Effects of Aquarium Collectors on Coral Reef Fishes in Kona, Hawaii

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Abstract: *No previous studies have conclusively documented the magnitude of the effect of aquarium collecting on natural populations. In Hawaii concern over the effects on reef fish populations of collecting for the aquarium trade began in the early 1970s, primarily in response to multiple-use conflicts between aquarium-fish collectors and recreational dive-tour operators. In 1997–1998 we used a paired control-impact design to estimate the effect of aquarium collectors. We compared differences in fish abundance along visual belt transects between collection sites, where collecting was known to occur, and control sites, where collecting was prohibited. To test the assumptions of our observational design, we surveyed a combination of species captured by aquarium collectors and those not captured. The extent of bleaching, broken coral, and coral cover was also surveyed. Seven of the 10 aquarium species surveyed were significantly reduced by collecting. The abundance of aquarium fish at collection sites ranged from 38% lower (*Chaetodon multicinctus*) to 75% lower (*C. quadrimaculatus*) than that at control sites. In contrast, only two of the nonaquarium species displayed a significant collection effect. There were no significant differences in damaged coral between control and collection sites to indicate the presence of destructive fishing practices. In addition, there were no increases in the abundance of macroalgae where the abundance of herbivores was reduced by aquarium collecting. Although our results suggest that aquarium collectors have a significant effect on the abundance of targeted aquarium fishes, better knowledge of the intensity and location of collecting activities is required to make a rigorous assessment of the effects of collecting on nearshore fish populations. Several lines of evidence suggest that the current system of catch reporting underestimates actual removals.*

Efectos de Colectores de Acuario sobre los Peces de Arrecifes de Coral en Kona, Hawai

Resumen: *La magnitud del efecto de la recolección para acuarios sobre poblaciones naturales no ha sido documentada concluyentemente en ningún estudio previo. La preocupación por los efectos de la recolección para el comercio de acuarios sobre las poblaciones de peces de arrecifes comenzó a principios de los años 70 en Hawai principalmente en respuesta a los conflictos de uso-múltiple entre colectores de peces para acuarios y operadores de viajes de buceo recreativo. En 1997–1998 utilizamos un diseño apareado de control de impacto para estimar el efecto de colectores de acuario. Comparamos diferencias en la abundancia de peces a lo largo de transectos visuales en sitios de recolección, donde se sabía que ocurría recolección, en relación con sitios control en los que la recolección estaba prohibida. Para probar los sopuestos de nuestro diseño observativo examinamos una combinación de especies capturadas por los colectores de acuario y otra de especies no capturadas. Se examinó también la extensión de blanqueo, coral roto y cobertura de coral. Siete de las 10 especies de acuario examinadas estaban reducidas significativamente por la recolección. Las abundancias de peces de acuario en sitios de recolección variaron de 38% menos (*Chaetodon multicinctus*) a 75% menos (*C. quadrimaculatus*) individuos que en los sitios control. En contraste, sólo dos de las especies no recolectadas para acuario mostraron un efecto significativo de recolección. No hubo diferencias significativas en el coral dañado entre los sitios control y de recolección que indiquen la presencia de prácticas pesqueras destructivas. Además, no hubo incrementos en la abundancia de microalgas donde la abundancia de herbívoros se redujo*

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por la recolección para acuarios. Aunque nuestros resultados sugieren que los colectores de acuarios tienen un efecto significativo sobre la abundancia de los peces de su interés, hace falta un mayor conocimiento de la intensidad y localización de las actividades de recolección para evaluar rigurosamente los efectos de la recolección sobre las poblaciones de peces costeros. Varias líneas de evidencia sugieren que el sistema actual de registros de captura subestima las remociones reales.

Introduction

Global trade in ornamental fishes is a major industry involving approximately 350 million fish annually with a value of $963 million (Young 1997). Although marine fishes account for only 10–20% of the total ornamental catch, rapid increases in the collection of marine species occurred in the 1980s (Andrews 1990). Moreover, whereas freshwater fishes are largely derived from cultivated stocks, <1% of marine fishes are cultivated, and the majority are taken from wild populations (Wood 2001). Almost all marine ornamental fish are of tropical origin, and many are removed from coral reefs. Because aquarium-fish collectors are highly selective and often capture large quantities of individuals of high value, the potential for overexploitation is high (Wood 1985, 2001).

Although numerous authors have discussed the potential effect of the aquarium trade on marine fishes in Australia (Whitehead et al. 1986), Djibouti (Barratt & Medley 1990), Hawaii (Taylor 1978; Walsh 1978; Randall 1987), Indonesia (Wood 1985), the Philippines (Albaladejo & Corpuz 1981), Puerto Rico (Sadovy 1992), and Sri Lanka (Edwards & Shepherd 1992), few studies have estimated the effects of collecting on natural populations. The most common approach has been to examine the rate of international trade (Lubbock & Polunin 1975; Wood 1985; Andrews 1990; Edwards & Shepherd 1992; Young 1997). Other approaches include qualitative or quantitative observations of fish densities in collected areas (Albaladejo & Corpuz 1981; Barratt & Medley 1990) or comparisons of collection rates to crude estimates of sustainable yield based on field estimates of density (Edwards & Shepherd 1992). Although Nolan (1978) concluded that aquarium collectors did not have a significant effect on natural populations in Hawaii, the results are suspect because of problems with suitable controls in the observational design. Thus, no study has conclusively documented the magnitude of aquarium collecting on natural populations, despite repeated calls for such studies to help develop sustainability in the aquarium trade (Walsh 1978; Wood 1985; Young 1997).

Many of the marine ornamentals originating from the United States are captured in Hawaii, which is known for its high-quality fishes and rare endemic species of high value (Wood 1985). Concern over the effects of aquarium collecting on reef fish populations arose in the early 1970s, principally for the Kona coast of the island of Hawaii (Taylor 1978; Walsh 1978). Controversy has centered on multiple-use conflict between aquarium-fish collectors and recreational dive-tour operators over apparent declines in nearshore reef fishes (Taylor 1978; Grigg 1997; Young 1997; Clark & Gulko 1999). These concerns prompted the Hawaii Division of Aquatic Resources (DAR) to instigate monthly collection reports from all permit holders in 1973 (Katekaru 1978), and these reports have been the primary basis for management of the aquarium industry in Hawaii (Miyasaka 1994, 1997).

Based on collection reports, about 90,000 fish, with a reported total value of $50,000, were harvested in 1973 under 75 commercial permits (Katekaru 1978). In 1995 the annual harvest had risen to 422,823 fish (total value of $844,843) under 160 commercial permits (Miyasaka 1997). Although aquarium collecting was primarily centered on the island of Oahu in the 1970s and 1980s, the Kona and Milolii areas of the island of Hawaii became the predominant collecting areas in the late 1980s and early 1990s. Between 1993 and 1995, the harvest from Kona increased 67% and accounted for 59% of the state harvest with 47 commercial permits (Miyasaka 1997).

Although 103 fish species were collected statewide in 1995, over 90% of the harvest was focused on 11 species: the Achilles tang (*Acanthurus achilles*), Potter's angelfish (*Centropyge potteri*), raccoon butterflyfish (*Chaetodon lunula*), multiband butterflyfish (*Chaetodon multicinctus*), ornate butterflyfish (*Chaetodon ornatissimus*), four-spot butterflyfish (*Chaetodon quadrimaculatus*), goldring surgeonfish (*Ctenochaetus strigosus*), longnose butterflyfish (*Forcipiger flavissimus*), clown tang (*Naso lituratus*), moorish idol (*Zanclus cornutus*), and yellow tang (*Zebrasoma flavescens*), with *Z. flavescens* accounting for 52% of the total collection (Miyasaka 1997; DAR, unpublished data). Thus, given the increasing rate of removal focused on a small number of species, the potential for overexploitation of these reef fishes is high.

In addition to the direct effects of collecting fish for the aquarium trade, there has been considerable concern about destructive practices associated with fish capture. These practices include the use of poisons and explosives to capture fish and damage to coral during collecting (Lubbock & Polunin 1975; Wood 1985, 2001; Randall 1987; Johannes & Riepen 1995; Young 1997). An additional concern is the effect on the coral reef community of large reductions in the number of herbivorous fishes, such as the yellow tang. Because herbivorous fishes may control the abundance of algae on coral reef ecosystems, their removal may cause shifts in community structure (reviewed by Hixon 1997).

Our goal was to obtain quantitative estimates of the effects of aquarium collectors on fishes on the Kona coast of Hawaii. Moreover, in response to reports of broken and bleached coral associated with destructive fishing practices, we also investigated changes in the associated coral reef habitat at each study site.

Methods

Observational Design

We used a paired control-impact design to estimate the effect of aquarium collectors on reef-fish abundance. The magnitude of the effect was estimated by comparing fish abundance at collection sites where aquarium-fish collecting was known to occur with geographically adjacent control sites where collecting was prohibited. Because the study was initiated after collection had begun, we assumed there were no differences between control and collection sites in the abundance of aquarium fishes prior to the onset of aquarium harvesting (i.e., their natural abundances were similar) (Osenberg & Schmitt 1996). We also assumed that all differences between the control and collection sites were due to aquarium-fish collecting and not other factors, such as fishing. As part of our study design, we gathered data to test these assumptions.

We established four study sites that served as two replicate control-collection pairs (Fig. 1). One pair of study sites was located at Honokohau (lat 19°40.26′N, long 156°01.82′W) and Papawai (lat 19°38.83′N, long 156°01.38′W). Papawai, a fishery management area (FMA) where collection of aquarium fishes has been prohibited since 1991 (Department of Land and Natural Resources 1996), served as our control site. Honokohau was frequented by aquarium collectors and served as a collection site. This pair of sites is hereafter referred to as the Honokohau study area. The second pair of sites was located at Red Hill North (lat 19°32.90′N, long 155°57.74′W) and Red Hill South (lat 19°30.32′N, long 155°57.17′W). Red Hill South is an FMA where the collection of aquarium fishes has been prohibited since 1991 (Department of Land and Natural Resources 1996), and it served as our control site. Red Hill North was frequented by aquarium collectors and served as a collection site. This pair of sites is hereafter referred to as the Red Hill study area.

At each study site, four permanent 50-m transect lines were established at 10- to 15-m depths by installing stainless steel eyebolts at the beginning and end points of each line. Transects served as reference lines for both the fish and coral surveys. We used a visual strip-transect search method to estimate fish abundances (Sale & Douglas 1981). A pair of divers swam side by side down either side of the transect line and counted all fishes seen within a corridor 3 m wide and extending to the surface.

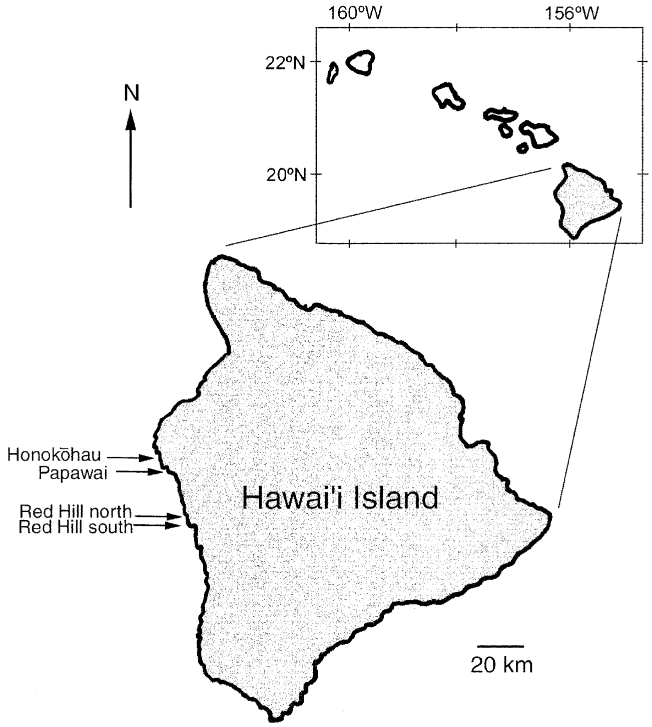

Figure 1. Map of study sites located off the island of Hawaii.

Surveys began at Honokohau in March 1997 and at Red Hill in September 1997 and ended at both areas in December 1998. All sites were sampled at 2- to 5-month intervals, for a total of eight surveys at Honokohau and five at Red Hill. During each survey we estimated the abundance of 21 fish species. These species included 11 aquarium fishes selected on the basis of high levels of capture, accounting for over 92% of the fish collected in Hawaii (DAR, unpublished data). Due to uncertainty in species identification, we pooled longnose butterflyfish as *Forcipiger* spp., which may include both *F. longirostris* and *F. flavissimus*, although most of the fish counted were probably the latter (personal observations). The remaining 10 fish species we surveyed were not targeted by aquarium collectors but were in guilds similar to those of collected species. These species were selected to provide tests of the assumptions of the observational design. Although the assumption of no difference between the control and collection sites prior to the study could not be tested directly, one prediction of this assumption was that uncollected species should not differ between control and collection sites. Accordingly, *Acanthurus nigrofuscus, A. nigroris, A. triostegus, Chaetodon lunulatus, C. unimaculatus, Paracirrhites arcatus, P. forsteri, Plectroglyphidodon johnstonianus, Stegastes fasciolatus*, and *Thalassoma duperrey* were also surveyed. The overall structure of the fish communities at control and collection sites should also be similar if the sites are ecologically similar. Thus, to test this prediction, during the next-to-last survey at each site all reef fishes seen were counted and identified to species.

Of the 21 species surveyed, 2 species (*C. lunula* and *C. unimaculatus*) were too rare for analysis, with one individual of each species observed during the entire study. These species were excluded from further analysis.

Divers were undergraduate students who had completed a rigorous coral reef monitoring course and were trained in species identification and standardized survey methodology (Hallacher & Tissot 1999). To minimize observer bias, the same diver pairs were used at each control-collection study site during each survey. Divers did, however, vary among surveys. To minimize temporal variation, all surveys were conducted during midday (generally from 0900 to 1500 hours), and both control and collection sites were surveyed either on the same day or on consecutive days.

To provide an additional test of similarities between control and collection sites and to test for destructive harvesting methods associated with aquarium collecting, we also conducted surveys on corals, macroalgae, and the general substratum of each transect. Divers took photographs of the substratum with a Nikonos V camera with a 15-mm lens attached to a PVC quadrat covering an area of approximately 0.50 m^2 (0.8 × 0.6 m). Along each 50-m transect line, 18 photographs were taken at randomly selected coordinates at all study sites at both the beginning and end of the study. Percent cover estimates were made of all living and nonliving substrata in each photograph by projecting the slide over a series of 50 random coordinates and recording the observed substratum under each point. In addition, the percent cover of bleached and broken coral was estimated for each slide. We identified broken coral as recently damaged coral fragments with no algal overgrowths. We identified bleached coral as unusually pale portions of the coral colony located at the tips or edges of coral colonies. To minimize observer bias, a single observer analyzed all the photographic data.

Data Analysis

We analyzed fish data with two-way repeated-measure analysis of variance (ANOVA). Fixed factors included control and collection study sites ("effect"), replicate study areas (Honokohau and Red Hill or "area"), and the interaction between effect and area. Although each survey provided an estimate of the level of collection through control-collection differences, because the same individual fish may have been counted between surveys, surveys were treated as a random, repeated measure in the analysis (Zar 1996). A significant "collection" effect indicates a similar difference between control and collection sites at both study areas. A significant "collection-area" effect indicates a difference between control and collection sites that varies between study areas. A significant "area" effect indicates spatial differences in abundance among study areas. Because our goal was to obtain estimates of the magnitude of collection effects, only factors associated with a significant collection effect were interpreted (e.g., only collection or collection-area interactions, not temporal variation).

We calculated the percent difference in abundance as the difference between control and collection sites using the formula

$$\text{percent difference} = \frac{D_{\text{collection}} - D_{\text{control}} \times 100}{D_{\text{control}}},$$

where D is density expressed as number of individuals per 100 m^2. Thus, a negative percent difference associated with a significant collection effect indicates the presence of significantly fewer fish at collection sites than at control sites, whereas a positive value indicates the opposite.

We analyzed coral cover, bleaching, and breakage data with a three-way ANOVA, with effect, area, and time (beginning of study vs. end of study) as fixed factors. Data from photoquadrats along transects were treated as a random nested factor.

Prior to all analyses, we examined data for homogeneity of sample variances. We used transformed data in cases where the original data demonstrated heteroscedasticity. We did not examine normality because samples were small ($n = 4$) and normality is not an important assumption for ANOVA (Box 1953). Following ANOVA, we used the procedure described by Underwood (1997) to pool nonsignificant factors.

We used species richness (S), evenness (J), and the Shannon-Wiener composite diversity index (H') to examine overall fish and coral-algal-substratum community structure. We compared community structures by using the percent similarity index (Krebs 1986). These indices tested the prediction that the overall structure of the fish and coral-algal-substratum communities at control and collection sites would be similar.

Results

There was a significant difference in the abundance of aquarium fishes between control and collection sites but no differences in the abundance of nonaquarium species between these sites (Table 1, Fig. 2). Seven of the 10 aquarium species displayed a significant collection effect in the two-way repeated-measure ANOVA. In contrast, only two of the nine nonaquarium species, *P. arcatus* and *S. fasciolatus,* displayed a significant collection effect (Table 1, Figs. 3 & 4).

Of the 10 aquarium species, three exhibited a significant collection-only effect (Fig. 3). All of these species

Table 1. Mean (SE) percent change in fish abundance between sites with aquarium-fish collection and without aquarium-fish collection for each study area.

		Percent change[a]								
		overall		*Honokohau*		*Red Hill*		p^b		
Species	*df*	*mean*	*SE*	*mean*	*SE*	*mean*	*SE*	*effect (E)*	*area (A)*	*E ∗ A*
Aquarium species										
Chaetodontidae										
Chaetodon multicinctus	1,88	−38.2	6.57	−42.0	9.05	−32.3	9.63	0.02	–	–
Chaetodon ornatissimus	1,88	−39.5	20.2	−37.0	25.8	−43.4	36.4	–	<0.01	–
Chaetodon quadrimaculatus	1,87	–	–	−94.4	4.81	21.8	94.7	0.01	<0.01	–
Forcipiger spp.	1,86	–	–	−60.9	6.20	−43.6	19.5	0.01	<0.01	0.01
Pomacanthidae										
Centropyge potteri	1,87	–	–	−29.2	15.8	−73.1	12.3	0.03	<0.01	–
Acanthuridae										
Acanthurus achilles	1,88	−57.1	10.2	−64.0	13.3	−46.0	16.3	<0.01	–	–
Ctenochaetus strigosus	1,88	−14.7	8.20	−33.6	4.96	15.4	9.65	–	–	–
Naso lituratus	1,88	31.2	34.2	66.5	50.8	−25.2	25.1	–	–	–
Zebrasoma flavescens	1,87	–	–	−49.8	6.89	−43.2	6.47	<0.01	<0.01	–
Zanclidae										
Zanclus cornutus	1,88	−46.5	11.9	−45.9	16.1	−47.5	19.2	<0.01	–	–
Nonaquarium species										
Cirrhitidae										
Paracirrhites arcatus	1,86	–	–	−12.1	14.1	−75.3	3.16	<0.01	<0.01	<0.01
Paracirrhites forsteri	1,88	58.4	59.3	168.3	85.7	−73.6	14.5	–	–	–
Chaetodontidae										
Chaetodon lunulatus	1,88	−70.0	10.4	−70.0	10.4	–	–	–	–	–
Pomacentridae										
Plectroglyphidodon johnstonianus	1,88	−31.3	12.6	−12.1	15.2	−61.9	14.2	–	–	–
Stegastes fasciolatus	1,87	–	–	488	281	50.0	22.4	0.04	<0.01	
Labridae										
Thallasoma duperrey	1,88	17.4	12.4	31.6	17.0	−5.3	13.2	–	–	–
Acanthuridae										
Acanthurus nigrofuscus	1,87	27.3	22.8	15.2	26.7	46.7	43.5	–	<0.01	–
Acanthurus nigroris	1,88	67.2	63.6	−18.0	36.7	186.5	140.0	–	–	–
Acanthurus triostegus	1,88	−4.26	20.8	−5.68	32.4	<0.10	<0.10	–	–	–

[a]*A negative mean percent change indicates fewer individuals at effect relative to control sites.*
[b]*The* p *values and degrees of freedom (df) are reported for a two-way repeated-measure ANOVA on density.*

displayed a similar significant difference between control and collection sites at both study areas in which individuals were significantly more abundant at the control sites. These species, and the magnitude of their overall percent difference at collection sites, were as follows: *A. achilles,* −57%; *C. multicinctus,* −38%; and *Z. cornutus,* −47% (Table 1). (The negative percent indicates fewer individuals at collection than at control sites.)

Four species exhibited a significant collection and area effect (Table 1; Fig. 4). These species displayed significant differences between control and collection sites, but their overall abundance varied between study areas. Both *C. potteri* and *S. fasciolatus* were more abundant at Honokohau than at Red Hill, whereas *C. quadrimaculatus* and *Z. flavescens* were more abundant at Red Hill than at Honokohau (Fig. 4). The magnitude of their overall percent difference (in parentheses) at collection sites were as follows: aquarium species: *C. potteri,* −56%; *C. quadrimaculatus,* −75%; *Z. flavescens,* −46%; nonaquarium species: *S. fasciolatus,* +64% (Table 1).

Two species exhibited a significant collection-area interaction effect, where differences between control and collection sites varied between study areas (Table 1; Fig. 4). In the aquarium species *Forcipiger* spp., percent difference was greater at Honokohau (−61%) than at Red Hill (−44%). In contrast, the nonaquarium species *P. arcatus* displayed a lower percent difference at Honokohau (−18%) than at Red Hill (−75%) (Table 1; Fig. 4).

The overall fish community structure of the paired control and collection sites was remarkably similar. The H' diversity index at control and collection sites, respectively, was 1.18 and 1.16 at Honokohau and 1.16 and 1.17 at Red Hill. Similarly, the evenness index at control and collection sites, respectively, was 0.72 and 0.69 at Honokohau and 0.69 and 0.69 at Red Hill. At Honokohau, 44 species were seen at the control site, whereas 48 species were seen at the collection site. Forty-nine species were observed at both control and collection sites at Red Hill. Overall fish densities were 27% higher at Red Hill (mean density = 146 fish/100 m^2) than at Honokohau

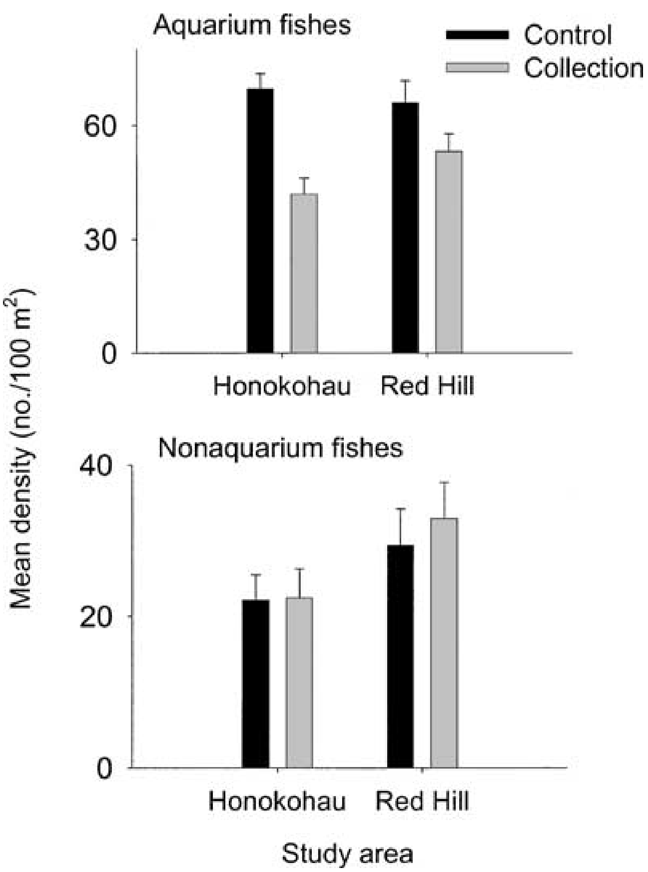

Figure 2. Mean fish density (±1 SE) for pooled aquarium and nonaquarium species at control and collection sites in both study areas.

(107 fish/100 m^2). Accordingly, control-collection pairs exhibited higher percent similarity (0.85–0.88) than that among study areas (0.75).

Live coral cover was significantly different between control and collection sites and between initial and final surveys, and there was a significant collection-survey interaction (all $p < 0.05$; df = 1,566; Fig. 5). Coral cover at all sites increased an average of 2.8% per year and was similar at both Honokohau sites but higher at the collection than at the control site at Red Hill. At Red Hill, coral cover increased 4.6% at the collection site and 2.3% at the control site (Fig. 5).

The amount of bleached coral was significantly different among areas ($p < 0.01$; df = 1,561): mean cover of bleached coral was 2.8% at Honokohau and 4.6% at Red Hill (Fig. 5). No other factors or interactions were significant. The percent cover of broken coral exhibited a significant difference among surveys ($p = 0.01$, df = 1,559): the mean cover of broken coral was 12% at the beginning of the study and 17% at the end (Fig. 5). No other factors or interactions were significant.

The abundance of macroalgae was low at all sites. No macroalgae was seen in the photoquadrats at Honokohau, and cover was <0.01% at the Red Hill sites. In contrast, coralline algae was fairly common at all sites.

The overall coral-substratum community structure of paired control and collection sites was similar. Species diversity, evenness, and richness were similar at all sites, and control-collection pairs exhibited higher percent similarity in community structure (79–82%) than that among study areas (63%).

Discussion

Seven of the 10 fishes targeted by the aquarium trade were significantly lower in abundance in areas subjected to collecting than in areas where collecting was prohibited. The magnitude of these differences ranged from −38% for *C. multicinctus* to −75% in *C. quadrimaculatus*. In contrast, only two of the nine nontarget species were significantly less abundant in collecting than in control areas, bolstering the conclusion that aquarium collectors have significant effects on the abundance of targeted fishes on the Kona coast of Hawaii.

Evaluation of Assumptions

The most critical assumption made when estimating the effects of differences between control and collection sites is that the parameter of interest is similar at both sites prior to the effect (Osenberg & Schmitt 1996). Otherwise, spatial variation in initial abundance can confound control-effect differences. For example, Nolan's (1978) study on aquarium collectors compared a collection site from the Kona area to a control, or "seldom-collected" site about 30 km away in north Kohala. His conclusion that collectors have no significant effect on abundance was based on finding a greater number of aquarium fishes at the collection site than at the control site. However, given the large distance between control and collection sites and the fact that aquarium collectors operated at both sites, this conclusion is unwarranted because of the high potential for confounding spatial variation with potential human effects.

Pairs of geographically adjacent sites minimize spatial variation, but this potential problem remains for all control-effect designs if there are no data prior to the onset of the effect (Osenberg & Schmitt 1996). Although the assumption of no prior differences cannot be tested explicitly, it can be inferred from several lines of evidence, including examination of spatial variation in fishes that are ecologically similar but not subjected to collecting and comparisons among the habitat of both sites. To evaluate this assumption, we used a combination of nontarget species that were ecologically similar to target species, species that were indicators of particular habitats, and examination of the coral habitat.

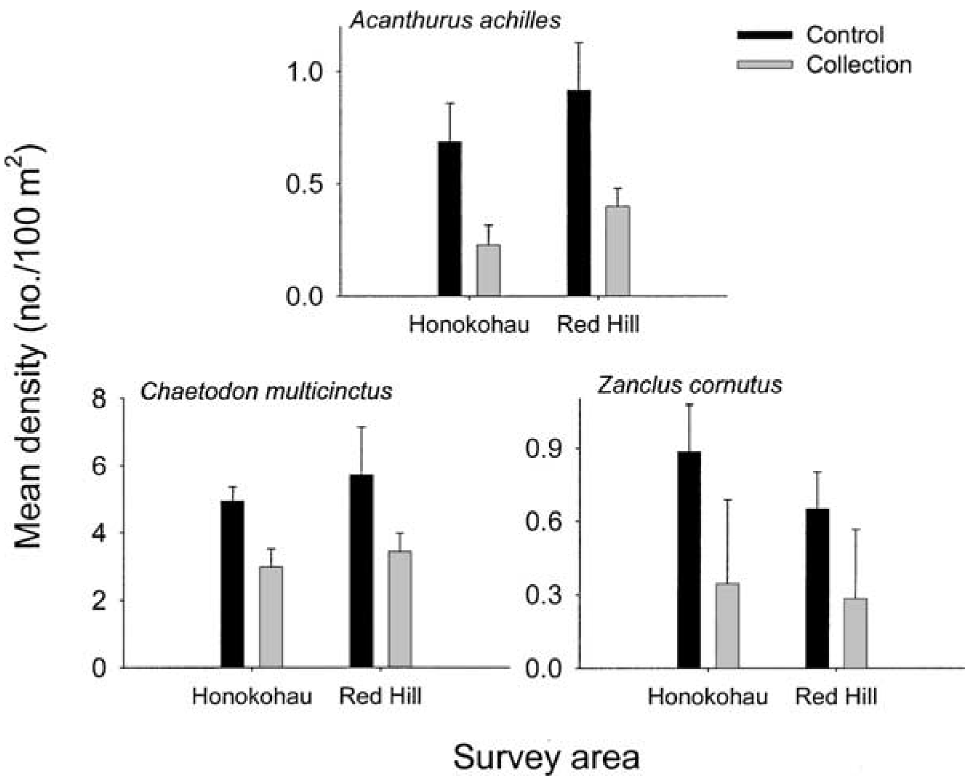

Figure 3. Mean fish density (±1 SE) for aquarium species that displayed significant collection-only effects. These three species are targeted by collectors of aquarium fish.

For example, the nontarget brown surgeonfish (*A. nigrofuscus*) and the targeted yellow tang (*Z. flavescens*) are both generalized herbivores that feed on filamentous algae, occupy the same depth ranges and habitats, and exhibit similar patterns of spawning and larval recruitment (Randall 1985; Walsh 1987; Lobel 1989). Yellow tangs were 47% less abundant at collection than at control sites, whereas brown surgeonfish did not differ significantly between the sites. Similarly, no differences were observed between control and effect sites among species that feed or live in close association with coral (*C. lunulatus, P. johnstonianus*), whereas their targeted counterparts (*C. multicinctus, C. ornatissimus, C. quadrimaculatus)* exhibited significantly lower abundances at effect sites. Moreover, nontarget species with generalized diets and distributions across the reef (*A. nigroris*, *A. triostegus*, *P. forsteri, S. fasciolatus, T. duperrey*) also did not vary, whereas ecologically similar aquarium species (*A. achilles*, *C. potteri*, *Z. cornutus*) were significantly different.

An additional line of evidence supporting the assumptions of our observational design is that the overall fish community structure of control and collection sites was remarkably similar in species diversity, richness, and evenness, with the percent similarity index ranging from 85% to 88%. At the habitat level, control and effect sites were also similar with respect to the diversity of coral, algae, and nonliving substratum composition, with percent similarity ranging from 79 to 82%. Thus, at several levels there was considerable support for the assumption that the reef communities were similar at both control and effect sites.

Another important assumption is that differences in abundance between control and effect sites were due to aquarium-fish collecting and not other processes that selectively affect these species, such as fishing. We addressed this assumption by selecting collection sites largely inaccessible from shore, thereby minimizing the effects of shore-based fishing. Moreover, both the aquarium fish *C. strigosis* and the nontarget species *A. triostegus* are commercially and recreationally fished in Hawaii. However, *A. triostegus* did not vary significantly between control and effect sites, indicating that fishing impacts were not significantly different in these areas.

Illegal collecting at control sites would also confound control-effect differences. Although some illegal collecting may be occurring in Kona, it is probably uncommon and unlikely to have a significant effect on fish abundances in existing protected areas (W. Walsh, personal communication). Thus, the only clear difference between the control and effect sites in this study was aquarium-fish collecting, as evidenced by the significantly lower abundance of aquarium species at the collection sites.

Indirect Effects of Aquarium Collecting

Destructive practices associated with the collection of fish are common and include breaking coral to capture

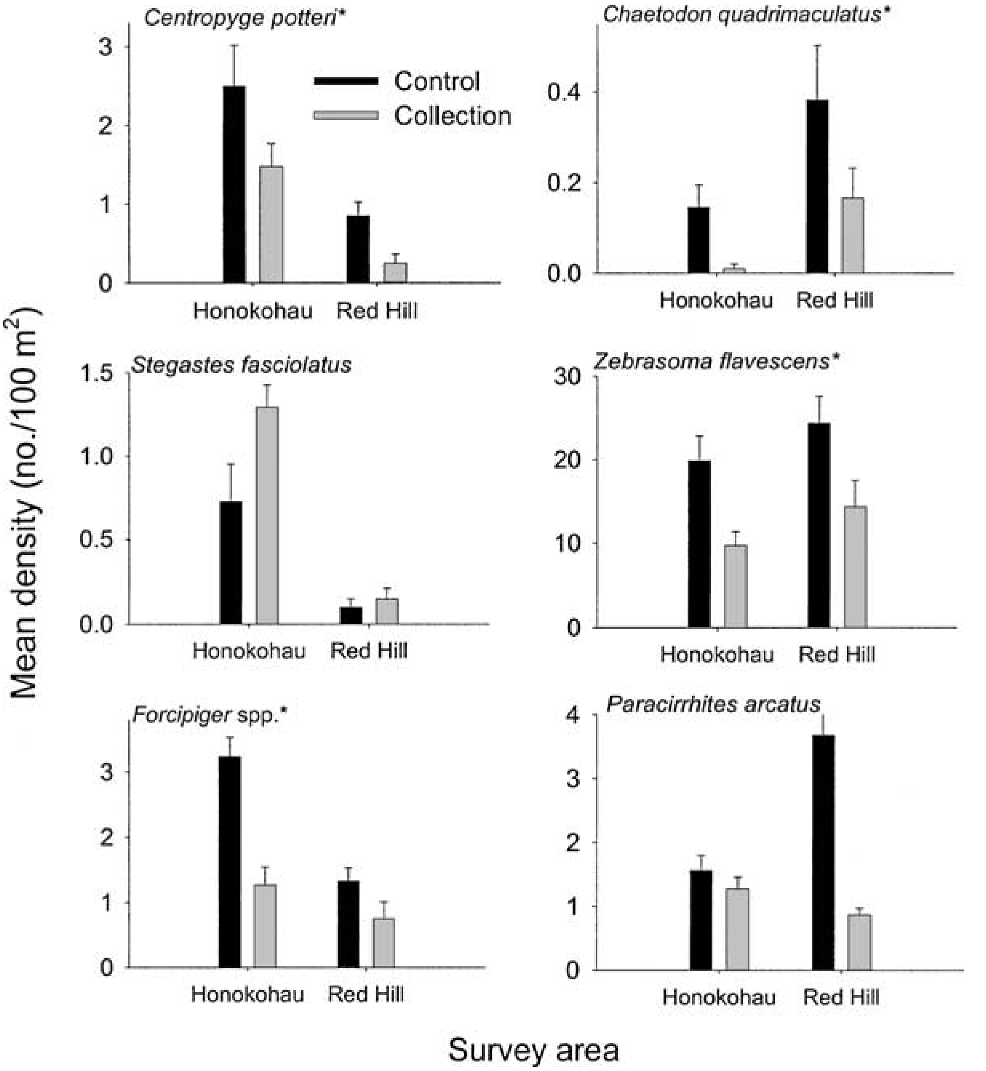

Figure 4. Mean fish density (±1 SE) for aquarium and nonaquarium species that displayed significant collection, area, or collection-area interaction effects. Species targeted by aquarium collectors are indicated with an asterisk (*).

live animals, snagging nets on coral, and using bleach and cyanide to stun target species (Randall 1987; Johannes & Riepen 1995; Wood 2001). Both the breaking of coral and the use of bleach to collect aquarium fish have been observed in Hawaii, although they are prohibited by law (W. Walsh, personal communication). We examined differences in coral cover and the incidence of broken and bleached coral as indicators of these effects. Although some differences were noted in the extent of bleaching and coral cover among study areas, there were neither consistent nor significant differences between control and effect sites that would indicate the presence of destructive fishing practices.

An issue of more general interest is the extent to which large-scale removal of herbivorous fishes can alter reef community structure. Four of the aquarium fishes (*A. achilles, C. potteri, N. lituratus, Z. flavescens*) accounted for 61% of the herbivorous fishes at the Honokohau and Red Hill control sites. These species were reduced in overall mean abundance by 32% at the effect sites relative to the control sites. Given that herbivorous grazers control algal populations that can overgrow corals (review by Hixon 1997), it is of interest to examine the community structure in areas where herbivory is reduced. Macroalgae were rare at all study sites, suggesting that reductions in herbivory associated with aquarium-fish collecting did not have a significant effect on this group of algae. However, our study may not be a good test of this hypothesis for several reasons. First, based on the model of Littler and Littler (1984), algae may be limited more by nutrients than herbivores. Second, with the exception of *N. lituratus*, the herbivorous aquarium fishes fed primarily on filamentous algae, not macroalgae. Filamentous algae are not easily surveyed by our photographic methods, so we collected no data on their abundance. Lastly, other reef herbivores, such as sea urchins, may control macroalgal populations, so reductions due to aquarium collecting may not be functionally significant. Given the global scope of aquarium harvesting on coral reefs, this question warrants further investigation.

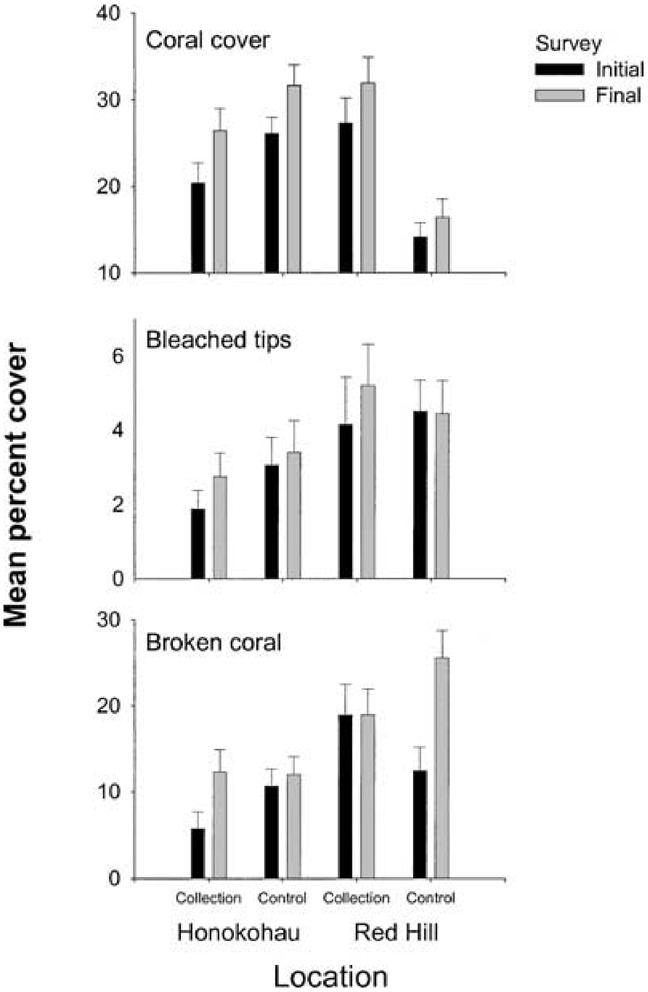

Figure 5. Changes in the mean percent (±1 SE) coral cover, bleached coral, and percent broken coral at control and collection sites in each study area at the beginning and end of the study.

Implications for Fishery Management

Aquarium collectors had significant effects on 7 of the 10 species of reef fish we examined. To determine whether these abundance patterns were clearly due to aquarium fish collecting will require better knowledge of the intensity and location of collecting activities. Although there are currently about 50 permits issued to collectors in western Hawaii, the number of active collectors is likely to be lower (W. Walsh, personal communication). The current system of catch reporting in Hawaii is limited to monthly collecting reports, with the 235-km coastline of western Hawaii divided into three large sections (Miyasaka 1997). Moreover, because these reports are not compared with actual catches, there is no assurance that the reports are accurate. Analysis of the current catch reports indicates that a significant portion of the monthly reports are not filed, although collectors are required to file a report even if no fish are collected (W. Walsh, personal communication). More specific information about location, catch, and effort are essential to support the results of this study. Moreover, random monitoring of collectors' catch reports would provide some level of quality assurance for these data.

We focused on major targeted species and did not collect data on rare species. Of the 103 species collected statewide, many are considered uncommon or rare and could also be threatened by overexploitation. For example, based on 1994–1995 collection reports, 204 Tinker's butterflyfish (*Chaetodon tinkeri*), a rare, deep-water species, were collected in western Hawaii and may possibly be overcollected. Other rare aquarium species, such as the Hawaiian turkeyfish (*Pterois sphex*) and the flame angelfish (*Centropyge loricula*), are also of concern and should be considered in future monitoring and management plans.

The magnitude and extent of the effects we documented and their relationship to the sustainability of aquarium collecting are problematic but warrant further investigation. In response to continued public outcry over the collection of aquarium fish, the Hawaii state legislature passed a bill in 1998 that focused on improving management of reef resources by establishing the West Hawaii Regional Fishery Management Area. A major component of the bill is to improve management of the aquarium industry by declaring a minimum of 30% of the western Hawaii coastline as fish replenishment areas (FRAs), protected areas where aquarium-fish collecting is prohibited. Based largely on input from the West Hawaii Fisheries Council, a community-based group of individuals, a network of nine FRAs was established in January 2000 as part of a plan to manage the aquarium industry. Current efforts are focused on monitoring these areas to evaluate the effectiveness of the reserve network as a fishery management tool.

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