

EFFECTS OF CLIMATE CHANGE AND FISHING PRESSURE ON CIGUATERA PREVALENCE IN HAWAIIAN
REEF FISHES: IMPLICATIONS TO PUBLIC HEALTH IN A CHANGING CLIMATE

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By:
Nikola Rodriguez

Thesis Committee:
Timothy B. Grabowski, Chair
Matthew L. Knope
Ingo Koomoa-Lange
Sarah Fritts

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ABSTRACT

Ciguatera fish poisoning (CFP) is caused by consuming reef fishes containing toxins produced by epiphytic dinoflagellates in the genus *Gambierdiscus*. Changing reefscales due to climate change and altered reef fish assemblages from overfishing may increase the range of and habitat available to *Gambierdiscus* spp. while altering how ciguatoxins (CTX) move through coral reef food webs. However, it is not clear how these factors may interact to influence the probability of ciguatoxic fishes and thus the risk of CFP to local communities dependent upon these fisheries. Therefore, the objectives of this study are to 1) evaluate the relationship between a suite of habitat characteristics at multiple spatial scales, including those related to changing temperature regimes and fishing pressure on the probability of fish testing positive for CTX; 2) evaluate the relationship of the same habitat characteristics on the concentration of CTX; and 3) assess the degree to which local fishing communities practices and beliefs that are used to limit risk of CFP agree with the findings of the first two objectives. I evaluated the presence and concentration of ciguatoxins in two common reef fish species: the high-level predator, Peacock Grouper (*Cephalopholis argus*), hereafter referred to by its Tahitian name – Roi, and a frequently sought-after herbivore, Goldring Bristletooth (*Ctenochaetus strigosus*), known as Kole in Hawaiian, sampled bi-annually across four sites along west Hawai‘i Island. For Roi, both the probability of testing positive for CTX and CTX concentration exhibited a positive relationship to length and negative relationship to the number of days under a coral bleaching alert and fishing pressure. For Kole, the probability of testing positive for CTX was negatively related to length, the number of coral bleaching alert days, effluent, fishing pressure. The concentration of CTX in Kole was also negatively related to length, effluent, fishing pressure, and mean percent live coral cover. Most anglers and spearfishers are unlikely to restrict their fishing activity in response to

CFP risk, instead tending to avoid species, size classes, or fishing areas perceived as high risk. However, my results suggest that fish behaviors are likely to become less effective as changing temperature regimes, loss of live coral cover, and human fishing pressure may be altering the prevalence and distribution of ciguatoxic fishes. The results of the study will allow resource managers to better communicate the risk of CFP to anglers and spearfishers so they can mitigate the dangers of ciguatera fish poisoning in a fast-changing climate.

1. INTRODUCTION

Ciguatera fish poisoning (CFP) is considered the most common marine toxin-related illness affecting humans in the tropics and sub-tropics (Friedman et al. 2008, 2017). Due to globalization and increased fish and seafood exports (Rey 2007; Dickey and Plakas 2010) ciguatera cases are being reported in non-tropical regions (Lewis et al. 2000; Loffler et al. 2022). Ciguatera poisoning has become a worldwide problem that is largely neglected (Gingold et al. 2014). The term ciguatera originates from the word “cigua”, a Spanish common name for a marine snail that is consumed throughout the Caribbean, which had been linked to CFP (Randal 1958; Rey 2007). In 1521, the first historical event involving CFP was documented by the Spanish army while in the Gulf of Guinea. Several captains of the Spanish army became sick with CFP, which led to the death of a captain and others (FAO & WHO 2020). Accounts of illnesses consistent with CFP can be found in reports from oceanic voyages through the tropical regions worldwide. For example, In 1774, Captain Cook’s crew was taken sick with CFP and was documented in Cook’s journal (Doherty 2005). While rarely fatal, CFP is characterized by gastrointestinal, cardiovascular, and neurological symptoms ranging from mild and short term (days to weeks), to debilitating and long-term (months to potentially years), and continued exposure to ciguatoxins can exacerbate symptoms (Freidman et al. 2008, 2017). There have been over 175 symptoms associated with ciguatera (Gatti et al. 2008). The effects of CFP are multifaceted and have extensive economic and ecological impacts beyond public health (Brody 1972; Freidman et al. 2017). For example, a CFP scare in Hawai‘i during the 1980s involving Ulua Aukea (*Caranx ignobilis*) Giant Trevally led to a >90% decline in commercial landings and this fishery never recovered (Gaffney 2000). Concerns about CFP can also inhibit the development of fisheries, such as in the case of Roi (*Cephalopholis argus*) Peacock Grouper. This grouper was

introduced to Hawai‘i during 1955 – 1961 to establish a new nearshore fishery, but studies indicating the species frequently carried a high level of ciguatoxin inhibited the fishing community from targeting it (Afton 2003; Dierking 2007; Dierking and Campora 2009). The lack of fishing pressure on Roi has been identified as a potential factor in the rapid growth and spatial expansion of its population in Hawai‘i (Dierking 2007).

Ciguatera fish poisoning is caused by the consumption of reef fishes containing ciguatoxins produced by epiphytic photosynthetic dinoflagellates in the genus *Gambierdiscus*. There have been over 425 species of fish that have been linked to CFP events (Perez-Arellano et al. 2005). In humans, CFP is caused by consumption of tropical reef fishes, such as jacks (Carangidae), groupers (Serranidae), snappers (Lutjanidae), surgeon fishes (Acanthuridae), and barracudas (Sphyreanidae), that have bioaccumulated naturally occurring ciguatoxins (CTX) through the food chain (Randall 1958; Rey 2007). Ciguatoxins act on the voltage gated sodium channels (VGSC) and are the most potent activators of VGSC, causing increased sodium influx and depolarization of the cell membrane, which results in persistent neurological changes in humans that consume contaminated fish (Martin et al. 2015). Ciguatoxins enter coral reef food webs when herbivorous fishes incidentally consume the dinoflagellates and their toxins, which accumulate in their flesh. These herbivores then are consumed by piscivorous fish which bioaccumulate and biomagnifies the CTXs in their flesh. While available literature suggests that CTXs have little to no impact on fishes, humans consuming fishes containing CTXs can experience a wide range of neurological and gastro-intestinal effects (Freidman et al. 2017). The estimated economic impact of CFP is \$37.3 million yr⁻¹ (adjusted for inflation) in the United States alone (Anderson 2000). However, CFP is no longer only a problem of the tropics and subtropics and has started to occur outside of these regions due to fish exports; therefore, the

economic impacts are likely underestimated. Despite this knowledge, the ecology of *Gambierdiscus* spp. is not well understood and drivers behind evident increases in distribution are difficult to pinpoint due to the ability of *Gambierdiscus* spp. to thrive on a range of surfaces and survive across wide temperature and salinity ranges (Parson et al. 2012). Reported cases of CFP are patchy in time and space, underreported, and have a high degree of misdiagnosis (Bienfang et al. 2008; Freidman et al. 2008, 2017). The patchiness makes it challenging to understand the ecology of *Gambierdiscus* spp. and the underlying prevalence of CTXs in fish populations based on studying reports of CFP cases. Furthermore, there is evidence that changing reefscapes associated with warming temperature regimes, coral bleaching, coastal eutrophication, and shifts in reef fish assemblage structure may alter *Gambierdiscus* spp. prevalence and risk of CFP, but this has not been thoroughly investigated. (Koehler and Koehler 1992; Loeffler et al. 2015; Freidman et al. 2017).

Gambierdiscus spp. have been described as ‘opportunistic’ and ‘weedy’ with respect to substrate and habitat types (Loeffler et al. 2015), for example, they can colonize a variety of macroalgae species, or even dead coral, and can inhabit a wide depth range (Grzebyk et al. 1984; Kohler and Kohler 1992; Loeffler et al. 2015). In contrast, water motion and areas of high run-off have been found to promote low dinoflagellate abundance (Gillespie et al. 1985; Grzebyk et al. 1994; Richlen and Lobel 2011; Loeffler et al. 2022). It seems that the same fine sediments that smother dead corals and turf algae, also inhibit the growth of dinoflagellates, such as *Gambierdiscus* spp. The same has been found in areas with strong wave energy and strong nearshore and tidal ocean currents (Grzebyk et al. 1994; Richlen and Lobel 2011; Loeffler et al. 2022). On coral reefs with low herbivore abundance, *Gambierdiscus* spp. densities have been observed to increase by 374% from previously observed densities; suggesting that the areal density of *Gambierdiscus* spp. may

be affected by changes in herbivorous fishes feeding habits, selectivity, and grazing rates (Loeffler et al. 2015). The increased availability of macroalgae due to the decreased rate of ingestion provides a greater availability of suitable substrate for *Gambierdiscus* spp. (Loeffler et al. 2015). Availability of suitable habitat for *Gambierdiscus* spp. can also be affected by changes in the composition of the reef substrate, such as mass bleaching events increasing the substrate available to macroalgae in the form of dead coral. The increasing severity and frequency of mass bleaching events is directly related to climate change (Gove et al. 2019) and the rise in sea surface temperature is directly tied to *Gambierdiscus* spp. abundance and range (Koehler and Koehler 1992). For example, the west coast of Hawai'i Island experienced a mass coral bleaching event in 2015 and two less severe events in 2006 and 2014 (Bahr et al. 2015); due to increased sea surface temperatures, resulting in 90% of corals bleaching across the region (Gove et al. 2019) and a $49.7 \pm 2.7\%$ decline in average relative coral cover from 2014 – 2016 (Walsh et al. 2019). In specific areas, such as Puakō, coral cover has been reduced from approximately 80% in the 1970s to an average of about 11% in 2016 surveys (Walsh et al. 2019). In the areas where live coral once was, turf algae and crustose coralline algae have taken their place (Walsh et al. 2019). However, there has been no attempt to quantify the effect of these changes on *Gambierdiscus* spp. abundance or the occurrence of CFP.

Ciguatera fish poisoning is endemic in the Pacific and South Pacific, especially the Hawaiian archipelago. However, ciguatera cases are thought to be highly underreported (Copeland et al., 2014; Bienfang et al. 2016). This is largely due to the range of symptoms of CFP and misdiagnosis (Sims 1987). There is no blood test to test for CFP. The current method to check for CFP is to test remnants of the fish that was eaten by the infected person. There are many preventative methods that people use to mitigate their risk of CFP, such as not eating specific

parts of a fish, not eating specific species of fish, and not eating fish from specific locations. Some preventative methods are backed by scientific research, such as not eating the head or belly (Chan 2016), and others are thought to be folk remedies that are passed down generationally. The perceived risk of ciguatera in the local angler and spearfishing community is not well documented. My study seeks to better understand the perceived risk of CFP and assess if it is similar to the actual risk of CFP in Hawai‘i.

On the west side of Hawai‘i Island, total algal cover has been increasing in MPAs and areas open to fishing since 2003 (Gove et al. 2019). While algae cover is important to support herbivorous fish populations, it can outcompete corals for space, inhibit coral recruitment, reduce coral survival (Gove et al. 2019) and increase *Gambierdiscus* spp. abundance (Loffler et al. 2015). Herbivore fishes’ grazing habits control algae growth and limit the habitat available for *Gambierdiscus* spp. However, grazing is also the primary conduit for CTXs to enter the food web. Therefore, reductions to herbivore abundance should alter the pathways available for CTXs to get into predatory fishes and human food supply chains. The overall goal of my study is to begin to disentangle the complex relationship between the effects of anthropogenic climate change, fishing pressure on herbivorous reef fishes, and other local environmental factors on the prevalence of ciguatoxic fishes and the concentration of CTX within their tissues along the west coast of Hawai‘i Island and assess local anglers and spearfishers perceived risk of CFP compared the actual risk of CFP.

2. MATERIALS & METHODS

2.1. Study Area

Roi and Kole were sampled from four locations along the western coastline of Hawai‘i Island, Puakō, ‘Anaeho‘omalū Bay, Halepa‘o and Ke‘ei (Figure 1), from March 2021 through February

2023. The reefs along the western coastline of Hawai‘i Island are characterized as fringing reefs at shallower depths (0-10m) and transition to ledges and patch reefs at deeper depths (10-25m). I selected these collection sites to encompass a representative range of mean percent coral cover and mean herbivore biomass (g/100m²). Mean percent coral cover for the locations (Table 3) varied from 4.13% (± 0.89 SE) at Puakō to 17.30 (± 3.12 SE) at Ke‘ei and mean herbivore biomass at each location varied from 1827.46 (± 257.94) g/100m² at ‘Anaeho‘omalū Bay to 9313.15 (± 1532.95) g/100m² at Halepa‘o (Table 9; DAR *unpublished data*).

The reefs of west Hawai‘i were differentially impacted by a major bleaching event during 2015 that resulted in an average loss of coral cover of 49.7% (Walsh et al. 2019). Subsequent recovery from the 2015 bleaching event has been similarly variable between long-term monitoring sites along the coast with continued coral cover declines ranging from 7.2% – 23.8% in the region and at Puakō, respectively (Walsh et al. 2019). The major coral bleaching event that occurred was documented by Hawai‘i Division of Aquatic Resources (DAR) and The Nature Conservancy (TNC) through fish and benthic surveys from 2015-2021 (Walsh et al. 2019); allowing me to study how reductions in coral cover may relate to the occurrence of CTXs in reef fishes. In order to encompass a range of coral cover loss and herbivore biomass, my study sites along West Hawai‘i were selected in consultation with the staff at West Hawai‘i branch of the Division of Aquatic Resources (DAR) in Kailua Kona, HI.

2.2 Data collection:

Fish Samples. - Fish samples were collected haphazardly along the coastline of each sampling area during spring/summer and fall/winter seasons, with collection depth varying between 0-25-m depth. A total of 168 fish samples were collected by spearfishers using a three-prong spear

and/or speargun. I recorded the collection location of individuals using a handheld GPS attached to a dive float and/or personal freediving watch. The fish were tagged through the opercula and mouth using a zip tie with site and GPS waypoint information. All specimens were put on ice upon exiting the water and were either processed or frozen within 24 hours of collection. I measured and recorded the total length (TL) to the nearest 0.1 cm of the Roi and I measured the fork length (FL) to the nearest 0.1 cm of the Kole before samples were processed.

Tissue Samples. - The sampled fish were either fresh or previously frozen when tissue samples were removed. I collected two tissue samples, ranging between 5-20-g, without bone or skin, from each fish to test for ciguatoxin. If the specimen was frozen, I thawed the fish before removing the tissue sample. I washed and patted dry each tissue sample before dehydrating at 74°C for 6 hrs. and vacuum sealing into individual plastic storage bags.

Dry Tissue Extraction – Lab personnel at the Federal Institute of Risk Assessment (BfR) in Berlin, Germany performed extractions on the dehydrated tissue samples using a novel method. They powdered and rehydrated the dehydrated tissue samples with 4-mL Mili-Q water then left the samples to rest for 60 minutes to form 1-g dry tissue extract (DTE). They added 5-mL of 90% MeOH to the sample to extract ciguatoxins then thoroughly blended with an Ultra-Turrax T-25 Digital Homogenizer (Ika Works, Wilmington, North Carolina) for ~1 minute at >10,000 RPM. Supernatant was separated by centrifugation for 5 minutes at 3500 RPM and decanted into a 50-mL falcon tube. Samples were re-extracted by adding 5-mL of 80% MeOH and mixed using a vortex mixer for 30 seconds. The supernatant was separated from the re-extracted sample by centrifugation for 5 minutes at 3500 RPM. Supernatants were combined and residual protein was removed by centrifugation at 4000RPM for 3 minutes. They decanted the supernatants into a new glass vial and prepped to remove lipids by adding 5-mL hexane and mixing with vortex

mixer for 30 seconds then centrifugation at 3500 RPM for 4 minutes to allow the separation of solvents. They then discarded the upper hexane layer. This process was repeated as needed for defatting of the sample which is when the supernatants become colorless. They then added 5-mL of Mili-Q water and 5-mL dimethyl chloride (DCM) and agitated the solution for 30 s using a vortex mixer, then centrifuged for 3 minutes at 3500 RPM. They then transferred the bottom DCM layer to a new clean glass tube. They then added 5-mL DCM to the remaining top layer and repeated the last steps then combine the two DCM wash layers. They then evaporated the DCM layers to dryness. The dry extract residue was redissolved in 500 μ L 100% MeOH and transferred to a final liquid chromatography (LC) vial, this step was repeated with another 500 μ L 100% MeOH vessel wash. The final concentration was 1-g DTE/mL. Samples were stored at -20°C until tested.

Toxicity Evaluation - Dry tissue extractions were screened for CTX at the BfR following a method for a semi-quantitative *in vitro* neuro-2a cytotoxicity assay described in Loeffler et al. (2022). Briefly, mouse neuroblastoma cells were propagated and maintained in RPMI media supplement with antibiotics, glutamine, sodium pyruvate, and het-inactivated FBS. A full dose-response curve of 8-dilution series for the sample extracts were prepared with sensitized and non-sensitized cells to determine the concentration at which cell viability was reduced by 50% (EC_{50}) compared with a CTX1B standard. All samples, standard, and relevant controls were assayed in triplicate. Results were expressed as CTX1B equivalent (eq.) $ng\ g^{-1}$, ww. The limit of detection (<LOD at LC_{30}) for the assay in the *C. argus* fish matrix was determined to be 0.001 $ng\ g^{-1}$, ww CTX1B eq., and the limit of quantification was 0.005 $ng\ g^{-1}$ CTX1B eq. All samples of toxin concentrations $>0.01\ ng\ g^{-1}$ CTX1B eq. as determined by N2a-assay were analyzed by LC/MS/MS.

CTX-1B Analysis by Liquid Chromatography with Tandem Mass Spectrometry – Lab personnel at the BfR in Berlin, Germany, validated the presence of the regional biomarker CTX-1B in the fish tissue extracts by using high-performance liquid chromatography (HPLC) with mass spectrometric detection (LC-MS/MS), as described in Loeffler et al. (2022). They tested a subsample of Roi tissue (n = 22) that was determined to have toxin concentrations >0.01 ng g⁻¹ CTX1B eq. through the N2a-assay method. They conducted a LC-MS/MS analysis using an Agilent 1260 LC (Agilent, Waldbronn, Germany) and ABSciex 4000 QTrap mass spectrometer (Sciex, Darmstadt, Germany). They examined the extracts for the presence of C-CTX-1 and CTX-1B using C-CTX-1 and CTX1B reference curve materials.

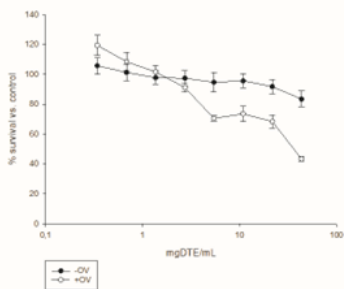


Image 1. Chromatograph of sample extract ID: HP23 showing trace amounts of ciguatoxin compounds being detected.

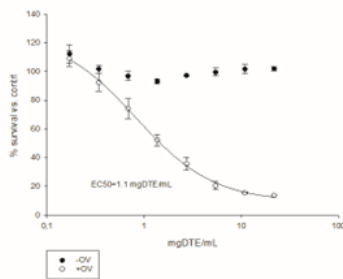


Image 2. Chromatograph of sample ID: HP 47 showing a positive curve for ciguatoxin compounds.

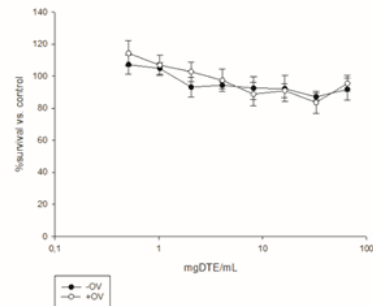


Image 3. Chromatograph of sample ID: KE54 showing a negative curve for ciguatoxin compounds.

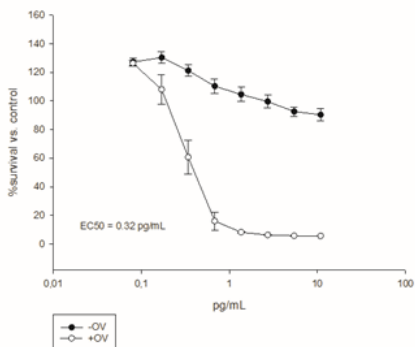


Image 4. Chromatograph of CTX-3C Standard showing a positive curve for ciguatoxin compounds.

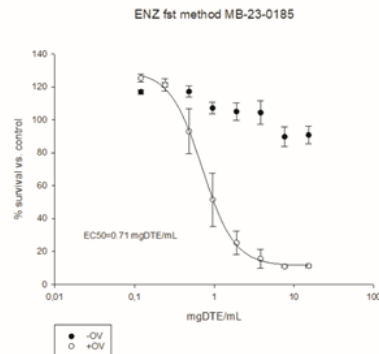


Image 5. Chromatograph of Sample ID: HP48 showing a positive curve for ciguatoxin compounds. LC-MS/MS sample confirmed for CTX-1B, 52-epi-54-deoxy CTX-1B, and 54-deoxy CTX-1B.

Otolith Preparation. - I extracted and prepared the sagittae from specimens (n=168) for aging using the methods described by Long and Grabowski (2017). The right or left sagittae was randomly selected from each individual and embedded in epoxy. I cut a 0.5-mm transverse section from each sagitta, which included the nucleus, using an IsoMet low speed precision cutter (Buehler, Lake Bluff, Illinois) fitted with diamond wafering blades. I mounted the sections to glass slides using Crystal Bond thermoplastic mounting adhesive (Aremco, Valley Cottage, New York). I wet polished the sections using increasingly fine grit sandpaper to expose the nucleus. The age of each individual was estimated by two independent readers. A third reader was used to resolve any discrepancies between the two readers' age estimates. In the case that a consensus was unable to be reached by the readers the individual was removed from the sample.

Habitat Characterization. – I assembled a suite of habitat characteristics describing conditions within the 40-m or 20-m radius circle centered on the capture location of each fish using existing data layers (Table 6 and 7). The percent substrate composition in the home range circles centered on the capture location of each fish was estimated using the HIMARC substrate composition data layer synthesized from the National Oceanic and Atmospheric Administration National Centers for Coastal Ocean Science (NCCOS) 2007 benthic habitat maps (Battista et al. 2007) and Global Airborne Observatory (GAO) data on sand cover (Asner et al. 2020). The HIMARC data assigns 100-m² grids to the substrate classes: coral, boulder, other hard bottom, and soft bottom. The coral variable was calculated as the percentage of substrate with 10-50% coral cover and higher, regardless of benthic structure type. The boulder class differed from coral, other hard bottom included individual patch reef, pavement with sand channels, rubble, scattered coral/rock, spur and groove, aggregated patch reef, aggregated reef and differed from coral, rock bottom and pavement, and soft bottom class includes sand/mud. The GAO raster layer was used with an 85%

threshold value to identify sand pixels and classified as “soft bottom” data classification to fill the data gaps in the NOAA NCCOS data layer. To fill any other data gaps in 0-30-meter depth contour that the NOAA NCCOS and GAO data could not identify the Nibble tool in ArcGIS Pro v 3.2 (Esri, Redlands, California) was used (Battista et al. 2007). I estimated the mean depth in each 40-m home range circle centered on a fish capture point using existing bathymetry data for the Main Hawaiian Islands (Simth 2016). Table 1 was treated as a proxy for coral bleaching and were calculated by the NOAA Coral Reef Watch v1.0 data (NOAA Coral Reef Watch 2023). These temperature data are then used to assess coral bleaching alert areas (BAA) based on degree heating weeks and sea surface temperature anomalies (NOAA Coral Reef Watch 2023). I summed the number of days each Roi or Kole experienced a coral bleaching alert at a BAA level of “Bleaching Warning,” “Bleaching Alert Level 1,” and “Bleaching Alert Level 2” over the last 3, 5, and 7 years (Table 2+1; NOAA Coral Reef Watch 2023).

Several other environmental variables could be estimated from existing data layers created by the 2016 Hawai‘i Ocean Tipping Points Project (Wedding et al. 2018; Table 2). I estimated long term mean wave power for the area around each fish capture point using the output from an hourly 500-m simulating waves nearshore (SWAN) model based on wave power data collected from 1979 – 2013 (Li et al. 2016; Kappel et al. 2017; Wedding et al. 2018). I estimated total effluent from onsite sewage disposal systems, such as cesspools and septic tanks, from data collated from the University of Hawai‘i and the State of Hawai‘i Department of Health (Kappel et al. 2017; Wedding et al. 2018). The estimated mean total annual catch of reef fish was estimated from commercial data collected by DAR during 2003-2013 and non-commercial data collected by phone and intercept surveys as part of the Marine Recreational Information Program (MRIP) during 2004-2013 (Kappel et at. 2017; McCoy et al. 2018; Wedding et al. 2018).

Current mean percent coral cover and mean herbivore biomass ($\text{g}/100\text{m}^2$, $\pm\text{SE}$) data for each collection area was provided by DAR (DAR *unpublished data*). The mean herbivore biomass data was derived from current ‘WHAP’ surveys. ‘WHAP’ surveys are fixed -transect surveys that were developed to evaluate the effects of spatial management areas on reef fish abundance, with specific focus on the commercial aquarium fishery (Walsh et al. 2019). Four visual transect surveys (25-m x 4-m) are conducted at permanent monitoring sites in West Hawai‘i four times a year. The transect lines range in depth from approximately 9-m to 15-m and are about 10-m apart from one another (Walsh et al. 2019).

2.2 Human Dimension Aspect

Non-structured interviews of spearfishers and anglers.- I had informal conversations with 27 spearfishers and anglers to learn about their knowledge of ciguatera. During our conversations, I asked all individuals where they learned about ciguatera, what factors do they think increase their risk of getting ciguatera and what do they do to prevent themselves from getting sick from ciguatera?

Data analysis.- I evaluated whether mean length and age of the sampled fishes varied across collection sites using analysis of variance (ANOVA). I assessed the degree to which habitat variables, such as the percent cover of various substrate classes, mean depth, wave energy, effluent, and fishing pressure (Table 6 and 7), collected within the 40-m or 20-m radius circle centered on the capture location of each fish, varied by collection location using multivariate analysis of variance (MANOVA). Pairwise differences from both the ANOVAs and MANOVA were assessed using post-hoc tests with a Bonferroni adjustment for multiple comparisons (Westfall and Young 1993).

All continuous variables used as covariates (Table 2) were standardized to mean = 0.0 and standard deviation = 1.0. I developed a candidate model set of 24 generalized linear regression models using differing combinations of the standardized environmental and fish-specific variables to predict the probability of a sampled fish testing positive for ciguatoxins. I used Akaike information criterion (AIC) model selection (Burnham and Anderson 2002) to evaluate the best fit model from this candidate set. The AIC selection procedure quantifies the trade-off between model fit and complexity, with lower AIC values indicating better-fitting and more parsimonious models (Burnham and Anderson 2002; Appendix 1 and 2). For the analyses, I calculated the Akaike's Information Criterion for small sample sizes (AIC_c), ΔAIC_c and Akaike weights (w_i). Models with a ΔAIC_c of ≤ 2.0 were considered to perform comparably to the top model. If there was evidence supporting more than one top model, I performed full model averaging of the entire candidate model set (Burnham and Anderson 2002; Symonds and Moussalli 2010).

The same set of 24 candidate models tested to evaluate the probability of a sampled fish testing positive for ciguatoxins were modified to evaluate the factors influencing the toxicity of sampled fish. Because the dependent variable, concentration of ciguatoxin in the fish tissue (CTX-1B/EC50), was continuous and zero-inflated, I used a generalized model with a Tweedie distribution. The Tweedie distribution is a non-negative distribution that is well suited for data with a mixture of zeros and positive values (Tweedie 1984; Dunn and Smyth 2007). The same model selection and multi-model averaging procedures described above were followed for the models assessing factors affecting ciguatoxin concentration. All statistical analysis were performed in R v. 4.0.2 (R Core Team 2021) and used an $\alpha = 0.05$ for hypotheses testing.

3. Results

3.1 Ciguatoxin results

I collected and tested a total of 88 Roi was from four collection sites along the west coast of Hawai‘i Island during March 2021 – September 2022 and found that ciguatoxins were present in Roi from all sites, with prevalence rates of 35% at Puakō, 25% at Halepa‘o and Ke‘ei, and 22% at ‘Anaeho‘omalū Bay. The overall ciguatera prevalence rate was 27% for all Roi samples. For the Roi that tested positive for CTX, the overall mean concentration was $0.41 \pm 2.37 \mu\text{g}/\text{kg}$. The mean concentration of CTX1B was similar across the sites ($F_{5,80} = 1.89, P = 0.14$). The mean total length and age of Roi were similar across sites ($F_{5,88} \leq 1.33, P \geq 0.27$, Table 4). However, there were differences among collection sites in the variables measured within the 40-m buffer surrounding the location fish were captured. Mean depth was shallower at the northern sites, Puakō and ‘Anaeho‘omalū Bay, and deeper at the southern sites Halepa‘o and Ke‘ei. ($F_{3,84} = 12.93, P > 5.03\text{e-}07$, Table 4). Mean wave power was different across all collection sites with Halepa‘o having the highest mean wave power and Puakō having the lowest mean wave power ($F_{3,84} = 207, P < 2\text{e-}16$, Table 4). Further, mean effluent at Puakō and Ke‘ei was higher than that at ‘Anaeho‘omalū Bay and Halepa‘o ($F_{3,84} = 15.37, P > 4.67\text{e-}08$, Table 4). Mean estimated total annual reef fish landings at Ke‘ei were lower than Puakō ($F_{3,84} = 6.25, P > 0.00$, Table 4), while landings at ‘Anaeho‘omalū Bay and Halepa‘o were comparable to the other locations. Other habitat parameters, such as substrate composition, within the 40-m radius circles surrounding the capture locations of Roi were comparable among collection areas ($F_{3,88} \leq 2.61, P \geq 0.00$, Table 4).

Two candidate models performed equally well, i.e., had $\Delta\text{AIC}_c < 2.0$, at predicting the probability of Roi testing positive for CTX (Table 5; Figure 2) and combined accounted for 72% of the model weight (Table 5). Total length and BAA 3yr were in both top models, while fishing

pressure was only in one of them. After model averaging, the probability of a Roi testing positive for CTX was higher in larger individuals (Table 5) from locations that experienced fewer bleaching alert days in the 3 yrs. prior to capture (Table 5) and lower annual reef fish landings (Table 5) than smaller Roi from locations that experienced more bleaching alert days and greater annual reef fish landings. Effluent and boulder cover also have a negative relationship with the probability of Roi testing positive for CTX and may offer some explanatory power in the averaged model (Table 7).

The best-performing models for predicting the probability of a Roi testing positive of CTX were also the two top models for predicting the concentration of ciguatoxin CTX1B in Roi (Table 6; Figure 3). The top two models accounted for 67% of the total model weight (Table 6) and suggest that that larger Roi (Table 6, Figure 3) captured from locations experiencing fewer bleaching alert days in the 3 yrs prior to capture (Table 6) and lower annual reef fish landings (Table 6) have a higher toxicity level than Roi of smaller size from locations experiencing more bleaching days in the 3 yrs prior to capture and higher annual reef fish landings. The averaged model also suggests that effluent (Table 7) can be used to predict the concentration of ciguatoxin in Roi.

I collected and tested a total of 80 Kole from four collection sites along the west coast of Hawai'i Island during March 2021 – September 2022 and found that ciguatoxins were present in Kole from three out of the four sites, with prevalence rates of 72% at 'Anaeho'omalū Bay (n = 32) and Halepa'o (n = 32), 70% Ke'ei (n = 10), and 0% at Puakō (n = 6). The overall ciguatera prevalence rate was 66% for all Kole samples. For the Kole that tested positive for CTX, the overall mean concentration was 0.20 ± 0.03 $\mu\text{g}/\text{kg}$. The mean concentration of CTX1B was highest at 'Anaeho'omalū Bay (0.31 ± 0.05 $\mu\text{g}/\text{kg}$) and similar across the other three sites ($F_{5,80} =$

6.22, $P < 0.01$). The mean age of Kole was similar across sites ($F_{5,80} = 1.30$, $P = 0.28$, Table 15). However, there were differences in TL among sites ($F_{5,80} = 3.76$, $P = 0.01$, Table 14) and the collection sites in the variables measured within to 20-m buffer surrounding the location fish were captured. Similar to the Roi samples, mean depth was shallower at the northern sites, Puakō and ‘Anaeho‘omalū Bay, and deeper at the southern sites Halepa‘o and Ke‘ei. ($F_{5,80} = 10.81$, $P = 2.99 \times 10^{-6}$, Table 14). Mean wave power was different across all collection sites with Halepa‘o having the highest mean wave power and Puakō having the lowest mean wave power ($F_{3,80} = 155.4$, $P = 2 \times 10^{-16}$, Table 14). Further, mean effluent at Puakō and Ke‘ei was higher than that at ‘Anaeho‘omalū Bay and Halepa‘o ($F_{3,84} = 31.61$, $P = 1.21 \times 10^{-14}$, Table 14). Mean estimated total annual reef fish landings at Ke‘ei were similar to Puakō ($F_{3,80} = 6.70$, $P = 0.00$, Table 14), while landings at Halepa‘o were comparable ‘Anaeho‘omalū Bay and to the other locations. Other habitat parameters, such as substrate composition, within the 20-m radius circles surrounding the capture locations of Kole were comparable among collection areas ($F_{3,80} = 2.26$, $P = 0.09$, Table 15) except for coral substrate ($F_{3,80} = 5.94$, $P = 0.00$, Table 15).

Two candidate models performed equally well, i.e., had $\Delta AIC_c < 2.0$, at predicting the probability of Kole testing positive for CTX (Table 12; Figure 4) and combined accounted for 56% of the model weight (Table 12). Fishing pressure (Table 12) was in both top models, while mean coral cover (Table 12) was only in the first model and total length (Table 12) and BAA 3yr (Table 12) were in the second model. The probability of a Kole testing positive for CTX was higher in smaller individuals captured from locations experiencing fewer bleaching alert days in the 3 yrs. prior to capture and with less effluent, lower annual reef fish landings, and increased mean percent live coral cover relative to larger Kole from locations that experienced higher levels of effluent, greater annual reef fish landings and lower percent live coral cover. Boulder

cover also has a negative relationship with the probability of Kole testing positive for CTX and may offer some explanatory power in the averaged model (Table 7).

Three candidate models performed equally well for predicting the concentration of ciguatoxin CTX1B in Kole (Table 13; Figure 5). The top three models accounted for 100% of the total model weight (Table 13). After model averaging, the concentration of ciguatoxin CTX1B in Kole was higher in smaller Kole (Table 7, Figure 5) captured from locations experiencing lower input of effluent, lower annual reef fish landings, and lower mean percent live coral cover have a higher toxicity level than Kole of larger size from locations experiencing more bleaching days in the 3 yrs. prior to capture, high inputs of effluent, higher annual reef fish landings and higher mean present live coral cover (Table 7).

3.2 Human Aspect Results

Of the 27 individuals, 25% said they learned about CFP from their ohana, i.e., family members, while 17% of the individuals said they learned about CFP from other divers or fishers and 17% said they learned about CFP from the internet. Only 8% said they had learned about CFP from scientists and 8% said they learned about CFP from scientific journals, magazines, and TV.

Approximately 23% said that consuming fish captured from locations near resorts, golf courses, or highly populated areas would increase their chance of contracting CFP. A slightly smaller proportion, 19%, identified that fish species was a factor and noted that they did not fish for or consume Roi or ulua, i.e. adult jacks *Caranx* spp. Three other factors were identified by the fishers: the amount of fish consumed; the parts of the fish consumed, such as the belly or the head; and the size of the fish (12% for all factors). 4% of the people believe that if you don't eat the head or belly then you will be fine, 4% said how you clean the fish, 4% said water condition,

4% said if you had CFP before you will be more sensitive, and 4% said some people are more sensitive than others to ciguatoxin.

Fishers described employing a variety of strategies to minimize their risk of contracting CFP.

Among the most common strategies employed by fishers was: only eating the smaller predators (19%); catching and consuming fishes from specific locations (13%); moderating the amount or frequency of reef fish consumption if it was thought to be high risk (8%). Rarer strategies included feeding a portion of their catch to cats or other animals and monitoring their condition for signs of CFP (3%); only consuming specific groups of reef fishes such as ‘u‘u (Hawaiian Bigscale Soldierfish); (25%); abstaining from consuming reef fishes (3%); or avoiding specific parts, such as the head or belly (3%). However, 26% of fishers felt that the only effective means of preventing CFP was to avoid consuming any reef fishes, but either by choice or necessity decided to take their chances and consume reef fishes without any precautions.

4. Discussion

Ciguatoxic Roi were sampled from all four collection sites at a prevalence rate comparable to those previously reported from West Hawai‘i (Hokama et al. 1993, Dierking and Campora 2009, Bienfang et al. 2012). While ciguatoxic Kole were collected at a considerably higher rate than previously reported (Hokama et al. 1993), prevalence was comparable at three of the four sites examined. This consistency suggests that *Gambierdiscus* spp. are pervasive on the reefs of West Hawai‘i. In the past, some areas, such as Puakō, were considered hotspots due to an elevated number of CFP incidences reported to the Hawai‘i Department of Health (DOH; Hokama et al. 1993, Abbot and Wilder 1995, Dierking and Campora 2009, White 2002, Copeland et al. 2014). However, my results suggest that the probability of a fisher capturing a ciguatoxic fish in West Hawai‘i does not exhibit a particularly great degree of spatial variability. Hawai‘i Island has

previously been documented to have higher ciguatera incidents than the other islands in the archipelago (Botana 2000). Interestingly, the one site where none of the Kole tested positive for CTX, Puakō, was a location where individuals of the species had previously been found to be ciguatoxic (Hokama et al. 1993). While further work is needed to determine whether this is indicative of a low rate of CTX prevalence in the Puakō Kole population or due to sampling, it does suggest there may be some temporal variability in prevalence rates at a site.

Total length, the number of days a fish experiences temperatures high enough to trigger a coral bleaching alert over the past three years, the input of effluent, and fishing pressure experienced within the Roi and Kole home ranges seem to be the factors that best estimate the probability of a Roi and Kole testing positive for CTXs and predict the concentration of CTXs in Roi and Kole's tissues. Larger Roi having a higher prevalence of ciguatoxicity than smaller conspecifics captured from the same location has been described in Hawai'i (Dierking et al. 2005, Dierking and Campora 2009, Loeffler et al. 2022) and the Pacific (Lehane and Lewis 2000) and the inverse relationship for Kole. The relationship between length and ciguatoxicity has been reported in a range of taxa, including Serranidae (Dierking and Campora 2009, Darius et al. 2022), Scaridae (Darius et al. 2022) and Acanthuridae (Darius et al. 2022). This relationship between length and ciguatoxicity is attributed to several factors related to the way ciguatoxins are thought to pass through and biomagnify in coral reef food webs (Randall 1958). Larger fish have had greater opportunity to consume ciguatoxic prey (Dickey and Plakas 2010; Yogi et al. 2011) and are capable of consuming larger prey, which in turn, may have higher rates of ciguatoxicity than smaller prey (Randall 1958). Despite being correlated with TL, age was not found to have any predictive power on the presence or concentration of CTX in Roi or Kole, similar to findings in other studies of serranids, acanthurids, and scarids (Darius et al. 2022).

This may be attributable to a decoupling between TL and age that occurs in many reef fish taxa due to individuals reaching adult sizes at young ages followed by relatively long, > 25-30 yr, lifespans with very low annual growth rates (Choat and Axe 1996; Choat and Robertson 2002).

In contrast to fish length, the relationship between coral bleaching events and ciguatoxicity is not as well established in the literature. Coral bleaching events may result in the loss of coral cover and potentially create more suitable habitat for *Gambierdiscus* spp. due to increased algae surface area (Randall 1958; Koehler and Koehler 1992; Loeffler et al. 2015; Freidman et al. 2017). Therefore, the inverse relationship between time spent under a coral bleaching alert and ciguatoxicity was unexpected. However, the variable used to account for coral bleaching in my dataset was a proxy for bleaching due to there not being a direct measure of coral cover loss available for West Hawai‘i. The coral bleaching alert level days are measures of temperature history and thus its predictive power may reflect the thermal biology of *Gambierdiscus* spp. and not fundamental phase shifts in substrate composition on coral reefs. Leifer et al. (2021) found an inverse relationship between the abundance and toxicity of *Gambierdiscus* spp. in the U.S. Virgin Islands. While *Gambierdiscus* spp. abundance peaks in the summer months, toxicity peaked during the cooler times of the year when water temperature were between approximately 26 – 28°C (Stevens et al. 2022). In Hawai‘i, there are only two seasons with “summer,” between May – October and “winter,” being from October – April (Price 1983; Stevens et al. 2022). The sea surface temperatures vary seasonally by only approximately 3°C from a low of 23°C from late February – March to a high of 26°C from late September to October (Price 1983). My results suggest that Hawai‘i’s seasonal trends may create a lag between *Gambierdiscus* blooms and transfer of toxins into the food web (Parson et al. 2010; Clausing et al. 2016) and that periods of elevated temperature, such as those that result in coral bleaching alerts being issues, act to

augment those lags. As global temperatures continue to warm, periods of elevated ocean temperature around Hawai‘i are predicted to increase in intensity, frequency, and duration (Jokiel and Brown 2004; Baker et al. 2008; Gove et al. 2022). Therefore, there is the potential for the intervening cooler periods to see standing populations of *Gambierdiscus* spp. that are larger than currently seen in Hawai‘i with more available habitat (Randall 1958; Koehler and Koehler 1992; Loeffler et al. 2015; Freidman et al. 2017) producing higher concentrations of CTX (Leifer et al. 2021). Alternatively, *Roi* holds ciguatoxins in its flesh for longer periods of time (Banner et al. 1966) and the toxicity of *Gambierdiscus* is higher due to ideal water temperatures; however, it also leaves the question of whether a relationship exists between ciguatoxicity and benthic habitat shifts on reefs experiencing bleaching unresolved and raises a further question as to whether a potential increase in available habitat offsets the decreased toxin production by *Gambierdiscus* spp. at higher temperatures.

Interestingly, effluent input had an inverse relationship with CTX concentrations in Kole but no influence on the probability of a fish testing positive for CTX. A positive correlation has been reported between ciguatera dinoflagellate abundance and nutrient concentrations (Carlson and Tindall 1985); however, there has been no correlation between nutrients concentration and ciguatoxicity (Sperr and Doucette 1996; Parson and Preskitt 2007). Many species of cyanobacteria, dinoflagellates, and other potentially harmful bloom-forming algal species increase toxin production during periods of decreased nutrient availability, particularly phosphorous (Brandenburg et al. 2020), but it is not clear if this is the case for *Gambierdiscus* spp. (Anderson et al. 2008). However, if this were the case then it may be an explanation for the relationship between CTX concentrations and effluent observed in Kole.

Decreased fishing pressure increases the abundance of herbivores in an area (Walsh et al. 2019), increasing the presence and densities of vectors that transfer ciguatoxins into the food web (Rongo and van Woesik 2013). Given the high prevalence rate of Kole, a common reef herbivore, observed in my study it is easy to see how an increase in the standing stock of this and similar species could facilitate the movement of CTX into higher trophic levels. Further, a large standing stock of reef herbivores may also act to limit the availability of preferred *Gambierdiscus* spp. habitat through their grazing activities on turf algae (Loffler et al. 2015) and limit the loss of live coral cover (Kumpel and Altieri 2017). While the potential increase in the prevalence of ciguatoxic fishes that might occur when herbivorous reef fishes are protected is not a valid argument against implementing what have been identified as much-needed herbivore management rules (Donovan et al. 2023), my results support the development of effort to ensure fishers are aware of the potential increased risk of CFP. There is also the potential of a negative societal effect of CFP (Bienfang et al. 2008). Public fears of getting CFP can decrease fishing pressure on a particular fish species or area (Bienfang et al. 2008), creating a what could be considered a natural MPA where fish populations have the ability to increase (Walsh et al. 2019; Donovan et al. 2023). The increase in fish populations due to decreased fishing pressure may create an increase of ciguatoxins to enter the food web and to accumulate in fish species that are no longer being targeted. Marine Protected Areas increase the overall prevalence and abundance of herbivorous fishes (Walsh et al. 2019; Donovan et al. 2023), increasing the vectors for ciguatoxins to enter the food web. Stakeholders of MPA areas may want to consider creating a mitigation plan for CFP when deciding if and how fishing will be allowed in the areas.

If patterns persist, there will be more bleaching events on the west coast of Hawai'i Island and a continued annual average decline of 7% in coral cover across the region (Walsh et al. 2019).

With the continued loss of coral cover and increased suitable habitat for *Gambierdiscus* spp. (Loffler et al. 2015) there is the potential for an increase in *Gambierdiscus* densities and CTX to accumulate in both herbivore and predator fishes alike. Rising sea surface temperatures may create more ideal environments for *Gambierdiscus* communities to expand and establish in areas that they once were not as prevalent (Koehler and Koehler 1992; Gove et al. 2019; Leifer et al. 2021). In the cooler seasons, sea surface temperatures may drop to temperatures that are ideal for the newly established *Gambierdiscus* communities to allow their toxicity levels to peak (Leifer et al. 2021); creating new pathways for CTX to enter the food chain. However, MPAs will continue to experience changes from global warming, such as bleaching events, but they experience minimal to no fishing pressure and have higher herbivore abundance. High herbivore and fish abundance in MPAs creates more vectors for CTX to enter the food web (Rongo and van Woesik 2013).

The local knowledge of anglers and spearfishers in Hawai‘i does not directly align with the findings of my project. The one factor that is consistent with what most spearfishers and anglers use to aid themselves in predicting if their fish is ciguatoxic is the size of the fish (Lehane and Lewis 2000; Dierking et al. 2005; Dierking and Campora 2009; Darius et al. 2022; Loeffler et al. 2022). Most people learn about CFP from their family and close friends growing up. This type of generational knowledge does not account for environmental changes caused by anthropogenic climate change. Locations that experience a greater number of days at bleaching alert levels and higher levels of effluent are areas that are presumed to be high risk by locals because disturbances (Rongo and van Woesik 2013) and effluent (Anderson et al. 2008) have been related to CP. However, this is the inverse of what my study found for predicting CTX in Roi and Kole, respectively. It is important for the findings of my project and projects alike to be

communicated to local anglers and spearfishers so that they can modify and improve their mitigation strategies for getting CFP. However, when I spoke to local spearfishers and anglers they were not learning about CP from scientist or scientific research unless they were being recruited to help collect fish samples in their local areas. Ciguatera fish poisoning is a food security and a public health issue in the Pacific. Up to date information on the factors that influence ciguatoxins in fish needs to be communicated to the people who utilize ocean resources for sustenance and survival.

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Table 1. Bleaching Alert Area stress levels based on current values (at the time) of the Coral Bleaching HotSpot and Degree Heating Week (NOAA Coral Reef Watch 2023).

Stress Level	Definition	Effect
Bleaching Warning	$1 \leq \text{HotSpot}$ and $0 < \text{DHW} < 4$	Possible Bleaching
Bleaching Alert Level 1	$1 \leq \text{HotSpot}$ and $4 \leq \text{DHW} < 8$	Significant Bleaching Likely
Bleaching Alert Level 2	$1 \leq \text{HotSpot}$ and $8 \leq \text{DHW}$	Severe Bleaching and Significant Mortality Likely

Table 2. Description and sources of data used to create data for variables used as covariates to model Peacock Grouper (*Cephalopholis argus*), known locally in Hawai‘i by its Tahitian name – Roi, and Goldring Bristletooth (*Ctenochaetus strigosus*), locally known in Hawai‘i as Kole, in multi-state occupancy models using ciguatoxin data analyzed from fish samples collected on the west side of Hawai‘i Island during March 2021- September 2022. Home range was defined as a 40-m radius circle around the capture location of each Roi and a 20-m radius circle around the capture location of each Kole. A full description of candidate models can be found in Table 3.

Variable name	Description	Source
coral	proportion of area within the survey site classified as coral being the dominant biological cover (>10%) regardless of benthic structure type	NCCOS HIMARC Habitat Classes; Battista et al. (2007)
boulder	proportion of area within the survey site classified as rock/boulder	NCCOS HIMARC Habitat Classes; Battista et al. (2007)
other hard bottom	proportion of area within the site classified as individual patch reef, rubble, aggregated patch reef, or aggregated reef	NCCOS HIMARC Habitat Classes; Battista et al. (2007)
soft bottom	proportion of area within I survey site classified as sand/mud	NCCOS HIMARC Habitat Classes; Battista et al. (2007)
mean wave	long-term mean wave power (kW/m) during 2000-2013 estimated by Simulating Waves Nearshore (SWAN) model based on data from 1979-2013	Ocean Tipping Points: Hawai‘i Case Study; Kappel et al. (2017)
effluent	total effluent from onsite sewage disposal systems (gallons/day) entering nearshore waters (500-m grid) based on Whittier and El-Kadi (2009, 2014)	Ocean Tipping Points: Hawai‘i Case Study; Kappel et al. (2017)

fishing pressure	estimated mean total annual catch of reef fishes (kg/ha) based on NOAA Marine Recreational Information Program (MRIP) data and DAR commercial reporting data	Ocean Tipping Points: Hawai'i Case Study; Kappel et al. (2017)
mean depth	mean depth of area within the survey site	Multibeam Backscatter and Bathymetry Synthesis for the Main Hawaiian Islands: Final Technical Report; Smith (2016)
bleaching alert 3yr	number of days in the past 3 yrs prior to capture a fish experienced NOAA Coral Reef Watch Bleaching Alert level Warning conditions or above	NOAA Coral Reef Watch (2023)

Table 3. Candidate models set to be evaluated using a logistic model to assess the probability (p) of occurrence of ciguatoxins and toxicity Peacock Grouper (*Cephalopholis argus*), known locally in Hawai‘i by its Tahitian name – Roi, and Goldring Bristletooth (*Ctenochaetus strigosus*), locally known in Hawai‘i as Kole, captured from locations along the west coast of Hawai‘i Island during March 2021 – September 2022. The same set of candidate models were used to assess factors influencing the concentration of ciguatoxins in fish tissue (CTX-1B) using a generalized linear model with a Tweedie distribution. The variables coral, boulder, other hard bottom, and soft bottom represent the percent composition of the respective substrate class within the 40-m radius home range circles (Table 2).

Model Number	Model
1	$p(.)$
2	$p(\text{TL, BAA 3yr})$
3	$p(\text{TL, BAA 3yr, fishing pressure})$
4	$p(\text{TL, fishing pressure})$
5	$p(\text{TL, fishing pressure, effluent})$
6	$p(\text{mean herbivore biomass, BAA 3yr})$
7	$p(\text{TL, effluent})$
8	$p(\text{TL, mean depth})$
9	$p(\text{TL, coral, boulder, BAA 3yr,})$
10	$p(\text{TL})$
11	$p(\text{TL, coral, boulder, mean herbivore biomass})$
12	$p(\text{TL, mean wave power})$
13	$p(\text{TL, age})$
14	$p(\text{TL, coral, boulder})$
15	$p(\text{TL, mean percent coral cover, mean herbivore biomass})$
16	$p(\text{BAA 3yr})$
17	$p(\text{mean herbivore biomass, fishing pressure})$
18	$p(\text{mean percent coral cover, fishing pressure})$
19	$p(\text{fishing pressure, mean herbivore biomass, mean depth})$
20	$p(\text{coral, boulder, other hard bottom, soft bottom})$
21	$p(\text{mean percent coral cover, effluent})$
22	$p(\text{mean percent coral cover})$
23	$p(\text{mean herbivore biomass})$
24	$p(\text{mean wave power})$
25	$p(\text{TL, BAA 3yr, fishing pressure, effluent, mean herbivore biomass, mean depth, mean percent coral cover, mean wave power, age, coral, boulder, other hard bottom, soft bottom})$

Table 4. Mean (\pm SE) and range of variables for Peacock Grouper (*Cephalopholis argus*; $n = 88$), known locally in Hawai‘i by its Tahitian name – Roi, collected from four sites along the west side of Hawai‘i Island during March 2021 – September 2022. The value in parentheses corresponds to the number of unique observations of that variable.

Site	TL (cm)		Age (yrs)		Mean wave power (kW/m)		Effluent (gallons/day)		Total annual reef fish landings (kg./ha)		Mean depth (m)		% live coral cover (site)	Herbivore biomass (g/100m ²)
	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Mean \pm SE (n)
Puakō	34.50 \pm 1.50 (23)	25.0-48.5	8 \pm 1 (19)	2-14	2.06 \pm 0.04 (14) ^A	1.87-2.25	5872 \pm 893 (14) ^A	1302 – 10495	33.0 \pm 1.2 (14) ^B	1.2-39.9	5.09 \pm 0.7 (14) ^A	1.9-6.9	4.13 \pm 0.89 (1)	2827.84 \pm 135.62 (1)
‘Anaeho‘omalū	33.00 \pm 1.60 (27)	17.0-49.8	8 \pm 1 (26)	3-22	2.62 \pm 0.00 (16) ^B	2.61-2.64	39 \pm 4 (11) ^B	19-85	25.7 \pm 2.1 (16) ^A	6.3-39.4	6.4 \pm 0.7 (16) ^B	2.4-13.7	14.23 \pm 2.16 (1)	1827.46 \pm 257.94 (1)
Halepa‘o	31.50 \pm 1.90 (16)	20.0-46.8	9 \pm 1 (15)	3-22	4.25 \pm 0.02 (12) ^C	4.17-4.38	846 \pm 89 (12) ^B	275-1166	28.1 \pm 2.0 (12) ^B	19.5-36.4	11.7 \pm 0.7 (12) ^B	8.4-16.3	14.66 \pm 4.03 (1)	9313.15 \pm 1523.95 (1)
Ke‘ei	31.00 \pm 1.90 (22)	18.5-49.5	10 \pm 1 (20)	3-19	3.75 \pm 0.07 (22) ^D	3.56-4.14	6374 \pm 202 (22) ^A	3899-8429	20.8 \pm 3.3 (22) ^B	3.7-40.2	13.1 \pm 1.8 (21) ^B	1.4-23.9	17.30 \pm 3.12 (1)	3537.16 \pm 378.61 (1)
Combined	31.70 \pm 0.80 (88)	17.9-49.8	7 \pm 1 (81)	2-22	3.05 \pm 0.10 (74)	1.87-4.38	4266 \pm 404 (66)	19-10495	27.0 \pm 1.3 (73)	4.0-40.0	8.8 \pm 0.7 (72)	1.4-23.9	12.58 \pm 2.90 (4)	4376.40 \pm 1682.53 (4)

Table 4 (continued). Mean (\pm SE) and range of variables for Peacock Grouper (*Cephalopholis argus*; $n = 88$), known locally in Hawai‘i by its Tahitian name – Roi, collected from four sites along the west side of Hawai‘i Island during March 2021 – September 2022.

Site	Coral		Boulder		Other hard bottom		Soft bottom		BAA 3yr	
	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range
Puakō	0.90 \pm 0.01 (6)	0.84-0.96	0 \pm 0.00 (1) ^A	0-0.00	0 \pm 0.00 (2)	0-0.01	0.06 \pm 0.02 (2) ^A	0-0.14	64 \pm 1 (2)	61-64
‘Anaeho‘omalū	0.96 \pm 0.02 (27)	0.63-1.00	0.04 \pm 0.02 (26) ^B	0-0.37	0 \pm 0.00 (1)	0	0.00 \pm 0.01 (11) ^B	0-0.01	64 \pm 1 (3)	59-67
Halepa‘o	0.29 \pm 0.12 (7)	0-1.00	0.04 \pm 0.02 (5) ^B	0-0.17	0 \pm 0.00 (1)	0	0.00 \pm 0.00 (5) ^B	0-0.02	65 \pm 0 (1)	65
Ke‘ei	0.47 \pm 0.10 (5)	0-1.00	0.16 \pm 0.07 (3) ^B	0-1.00	0 \pm 0.00 (1)	0	0.00 \pm 0.00 (2) ^B	0-0.03	63 \pm 1 (2)	61-66
Combined	0.69 \pm 0.80 (19)	0-1.00	0.06 \pm 0.00 (9)	0-1.00	0 \pm 0.00 (3)	0-0.01	0.02 \pm 0.01 (8)	0-0.14	64.16 \pm 0.31 (6)	59-67

Table 5. The top best-fit AIC models and values predicting the probability of Peacock Grouper (*Cephalopholis argus*), known locally in Hawai‘i by its Tahitian name – Roi, captured from locations along the west coast of Hawai‘i Island during March 2021 – September 2022 testing positive for ciguatoxins. TL=total length (cm), BAA 3yr. = the number of bleaching alert level days in the three years prior to capture, and fishing pressure = estimated total annual reef fish landings (kg/ha). AIC_c = Akaike’s Information Criterion for small sample sizes, ΔAIC_c = differences in AIC_c relative to the top model w_i = Akaike model weights. A full ranking of candidate models can be found in Appendix 1.

Model Rank	Model	K	n	AIC_c	ΔAIC_c	Likelihood	w_i
1	$p(TL, BAA\ 3yr)$	3	82	73.93	0.00	1.00	0.50
2	$p(TL, BAA\ 3yr, fishing\ pressure)$	3	82	75.59	1.66	0.44	0.22
18	$p(global)$	16	82	95.01	21.08	2.60E-05	1.30E-05
21	$p(.)$	1	82	97.42	23.49	7.90E-06	4.00E-06

Table 6. The top AIC model and values when the predicting the concentration of ciguatoxins in fish tissue (CTX-1B) of Peacock Grouper (*Cephalopholis argus*), known locally in Hawai‘i by its Tahitian name – Roi, captured from locations along the west coast of Hawai‘i Island during March 2021 – September 2022. TL=total length (cm), BAA 3yr. = the number of bleaching alert level days in the three years prior to capture, and fishing pressure = estimated total annual reef fish landings (kg./ha). AIC_c = Akaike’s Information Criterion for small sample sizes, ΔAIC_c = differences in AIC_c relative to the top model, w_i = Akaike model weights. A full ranking of candidate models can be found in Appendix 2

Model Rank	Model	K	n	AIC_c	ΔAIC_c	Likelihood	w_i
1	CTX1B (TL, BAA 3yr)	3	82	294.12	0.00	1.00	0.45
2	CTX1B (TL, BAA 3yr, fishing pressure)	4	82	295.57	1.45	0.49	0.22
8	CTX1B(global)	16	82	302.36	8.24	0.02	0.01
20	CTX1B(.)	1	82	351.09	56.97	0.00	0.00

Table 7. Full AIC model average and values predicting the probability of Peacock Grouper (*Cephalopholis argus*), known locally in Hawai‘i by its Tahitian name – Roi and Goldring Bristletooth (*Ctenochaetus strigosus*), locally known in Hawai‘i as Kole, captured from locations along the west coast of Hawai‘i Island during March 2021 – September 2022 testing positive and the toxicity level for ciguatoxins. TL=total length (cm), BAA 3yr. = the number of bleaching alert level days in the three years prior to capture, and fishing pressure = estimated total annual reef fish landings (kg./ha). AIC_c = Akaike’s Information Criterion for small sample sizes, ΔAIC_c = differences in AIC_c relative to the top model, w_i = Akaike model weights. A full ranking of candidate models can be found in Appendix 1 and 2.

Variables	Roi		Kole	
	CTX Positive	Toxicity level	CTX Positive	Toxicity level
Intercept	-1.33	0.74	1.70	1.69
TL (cm)	1.14	0.54	-0.61	-0.10
Age	0.00	0.00	-0.00	0.00
Mean wave power (kW/m)	-0.00	-0.01	0.00	-0.00
Effluent (gallons/day)	-0.04	-0.03	-0.38	-0.82
Total annual reef fish landings (kg/ha)	-0.20	-0.05	-0.17	-0.03
Mean depth (m)	-0.00	-0.00	-0.00	0.00
% live coral cover (site)	-0.00	0.01	0.25	-0.01
Herbivore biomass (g/100m ²)	0.00	0.00	0.01	0.00
Coral	0.01	-0.00	-0.01	0.00
Boulder	-0.04	-0.01	-0.02	0.00
Other hard bottom	0.00	-0.00	-0.00	-0.00
Soft bottom	0.00	0.00	-0.00	-0.00
BAA 3yrs	-0.71	-0.20	-0.48	-0.00

Table 8. The top two AIC model variables, coefficient values (\pm SE) when assessing the probability Peacock Grouper (*Cephalopholis argus*), known locally in Hawai‘i by its Tahitian name – Roi, captured from locations along the west coast of Hawai‘i Island during March 2021 – September 2022 testing positive for ciguatoxins. TL=total length (cm), BAA 3yr. = the number of bleaching alert level days in the three years prior to capture, and fishing pressure = estimated total annual reef fish landings (kg./ha). The value in parentheses corresponds to the *P*-value of that variable.

Model	TL	BAA 3yr	Fishing Pressure
<i>p</i> (TL, BAA 3yr)	1.02 \pm 0.32 (< 0.001)	-0.91 \pm 0.32 (< 0.001)	
<i>p</i> (TL, BAA 3yr, fishing pressure)	1.15 \pm 0.33 (< 0.001)	-0.76 \pm 0.39 (0.05)	-0.34 \pm 0.47 (0.46)

Table 9. The top AIC model variables and coefficient values (\pm SE) when the predicting the concentration of ciguatoxins in fish tissue (CTX-1B) of Peacock Grouper (*Cephalopholis argus*), known locally in Hawai‘i by its Tahitian name – Roi , captured from locations along the west coast of Hawai‘i Island during March 2021 – September 2022. TL= total length (cm), BAA 3yr. = the number of bleaching alert level days in the three years prior to capture, and fishing pressure = estimated total annual reef fish landings (kg./ha).The value in parentheses corresponds to the *P*-value of that variable.

Model	TL	BAA 3yr	Fishing Pressure
CTX1B(TL, BAA 3yr)	0.51 \pm 0.11 (< 0.001)	-0.26 \pm 0.11 (0.02)	
CTX1B(TL, BAA 3yr, fishing pressure)	0.53 \pm 0.10 (<0.001)	-0.22 \pm 0.13 (0.08)	-0.09 \pm 0.13 (0.50)

Table 10. Mean (\pm SE) and range of variables for Goldring Bristletooth (*Ctenochaetus strigosus*; n = 80), locally known in Hawai‘i as Kole, collected from four sites along the west side of Hawai‘i Island during March 2021 – September 2022. The value in parentheses corresponds to the number of unique observations of that variable. The letter in the superscript corresponds to the Pos-hoc test.

Site	TL (cm)		Age (yrs)		Mean wave power (kW/m)		Effluent (gallons/day)		Total annual reef fish landings (kg./ha)		Mean depth (m)		% live coral cover (site)	Herbivore biomass (g/100m ²)
	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Mean \pm SE (n)
Puakō	15.1 \pm 0.62 (10) ^A	11.5-19.5	5 \pm 1 (7)	1-8	1.96 \pm 0.01 (13) ^D	1.89-2.04	9417 \pm 722 (14) ^A	5193–13054	35.9 \pm 1.2 (14) ^A	27.5-39.4	5.11 \pm 0.4 (14) ^A	3.0-7.9	4.13 \pm 0.89 (1)	2827.84 \pm 135.62 (1)
‘Anaeho‘omalu	14.2 \pm 0.21 (19) ^B	12.0-16.6	4 \pm 1 (6)	2-8	2.62 \pm 0.00 (25) ^C	2.61-2.65	29 \pm 3 (8) ^C	16-41	27.3 \pm 2.2 (30) ^B	6.1-39.9	6.1 \pm 0.6 (30) ^A	1.3-14.8	14.23 \pm 2.16 (1)	1827.46 \pm 257.94 (1)
Halepa‘o	15.2 \pm 0.29 (20) ^{AB}	12.5-18.7	4 \pm 1 (6)	2-7	4.52 \pm 0.09 (22) ^A	4.17–5.20	1035 \pm 47 (11) ^C	606-1215	30.4 \pm 1.11 (23) ^{AB}	19.5-37.3	9.5 \pm 0.5 (23) ^B	5.0-16.5	14.66 \pm 4.03 (1)	9313.15 \pm 1523.95 (1)
Ke‘ei	13.9 \pm 0.35 (19) ^A	10.9-18.0	4 \pm 1 (5)	2-6	3.75 \pm 0.07 (25) ^B	3.56-4.14	6374 \pm 202 (28) ^B	3899-8429	20.8 \pm 3.3 (28) ^A	3.7-40.2	13.1 \pm 1.8 (28) ^B	1.4-23.9	17.30 \pm 3.12 (1)	3537.16 \pm 378.61 (1)
Combined	14.5 \pm 0.2 (44)	10.9-19.5	4 \pm 1 (8)	1-8	3.29 \pm 0.10 (85)	1.89-5.20	5520 \pm 448 (61)	16-13054	31.6 \pm 0.75 (95)	6.1-39.86	7.7 \pm 0.3 (95)	1.3-16.5	12.58 \pm 2.90 (4)	4376.40 \pm 1682.53 (4)

Table 10 (continued). Mean (\pm SE) and range of variables for Goldring Bristletooth (*Ctenochaetus strigosus*; n = 80), locally known in Hawai‘i as Kole, collected from four sites along the west side of Hawai‘i Island during March 2021 – September 2022. The value in parentheses corresponds to the number of unique observations of that variable. The letter in the superscript corresponds to the Post-hoc test.

Site	Coral		Boulder		Other hard bottom		Soft bottom		BAA 3yr	
	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range	Mean \pm SE (n)	Range
Puakō	0.97 \pm 0.01 (4) ^A	0.92-1.0	0 \pm 0 (1)	0-0	0.0009 \pm 0.00 (2)	0-0.012	0 \pm 0 (1)	0-0	67 \pm 0 (1)	67
‘Anaeho‘omalū	0.91 \pm 0.05 (5) ^B	0-1	0.09 \pm 0.05 (6)	0-1	0 \pm 0.00 (1)	0	0.000 \pm 0.005 (2)	0-0.009	63.6 \pm 0.64 (3)	59-67
Halepa‘o	0.68 \pm 0.08 (6) ^A	0-1	0.10 \pm 0.02 (4)	0-0.18	0 \pm 0 (1)	0	0.002 \pm 0.001 (3)	0-0.02	62.9 \pm 0.58 (2)	60-65
Ke‘ei	0.47 \pm 0.10 (2) ^{AB}	0-1	0.04 \pm 0.03 (2)	0-0.5	0 \pm 0 (1)	0	0 \pm 0 (1)	0-0	65.06 \pm 0.50 (2)	61-66
Combined	0.88 \pm 0.03 (13)	0-1	0.06 \pm 0.01 (8)	0-1	0 \pm 0 (2)	0-0.012	0 \pm 0 (4)	0-0.023	64.30 \pm 0.32 (6)	59-67

Table 11. The top best-fit AIC models and values predicting the probability of Goldring Bristletooth (*Ctenochaetus strigosus*; n = 109), locally known in Hawai‘i as Kole, captured from locations along the west coast of Hawai‘i Island during 2021-2022 testing positive for ciguatoxins. Total length (cm), BAA 3yr. (the number of bleaching days in the past three years), and fishing pressure (total annual reef fish landings (kg./ha)). AIC_c = Akaike’s Information Criterion for small sample sizes, Δ AIC_c = differences in AIC_c, w_i = Akaike weights. A full ranking of candidate models can be found in Appendix I.

Model Rank	Model	K	n	AIC _c	Δ AIC _c	Likelihood	w_i
1	p (mean coral cover, fishing pressure)	3	80	88.33	0	1	0.35
2	p (TL, BAA 3yr, fishing pressure)	4	80	89.42	1.09	0.58	0.21
3	p (.)	1	80	103.52	15.19	0.00	0.00
4	p (global)	14	80	105.87	17.54	0.00	5.50e-05

Table 12. The top AIC model and values when the predicting toxicity (CTX-1B) of Goldring Bristletooth (*Ctenochaetus strigosus*; n = 109), locally known in Hawai‘i as Kole, captured from locations along the west coast of Hawai‘i Island during 2021-2022. TL (cm) and BAA 3yr (number of bleaching days in the past 3 years. AIC_c = Akaike’s Information Criterion for small sample sizes, ΔAIC_c = differences in AIC_c, w_i = Akaike weights. A full ranking of candidate models can be found in Appendix I.

Model Rank	Model	K	n	AICc	ΔAICc	Likelihood	w _i
1	CTX1B (TL, effluent)	3	80	591.57	0.00	1.00	0.52
2	CTX1B (TL, fishing pressure, effluent)	4	80	592.95	1.38	0.50	0.26
3	CTX1B (mean coral cover, effluent)	3	80	593.24	1.67	0.43	0.22
4	CTX1B(.)	1	80	625.17	33.60	0.00	0.00
5	CTX1B(global)	14	80	606.99	15.42	0.00	0.00

Table 13. The top two AIC model variables, coefficient values (± SE) when assessing the probability of Goldring Bristletooth (*Ctenochaetus strigosus*; n = 80), locally known in Hawai‘i as Kole, captured from locations along the west coast of Hawai‘i Island during 2021-2022 testing positive for ciguatoxins. Total length in cm, fishing pressure in kg/ha/yr., BAA 3yr is the number of bleaching days in the past three years and mean coral cover represents the mean percentage of live coral. The value in parentheses corresponds to the p-value of that variable.

Model	TL	Fishing Pressure	BAA 3yr	Mean Coral Cover
P(mean coral cover, fishing)		-1.07 ± 0.41 (0.01)		1.41 ± 0.71 (0.05)
P(TL, BAA 3yr, fishing pressure)	-0.80 ± 0.31 (0.01)	-0.87 ± 0.47 (0.06)	-0.78 ± 0.31 (0.01)	

Table 14. The top AIC model variables and coefficient values (\pm SE) when the predicting toxicity (CTX-1B) of Goldring Bristletooth (*Ctenochaetus strigosus*; n = 80), locally known in Hawai‘i as Kole, captured from locations along the west coast of Hawai‘i Island during 2021-2022. Total length in cm, fishing pressure in kg/ha/yr., and BAA 3yr is the number of bleaching days in the past three years, effluent in gallons/day, and mean coral cover represents the mean percentage of live coral. The value in parentheses corresponds to the p-value of that variable.

Model	TL	Effluent	Fishing Pressure	Mean Coral Cover
CTX1B(TL, effluent)	-0.13 \pm 0.10 (0.22)	-0.84 \pm 0.13 (9.43e-09)		
CTX1B(TL, fishing pressure, effluent)	-0.13 \pm 0.10 (0.22)	-0.77 \pm 0.17 (8.97e-06)	-0.09 \pm 0.13 (0.50)	
CTX1B(mean coral cover, effluent)		-0.84 \pm 0.14 (5.77e-08)		-0.03 \pm 0.11 (0.75)

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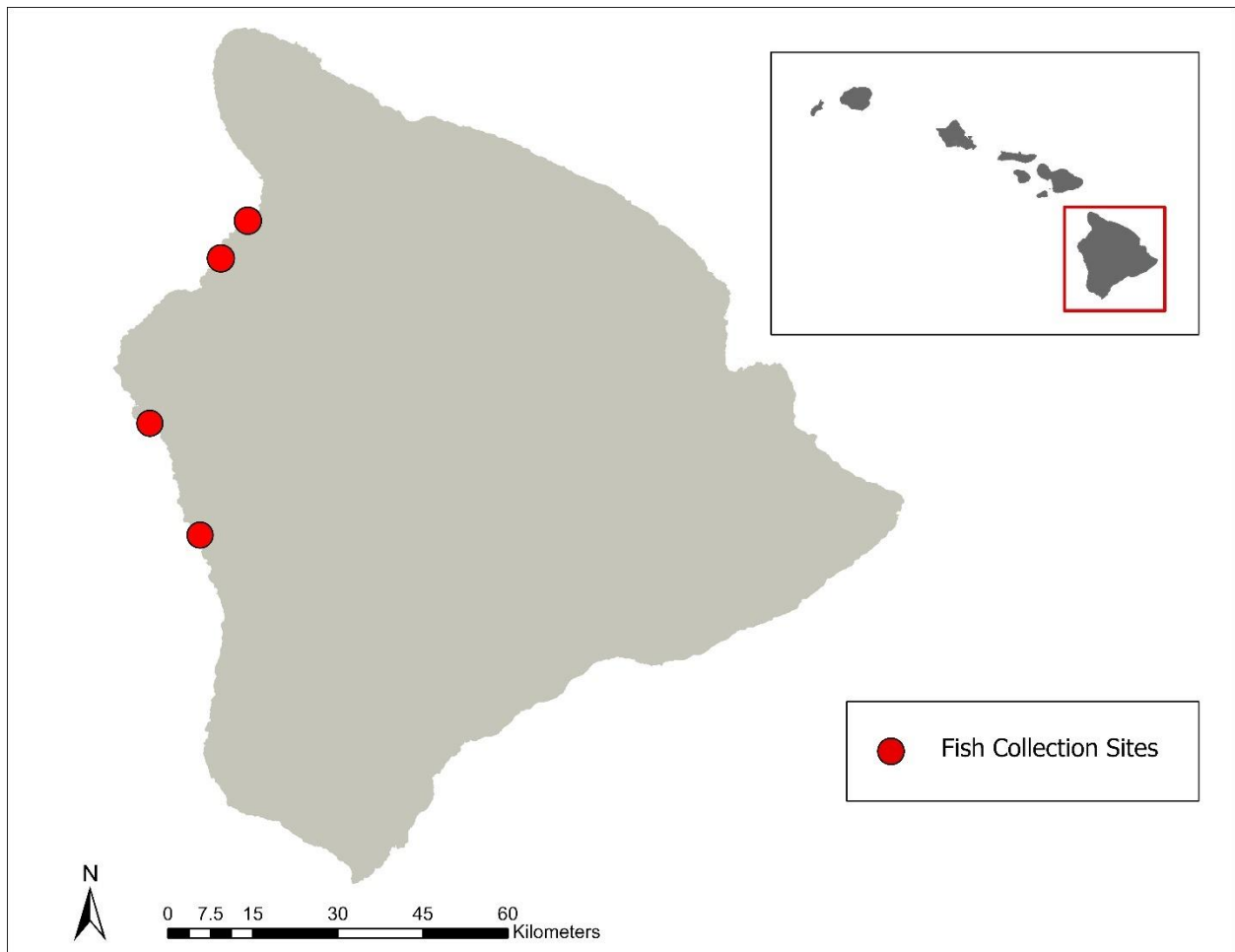


Figure 1. Collection sites for Peacock Grouper (*Cephalopholis argus*), known locally in Hawai'i by its Tahitian name – Roi and Goldring Bristletooth (*Ctenochaetus strigosus*), locally known in Hawai'i as Kole on the west coast of Hawai'i Island.

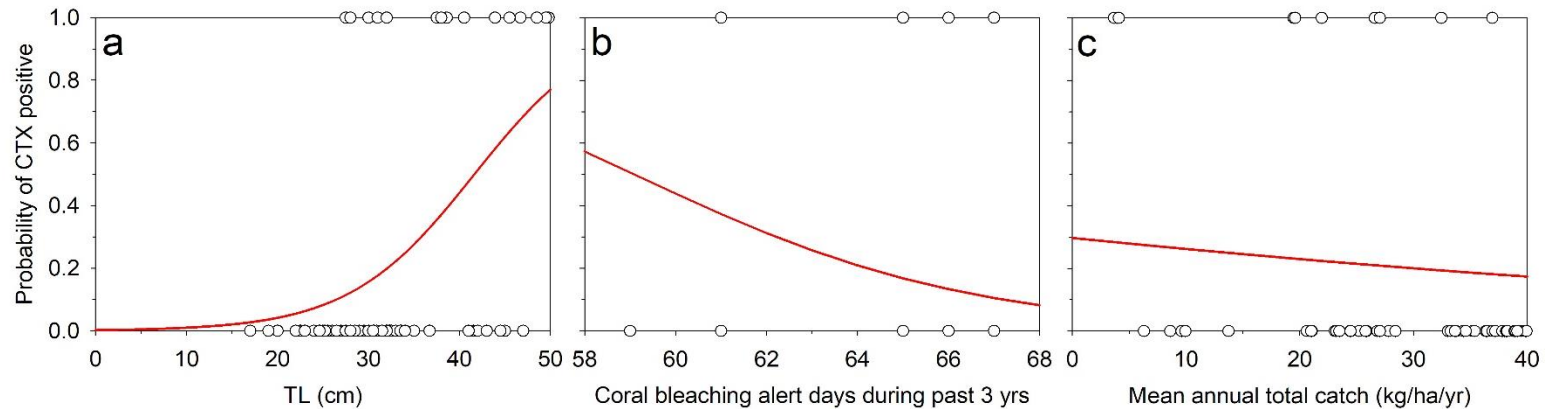


Figure 2. Averaged mean values for total length (cm), bleaching alert days in the past three years, and the mean annual total reef fish catch (kg/ha/yr) and the probability of Peacock Grouper (*Cephalopholis argus*), known locally in Hawai‘i by its Tahitian name – Roi testing positive for ciguatera. The probability of Roi testing positive for ciguatera increases with total length, decreases with bleaching days over the past three years, and decreases with higher mean annual reef fish catch per year.

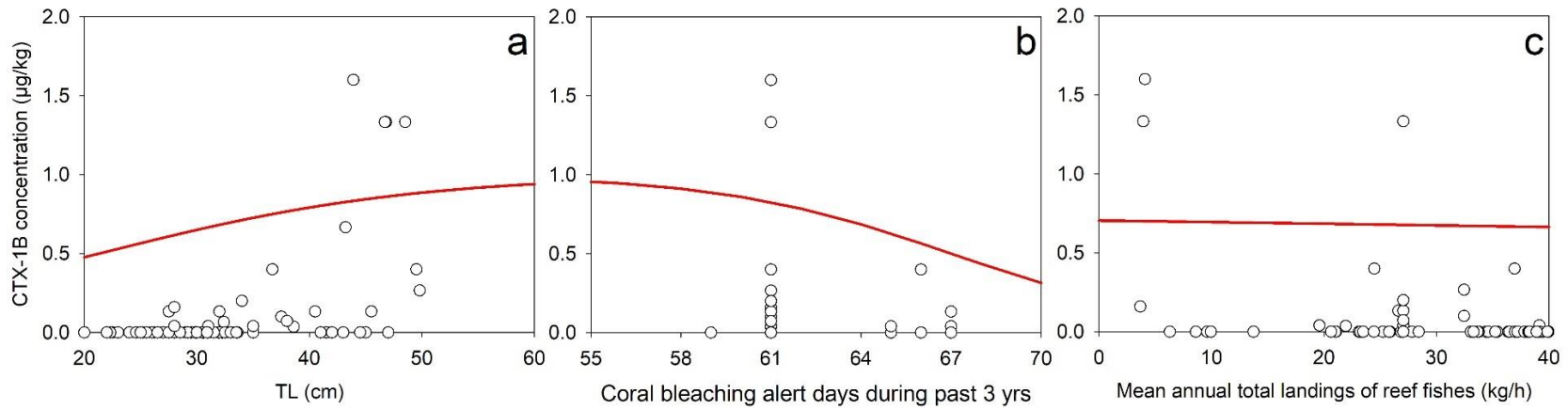


Figure 3. Averaged mean values for total length (cm), bleaching alert days in the past three years, and the mean annual total reef fish catch (kg/ha/yr) and the toxicity level (CTX1B; µg/kg) of Peacock Grouper (*Cephalopholis argus*), known locally in Hawai‘i by its Tahitian name – Roi. The toxicity level of Roi increases with total length, decreases with bleaching days over the past three years, and decreases with higher mean annual reef fish catch per year.

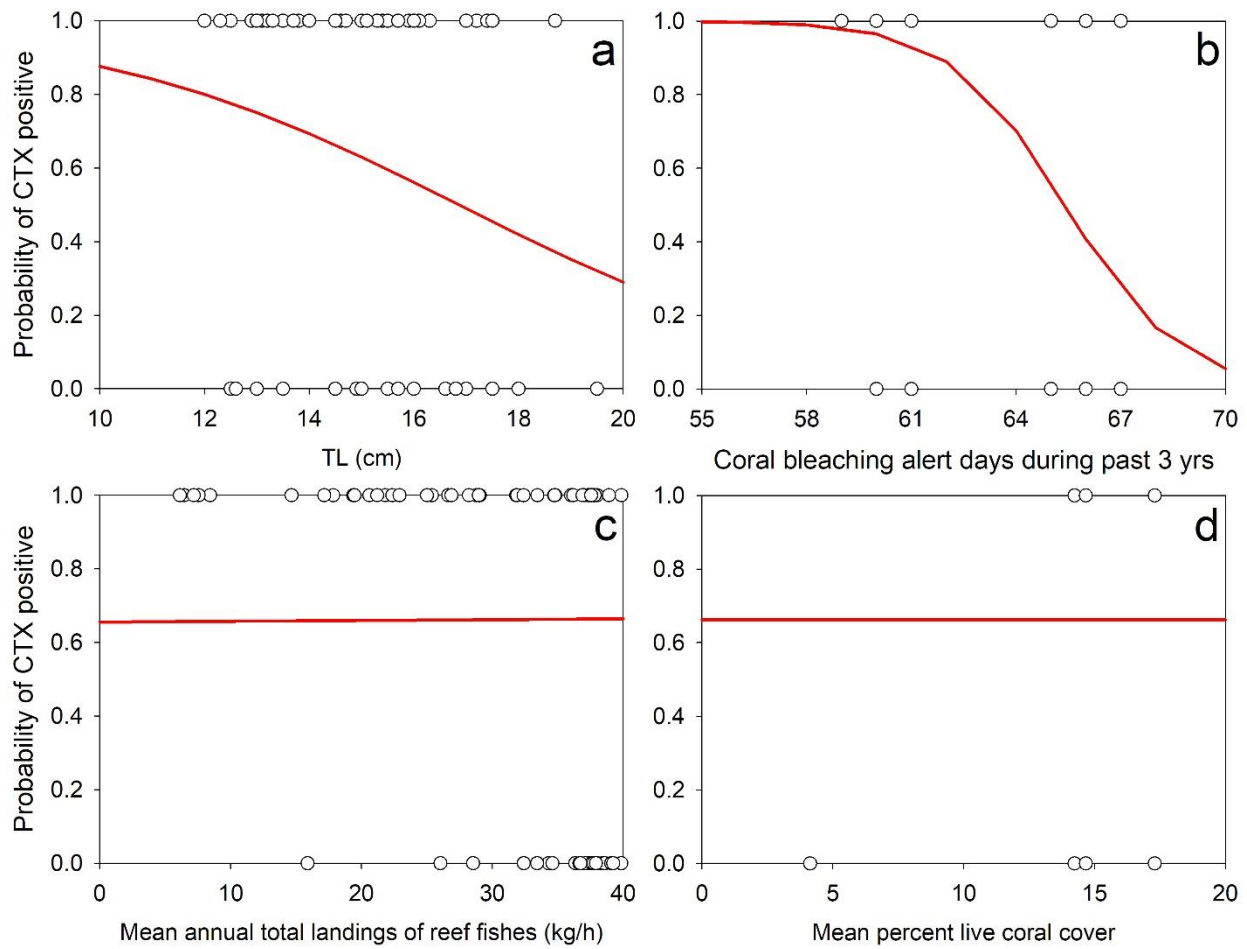


Figure 4. Averaged mean values for total length (cm), bleaching alert days in the past three years, the mean annual total reef fish catch (kg/ha/yr) and mean percent live coral cover and the probability of Goldring Bristletooth (*Ctenochaetus strigosus*), locally known in Hawai‘i as Kole testing positive for ciguatera. The probability of Kole testing positive for ciguatera increases with total length, decreases with bleaching days over the past three years, decreases with higher mean annual reef fish catch per year and decreases with higher mean percent live coral cover.

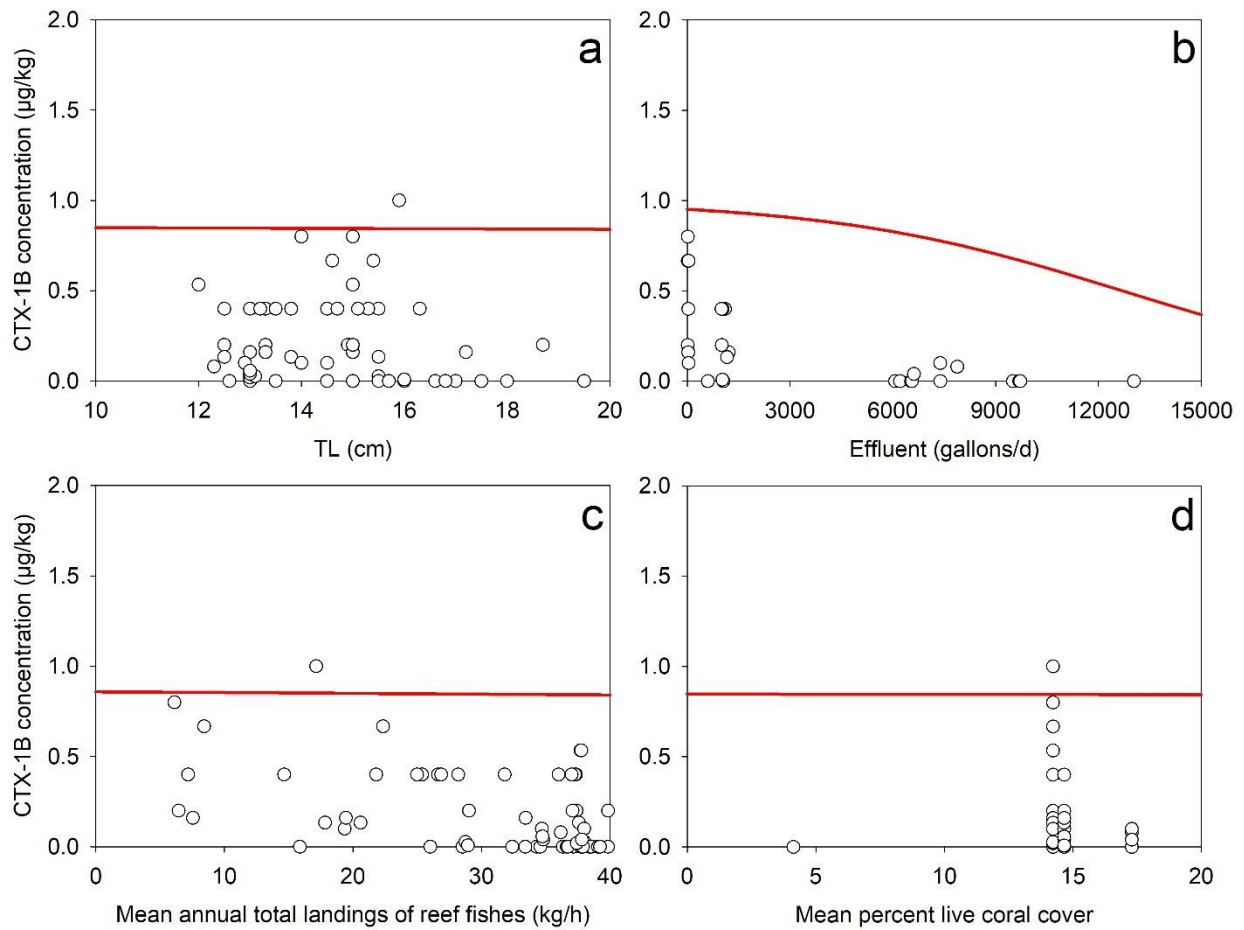


Figure 5. Averaged mean values for total length (cm), effluent (gallons/day), the mean annual total reef fish catch (kg/ha/yr), and mean percent of live coral cover and the toxicity level (CTX1B; µg/kg) of Goldring Bristletooth (*Ctenochaetus strigosus*), locally known in Hawai‘i as Kole. The toxicity level of Kole decreases with total length, decreases with bleaching days over the past three years, and decreases with higher mean annual reef fish catch per year.

Appendix 1. The full selection of AIC models and values predicting the probability of Peacock Grouper (*Cephalopholis argus*), known locally in Hawai‘i by its Tahitian name – Roi, captured from four locations along the west coast of Hawai‘i Island during March 2021 – September 2022 testing positive for ciguatoxins. A full description and sources of data used to create data for variables used as covariates to model Roi can be found in Table 2.

#	MODEL	<i>K</i>	<i>N</i>	AICc	Δ AICc	Likelihood	w_i
1	$p(\text{TL, BAA 3yr})$	3	82	73.93	0.00	1.00	0.50
2	$p(\text{TL, BAA 3yr, fishing pressure})$	4	82	75.59	1.66	0.44	0.22
3	$p(\text{TL, fishing pressure})$	3	82	77.5	3.57	0.17	0.08
4	$p(\text{TL, coral, boulder, BAA 3yr})$	6	82	77.63	3.7	0.16	0.08
5	$p(\text{TL, fishing pressure, effluent})$	4	82	78.35	4.42	0.11	0.06
6	$p(\text{TL, effluent})$	3	82	80.42	6.49	0.04	0.02
7	$p(\text{TL})$	2	82	81.31	7.38	0.02	0.01
8	$p(\text{TL, mean depth})$	3	82	82.34	8.41	0.01	0.01
9	$p(\text{TL, age})$	3	82	83.09	9.16	0.01	0.01
10	$p(\text{TL, wave power})$	3	82	83.39	9.46	0.01	0.00
11	$p(\text{TL, coral, boulder})$	4	82	84.21	10.28	0.01	0.00
12	$p(\text{TL, mean percent coral, herbivore biomass})$	4	82	85.47	11.54	0.00	0.00
13	$p(\text{TL, coral, boulder, herbivore biomass})$	6	82	86.25	12.32	0.00	0.00
14	$p(\text{BAA 3yr})$	3	82	86.49	12.56	0.00	0.00
15	$p(\text{herbivore biomass, BAA 3yr})$	5	82	87.88	13.95	0.00	0.00
16	$p(\text{mean percent coral, fishing pressure})$	3	82	92.12	18.19	0.00	0.00
17	$p(\text{coral, boulder, hard bottom, soft bottom})$	5	82	93.71	19.78	0.00	0.00
18	$p(\text{global})$	16	82	95.01	21.08	0.00	0.00
19	$p(\text{mean percent coral, effluent})$	3	82	95.79	21.86	0.00	0.00
20	$p(\text{herbivore biomass, fishing pressure})$	3	82	96.42	22.49	0.00	0.00
21	$p(\cdot)$	1	82	97.42	23.49	0.00	0.00
22	$p(\text{herbivore biomass, fishing pressure, mean depth})$	4	82	98.07	24.14	0.00	0.00
23	$p(\text{wave power})$	2	82	98.59	24.66	0.00	0.00
24	$p(\text{mean percent coral})$	2	82	98.64	24.71	0.00	0.00
25	$p(\text{herbivore biomass})$	2	82	99.52	25.59	0.00	0.00

Appendix 2. The full selection AIC models and values when the predicting the concentration of ciguatoxins in the tissue (CTX-1B) of Peacock Grouper (*Cephalopholis argus*), known locally in Hawai‘i by its Tahitian name – Roi, captured from four locations along the west coast of Hawai‘i Island during March 2021 – September 2022. A full description and sources of data used to create data for variables used as covariates to model Roi can be found in Table 2.

#	Model	K	n	AICc	Δ AICc	Likelihood	w_i
1	CTX1B(TL, BAA 3yr)	3	82	294.12	0.00	1.00	0.45
2	CTX1B(TL, BAA 3yr, fishing pressure)	4	82	295.57	1.45	0.49	0.22
3	CTX1B(TL, fishing pressure, effluent)	4	82	296.67	2.55	0.28	0.13
4	CTX1B(TL, BAA 3yr, coral, boulder)	5	82	297.05	2.93	0.23	0.10
5	CTX1B(TL, fishing pressure)	3	82	298.75	4.63	0.10	0.04
6	CTX1B(TL, effluent)	3	82	300.03	5.91	0.05	0.02
7	CTX1B(TL)	2	82	302.16	8.04	0.02	0.01
8	CTX1B(global)	16	82	302.36	8.24	0.02	0.01
9	CTX1B(TL, mean depth)	3	82	303.20	9.08	0.01	0.00
10	CTX1B(TL, age)	3	82	303.29	9.17	0.01	0.00
11	CTX1B(TL, wave power)	3	82	303.55	9.43	0.01	0.00
12	CTX1B(TL, coral, boulder)	4	82	304.38	10.26	0.01	0.00
13	CTX1B(TL, coral, boulder, herbivore biomass)	5	82	306.06	11.94	0.00	0.00
14	CTX1B(TL, mean present coral cover, herbivore biomass)	4	82	306.29	12.17	0.00	0.00
15	CTX1B(BAA 3yr)	2	82	335.22	41.10	0.00	0.00
16	CTX1B(herbivore biomass, BAA 3yr)	3	82	335.79	41.67	0.00	0.00
17	CTX1B(coral, boulder, hard bottom, soft bottom)	4	82	343.09	48.97	0.00	0.00
18	CTX1B(mean present coral cover, fishing pressure)	3	82	347.51	53.39	0.00	0.00
19	CTX1B(herbivore biomass, fishing pressure)	3	82	349.49	55.37	0.00	0.00
20	CTX1B(.)	1	82	351.09	56.97	0.00	0.00
21	CTX1B(wave power)	2	82	351.11	56.99	0.00	0.00
22	CTX1B(herbivore biomass, fishing pressure, mean depth)	4	82	351.49	57.37	0.00	0.00
23	CTX1B(mean present coral cover, effluent)	3	82	352.04	57.92	0.00	0.00
24	CTX1B(mean present coral cover)	2	82	352.95	58.83	0.00	0.00
25	CTX1B(herbivore biomass)	2	82	353.18	59.06	0.00	0.00

Appendix 3. The full selection of AIC models and values predicting the probability of Goldring Bristletooth (*Ctenochaetus strigosus*; $n = 80$), locally known in Hawai‘i as Kole, captured from four locations along the west coast of Hawai‘i Island during March 2021 – September 2022 testing positive for ciguatoxins. A full description and sources of data used to create data for variables used as covariates to model Kole can be found in Table 2.

#	MODEL	K	n	AICc	Δ AICc	Likelihood	w_i
1	$p(\text{mean precent coral, fishing pressure})$	3	80	88.33	0.00	1.00	0.35
2	$p(\text{TL, BAA 3yr, fishing pressure})$	4	80	89.42	1.09	0.58	0.21
3	$p(\text{TL, fishing pressure, effluent})$	4	80	90.35	2.02	0.36	0.13
4	$p(\text{TL, BAA 3yr})$	3	80	91.48	3.15	0.21	0.07
5	$p(\text{TL, effluent})$	3	80	91.52	3.19	0.20	0.07
6	$p(\text{TL, fishing pressure})$	3	80	91.6	3.27	0.19	0.07
7	$p(\text{mean precent coral, effluent})$	3	80	91.92	3.59	0.17	0.06
8	$p(\text{TL, coral, boulder, BAA3})$	5	80	95.26	6.93	0.03	0.01
9	$p(\text{TL, mean precent coral, herbivore biomass})$	4	80	96.49	8.16	0.02	0.01
10	$p(\text{mean precent coral})$	2	80	96.57	8.24	0.02	0.01
11	$p(\text{herbivore biomass, fishing pressure})$	3	80	96.95	8.62	0.01	0.00
12	$p(\text{BAA 3yr})$	2	80	97.19	8.86	0.01	0.00
13	$p(\text{herbivore biomass, fishing pressure, mean depth})$	4	80	99.08	10.75	0.00	0.00
14	$p(\text{TL, wave power})$	3	80	99.31	10.98	0.00	0.00
15	$p(\text{herbivore biomass, BAA3})$	3	80	99.34	11.01	0.00	0.00
16	$p(\text{TL, mean depth})$	3	80	99.47	11.14	0.00	0.00
17	$p(\text{TL})$	2	80	100.95	12.62	0.00	0.00
18	$p(\text{TL, age})$	3	80	102.89	14.56	0.00	0.00
19	$p(\cdot)$	1	80	103.52	15.19	0.00	0.00
20	$p(\text{TL, coral, boulder})$	4	80	103.62	15.29	0.00	0.00
21	$p(\text{wave})$	2	80	103.79	15.46	0.00	0.00
22	$p(\text{TL, coral, boulder, herbivore biomass})$	4	80	104.95	16.62	0.00	0.00
23	$p(\text{herbivore biomass})$	2	80	105.53	17.20	0.00	0.00
24	$p(\text{global})$	14	80	105.87	17.54	0.00	0.00
25	$p(\text{coral, boulder, hard bottom, soft bottom})$	5	80	110.43	22.10	0.00	0.00

Appendix 4. The full selection AIC models and values when the predicting the concentration of ciguatoxins in the tissue (CTX-1B) of Goldring Bristletooth (*Ctenochaetus strigosus*; n = 80), locally known in Hawai‘i as Kole, captured from four locations along the west coast of Hawai‘i Island during March 2021 – September 2022. A full description and sources of data used to create data for variables used as covariates to model Kole can be found in Table 2.

#	Model	K	n	AICc	Δ AICc	Likelihood	w_i
1	CTX1B(TL, effluent)	3	80	591.57	0.00	1.00	0.52
2	CTX1B(TL, fishing pressure, effluent)	4	80	592.95	1.38	0.50	0.26
3	CTX1B(mean precent coral cover, effluent)	3	80	593.24	1.67	0.43	0.22
4	CTX1B(global)	14	80	606.99	15.42	0.00	0.00
5	CTX1B(herbivore biomass, fishing pressure, mean depth)	3	80	608.78	17.21	0.00	0.00
6	CTX1B(mean precent coral cover, fishing pressure)	3	80	609.29	17.72	0.00	0.00
7	CTX1B(TL, BAA3, fishing pressure)	4	80	611.30	19.73	0.00	0.00
8	CTX1B(TL, fishing pressure)	3	80	611.49	19.92	0.00	0.00
9	CTX1B(herbivore biomass, fishing pressure)	3	80	612.43	20.86	0.00	0.00
10	CTX1B(TL, BAA3)	3	80	615.25	23.68	0.00	0.00
11	CTX1B(BAA3)	2	80	615.58	24.01	0.00	0.00
12	CTX1B(TL, coral, boulder, BAA3)	5	80	616.74	25.17	0.00	0.00
13	CTX1B(herbivore biomass, BAA3)	3	80	617.71	26.14	0.00	0.00
14	CTX1B(mean precent coral cover)	2	80	623.57	32.00	0.00	0.00
15	CTX1B(.)	1	80	625.17	33.60	0.00	0.00
16	CTX1B(wave)	2	80	626.45	34.88	0.00	0.00
17	CTX1B(TL)	2	80	626.72	35.15	0.00	0.00
18	CTX1B(herbivore biomass)	2	80	627.12	35.55	0.00	0.00
19	CTX1B(TL, mean precent coral cover, herbivore biomass)	4	80	627.33	35.76	0.00	0.00
20	CTX1B(TL, wave)	3	80	628.22	36.65	0.00	0.00
21	CTX1B(TL, mean depth)	3	80	628.84	37.27	0.00	0.00
22	CTX1B(TL, age)	3	80	628.85	37.28	0.00	0.00
23	CTX1B(TL, coral, boulder)	4	80	630.58	39.01	0.00	0.00
24	CTX1B(coral, boulder, soft bottom, hard bottom)	5	80	630.60	39.03	0.00	0.00
25	CTX1B(TL, coral, boulder, herbivore biomass)	5	80	632.44	40.87	0.00	0.00