

# Ciguatera in the Introduced Fish *Cephalopholis argus* (Serranidae) in Hawai'i and Implications for Fishery Management<sup>1</sup>

Jan Dierking<sup>2,3</sup> and Cara E. Campora<sup>4</sup>

**Abstract:** The Peacock grouper (*Cephalopholis argus*) was introduced to Hawai'i in 1956 to establish a new fishery. It has become abundant, but the fishery failed due to concerns about ciguatera fish poisoning, a neurological disease in humans caused by ingestion of fish containing ciguatoxin. The aim of this study was to provide better understanding of geographic patterns of ciguatoxicity in *C. argus* and of the correlation of toxicity with morphometric characters of this species, with the goal to assess the possibility of a safe fishery. Overall, 18.2% of *C. argus* specimens from sites around O'ahu and Hawai'i Island contained ciguatoxin in concentrations potentially harmful to humans. This was higher than the rate of occurrence in Hawaiian reef fishes in general, and on the scale of ciguatoxicity in species banned from sale in fish markets. Toxicity was high around both analyzed islands. However, toxic individuals were significantly less common around O'ahu than around Hawai'i Island (8% versus 24%). Regular geographic patterns in toxicity within islands (e.g., gradients along coastlines) were not present, and variability in toxicity within each sample site was high. Toxicity was significantly but weakly positively correlated with *C. argus* length but not with fish condition (measured by length at weight). In conclusion, high prevalence of toxic individuals, variability in toxicity on all analyzed spatial scales, and low explanatory power of morphometric characters make the avoidance of ciguatoxic *C. argus* individuals difficult. A safe fishery for this species in Hawai'i therefore does not appear feasible at present.

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<sup>2</sup>Corresponding author.

<sup>3</sup>Department of Zoology, University of Hawai'i at Mānoa, 2538 McCarthy, The Mall, Honolulu, Hawai'i 96822. Current address: Station Marine d'Endoume, Centre d'Océanologie de Marseille, UMR CNRS 6540, Université de la Méditerranée, Rue de la Batterie des Lions, 13007 Marseille, France (phone: +33 (0)491 041637; fax: +33 491 041635; e-mail: jan.dierking@univmed.fr).

<sup>4</sup>Department of Cell and Molecular Biology, University of Hawai'i at Mānoa, 1960 East-West Road, Honolulu, Hawai'i 96822.

DUE TO THEIR geographic isolation, the main Hawaiian Islands have reef fish communities characterized by the lack or limited presence of fish families with short to medium larval durations and late maturity, which include the commercially important snappers (Lutjanidae) and groupers (Serranidae), and by high rates of endemism in the extant fish families (Randall 1987). In the 1950s, this situation led to the instigation of an introduction program of snappers, groupers, and emperors (Lethrinidae) that had the objective to create new fisheries. Of 12 species in the program, only two snapper species and the Peacock grouper (*Cephalopholis argus* Bloch & Schneider) (common name in Hawai'i: *roi*), of which 2,385 individuals from Moorea (French Polynesia) were initially released, became established (Oda and Parrish 1981). After an initial time lag, *C. argus* populations have grown strongly since the 1980s, and the species now surpasses the biomass of all other nearshore reef fish pred-

ators in the main Hawaiian Islands combined. A fishery nevertheless did not develop after *C. argus* caused a number of ciguatera fish poisoning incidents in Hawai'i and was rejected by consumers thereafter (Dierking 2007).

Ciguatera fish poisoning is a neurological disease that causes severe clinical symptoms in humans (Palafox and Buenconsejo-Lum 2001). It is caused by ingestion of ciguatoxin, a natural polyether toxin that is produced by the benthic dinoflagellate *Gambierdiscus toxicus* (Yasumoto et al. 1980), as well as other species of the genus *Gambierdiscus*. Ciguatoxin enters the marine food chain when herbivores consume benthic macroalgae with attached *G. toxicus*. After ingestion, ciguatoxin is stored in body tissues and can subsequently be transferred to higher trophic levels of the food web when predators prey on toxic herbivores (Banner 1974). Ciguatera is confined to the subtropics and tropics, where it has important public health and economic implications (Lewis 2001). The annual number of reported incidents in humans ranges from 25,000 to 50,000 worldwide (Lehane and Lewis 2000) and from 35 to 70 in Hawai'i (Bruno and Effler 2001), and important fisheries have been closed due to ciguatera outbreaks (De Sylva 1994).

Due to consumer concerns about ciguatera fish poisoning, *C. argus* is of no commercial value in Hawai'i. Moreover, in contrast to originally envisioned benefits of the introduction, the large quantity of prey fishes consumed by *C. argus* populations is today considered a potential threat to native fishes and fisheries (Earle 2005). In contrast, most groupers worldwide are in decline due to their value as food fish and their vulnerability to fishing pressure, and are considered important in maintaining ecosystem functioning (Morris et al. 2000). *Cephalopholis argus* falls under the latter pattern in several of its native habitats (Heemstra and Randall 1993). It is overfished in Guam, where it is not ciguatoxic, and its wholesale value is \$20/kg in the Asian live reef fish trade (Lee and Sadovy 1998). Considering this situation, better understanding of ciguatera in *C. argus* in Hawai'i may have the potential to lead to a safe fishery in the future. Questions with direct

potential applications include How ciguatoxic are individuals of *C. argus* in Hawai'i, and, even if overall toxicity is high, are certain individuals (such as those below a certain size threshold or from certain areas) predictably safe for consumption?

However, few studies (and none on a grouper) have explicitly looked at the role of the geographic origin or morphometric characters in ciguatoxicity, and despite recent advances in the understanding of the biology of ciguatera, many questions remain (Lehane and Lewis 2000). In this situation, the aim of our study was to assess the feasibility of a *C. argus* fishery in the main Hawaiian Islands and to enhance general understanding of ciguatera by (1) screening *C. argus* populations for ciguatoxin concentrations, (2) analyzing geographic patterns in *C. argus* toxicity in the main Hawaiian Islands, and (3) analyzing the association of ciguatoxin concentration with morphometric characters.

#### MATERIALS AND METHODS

##### *Site Selection and Sampling*

A total of 291 specimens of *C. argus* from six sites around the island of O'ahu and 11 sites along the west coast of the island of Hawai'i (Figure 1) (estimated site extent 10,000 m<sup>2</sup>) was sampled by spearfishing on scuba in July 2003 (O'ahu,  $n = 106$ ; Hawai'i,  $n = 185$ ) (no specimens were caught at site KA-W07). Specimens were placed on ice after the dives and transported to the laboratory within 2 hr. There, standard length (SL) and total length (TL) of each specimen were recorded to the nearest millimeter, and wet weight (W) (O'ahu samples only, due to scale malfunctioning during Hawai'i Island fieldwork) to the nearest 5 g. Sex was determined based on visual inspection of gonads. Mean SL ranged from 13.2 to 44.0 cm and W from 0.185 to 2.100 kg. Muscle tissue samples (~0.5 cm<sup>3</sup>) from the head, body, and tail region of each specimen were frozen at -20°C for ciguatoxin analysis.

O'ahu is the human population center of the main Hawaiian Islands and has the highest number of recreational fishermen of any

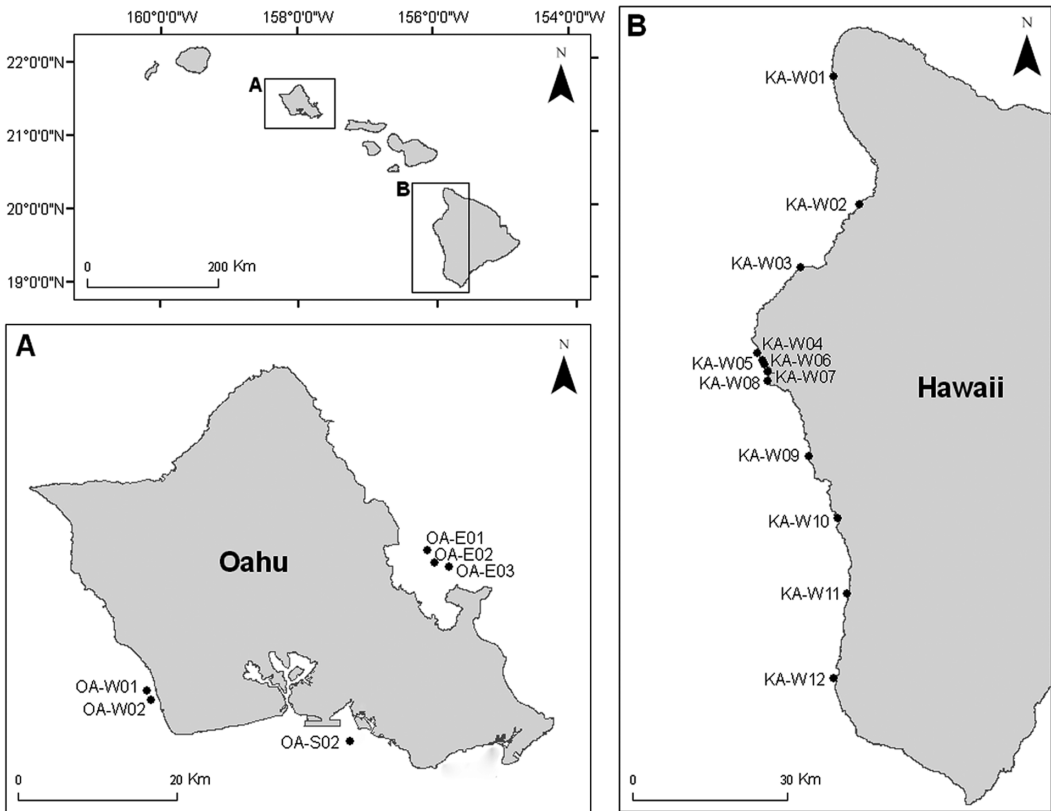


FIGURE 1. Map of the main Hawaiian Islands (inset) and the islands of O'ahu (A) and Hawai'i (B). Black dots mark sample sites (OA, O'ahu; KA, Hawai'i Island; W, West; S, South; E, East).

of the main Hawaiian Islands. Hawai'i Island has a smaller population, but fishing for home consumption is still common (Schmitt 2002). Ciguatera fish poisoning incidents are particularly common along the west coasts of O'ahu and Hawai'i Island (Bruno and Effler 2001). *Cephalopholis argus* densities along the latter coastline are among the highest in the main Hawaiian Islands, with on average 7.2 individuals/1,000 m<sup>2</sup> in coral reef habitats (Dierking 2007). This coast has also been the recent focus of resource management efforts to sustain reef fish populations (Tissot et al. 2004).

#### Fish Condition

Fish condition factors are based on the assumption that heavier fish of a given length

are in better condition (Bolger and Connolly 1989). The measure of fish condition used in this study was the relative condition factor  $K_n = W/aTL^n$ , where  $a$  and  $n$  are the intercept and slope of the exponential form of the length-weight equation of the population of interest. The length-weight equation was determined by least-squares regression of  $\log_{10} W$  versus  $\log_{10} TL$ . Due to the lack of  $W$  data for Hawai'i Island samples, the calculation of  $K_n$  was limited to O'ahu samples.

#### Ciguatoxin Analysis

Ciguatoxin concentrations in *C. argus* tissue were determined with the Membrane Immunoassay, which is based on the specific binding of a monoclonal antibody (MAB-ciguatoxin) to the ciguatoxin molecule (Ho-

kama et al. 1998). The Membrane Immunobead Assay is rapid and affordable, thus allowing large-scale screenings of fish populations that are difficult to accomplish with more cost- and time-intensive mass spectrometry (Lewis et al. 1999) or tissue culture (Bottein Dechraoui et al. 2005) approaches. The Membrane Immunobead Assay is the method used by the Hawai'i Department of Health for the validation of ciguater toxicity in fish implicated in ciguatera fish poisoning incidents (Hokama and Ebesu 2001).

Membrane Immunobead Assay procedures followed Hokama et al. (1998), with small modifications as described by Dierking (2007). Briefly, Membrane Immunobead Assay scores were obtained by visual comparison of test stick colorations with a standard scale (Table 1). Because muscle tissue from different body regions can vary in concentrations (Kimura et al. 1982), test scores (each with a possible range of 0–2 [Table 1]) of white muscle tissue from the head, body, and tail of each specimen were added to an overall fish score (possible range 0–6), which was interpreted regarding the toxicity and safety of the fish for human consumption (Table 2).

#### *Validation of Membrane Immunobead Assay Results with the Neuroblastoma Cell Bioassay*

Because the Membrane Immunobead Assay has not routinely been used in prior published studies, a subset ( $n = 30$ ) of *C. argus* muscle tissue samples (15 samples that tested

TABLE 1

Conversion Table for Determination of Monoclonal Immunobead Assay Scores and Ciguatoxin Concentrations from Coloration of the Monoclonal Immunobead Assay Membrane

Membrane Coloration <sup>a</sup>	Score	Ciguatoxin (ng/g)
No color	0	0
Faint blue	0.5	0.08
Distinct blue	1	0.16
Intense blue	2	0.32

<sup>a</sup> For a graphic display of membrane colorations for a wide range of ciguatoxin concentrations obtained by running Monoclonal Immunobead Assays on standards of known concentration, see Hokama et al. (1998).

TABLE 2

Conversion Table for Interpretation of Overall Fish Scores

Fish Score Range <sup>a</sup>	Score Class <sup>b</sup>	Interpretation
<0.5	Negative	Safe
0.5–2.0	Marginal	Safe (but small risk with frequent consumption)
>2.0–4.0	Positive	Unsafe (incident possible)
>4.0	Strongly positive	Unsafe (incident likely)

<sup>a</sup> Overall fish scores are the sum of the three individual scores obtained from the head, body, and tail of each specimen (see Table 1).

<sup>b</sup> Boundaries and interpretations were previously established by Hokama et al. (1998) based on Monoclonal Immunobead Assays of fish that had caused ciguatera fish poisoning and of fish that were consumed without causing incidents.

negative using the Membrane Immunobead Assay and 15 samples that tested borderline [ $n = 8$ ] or positive [ $n = 7$ ]) was retested with the accepted Neuroblastoma cell bioassay for the detection of ciguatoxin (Manger et al. 1995) (for prior applications see, e.g., Bottein Dechraoui et al. 2005).

The specific Neuroblastoma cell assay methodology followed Campora et al. (2008). In short, the presence of ciguatoxin in muscle tissue was determined by comparing the survival rate of neuroblastoma cells in treatment wells containing fish extract with that in control wells without extract, with lowered survival in treatment wells indicating cytotoxicity. Differences between control and treatment wells were assessed by one-way analysis of variance (ANOVA) followed by Tukey's test for multiple comparisons. Samples with significantly lower cell survival in treatment wells were scored as "positive," samples with posttest critical values above 3.50 but lack of significance ( $P > .05$ ) were scored as "borderline," and all other samples were scored as "negative."

The agreement of the proportion of negative, borderline, and positive results obtained with the Membrane Immunobead Assay and the Neuroblastoma cell assay was then assessed with a Chi-square test. In addition, the correlation of results (with test scores translated to numerical values: negative, 0; borderline, 0.5; positive, 1) was assessed by

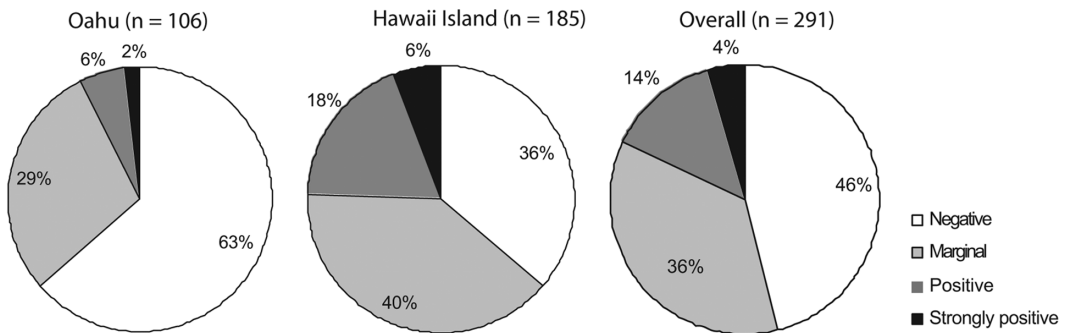


FIGURE 2. Ciguatoxicity of *C. argus* in the O'ahu, Hawai'i Island, and overall sample (sample sizes in parentheses). Fish in the negative and marginal score classes are considered safe, and fish in the positive and strongly positive classes are considered unsafe for human consumption.

calculating the Pearson correlation coefficient.

#### *Association of Ciguatoxicity with Geographic Factors and C. argus Morphometry*

Differences in the mean toxin concentration of *C. argus* from O'ahu and Hawai'i Island, and differences in the prevalence of toxic individuals around the two islands, were assessed with a two sample *t*-test and a Chi-square test, respectively. An analysis of covariance (ANCOVA) type general linear model with site as explanatory and ciguatoxin score as response variable, and *C. argus* SL as covariate, was used for the analysis of the relationship of geographic location, *C. argus* size, and ciguatoxicity. Patterns in toxicity along coastlines were analyzed by comparing side-by-side box plots of toxicity at each site. Finally, the Pearson correlation factor was calculated to test the association of fish condition and ciguatoxicity. Minitab (Version 14, Minitab, Inc., State College, Pennsylvania) was the statistical software for all analyses, with results considered significant at  $P < .05$ .

## RESULTS

### *Membrane Immunobead Assay Validation*

Using the Membrane Immunobead Assay, of 30 *C. argus* muscle tissue samples, 15 tested negative, 8 borderline, and 7 positive for the presence of ciguatoxin. Using the Neuro-

blastoma cell assay on the same samples, 20 samples tested negative, 5 borderline, and 5 positive. Overall, the proportion of negative, borderline, and positive results obtained with the two tests did not differ significantly (Chi-square analysis,  $P = .419$ ). Moreover, results were strongly and significantly correlated ( $r = 0.64$ ,  $P < .001$ ).

### *Overall Sample Description*

The screening of 291 specimens for toxicity provides a general overview of ciguatera in *C. argus* in the main Hawaiian Islands. Forty-six percent of specimens tested negative, 36% marginal, 14% positive, and 4% strongly positive for ciguatoxin (Figure 2), which means that 82% of fish were generally safe and 18% potentially unsafe for human consumption (Table 2). The mean fish toxicity score of 1.25 fell into the "marginal" score category, which would generally be considered safe for consumption (Table 2). However, variability was large, which is reflected in the large standard deviation and wide 95% confidence interval for ciguatoxin scores in the overall sample (Table 3).

### *Large-Scale Geographic Patterns in Ciguatoxin Concentrations*

Mean ciguatoxin concentration in *C. argus* was significantly lower for O'ahu than for Hawai'i Island (Table 3) (*t*-test with sample site mean as sampling unit [ $t = 3.82$ ,  $df =$

TABLE 3  
Ciguatera in the O‘ahu, Hawai‘i Island, and Overall Sample

Region	<i>n</i>	$\bar{x} \pm 1$ SD	95% CI	Range
O‘ahu	106	0.73 $\pm$ 1.07	0–2.8	0–6
Hawai‘i I.	185	1.55 $\pm$ 1.48	0–4.4	0–6
Overall	291	1.25 $\pm$ 1.40	0–4.0	0–6

Note: Mean toxicity differed significantly between islands ( $P < .01$ ). SD, standard deviation; CI, confidence interval.

10,  $P < .01$ ). The prevalence of individuals unsafe for human consumption was also significantly lower (7.5% for O‘ahu and 24.3% for Hawai‘i Island) (Chi-square test [ $n = 291$ ,  $df = 1$ ,  $P < .001$ ]) (Figure 2). Box plots of toxicity at the sample sites grouped in order of their relative geographic position

along coastlines did not reveal clear geographic patterns (Figure 3). In particular, individuals containing ciguatoxin in high concentrations occurred along all coastlines, and no spatial gradients in toxicity were apparent.

*Between-Site Differences and the Role of Length and Fish Condition in Ciguatoxicity*

Mean ciguatoxin concentration differed significantly between sites, and *C. argus* SL and ciguatoxin concentration were significantly positively associated (ANCOVA:  $F = 2.17$ ;  $df = 1, 16$ ; site:  $P = .006$ ; SL:  $P = .03$ ) (Table 4). The increase in toxicity with size occurred consistently across sites, as indicated by the nonsignificant interaction of site and SL when the interaction term “site\**C. argus* SL” was added to the general linear model ( $F = 0.72$ ,  $df = 16$ ,  $P = .77$ ). The proportion

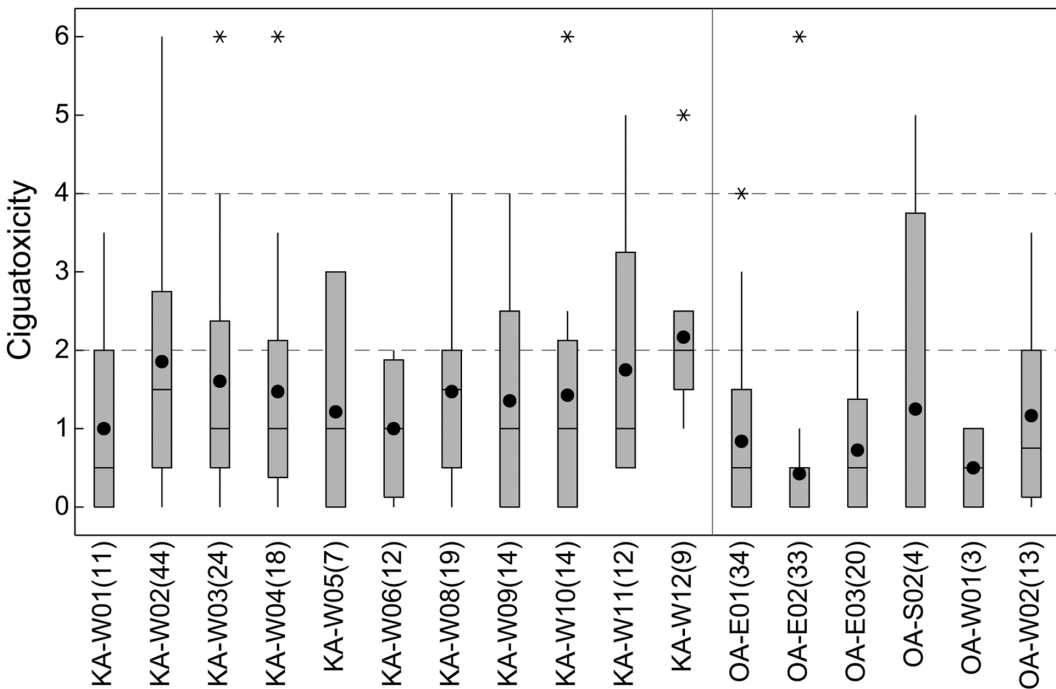


FIGURE 3. Box plots of the ciguatoxicity (measured by Membrane Immunobead Assay score) in *C. argus* populations at each site, in order of the relative position of sites along coastlines (also see Figure 1). (OA, O‘ahu; KA, Hawai‘i Island; sample sizes at each site in parentheses). Boxes represent the interquartile range, horizontal lines through the boxes the median, and black dots the mean. Outliers are marked by asterisks (\*). The dashed horizontal lines mark ciguatoxin score class boundaries, with fish below the lower boundary ( $\leq 2$ ) generally safe and those above generally unsafe for consumption. Fish above the upper boundary ( $> 4$ ) would likely have caused ciguatera incidents.

of variation explained by the association of ciguatoxicity with site and SL was 13.7%. Partitioning of variation showed that between-site differences in toxicity explained 12.2% and the association of toxicity and SL 1.5% of total variation in ciguatoxicity (Table 4). Within-site variation therefore represented 87.8% of total variation, of which all but the proportion explained by fish SL remained unexplained by the factors included in the analysis. The pattern of high variability in toxicity despite the significant increase in toxicity with fish length is illustrated by Figure 4. A second morphometric character, fish condition, was not significantly correlated with ciguatoxin concentration ( $P = .480$ ) (Figure 5).

DISCUSSION

The good overall agreement of results obtained by the Membrane Immunobead Assay

TABLE 4  
ANCOVA Table of the Main Effects General Linear Model of Site, *C. argus* SL (Covariate), and Ciguatoxicity (Dependent Variable)

Source of Variation	df	Sums of Squares	Adj. Mean Squares <sup>a</sup>	F	P	Variation Explained (%)
<i>C. argus</i> SL	1	15.7	8.52	4.74	.030	1.5
Site	16	62.4	3.89	2.17	.006	12.2
Error	273	490.7	1.79			
Total	290	568.7				
$r^2$						13.7

<sup>a</sup> Adjusted mean squares are based on adjusted sums of squares calculated with all model terms included in the model.

and the Neuroblastoma cell assay (i.e., insignificant differences in the proportion of negative, borderline, and positive samples [ $P = .419$ ] and significant correlation of test scores [ $P < .001$ ]) for the same subset of 30

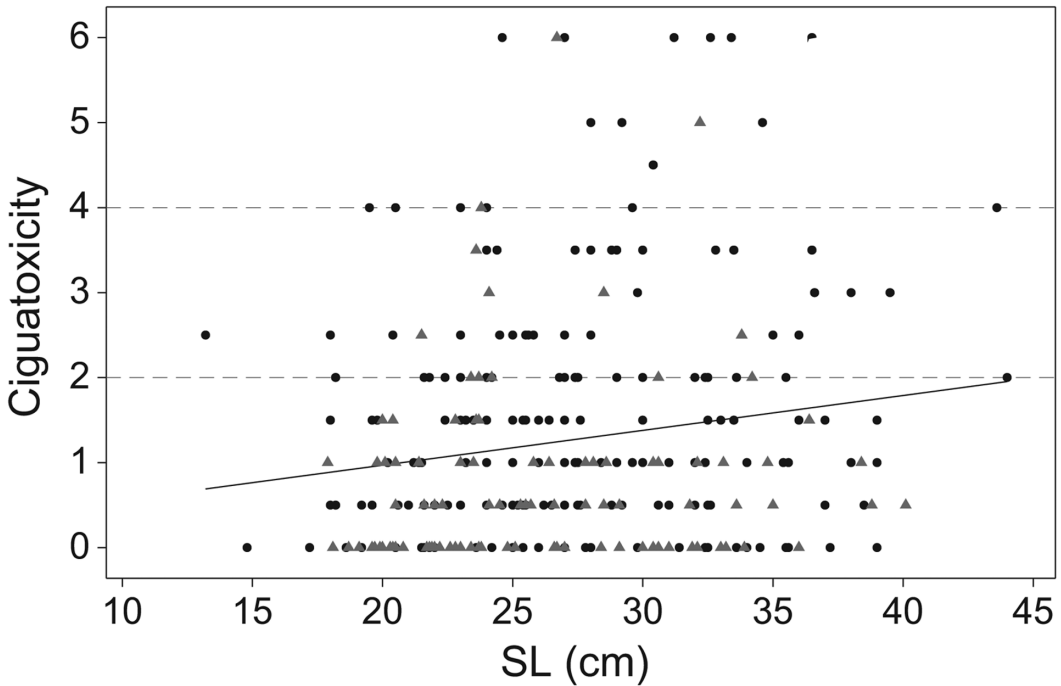


FIGURE 4. The relationship of toxicity (Membrane Immunobead Assay score) and SL in *C. argus* from O'ahu (gray triangles) and Hawai'i Island (black circles), with least squares regression line for the combined datasets. Dashed horizontal lines mark score class boundaries, with fish below the lower line generally safe and fish above this line potentially unsafe, and those above the upper line highly unsafe for consumption.

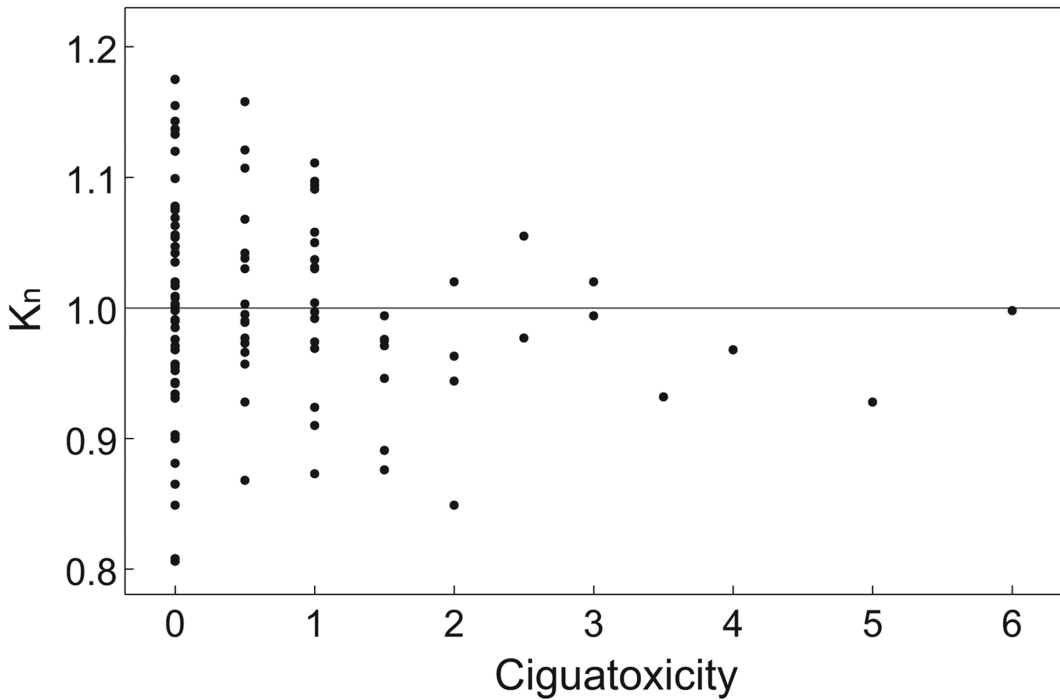


FIGURE 5. Relative condition  $K_n$  and ciguatoxicity (Membrane Immunobead Assay score) in *C. argus* from O'ahu.  $K_n = 1$  (marked by solid horizontal line) represents the mean body condition of the population.

*C. argus* specimens indicates that the conclusions derived from the Membrane Immunobead Assay in this study are valid. The higher proportion of samples containing ciguatoxin detected by the Membrane Immunobead Assay compared with the Neuroblastoma cell assay suggests that toxicity estimates in this paper are conservatively high. However, variation introduced by false positive tests would arguably be random and therefore does not appear likely to skew results.

#### *Ciguatera* in *C. argus* in the Main Hawaiian Islands

The first objective of this study was the general screening of *C. argus* populations in the main Hawaiian Islands for ciguatoxicity to assess the human health risk of an unlimited fishery (i.e., no use of spatial closures, slot sizes, or other measures to avoid ciguatoxic

fish). The mean ciguatoxin score of the overall population was 1.25, which would be generally safe for human consumption (Table 2). However, the variability in ciguatoxicity was high, and despite the low mean toxicity, 18.2% of individuals were too toxic for safe human consumption (Figure 2). It is important to note that it is unlikely that all unsafe individuals would have caused ciguatera fish poisoning incidents upon consumption, because human susceptibility to ciguatoxin varies and because the Membrane Immunobead Assay scoring scale was designed with a built-in safety margin to avoid false negative tests (i.e., classifying toxic fish as edible) (Hokama and Ebesu 2001). At the same time, although fish that test marginally for ciguatoxin (35.6% of total) are considered safe, frequent consumption of such individuals could still lead to ciguatera fish poisoning incidents, because ciguatoxin can bioaccumulate in human tissue (Lehane and Lewis 2000).



TABLE 5

Prevalence of Individuals Considered Unsafe for Human Consumption Due to Risk of Ciguatera in Different Species of Reef Fishes

Species/Group	Location <sup>a</sup>	Prevalence <sup>b</sup>	Test <sup>c</sup>	Source
<i>C. argus</i>	MHI	18.2	MIA	This study
<i>Seriola dumerili</i> <sup>d</sup>	MHI	14.7	Radioimmunoassay	Kimura et al. (1982)
<i>Caranx</i> spp. <sup>e</sup>	MHI	15.4	MIA	Hokama et al. (1998)
<i>Sphyræna barracuda</i> <sup>d</sup>	Florida	30	Cytotoxicity assay	Bottein Dechraoui et al. (2005)
Hawaiian reef fishes overall	MHI	4	MIA	Hokama et al. (1998)

<sup>a</sup> MHI, main Hawaiian Islands.<sup>b</sup> Proportion of fish considered unsafe for human consumption in each study.<sup>c</sup> MIA, Monoclonal Immunobead Assay.<sup>d</sup> Banned from fish markets due to ciguatera.<sup>e</sup> Considered as high-risk species.

The observed prevalence of toxic individuals was much higher than in Hawaiian reef fishes overall (Hokama et al. 1998) and on the scale of that of species considered high risk or banned from commercial sale due to ciguatera (e.g., Bottein Dechraoui et al. 2005) (Table 5). The latter include the greater amberjack (*Seriola dumerili*) in Hawai'i and great barracuda (*Sphyræna barracuda*) in Florida (De Sylva 1994). The finding of higher-than-average toxicity in *C. argus* agrees well with official Hawai'i Department of Health statistics, which show that despite the minor importance of this species compared with popular market reef fishes, it caused more ciguatera fish poisoning incidents than any other species in Hawai'i in recent years (21 incidents between 1996 and 2000, equivalent to 17% of all reported cases) (Bruno and Effler 2001). Considering the severity of ciguatera fish poisoning, a large-scale fishery for *C. argus* does not appear feasible.

It should be noted that a commercial kit to test fish for ciguatoxin (Cigua-Check by Oceanit) exists. In principle, wide availability of this (or of alternative) test(s) to fishermen could contribute to a safe commercialization of *C. argus*. However, the current cost to test a single fish is US \$10.99 (www.oceanit.com), which appears prohibitive, in particular when considering that this amount could be used to purchase nonciguatotoxic fish species directly.

### Geographic Patterns in Ciguatoxicity

Understanding of geographic patterns in *C. argus* toxicity in Hawai'i could still lead to safe fisheries of limited geographic extent. This study concentrated on patterns on three spatial scales within the main Hawaiian Islands: (1) between islands, (2) along coastlines, and (3) between sample sites. Regarding (1), mean toxicity differed significantly between islands (Table 3). The mean toxicity of *C. argus* from O'ahu ( $\bar{x} = 0.73$ ) fell into the negative Membrane Immunobead Assay score class (Table 2), which is considered safe for human consumption. Even the much higher mean toxicity for Hawai'i Island ( $\bar{x} = 1.55$ ) still fell into the marginal score class, generally considered as safe. However, due to high variability in toxicity, despite the low mean toxicity for O'ahu, toxic (outlier) scores occurred frequently, and 7.5% of individuals were unsafe for human consumption (Figure 2). For Hawai'i Island, where unsafe individuals were significantly more common (24.3% of total), the case was even less ambiguous. Overall, the risk of a fishery thus appears unacceptably high in both cases.

Second, considering the lack of recognizable patterns in mean toxicity along coastlines (Figure 3), as well as the fact that none of the coastlines and only 2 of 17 sample sites (KA-W06 and OA-W01) were completely free of toxic individuals (Figure 3), safe regional fisheries for *C. argus* do not appear

feasible either. Both safe sites were not representative of larger geographic trends, because toxic specimens occurred at the neighboring sites OA-W02, KA-W05, and KA-W08. These results stand in contrast to the pattern described by Lewis (2001) in the Republic of Kiribati, where the southern reef of Tarawa and the western reef Maraki have a high risk of ciguatera, whereas remaining reefs are low-risk areas. The Kiribati pattern could offer the resource management solution of closing only the toxic reef to fishing, but such an approach does not appear feasible for *C. argus* in Hawai'i.

Finally, mean toxicity differed significantly between sites (Table 4). At the same time, independent of mean toxicity, all sites were characterized by large variability in toxicity. This is illustrated by the broad score range expanding into the unsafe score range at all but three sites and by the occurrence of highly toxic outliers at six of the 17 sites (Figure 3). The high variability in toxicity within sites is reflected in the large proportion of overall variation in toxicity that is due to within-site variation (87.8% of total [Table 4]). The practical implication of the described patterns is that even individuals caught at sites with low mean toxicity cannot be considered safe for a fishery.

#### *Morphometrics and Ciguatoxicity*

A strong correlation between fish morphometrics and ciguatoxicity would enhance our ability to predict the toxicity of wild-caught *C. argus*. Individuals of widely varying size and condition were present at each sample site. Could the high variability of toxin concentrations within subpopulations be linked to variation in size or condition? Regarding size, the significant positive correlation of ciguatoxicity with SL shows that a link existed. However, length explained only a minor proportion of the variation in toxicity ( $r^2 = 1.5\%$  [Table 4]). Although large individuals were on average slightly more toxic than small ones, the many exceptions to this pattern (in particular, the frequent occurrence of large individuals free of ciguatoxin, and of small but highly toxic individuals [Figure 4])

suggest that bioaccumulation of ciguatoxin over time does not play an important role in *C. argus*. In contrast, ciguatoxicity and body size are strongly positively correlated in several other reef fishes (Lehane and Lewis 2000) (e.g., in the two-spot red snapper [*Lutjanus bohar*] in the Line Islands [Helfrich et al. 1968]). Although the latter pattern could offer the fishery management solution of marketing only fish below a predetermined "cut-off size," the divergent pattern in *C. argus* prevents the use of this approach to establish a safe fishery.

Ciguatoxin exerts negative effects that result in reduced condition in numerous species, including several freshwater and marine fishes (Lewis 2001, Landsberg 2002). In contrast, because fish condition was unrelated to toxicity in *C. argus* (Figure 5), ciguatoxic individuals of this species cannot be distinguished from nonciguatoxic individuals based on differences in weight-at-length. Condition is therefore not a useful factor in fishery management of *C. argus* in Hawai'i.

#### *The Patterns behind the Patterns*

The foodchain concept of ciguatera (Banner 1974) suggests that patterns of fish toxicity are linked to the frequency and extent of *G. toxicus* blooms, which to date are not well understood (Lehane and Lewis 2000). This section represents an attempt to elucidate bloom patterns in Hawai'i by deduction from the patterns in toxicity observed in *C. argus*. In particular, which pattern could account for the high within-site variability in toxicity and the seemingly unpredictable occurrence of toxic individuals? *Cephalopholis argus* lives in harems occupying home ranges with distinct spatial boundaries, which are actively defended against intrusion from neighbor harems. Home ranges are smaller (100 to 2,000 m<sup>2</sup> [Shpigel and Fishelson 1991]) than sample sites in this study (10,000 m<sup>2</sup>) (i.e., each sample site encompassed multiple home ranges). Gillespie et al. (1985) observed that ciguatera blooms can occur in small, localized patches. Presence of such a pattern in Hawai'i would mean that only some of the home ranges within sample sites overlap with blooms, and

result in highly variable uptake of ciguatoxin between *C. argus* from different harems at the same site. Variability in toxicity within sample sites observed here would thus be consistent with small, highly heterogeneous blooms being the norm in Hawai'i.

In conclusion, this study underlines the complexity of patterns of ciguatera in fish and suggests that *G. toxicus* blooms may be highly localized. The high prevalence of toxic *C. argus* individuals and the large variability in toxicity on all analyzed spatial scales, as well as the difficulty of predicting toxicity based on simple factors, currently stand in the way of a safe fishery for *C. argus* in Hawai'i.

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