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CORAL REEFS IN KANEOHE BAY, HAWAII: TWO CENTURIES OF WESTERN INFLUENCE AND TWO DECADES OF DATA

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ABSTRACT

Kaneohe Bay, an estuarine and coral reef ecosystem on the windward coast of Oahu, Hawaii, is often cited as an exemplary illustration of the resiliency of a natural system to environmental insult. Impacts to Kaneohe Bay coral reefs have resulted from various effects of natural processes such as freshwater flooding and erosional runoff. Additional impacts to the reef communities have resulted from anthropogenic activities concomitant with land use changes. Initially, agriculture and grazing, and subsequently urbanization, led to increased soil erosion and sedimentation, extensive reef dredging, channelization of streams, and eutrophic conditions ensuing from sewage discharges into the bay. Most of these land use changes occurred during the 1940's through 1970's, prior to and precluding comprehensive and/or quantitative studies of pristine reef conditions in the bay. One of the best documented anthropogenic changes in Kaneohe Bay focused on physical and ecological responses during a one-year period following sewage diversion. After twenty-five years of discharge, two large sewage outfalls were diverted from the bay in 1977–1978, followed by rapid and dramatic decreases in nutrient levels, turbidity, and phytoplankton abundance in the previously affected areas. There was a corresponding change in community structure from one dominated by the green bubble alga, *Dictyosphaeria cavernosa*, and filter or deposit feeders, to one or more closely approaching the "coral gardens" described by Kaneohe Bay visitors prior to W.W.II. By 1983, *D. cavernosa* had decreased to ¼ of its previous (1970) abundance while coral cover had more than doubled. The last point-source sewage discharge into the bay was diverted in 1986. Recovery of coral-dominated reef communities in Kaneohe Bay was expected to continue with a further decrease in algal cover and an increase in coral abundance. However, a 1990 survey indicated that, on a baywide basis, 1) algal cover had increased between 1983–1990 surveys, and 2) the rate of coral recovery established by surveys in 1970 and 1983 had slowed or, in some cases, reversed. Percent cover of *D. cavernosa* increased at 5 of 15 sites, while live coral showed slight to significant declines at nine sites compared to 1983 levels. This paper summarizes the recent history of Kaneohe Bay reefs in light of anthropogenic alterations, describes changes in reef communities in the bay over the past two decades, and discusses the potential environmental factors involved in these changes.

Kaneohe Bay has been one of the most intensively studied coral reef systems in the world. As one of the premier locations for tropical marine research and the site of Hawaii Institute of Marine Biology, various aspects of the diverse flora and fauna in its estuarine and reef habitats have been described in over 1,000 publications, reports, theses, and dissertations.

Environmental Setting.—The physical setting of Kaneohe Bay has been detailed in numerous publications (Banner, 1974; Cox, 1973; Smith et al., 1973, 1981; Devaney et al., 1982; Holthus, 1986; Jokiel et al., 1991; Hunter, 1993). Located on the northeast (windward) coast of Oahu, it is the largest embayment in the Hawaiian archipelago, approximately 13.5 km at its maximum length, up to 4.5 km wide from shore to the outer barrier reef, and bordered by 30.7 km of shoreline (Fig. 1). The seaward boundary of much of the calm, inner bay (1.1 to 3.6 km in width) is defined by the only barrier reef in the Hawaiian archipelago (and the northern-most barrier reef in the Pacific), cut by two natural channels. A dredged ship channel runs the length of the bay, connecting the

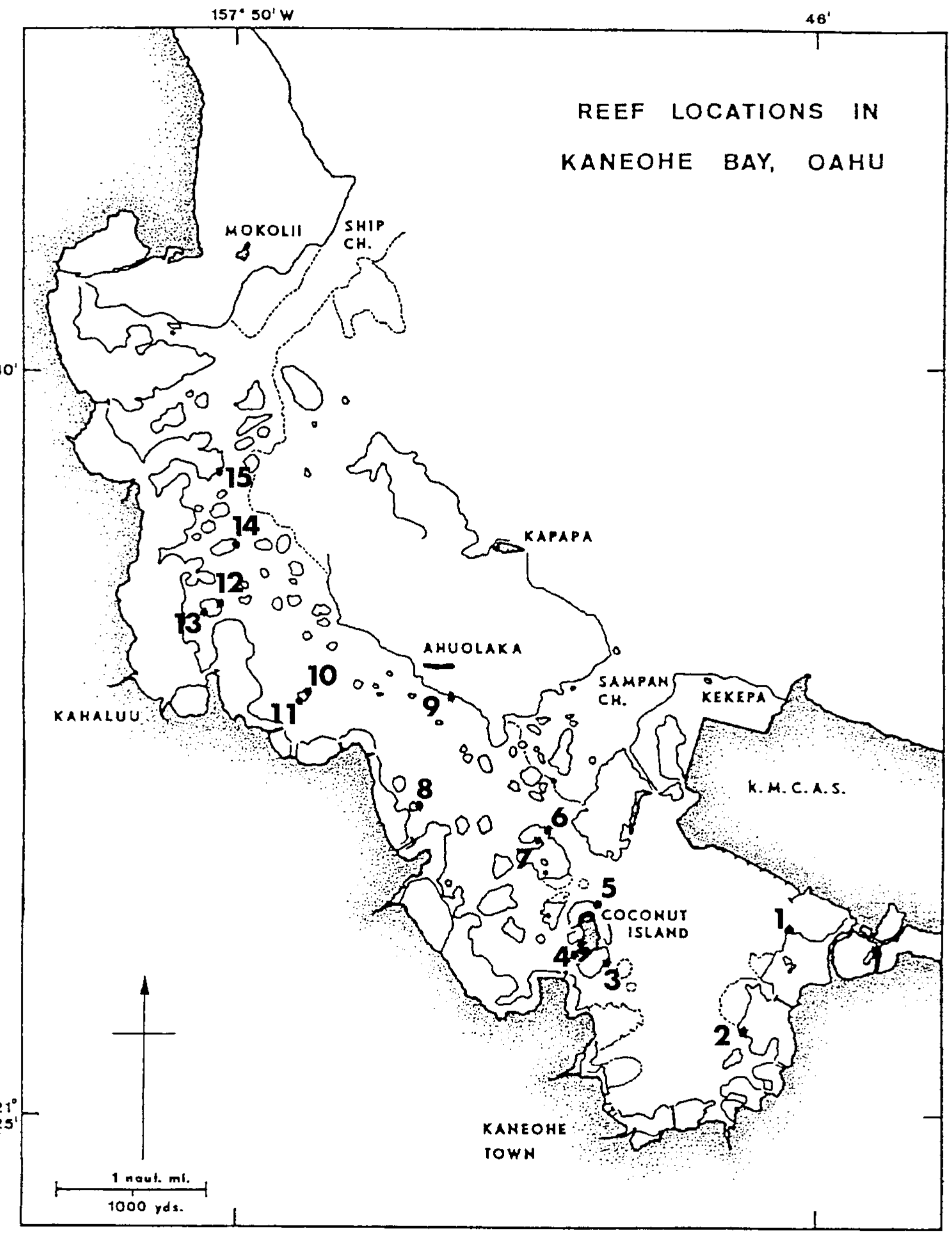


Figure 1. Map of Kaneohe Bay, Oahu and reef survey sites.

north (Mokoli'i Ship Channel) and south (Sampan Channel) passages and allowing deep-draft access.

Kaneohe Bay can be divided for purposes of discussion into regions based on estuarine and oceanic influences (from shoreward to seaward) consisting of the inner bay (fringing reefs, lagoon, and lagoonal patchreefs) and outer bay (barrier reef flats and slope). In addition, the bay can be characterized by distinct north-south gradients in rural to urbanized watersheds. Most of the population in the surrounding watersheds is concentrated in the southern sector. The bay waters adjacent to these watersheds have the most restricted water circulation and have also been the most affected by the impacts of urbanization.

Much of the shoreline of the bay is bordered by shallow fringing reefs punctuated by the entry of nine perennial streams and their associated estuarine components. Scattered throughout the bay, but concentrated near the channels, are 60 patch reefs ranging in size from 1.9×10^3 m^2–320.8×10^3 m^2. Mean depth of the inner bay is 8.4 m, with a maximum depth of about 17 m. Water circulation in the bay involves net transport of ocean seawater across the barrier reef toward shore, with most of the water exiting the bay through the two channels (Bathen, 1968). Depth-averaged bay salinity approximates oceanic conditions (35 ppt), with occasional decreases in salinity (to 15 ppt, Jokiel et al., 1993) occurring in near-shore waters due to storm runoff. Mean monthly seawater temperature in the bay varies from 19.5–28.9°C, about 0.7°C above average ocean temperatures.

Watersheds adjacent to Kaneohe Bay have a combined area of 97 km^2. These watersheds consist of gently rolling hills and valleys that abut nearly vertical cliffs at their landward boundaries. Deposition of land-derived sediments in the bay has been substantial due to soil erosion from natural processes, and from clearing for agriculture and construction activities (Smith et al., 1973; Bartram, 1976; Devaney et al., 1982; Hill and DeCarlo, 1991; Jokiel et al., 1991). Annual rainfall in the Kaneohe region averages 140–240 cm/year and total stream discharge rate is approximately 214,000 m^3/day, although episodic storms may result in flow rates almost an order of magnitude higher (up to 2,120,000 m^3/day; Jokiel et al., 1993). Severe rainfall events in 1965 and 1987 have led to significant mortality of benthic organisms on shallow (<120 cm) reef flats and slopes (Banner, 1968; Holthus et al., 1989; Jokiel, et al., 1993). Coral mortality due to the most recent (1987) freshwater "kill" extended to a depth of 120 cm below reef crests, particularly near stream mouths. As coral species show differential sensitivities to reduced salinities, episodic freshwater kills on Kaneohe Bay reefs appear to play an important role in structuring these reef communities.

Historical Overview.—The recent history of Kaneohe Bay (post-western contact in 1778) involves a series of changes in use of the bay and its surrounding watersheds (Devaney et al., 1982). From the mid-1800's through the early part of this century, land usage changed from primarily indigenous vegetation and taro patches to cultivation of pineapple, sugarcane, rice, and pasturage for cattle, horses, and goats. Just prior to and during World War II, the U.S. Navy constructed a military base on Mokapu Peninsula at the southern end of the bay (now Kaneohe Marine Corps Air Station), and dredged over 15 million cubic yards of reef from the bay to use as fill for approximately 280 acres of the new facility (Hollett and Moberly, 1976). The ship channel and numerous fringing and patch reefs were dredged for seaplane runway areas during this time period. Between bathymetric surveys conducted in 1927 and 1969, measured water depths decreased throughout the bay due to infilling and shoaling (Roy, 1970). Estimates of the composition of aragonite (reef-derived) material in shoaled sediments vary from 25–75% (Roy, 1970; Smith et al., 1973; Hollett, 1976) and a moderate to large proportion may have been derived from military dredge spoils (Devaney et al., 1982).

After World War II, Kaneohe experienced a "boom" as it began to develop into a bedroom community of Honolulu. The population increased 450% between 1940–1960, from 5,387 to 29,622. Housing developments, road construction, and other impacts of urbanization have accompanied these population increases. Eight of the nine streams entering Kaneohe Bay have been diverted and/or channelized for at least part of their lengths, with most of the alterations occurring between 1960–1973. According to 1975 estimates, more than 15 km (18%) of streams in the surrounding watersheds have been channelized or otherwise modified (Maciolek and Timbol, 1976). Approximately 43% of stream flow into the bay has been diverted through ditch tunnels for agricultural and domestic purposes and to provide flood control to adjacent areas (Takasaki et al., 1969; Smith et al., 1973).

Physical changes of Kaneohe Bay attributes were quantified by Hunter (1993). Alterations (seawalls, harbors, dredged, filled, or fishponds) have been made to 58% of the total bay shoreline, ranging from 5% in the northern bay, 68% in the central bay, and 88% of the southern bay shorelines. Approximately 14% (38% in the southern bay) of the total fringing reef area has been dredged or filled. Nineteen of the original 28 fishponds built by early Hawaiians were partially or completely filled to create more land for housing developments between 1946–1948; two additional fishponds were altered during construction of boat harbors. Just over 5% of the total patchreef area has been dredged, primarily for construction of seaplane runways and channel widening.

Currently, the watersheds around the southern and central sectors of the bay are largely urbanized (residential, commercial, and light industry), while most of those in the northern bay areas remain rural/agricultural. Total population of the surrounding areas has continued to grow from 2,990 in 1920, to 29,662 in 1960, and to 66,760 in 1990 (State of Hawaii, 1992). Two major highways constructed in the 1960's connected Kaneohe to Honolulu, further augmenting urbanization. With the completion of a third Honolulu-Kaneohe highway (H-3), the population size may be expected to increase further (State of Hawaii, 1992).

One of the best-studied and recognized impacts of urbanization on Kaneohe Bay focused on the effects of sewage disposal into bay waters (Smith et al., 1981; Maragos et al., 1985). Sewage was discharged into the bay (increasing to a high of 1.8×10^4 m^3/day in 1977) from three treatment plants: i) the Kaneohe Naval Station (now Kaneohe Marine Corps Air Station) began dumping primary effluent into the south bay in the 1940's, ii) the Kaneohe municipal plant began discharge of secondary-treated effluent (also into the southern basin) in 1963, and iii) the Ahuimanu secondary treatment plant began operation in 1970. Sewage discharge from the two larger plants was diverted from south Kaneohe Bay to a deep ocean outfall in 1977–1978; discharge into the north-central bay from the Ahuimanu plant was diverted in 1986. Approximately 85% of the current population is now served by municipal sewerage; the remaining 10,168 individuals utilize 2,880 cesspools (State of Hawaii, 1990).

State of Reefs in Kaneohe Bay: 1971–1990.—Prior to the late 1960's, descriptions of reefs in the bay were anecdotal. It seems clear that, through geological time to the present, fringing reef communities in the bay developed under significant terrestrial influences. In the latter part of the last century, Agassiz (1889) recorded that, although corals flourished on the seaward slopes of fringing reefs, they had succumbed to sedimentation in nearshore reef areas. However, in the early 1990's, reefs in the south bay were described as "coral gardens" (MacKaye, 1915) consisting of a variety of species and forms.

Concerns about the impacts of sewage discharge in the early 1970's prompted baywide surveys of coral and algal abundance (Banner and Bailey, 1970; Maragos, 1972; Smith et al., 1973). High nutrient levels at this time supported a benthic community dominated by filter and deposit feeders in the southern sectors of the bay, accelerating bioerosion of reefs in this area. Nutrients also supported a luxuriant growth of the "green bubble alga," *Dictyosphaeria cavernosa.* The alga overgrew living coral colonies, particularly in the central sectors of the bay where the standing crop of *D. cavernosa* reached 1,000 g dry weight/m^2 (Soegiarto, 1972). There was little to no coral (nor *D. cavernosa*) in the south bay, apparently from a combination of high turbidity, sedimentation, and, possibly, anoxic conditions fostered by high nutrient levels. Smith et al. (1981), anticipating the natural experiment presented by diversion of sewage discharge from the bay in 1977–1978, initiated a comprehensive study of the response of nutrients and biota between 1976 and 1979.

Nutrients, turbidity and chlorophyll *a* concentrations declined rapidly in the year after sewage diversion (Smith et al., 1981; Laws and Redalje, 1979, 1982). Although phytoplankton and *D. cavernosa* abundance began to decrease and numbers of filter-feeders showed a dramatic decline, benthic biomass and community composition in the south and central sectors of the bay did not return to "pre-sewage conditions" during the 1-year period of that study after diversion. Smith et al. (1981) proposed that 1) the post-diversion monitoring time interval was insufficient, 2) there had been irreversible shifts in community structure, or 3) earlier observed shifts were attributable to factors other than sewage enrichment. A series of field studies conducted over the past two decades provides insight into the long-term trends of recovery of Kaneohe Bay reefs after sewage diversion.

Methods

Coral and algal abundances were quantitatively censused at fifteen reef sites in 1970–1971 by Maragos (1972) and Jokiel (unpubl.). These sites (Fig. 1) were re-surveyed using similar methods in 1983, 6 years after sewage diversion (Maragos et al., 1985; Evans et al., 1986) and again in 1990 (Evans, unpubl.). Location of sites, methodology, and comparisons of the resulting data sets were facilitated by the overlap of investigators conducting the censuses (J. Maragos, 1970–1971/1983; C. Evans, 1983/1990).

In 1983 and 1990, two parallel vertical transects were located as nearly as possible (from memory, field notes, and markers) to the locations of the single transects originally established in 1970–1971. The locations of transects were within 1–5 m of their original locations, with the exception of Site 6 which was estimated to have been within 50 m of the 1970 location (Maragos et al., 1985). All surveys were conducted between June and August for each census, with the exception of Site 8 which was originally surveyed in October 1970.

Transects were established along 25 m lines running from reef crests to the bottom of reef slopes. Depth, slope angle, and areal coverage of biota and substratum type within contiguous 1 m^2 quadrats were recorded from single transects (1970–1971) or two parallel transects (1983 and 1990) at each site. Quadrats were sub-divided into 10 × 10 grids of 100 cm^2 squares. Species and substratum types occupying less than half of a square (>50 cm^2 = estimated resolution limits of this method) were recorded as present but were not otherwise quantified. Quadrat data were pooled at 1-m depth increments and averaged between transects (for 1983 and 1990 data) for estimates of mean percent cover within depths and over all depths at each site. Data were arcsine transformed prior to statistical analyses, and changes in percent cover were assessed by paired comparisons at each depth using Wilcoxon's signed rank tests. Study sites were grouped into zones within the bay to facilitate comparison with previous studies (Smith et al., 1981; Maragos et al., 1985).

Results

Changes in Coral and Algal Cover.—Mean percent cover of total coral and *D. cavernosa* at each of 15 sites for the three census periods is summarized in Table 1. On a baywide basis, coral abundance increased dramatically (+13.87%, P = 0.001) between 1970–1983, and then remained essentially unchanged between 1983–1990 (Fig. 2a). In contrast, while percent cover of *D. cavernosa* dropped 13% to 3% between 1971–1983, its abundance rose significantly (P = 0.003) to almost 8% over the next seven years (Fig. 2b). Between 1971–1983, 9 of the 15

Table 1. Mean percent cover of total coral and *Dictyosphaeria cavernosa* at 15 sites in Kaneohe Bay censused in 1970–1971, 1983, and 1990 surveys (P = exact probabilities from Wilcoxon's signed rank tests of arcsine transformed data)

Location:	South Bay			Transition Zone				Middle Bay				North Bay				Baywide means
Site#:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Total corals																
Census period																
1971	0.43	0.88	1.15	6.50	1.58	21.56	0.66	15.94	6.38	3.68	15.30	34.05	2.58	40.95	34.83	12.19
1983	3.50	2.46	21.55	7.59	19.87	16.49	31.42	47.43	18.05	32.17	38.47	47.64	33.55	49.49	21.12	26.06
1990	2.79	3.37	33.28	20.72	11.73	20.33	29.14	30.24	8.81	29.43	46.53	25.88	22.69	41.52	33.45	23.93
1971–1983																
P =	0.014	0.086	0.001	0.175	0.001	0.155	0.006	0.006	0.008	0.002	0.002	0.086	0.014	0.078	0.081	0.001
	*	ns	**	ns	**	ns	**	**	**	**	**	ns	*	ns	ns	**
1983–1990																
P =	0.406	0.242	0.030	0.009	0.107	0.221	0.187	0.008	0.004	0.291	0.378	0.088	0.014	0.399	0.147	0.068
	ns	ns	*	**	ns	ns	ns	**	**	ns	ns	ns	*	ns	ns	ns
Dictyosphaeria cavernosa																
Census period																
1971	0.00	0.00	0.00	13.91	0.00	15.75	37.75	12.68	39.09	38.95	36.52	0.08	0.00	0.42	3.44	13.23
1983	0.19	0.00	0.00	1.40	0.14	1.54	4.09	9.35	3.64	5.40	4.11	0.50	3.00	0.98	12.56	3.13
1990	0.11	0.23	0.02	2.27	11.86	13.86	20.29	10.72	30.86	13.96	3.11	0.43	0.47	0.35	14.33	7.92
1971–1983																
P =	0.090	—	—	0.014	0.090	0.040	0.014	0.081	0.005	0.009	0.008	0.054	0.159	0.500	0.022	0.003
	ns	—	—	*	ns	*	*	ns	**	**	**	ns	ns	ns	*	**
1983–1990																
P =	0.090	0.090	0.030	0.058	0.009	0.006	0.009	0.288	0.004	0.018	0.458	0.500	0.159	0.173	0.200	0.003
	ns	ns	ns	ns	**	**	**	ns	**	*	ns	ns	ns	ns	ns	**

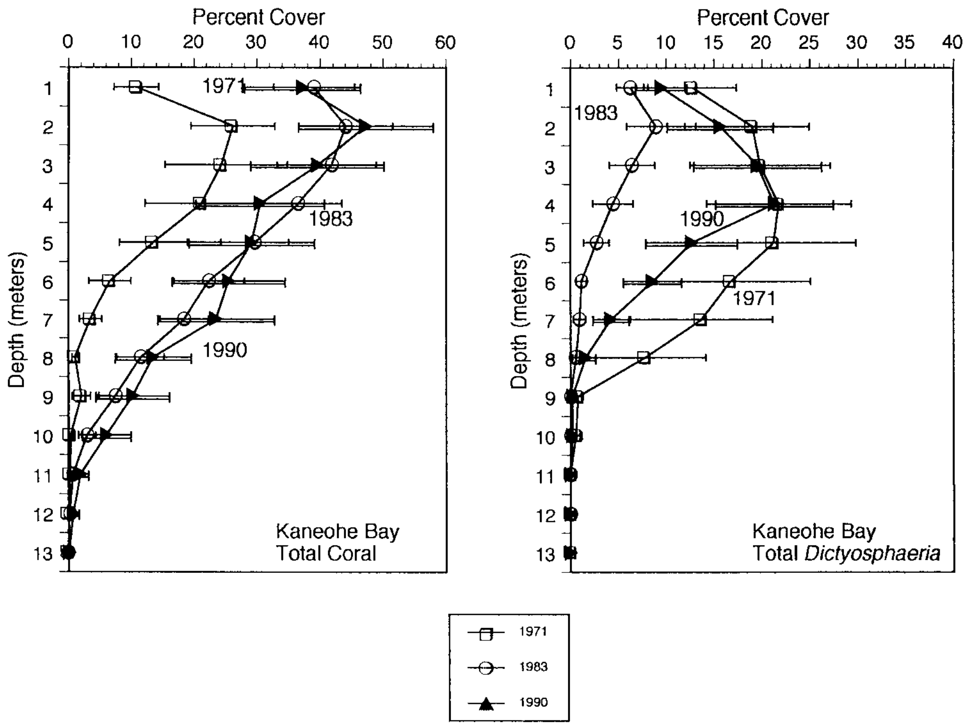


Figure 2. Depth profiles of mean percent cover of a) total coral and b) *Dictyosphaeria cavernosa* averaged over 15 survey sites in Kaneohe Bay censused in 1971, 1983, and 1990.

sites showed significant increases in coral cover ($\bar{x} = +21.74\%$, $P < 0.05$); percent cover of coral also increased significantly when averaged over all sites in the mid-bay zone (Sites 8–11, $P < 0.01$) and for all sites combined ($P < 0.01$). Between 1983 and 1990, two sites (#3 and 4) increased significantly in percent cover of coral ($\bar{x} = +12.43\%$, $P < 0.01$) and three sites (#8, 9 and 13) showed significant declines ($\bar{x} = -12.43\%$, $P < 0.05$); the remaining nine sites showed no significant change in coral cover.

Percent cover of *D. cavernosa* decreased significantly at six sites ($\bar{x} = -26.97\%$, $P < 0.05$) and increased at one site (#15) between 1971 and 1983. On a bay-wide basis, algal cover declined significantly ($\bar{x} = -8.31\%$, $P < 0.05$) and there was also a significant decline in the mid-bay zone ($\bar{x} = -26.19\%$, $P < 0.01$). Between 1983 and 1990, algal cover remained unchanged and low at eight sites ($\bar{x} = +0.90$, n.s.), unchanged and moderate at two sites (#8 and #15, +1.37%, n.s.), and increased significantly at five sites ($\bar{x} = +15.29\%$, $P < 0.05$). Bay-wide percent cover of *D. cavernosa* during this period increased more than two-fold ($\bar{x} = +4.78\%$, $P < 0.01$). Significant increases within bay zones were found only for the transition zone sites (#4, 5, 6 and 7, $\bar{x} = +10.39\%$, $P < 0.05$).

Variations in coral and *D. cavernosa,* abundance by depth are presented for eight representative survey sites in Figure 3. What is apparent from these graphs is that there have been different patterns of change in the relative abundance of coral and algal cover at different sites and depths.

Coral and algal cover remained very low and essentially unchanged on the southernmost reefs in the bay (Site 1 and Site 2, [not shown]). The southern part

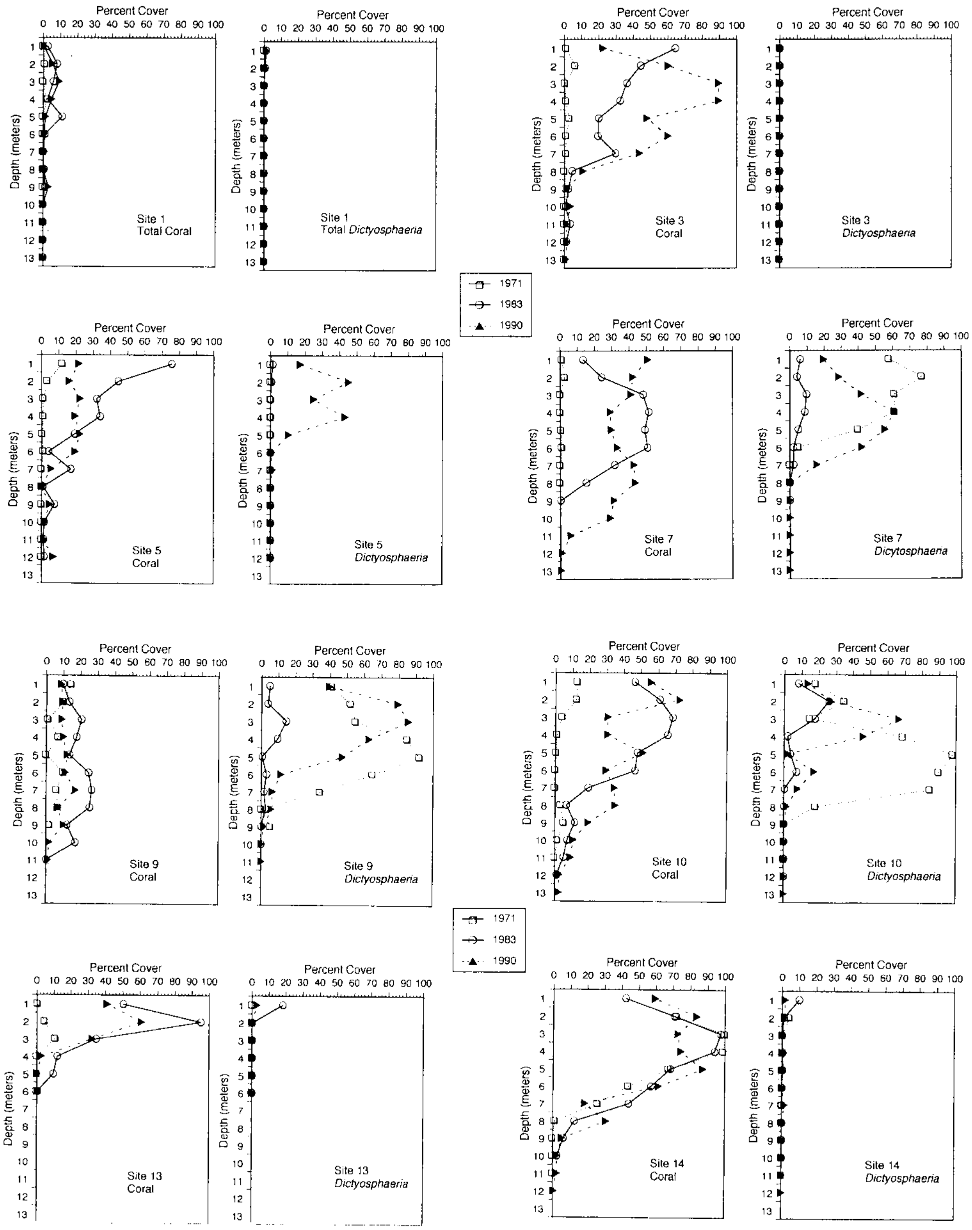


Figure 3. Depth profiles of percent cover of total coral and *Dictyosphaeria cavernosa* at eight reef sites in Kaneohe Bay censused in 1970–1971 (open squares), 1983 (open circles), and 1990 (closed triangles).

of the bay was heavily dredged in the late 1930's and early 1940's, and Site 1 still had considerable amounts of fine sediments (75% of total cover) vs. hard substratum (22%) in 1990. However, Site 2 had approximately 61% bare hard substratum that had not been recolonized by corals or algae. The reasons for this lack of recruitment are unknown.

In contrast, Site 3, on the south side of Coconut Island, showed a large and continuous increase in coral abundance between 1971–1983 and again between 1983–1990, while *D. cavernosa* remained uniformly low (<1% at all depths). A few hundred meters north, at Site 5, the increase in coral abundance seen between 1971–1983 declined between 1983–1990, particularly at depths <5 m, where *D. cavernosa* abundance rose. A similar pattern can be seen for Site 7, on the leeward side of a patchreef just north of Coconut Island. While *D. cavernosa* abundance at this site declined sharply between 1971–1983, algal cover approached pre-sewage diversion levels in 1990, particularly at depths >3 m.

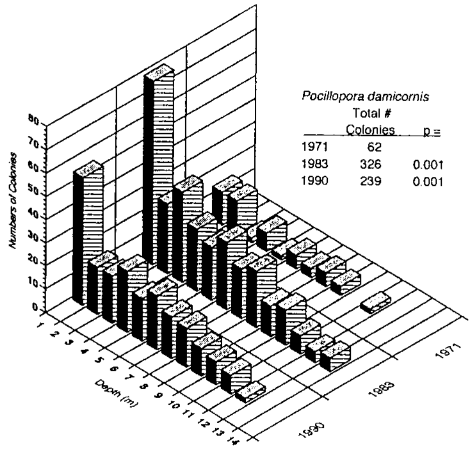
Total coral abundance declined and *D. cavernosa* cover increased on three out of four reefs (Sites 8, 9 and 10) in the central bay between 1983–1990. These sites had shown a reversed trend between 1971–1983. *D. cavernosa* occupied a shallow depth range on the reef slopes of Sites 9 and 10 in 1990 compared to its 1971 range at these sites. At the fourth central bay reef site (#11), coral abundance increased and algal cover declined at both the 1983 and 1990 censuses relative to 1971 levels.

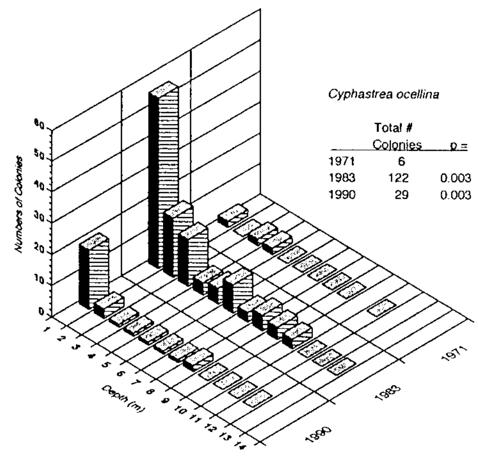
North bay sites showed the least amount of change in coral and algal cover over the 20-year period. Only Site 13 (nearer a reef mouth than any of the other sites) showed significant change in coral cover, with an increase between 1971–1983 and a (smaller) decline between 1983–1990. Site 15, the northern-most survey site, was the only reef on which coral declined and cover of *D. cavernosa* increased between 1971–1983; between 1983–1990, coral and algae both increased slightly at this site.

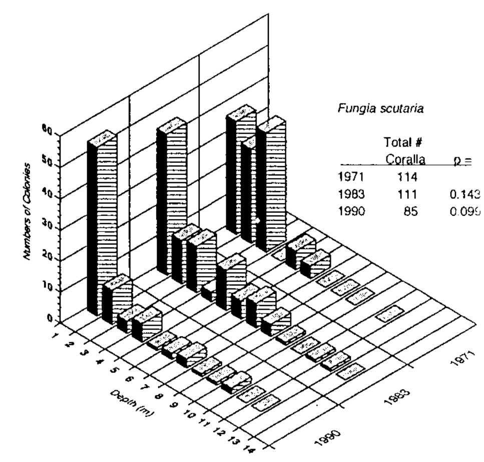
Site 14 (Fig. 3, bottom right) is notable in exhibiting the least amount of change in coral or algal abundance over the past two decades. In general, coral abundance increases from about 50% cover on the reef flat to nearly 100% at 3–4 m depth, and gradually declined down the reef slope to the mud bottom of the lagoon. (The decline in percent cover of coral at 3–4 m depth in 1990 appeared to be due to abrasion from a boat grounding.) Cover of *D. cavernosa* has remained low at this site (<1% overall) since 1971.

Overall declines in total coral abundance at <1 m depth in 1990 were positively correlated ($r^2 = 0.508$, $P < 0.01$) with mortality from the 1987 flood for the 11 sites for which 1988 and 1990 surveys overlapped. At Sites 3, 4 and 5 (all on Coconut Island) this mortality explained most of the measured negative change in coral cover. However, for the other 12 sites surveyed in 1990, significance values for declines in coral cover did not change when the upper 1 m was omitted from paired comparisons.

Changes in Coral Species Diversity.—The relative abundance of the two most common corals in Kaneohe Bay, *Porites compressa* and *Montipora verrucosa*, increased substantially between 1971 and 1983 (41–72% and 6–10% of total cover, respectively) and remained high and essentially unchanged between the 1983 and 1990 surveys (73% and 12%, respectively). Other common corals species in the bay, *Pocillopora damicornis*, *Cyphastrea ocellina*, and *Fungia scutaria* showed different patterns of occurrence and abundance (Fig. 4a, b, c). Abundance of *P. damicornis* and *C. ocellina* increased after sewage diversion, but showed a significant decline between 1983 and 1990. Most of the change in these two species, which typically occur mainly on reef flats, was seen at 1 m depth or less, suggesting that the 1987 freshwater kill may have been responsible for the observed declines. Declines at greater depths suggest that mortality of the large numbers of colonies on reef flats may have resulted in a depression of reproductive/recruitment success over the time interval between the freshwater kill and


Pocillopora damicornis
Total #
Colonies p =
1971 62
1983 326 0.001
1990 239 0.001
Numbers of Colonies
Depth (m)
1971
1983
1990


Cyphastrea ocellina
Total #
Colonies p =
1971 6
1983 122 0.003
1990 29 0.003
Numbers of Colonies
Depth (m)
1971
1983
1990


Fungia scutaria
Total #
Coralla p =
1971 114
1983 111 0.143
1990 85 0.095
Numbers of Colonies
Depth (m)
1971
1983
1990

1990 census (2½ years). In contrast, the abundance of *Fungia* increased at depths less than 1 m, but decreased on the reef slopes. Although *Fungia* is sensitive to decreased salinity (many "dead" coralla were observed after the 1987 flood), these coralla sprouted hydrocauli (asexual buds) from apparent residual tissues over the next several years (Jokiel et al., 1993) resulting in a rapid recovery of this species on reef flats. Of interest is the lack of recovery, and actual decline, of *Fungia* at depths >1 m in 1983 and again in 1990. It is possible that the decline in *Fungia* may be attributable to or exacerbated by an increase in souvenir collection of this "portable" species.

Discussion

Kaneohe Bay was described in 1973 as "a reef ecosystem under stress" (Smith et al., 1973). The authors attributed this stress to the large population increases in the surrounding watersheds during the previous 30 year period, and the concomitant impacts of urbanization (increased sedimentation from runoff, dredging, reef erosion, freshwater kills exacerbated by stream channelization, and nutrient stress from sewage outfalls in the south bay). As a result of such scientific attention and public outcry, local government responded and sewage outfalls were diverted from the bay. A rapid change was documented in nutrient concentrations, phytoplankton abundance, and water clarity in the south and central bay in the year following sewage diversion. Surveys within the first six years after diversion also indicated that coral communities had begun to recover (Smith et al., 1981; maragos et al., 1985; Evans et al., 1986). However, as indicated by the 1990 reef survey, these initial trends of recovery appear to have slowed or even reversed at some sites. Overall coral abundance in Kaneohe Bay has not continued to increase from 1983 levels, while the green bubble alga, *D. cavernosa,* previously believed to be an indicator of eutrophic conditions, has doubled in percent cover. Limitations in the scope and methodology of surveys to date, along with the potential for tremendous natural variability in reef ecosystems, emphasize the need for further data over longer time periods to confirm these trends.

At present, factors contributing to the health or decline of reefs in Kaneohe Bay are more subtle and complex than the point-source sewage outfalls of the past. Recent increases of *Dictyosphaeria cavernosa* may reflect a response to nutrient subsidies from sediment release and recycling, fixation and export of nutrients from reefs, land runoff, cesspools, municipal sewage bypasses, and human wastes from commercial and recreational boaters. Channelization of most streams in the southern and central sectors of the watershed has accelerated freshwater delivery to the bay during heavy rainfall events, resulting in potentially higher suspended sediment loads and more extreme fluctuations in salinity. A large highway construction project begun in 1988 increased sediment loads in a Kaneohe stream six-fold compared to preconstruction levels (Hill and DeCarlo, 1991).

A major storm in 1987 resulted in substantial mortality of shallow water benthos followed by a protracted period of phytoplankton growth (Taguchi and Laws, 1989; Jokiel et al., 1993). Chlorophyll *a* concentrations in the south bay during the month after the storm were nearly four times higher than peak concentrations

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Figure 4. Depth profiles for total number of colonies recorded during each census of: a) *Cyphastrea ocellina*, b) *Pocillopora damicornis*, and c) *Fungia scutaria* from 1971 (×2), 1983, and 1990 reef surveys of Kaneohe Bay.

measured during the height of sewage discharge; chlorophyll *a*, particulate N and particulate C have varied tremendously both before and since sewage diversion (Taguchi and Laws, 1989). Nutrients released during flooding and after the fresh-water kill may have augmented cycling of nutrients between the plankton and benthos, and ultimately favored growth of macroalgae. Although spills and bypasses of raw sewage occasionally occur (particularly during heavy rainfall events or routine plant maintenance operations), cesspool drainages and an antiquated sewage collection system may also provide a relatively small but chronic source of nutrients to bay waters. Planned and accidental bypasses of sewage into the bay are estimated at up to 32 million gallons per event; cesspools and faulty septic systems contribute approximately 800,000 gallons of sewage per day to groundwater, particularly in the central and north bay watersheds (State of Hawaii, 1990).

Alternatively to an increased nutrient scenario, 1990 reef surveys may reflect interannual variations in algal abundance that have not been previously quantified. What "should" a healthy reef look like in Kaneohe Bay, in terms of total coral and macroalgal abundance? The "inverted J" pattern of coral coverage (observed at Site 14 in the north bay) may represent the "normal" Kaneohe Bay reef type, based on observations of other reefs in more "pristine" areas of the bay. Coral cover at these sites is high (>50%) between 2–7 m depth and maximal (100%) at 3–4 m, decreasing down the slope to the bay bottom at 10–11 m. While *Dictyosphaeria cavernosa* is present on these reefs, its abundance is low, typically <1% of reef crest and slope areas, with patchy areas of up to 10% cover. Proximity to shore (and land influences) and overgrowth of algae appear to be prominent factors responsible for deviations from this "norm" on other reefs. Whether this pattern represents a historical "norm" (beyond the short period of time for which we have quantitative data) is open to conjecture, but is supported by the morphology of existent reef structures and proposed patterns for reef development in the bay (Roy, 1970).

Through geological time to the present, reef communities in Kaneohe Bay have been strongly influenced by proximity to land (inputs of sediments and fresh water), particularly when compared with more oceanic reefs. Perhaps the added influences of urbanization have pushed these reef communities beyond a recovery threshold. From both scientific and esthetic perspectives, the rapid initial changes in the bay after diversion of plant-source sewage discharges became a textbook example of the ability of ecosystems to recover from anthropogenic stress. However, other stresses have not been remediated: long-term impacts of dredging, sedimentation, stream channelization, nutrient subsidy, and the introduction of potential toxicants. Although the data presented in this summary are limited and preliminary, they provide the beginnings of the data base by which long-term changes on Kaneohe Bay reefs may be measured and evaluated. Further research will be necessary to determine if changes in coral and algal abundance represent equilibrium shifts and/or long-term trends. The ultimate effects of changes in the macro-algal/coral community structure on reef fish abundance have not been determined. One noteworthy observation was the lack of any qualitative differences in reef fish populations between coral- vs. algal-dominated patchreefs surveyed in the early 1970's (Losey, 1976).

Dynamics of the Kaneohe Bay ecosystem are the subject of current research projects including nutrient input sources and rates, net uptake parameters of reef communities, and investigations of the potential influence of algal grazers on *D. cavernosa* abundance. Of much interest also are recent findings that the phytoplankton community in the bay has shifted from N-limited to P-limited (E. Laws, pers. comm.). In addition, there appears to be a substantial subsidy (approximately 40 μM) of dissolved organic nitrogen to the bay water column (E. Laws, M. Atkinson, pers. comm.). Levels and potential bioaccumulation of toxic contaminants in bay fauna have also been the subject of recent attention. Samples of oyster tissues collected near the stream mouth in the southern sector of the bay showed high levels of some metals and the persistent pesticides, dieldrin and chlordane, that have been banned from use in Hawaii for more than 5 years (Stephenson and Hunter, 1992; Hunter et al., in press). Other recent work has begun to focus on the effects of various toxicants on corals and their larvae (Acevedo, 1991; Goh, 1991; Te, 1991).

The importance of periodic freshwater kills in structuring the ecological distributions of shallow-water reef corals in Kaneohe Bay has been documented after two major floods in 1965 and 1987 (Banner, 1968; Jokiel et al., 1993). Data on recovery of near-shore areas after the 1987 flood support and expands upon what has been learned over the past decade about the modes and relative contributions of sexual and asexual reproduction and recruitment of corals in the bay. In addition, studies on the effects of UV light, temperature, and water motion regimes conducted in Kaneohe Bay have contributed greatly to our understanding of coral distributions and environmental tolerances. Although a large body of work has been accumulated on Kaneohe Bay coral reef communities, much remains to be learned about the long-term dynamics of what is perhaps one of the best-developed (and best-studied) reef systems in the world adjacent to an urbanized and growing population center.

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