *Sargassum* example speaks to the more general challenge of designing a portfolio of policies and indicators that capture all domains of the 4Cs framework, when the phenomena underlying HAB disasters are changing over time.

Institutional flexibility (e.g., to modify HAB management approaches and how disaster policies interact across agencies) and tactical flexibility (e.g., to accommodate collection of new disaster-impact related data) can promote governance that is well-matched to emergent needs. New evisceration policies in the Dungeness crab fishery are a case in point, as they may reduce impacts on human well-being tracked under the *Connections* constituent (by allowing sustained time at sea fishing), though they may have mixed impacts on the *Conditions* constituent (if they avoid total elimination of crab-related income but eviscerated crab fetch a lower market price). This uncertainty around how attempts to keep pace with changing HAB contexts and responses will affect human well-being is emblematic of the signature problem of the Anthropocene: hitting a moving target [78]. More importantly, it illustrates the need for consistent attention not just during, but also between, HAB crises.

The 4Cs framework and its associated indicator development process offers a means of analyzing indicators in the context of HABs and HAB management responses, revealing helpful insights unique to these contexts. While the process laid out by Breslow et al. [12] is systematic and valuable here, we recognize that the assignment of indicators requires some degree of expert judgment, particularly as we applied it to US West Coast HAB literature developed independently of our focus. For example, a dependence on Dungeness crab was categorized to security, but might also have been categorized to resilience, given that reliance on a singular fishery suggests exogenous shocks to that fishery may inhibit resilience [40].

Another caveat to this study is that some of the indicators are measured using the same or similar data sources. The most extreme case of this was for the shellfish toxicity indicator which was identified from ten different publications but using data from different regions collected by different State agencies or calculated over different time periods. Each indicator extracted from the literature was considered independent in this study. This may have increased the count of indicators in some categories of human well-being (e.g., the Conditions constituent that indicators of shellfish toxicity were categorized to), but without detailed knowledge of the data used, which was not always presented in detail in the literature, these could not be screened out in a consistent way.

Examining the effects of HABs through the lens of the 4Cs framework for human well-being enabled a more holistic assessment of the wide range of impacts that can result from toxic HABs of *Pseudo-nitzschia* in US West Coast fishing communities. Applying the 4Cs framework in this way provides the necessary structure for compiling existing information on HAB effects on human well-being and advances the regional implementation of national research and assessment strategies to address the human dimensions of HABs [11, 79]. It provides a starting point for communities to develop suites of high-quality indicators to aid in decision support, and outlines some key considerations for prioritizing limited monitoring resources to facilitate equitable management outcomes. Shifting baselines due to climate change and the introduction of new policies will, however, be challenging for tracking indicators of the effects of HABs on human well-being.

Supporting information

S1 Table. Screening criteria and data considerations for indicators of HAB effects on human well-being.
(XLSX)

S1 Text. Detailed description of indicators of HAB effects on human well-being categorized to the 4Cs framework.
(DOCX)

Acknowledgments

We thank Mike Downs for contributions to the conceptualization of this project, and Erin Schnettler and Michael Ruccio for their thoughtful review.

Author Contributions

Conceptualization: Stephanie K. Moore, Chris J. Harvey, Carrie Pomeroy, Jameal F. Samhouri.

Data curation: Stephanie K. Moore.

Formal analysis: Stephanie K. Moore.

Investigation: Stephanie K. Moore, Maggie Broadwater, Curtis Cha, Quay Dortch, Justin Pearce.

Methodology: Stephanie K. Moore, Karma C. Norman, Jameal F. Samhouri.

Project administration: Stephanie K. Moore.

Validation: Maggie Broadwater, Quay Dortch, Justin Pearce.

Visualization: Stephanie K. Moore.

Writing – original draft: Stephanie K. Moore, Curtis Cha, Chris J. Harvey, Karma C. Norman, Jameal F. Samhouri.

Writing – review & editing: Stephanie K. Moore, Maggie Broadwater, Curtis Cha, Quay Dortch, Chris J. Harvey, Karma C. Norman, Justin Pearce, Carrie Pomeroy, Jameal F. Samhouri.

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