CHAPTER 6

The Status of the Reefs Along South Moloka‘i: Five Years of Monitoring

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In Hawai‘i, coral reefs are subjected to a variety of natural and anthropogenic stresses at several spatial and temporal scales (Grigg and Dollar, 1990). The intensity and duration of these factors can both directly and indirectly alter the physical and biological structure of the reef (Connell and others, 1997). Natural factors, such as acute wave disturbances (Dollar and Tribble, 1993), freshwater inputs (Jokiel and others, 1993), and predator outbreaks (Done, 1992) can affect the shallow-water reef communities at small spatial (10–100 m) and temporal (0–1 yr) scales. Chronic disturbances, such as non-point source pollution, are more difficult to detect because changes to the community landscape are subtle and occur over longer time periods (Pastorok and Bilyard, 1985). How different types of disturbance influence coral community structure is only beginning to be understood and quantified (Edmunds, 2000).

Disturbances can lead to a deteriorating or “unhealthy” coral population if recovery of the community does not occur or if the community is replaced by another perceived to be less desirable. DeVantier and others (1998) defined a “high quality” or “healthy” reef as one with high diversity of corals and associated biota and a strong reef-building capacity. The reef-building capacity is usually represented by high species richness and high absolute percent cover of hard corals (DeVantier and others, 1998). Szmant (1996) has incorporated temporal changes in her definition of reef health by stating that shifts from reefs dominated by corals to areas dominated by macroalgae signal the decline of a reef from a healthy state to an unhealthy one. These definitions, however, tend to depict reefs as static, steady-state systems without incorporating cyclical variation in substrate cover, coral growth, or recruitment. Categorizing reefs as “healthy” based primarily on high coral cover does not take into account geographic areas such as Hawai‘i that naturally have low to moderate coral cover. Many of these areas are in good condition compared to other regions of the world (Wilkinson, 2000). Long-term monitoring programs can clarify natural cycles present in the system over time and provide an overview of population trends in the reef community. In addition, long-term monitoring is necessary to understand the role of natural and anthropogenic processes in changes in reef ecosystems (Hughes and Connell, 1999).

Long-term monitoring involves repeated surveys of organisms and/or environmental parameters at selected sites over time (Rogers and others, 1994). Documenting changes in the community structure at various spatial and temporal scales using a well-designed monitoring program can assess the condition (such as deteriorating, improving, or undergoing a phase shift) of various reefs and focus research on causal links among the various factors (Hughes, 1993; Done and Reichelt, 1998). In Hawai‘i, long-term coral reef monitoring projects have been conducted to detect change in coral cover at a small spatial scale at Kahe Point (Coles, 1998), Hanauma Bay (C. L. Hunter, written commun., 2000), Honolua Bay, Kahekili Park, Puamana, and Olowalu on Maui (Brown, 1999), and Molokini (B. N. Tissot, written commun., 2000).

The fringing reef along the south shore of Moloka‘i is considered to be one of the best-developed reef tracts in the Hawaiian archipelago (Storlazzi and others, 2003). This reef tract, however, has been subjected to a variety of natural (Branham and others, 1971) and anthropogenic (Roberts, 2001; J. Reich, oral commun., 2001) stresses during the course of human habitation. Consequently, recent research efforts have focused on the response of the reef system to these stresses and the possible causal mechanisms.

The purpose of this chapter is to provide baseline spatial and temporal data for reefs along the south shore of Moloka‘i. Percent coral cover and population dynamics (for example, recruitment) of the abundant coral species at three sites are described using two approaches. First, visual quadrats and digital video transects were used to analyze historical development of each reef over the past 5 years. Second, a more detailed but smaller scale approach used fixed photoquadrats to track individual colonies over the same time period to document life-history patterns (for example, growth, recruitment, and mortality) of various species at each reef. These patterns helped characterize the present condition of these reefs and identified areas undergoing changes that could be explored with future research studies.

Methods

Study Sites

Three long-term monitoring sites were established along the south coastline of Moloka‘i to examine changes in coral cover over time (Pālā‘au, Kamiloloa, and Kamalō) (fig. 1). At each site two stations were sampled, at 3-m (10-ft) and 10-m (33-ft) depths. Sites were haphazardly selected along a perceived gradient of sediment stress and wave exposure. Historical erosion at Pālā‘au suggested that this site would show evidence of severe sediment deposition (Roberts, 2001). Eastward towards Kamiloloa, higher coral cover was predicted because of lower sedimentation levels and a more wave-sheltered environment. Finally, at the easternmost site of Kamalō, coral cover was expected to be highest and protected from all but the most severe storm events. These study sites were incorporated into the Hawai‘i Coral Reef Assessment and Monitoring Program (CRAMP) monitoring sites in 2000 as

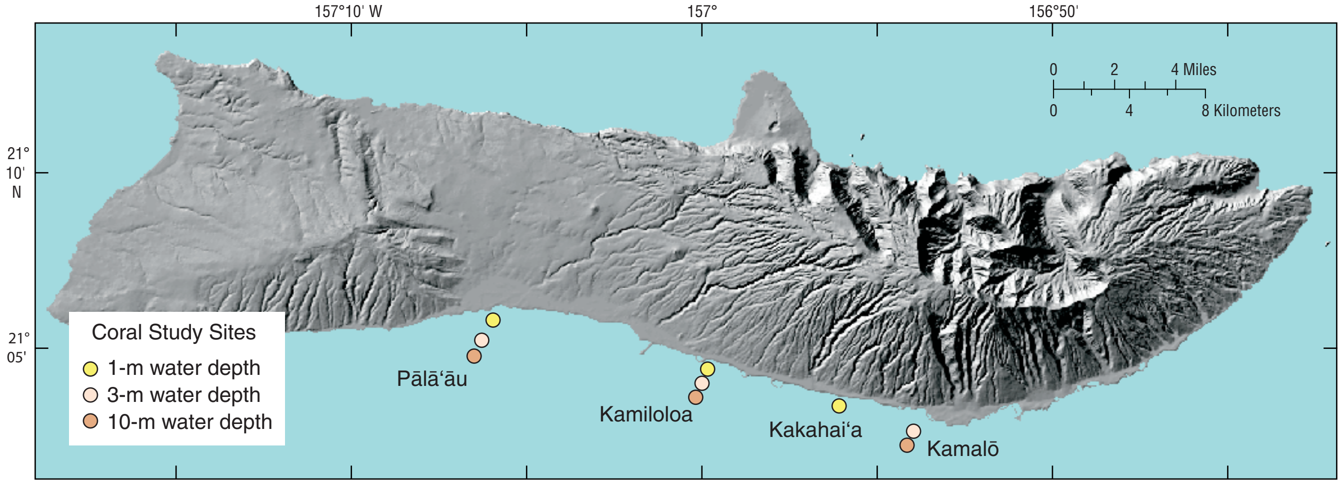

Figure 1. Study sites at Pālā‘au, Kamiloloa, and Kamalō along the south shore of Moloka‘i, Hawai‘i. At each site there are 3 stations, at depths of 1 m, 3 m, and 10 m (3.3 ft, 10 ft, and 33 ft). The 1-m station at Kakahai‘a served as the inshore station for Kamalō because of inaccessibility to suitable habitat near the Kamalō 3-m and 10-m stations.

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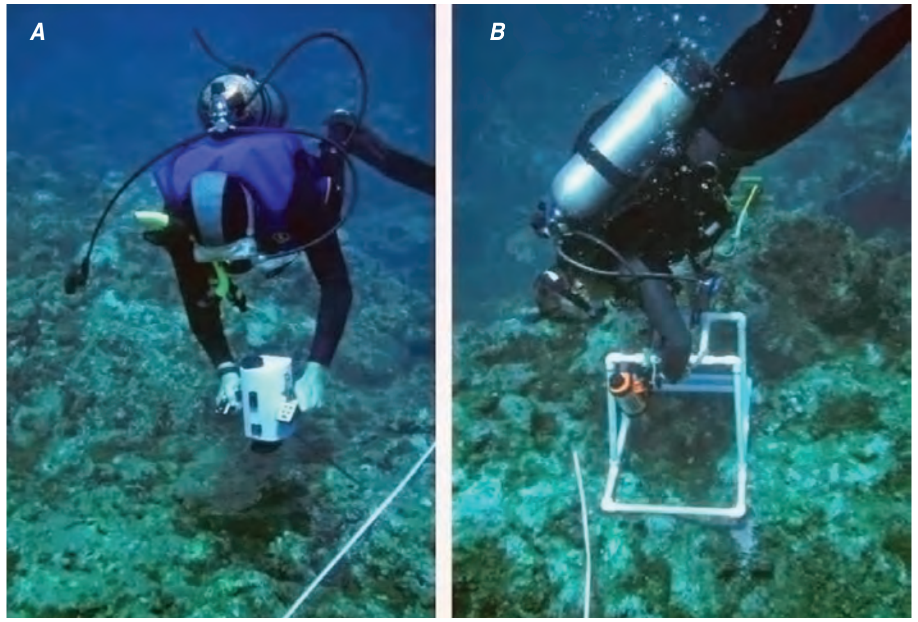

Figure 2. Digital video-transect (*A*) and photoquadrat (*B*) methods used to survey the benthic community. Ten permanent (fixed) 10-m (33 ft) transects were initially selected at random within a grid 2 m ×100 m (6.6 ft × 330 ft) along either the 3-m (10 ft) or 10-m isobath and videotaped annually from a height of 0.5 m (1.6 ft) above the substrate. Five photoquadrats at each station were randomly established in 2000 within the same grid and sampled at least once a year. At the shallow (1-m; 3.3-ft) station, sample size was increased to 10 photoquadrats to accommodate the more dynamic environment.

part of the larger statewide effort to document changes in coral cover (Jokiel and others, 2004).

Three additional stations were set up at 1-m depth (3.3-ft, on the reef flat) to document life-history patterns in highly turbid water (Pālā‘au, Kamiloloa, and Kakahai‘a). The shallow stations on the reef flat at Pālā‘au and Kamiloloa were inshore of the deeper 3-m and 10-m stations (fore reef). Kakahai‘a served as the inshore station for Kamalō because of inaccessibility to suitable habitat near the Kamalō 3-m and 10-m stations. These shallow stations were established at transitional locations on the reef flat where coral cover first became prevalent (approximately 5 percent) as one moved from shore out to the reef crest. Theoretically, these areas represented the landward edge of live coral and would most likely be influenced by anthropogenic processes nearshore.

Trends in Coral Cover

Sites were monitored annually from 2000 to 2004 using the CRAMP protocol (Brown and others, 2004; Jokiel and others, 2004) with digital video transects (fig. 2*A*). Percent cover was tabulated for coral (by species), macroinvertebrates (for example, urchins, sea stars), and other benthic substrate types (coralline algae, turf algae, macroalgae, and sand). Total mean percent coral cover, mean percent coral cover by species, species richness (number of species per transect) and diversity were calculated for each site.

Life-History Patterns

A set of five fixed photoquadrats at each 3-m and 10-m station was used to examine growth, recruitment, and mortality of individual corals (for example, Hughes, 1985; Porter and Meier, 1992) (fig. 2*B*). At the shallow 1-m stations, sample size was increased to 10 photoquadrats to compensate for the more dynamic environment. Scanned slides from the photoquadrat sampling were analyzed using image-processing software to determine horizontal areal coverage of each coral colony by species. The fate (dead, exposed, fusion, areal growth, re-emerged, recruit, and shrinkage) was tracked over the time period of the study. More detailed methods for photoquadrats are described in Brown (2004) and Brown and others (2004); examples of image analysis (fig. 3) and life-history processes (fig. 4) are included here. Only the recruitment data are presented because of the complexities of life-history dynamics that are beyond the scope of this chapter. Recruits were defined as new colonies with a minimum detectable size of 0.5 cm in diameter (area 0.2 cm^2) and no previous record of settlement in a particular location within the plot. Typically this size represents colonies of approximately 1 to 2 years of age and is defined as “visible recruitment” in contrast to “invisible recruitment” (<0.5 cm in diameter) (Fitzhardinge, 1993).

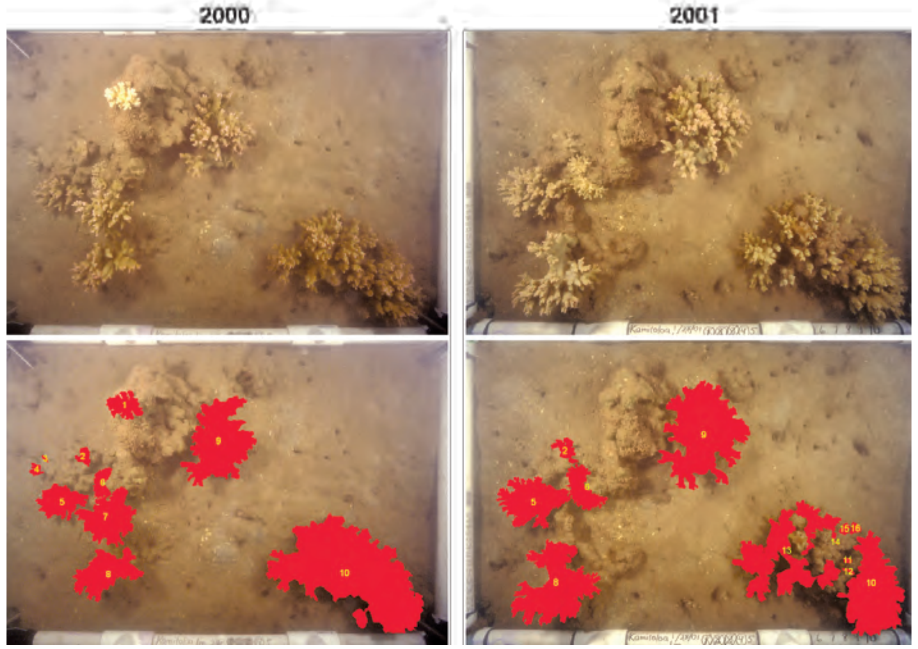

Figure 3. Examples of how coral colonies were tracked within a photoquadrat using computer image analysis. The top photographs depict the raw images in 2000 (left) and 2001 at the Kamiloloa 1-m (3.3 ft) station. The bottom row shows the labeled colonies after analysis. Each unique colony was labeled and measured for total two-dimensional area by digitally tracing the colony boundary using SigmaScan®.

Data Analysis

The long-term coral cover data were analyzed using a General Linear Model (GLM) repeated measures ANOVA design. Planned comparisons or contrasts were used to examine changes in total coral cover within each station from the initial survey to the last survey. The recruitment data were also analyzed using a General Linear Model (GLM) repeated measures ANOVA design. Planned comparisons or contrasts were then used to examine temporal trends in recruitment levels within each station and between stations across depths. For the purposes of this chapter, statistical patterns were reported without the accompanying probability values. A more detailed description of data analysis techniques can be found in Brown (2004).

Results

Trends in Coral Cover

A total of 13 coral species were documented across all of the six stations in the initial baseline survey in 2000 (table 1). Overall, the top 5 species with the highest coverage were *Montipora capitata* (21 percent), *Porites compressa* (9 percent), *Montipora patula* (8 percent), *Porites lobata* (3 percent), and *Pocillopora meandrina* (1 percent) (fig. 5). Coral cover was highest initially at the Kamalō 10-m and 3-m stations (75 percent at both stations) and lowest at the Kamiloloa 10-m station (<1 percent). At the Kamalō stations, *Montipora capitata* (25 percent at 10 m; 59 percent at 3 m) and *M. patula* (24 percent at 10 m; 9 percent at 3 m) had the highest percent cover, followed by *Porites compressa* (25 percent at 10 m; 1 percent at 3 m), *P. lobata* (<1 percent at 10 m; 3 percent at 3 m), and *Pocillopora meandrina* (<1 percent at 10 m; <1 percent at 3 m). The community assemblage at the Pālā‘au 10-m station was also dominated by *Montipora* species (*M. capitata* 33 percent; *M. patula* 13 percent), but there was a large component of *Porites* species (*P. compressa* 25 percent; *P. lobata* 1 percent). The Pālā‘au 3-m station actually had a higher percentage of *Porites* species (*P. compressa* 5 percent; *P. lobata* 13 percent) than *Montipora* species (*M. capitata* 7 percent; *P. lobata* 3 percent) and a small percentage of *Pocillopora meandrina* (2 percent). As noted previously, the Kamiloloa 10-m station had the lowest coral cover (<1 percent), which was distributed over 7 species. The Kamiloloa 3-m station had slightly higher coral cover (4 percent) but only 6 species were observed. *P. meandrina* was the most abundant coral at this shallow station (table 1).

The long-term trends in coral cover showed stations declining, recovering (increasing), and remaining stable (fig. 6). Since 2000, coral cover at the two stations at Pālā‘au has remained relatively stable (fig. 6). The one exception was the 10-m station, which experienced a significant drop in absolute cover of 12 percent (17 percent relative) in 2004. The decline in cover was primarily attributed to *Porites compressa* (10 percent absolute, 40 percent relative). In contrast, the 3-m station at Pālā‘au experienced a decrease of <2 percent (5 percent relative decrease) in total coral cover from 2000 to

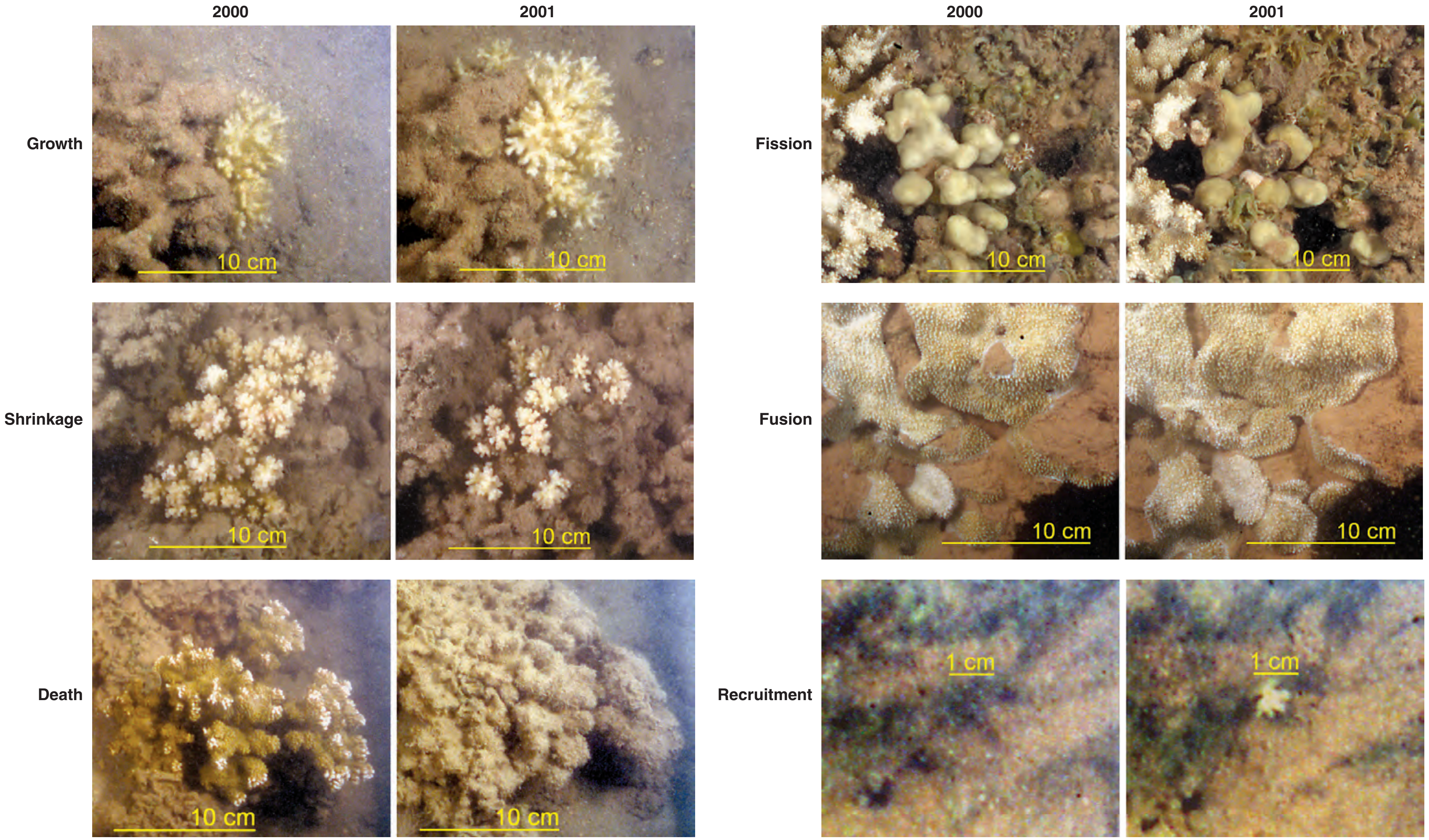

Figure 4. Examples of different life-history processes documented from 2000 to 2001 in photoquadrats. In the first year of this project, all colonies were given a unique number, even though it is highly probable that many of the colonies were the result of prior fission events. After the initial labeling, colonies (including fragments from documented fission events) were followed each year to calculate growth, shrinkage, and record total mortality. Colonies in the fission category represented any daughter colony separated from the parent colony. Fission also included fragmented colonies that fell into the plot and were still loose. Colonies that had undergone fusion were consolidated into one larger initial colony without any evidence of prior boundaries. Recruits were defined as new colonies with a minimum detectable size of 0.5 cm (0.2 in) in diameter (area 0.2 cm^2; 0.03 in^2) and no previous record of settlement in a particular location within the plot. Typically this size represents colonies around 1 to 2 years of age and is defined as “visible recruitment” in comparison to “invisible recruitment” (diameter <0.5 cm; 0.2 in).

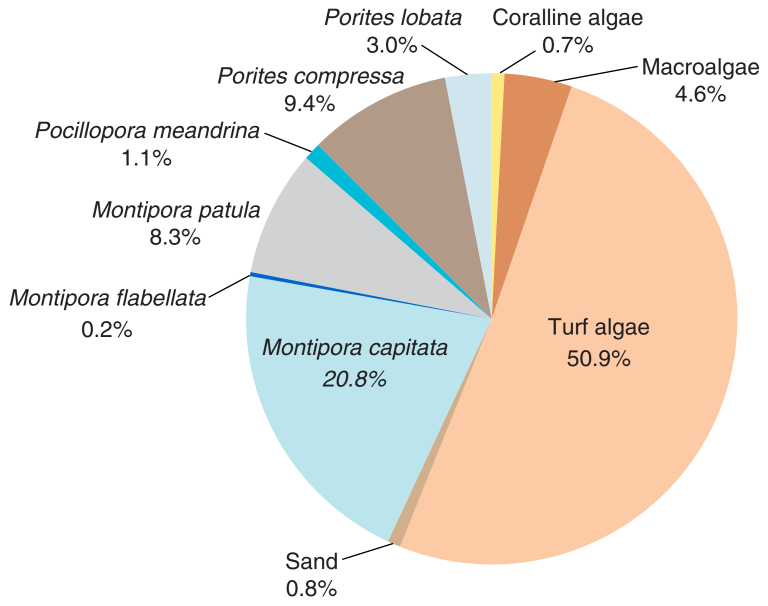

Figure 5. Chart showing mean percent substrate cover among all six of the 3-m (10-ft) and 10-m (33-ft) sites off south Moloka‘i in 2000. See table 1 for data and list of common names. Substrate types and coral species with 0.1 mean percent cover or less are not included on chart.

2004. This small decrease was not statistically significant and could easily be attributed to measurement error. Consequently, the reef at the 3-m station was considered to be stable.

Coral cover at the Kamiloloa 10-m station showed a statistically significant increase of 5 percent in absolute coral cover (646 percent relative increase) since 2000 (fig. 6). The two principal species accounting for the recovery were *Montipora capitata* (4 percent absolute increase, 1,550 percent relative) and *M. patula* (1 percent absolute increase, 1,300 percent relative). *Pocillopora meandrina* and *Porites lobata* were minor components of the assemblage. In contrast, coral cover at the Kamiloloa 3-m station has remained relatively stable over the past 5 years (fig. 6) even though there has been a 1 percent decrease (30 percent relative) in coral cover. This change was statistically significant but probably not ecologically important, because coral cover was initially very low. *P. meandrina*, which was the most abundant coral in terms of coverage, has declined by 2 percent (49 percent relative) during this time period. Other species (for example, *M. capitata* and *M. patula*) that were not recorded in the initial surveys have begun to appear in the benthos, suggesting that a community shift is occurring in the assemblage.

The Kamalō 10-m station experienced a statistically significant decline in coral cover of 16 percent (21 percent relative decline) from 2000 to 2002, but it has since stabilized around 62 percent. This is still significantly lower than in the initial survey (fig. 6). The decrease in cover was primarily because of loss of *Porites compressa*, which declined steadily from 25 percent to 6 percent (76 percent relative decline) over the past 5 years. In comparison, percent cover of *Montipora capitata* has remained constant around

25 percent while *M. patula* has actually increased 5 percent (22 percent relative). Coral cover at the 3-m station at Kamalō also suffered an initial decline of 22 percent (30 percent relative) from 2000 to 2001 (fig. 6). The coral community, however, seems to be recovering, as indicated by increases in coral cover for both *M. capitata* (6 percent absolute, 16 percent relative) and *M. patula* (6 percent absolute, 61 percent relative). The recent increase in cover, however, has not compensated for the initial loss, and consequently, cover at this station remains significantly depressed (fig. 6).

In summary, temporal trends across sites indicate that four of the six stations (Pālā'au 10 m, Kamiloloa 3 m, and Kamalō 3 m and 10 m) experienced a statistically significant drop in coral cover after the initial survey (fig. 6). In contrast, the Pālā'au 3-m station appeared to be holding steady, while coral cover at the centrally located Kamiloloa 10-m station increased significantly. Some of the changes in coral cover may not be ecologically important because of the confounding effects of possible measurement error with the low absolute values. In the case of the Kamalō 3-m station, recovery appears to be taking place after an initial decline in 2001. The trends will become clearer with continued monitoring over the next decade.

Table 1. Baseline percent cover by substrate type at the six south Moloka'i CRAMP stations in 2000. Dashes (–) indicate none observed.

Substrate Type	Taxon	Common Name[1]	Pālā'au 3 m	Pālā'au 10 m	Kamiloloa 3 m	Kamiloloa 10 m	Kamalō 3 m	Kamalō 10 m	Mean
Coralline algae			<0.1	0.6	<0.1	0.3	0.1	3.1	0.7
Macroalgae			0.2	2.6	4.3	19.6	0.4	0.1	4.5
Turf algae			69.3	22.9	87.4	78.7	24.4	21.1	50.6
Sand			0.1	–	4.5	0.2	–	–	0.8
Coral	*Leptastrea purpurea*	Crust coral	<0.1	–	<0.1	–	–	–	<0.1
	Montipora capitata	Rice coral	6.5	32.7	–	0.2	59.5	25.2	20.7
	Montipora flabellata	Blue rice coral	–	<0.1	–	–	0.8	0.1	0.2
	Montipora patula	Sandpaper rice coral	3.0	12.9	–	0.1	9.2	24.3	8.2
	Pavona maldivensis	Maldive coral	–	<0.1	–	–	–	–	<0.1
	Pavona varians	Corrugated coral	–	–	–	–	<0.1	<0.1	<0.1
	Pocillopora damicornis	Lace coral	<0.1	–	0.1	–	0.1	–	<0.1
	Pocillopora eydouxi	Antler coral	0.2	0.1	–	0.1	0.2	–	0.1
	Pocillopora meandrina	Cauliflower coral	1.5	0.6	3.5	0.1	0.6	0.2	1.1
	Porites brighami	Brigham's coral	–	–	<0.1	0.1	0.1	<0.1	<0.1
	Porites compressa	Finger coral	5.3	24.7	–	–	1.0	25.2	9.4
	Porites lobata	Lobe coral	13.0	1.5	0.1	0.3	3.0	0.2	3.0
	Unknown coral		0.1	0.1	<0.1	<0.1	0.2	–	0.1
	Total percent coral cover		29.6	72.4	3.7	0.9	74.6	75.2	42.7
	Species richness[2]		9	9	6	7	11	8	8

[1] Common names are from Fenner (2005).

[2] Species richness is the total number of coral species documented at a site.

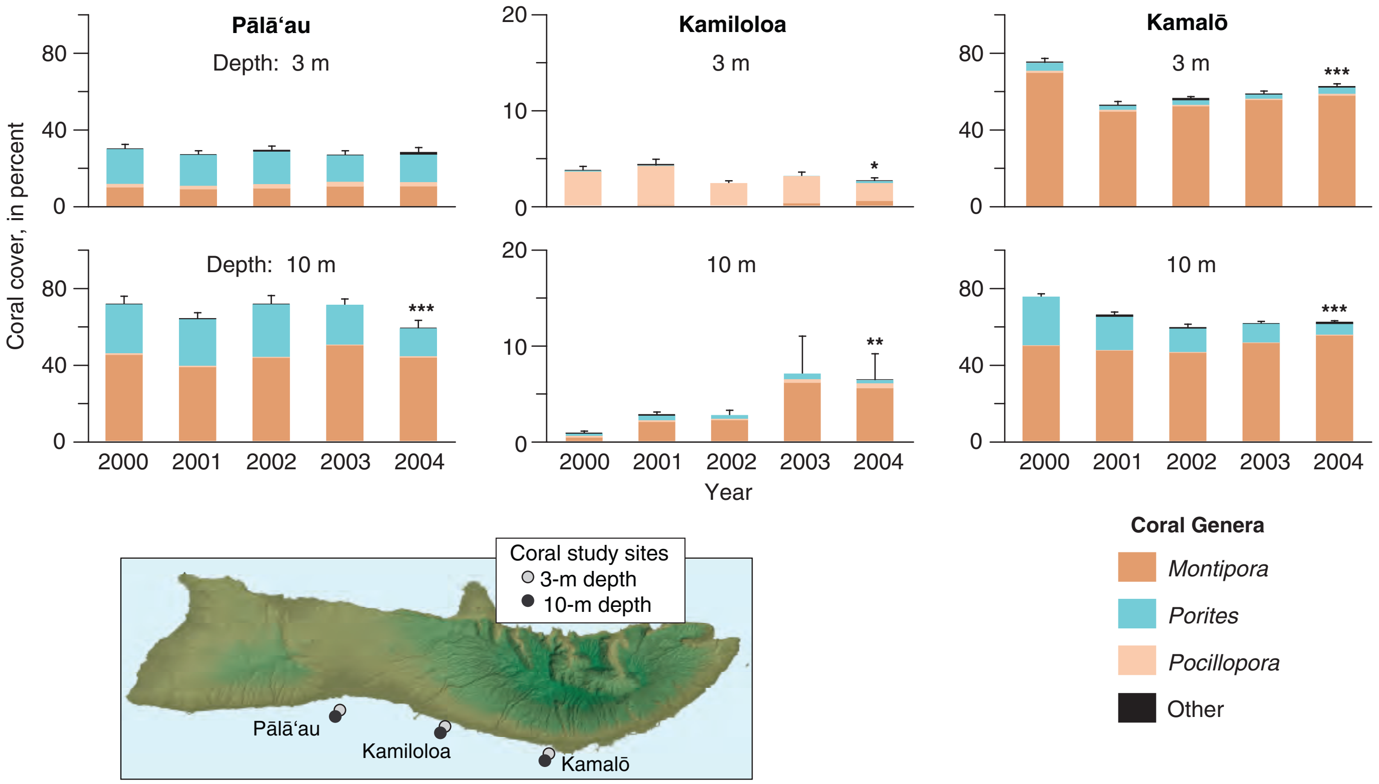

Figure 6. Trends in coral cover for the abundant genera at the deeper Moloka'i stations (3-m and 10-m; 10-ft and 33-ft) from 2000 to 2004. Mean ± 1 standard error with a sample size of 10 transects at each station. Significant changes in coral cover from the initial survey in 2000 to the last survey in 2004 are denoted on the figures (* = p <0.05, ** = p <0.01, *** = p <0.001). Note the different Y-axes for the Kamiloloa 3-m and 10-m stations.

Life-History Patterns—Recruitment

A total of 221 new coral recruits were documented in the 60 photoquadrats from 2000 to 2004. The five most abundant species of recruits were *Montipora capitata* (89), *M. patula* (32), *Pocillopora damicornis* (26), *Porites compressa* (23), and *Porites lobata* (22) (fig. 7). Another five species (*Cyphastrea ocellina, Montipora flabellata, Pavona maldivensis, Pocillopora damicornis,* and *Porites lichen*) formed 13 percent of the new recruits in the photoquadrats. The majority of *Montipora* recruits were observed at the Kamiloloa 3-m and 10-m stations (fig. 8). Spatially, *Porites* recruits formed a larger component of the recruiting classes at the Pālā'au 3-m, Kakahai'a 1-m, and Kamalō 3-m stations than at the Kamiloloa stations. In comparison, pulses of *Pocillopora* recruitment were sporadic and appeared during various times at the Pālā'au 1-m, Pālā'au 10-m, Kamiloloa 1-m, Kamiloloa 3-m, and Kakahai'a 1-m stations.

Recruitment rates varied by depth within a site. The number of new recruits at the Pālā'au 1-m and 3-m stations declined after 2001, but this was not a statistically significant change (fig. 8). The recruitment rate in 2001 was 2.7 recruits/m^2/yr at the 1-m station and 3.0 recruits/m^2/yr at the 3-m station. These levels decreased to 0.3 and 0.6 recruits/m^2/yr, respectively, by 2004. In contrast, recruitment levels increased at the 10-m station from 0 recruits/m^2/yr in 2001 to 2.4 recruits/m^2/yr by 2004. This increase was not statistically significant because of the high variation in recruitment numbers.

At Kamiloloa, recruitment rates at the 1-m station were relatively stable across the 4 years and ranged from 0.9 to 1.8 recruits/m^2/yr (fig. 8). The recruitment rate at the 3-m station was 6.1 recruits/m^2/yr in 2001 and then jumped up to 8.5 recruits/m^2/yr in 2002. In 2003 and 2004, recruitment dropped off to 2.4 and 3.0 recruits/m^2/yr, respectively. The 10-m station at Kamiloloa followed a similar pattern, with high recruitment in 2001 (17.0 recruits/m^2/yr) followed by an increase in 2002 (23.0 recruits/m^2/yr) and then a subsequent decline in 2003 and 2004 to 3.0 recruits/m^2/yr. The declines in 2003 and 2004 from the preceding years were statistically significant.

Recruitment rates at the Kakahai‘a 1-m station showed a general decline from 5.2 recruits/m^2/yr in 2001 to 0.9 recruits/m^2/yr in 2004 (fig. 8). This decrease was not statistically significant even though it represented a fivefold drop in recruitment. The most likely explanation for the apparent decrease is that recruitment fluctuated dramatically among the photoquadrats, especially in 2001.

The 3-m and 10-m stations at Kamalō displayed an even more pronounced and steady decline in recruitment than at Kakahai‘a (fig. 8). At the 3-m station, recruitment rates dropped from 2.4 recruits/m^2/yr in 2001 to 0 recruits/m^2/yr in 2004. The 10-m station experienced a tenfold decrease in recruitment, from 6.1 recruits/m^2/yr in 2001 to 0.6 recruits/m^2/yr in 2004. Despite the dramatic reduction in recruitment rates, these declines were not statistically significant because of the high variability in recruitment rates among photoquadrats.

In summary, recruitment rates at Pālā‘au were generally lower in comparison to the other sites at each of the depths sampled (fig. 8). In comparison, Kamiloloa had the highest recruitment rates, and this was attributed to the high initial recruitment of *Montipora* spp. Over time, most of the stations experienced a drop in recruitment rates, except for the Pālā‘au 10-m station, which increased, and the Kamiloloa 1-m station, which remained at a consistently low level. Deeper stations generally had higher recruitment rates than the corresponding shallow stations at a given site. The Pālā‘au 10-m station, however, had low initial recruitment rates compared to the shallow stations, but in 2004 recruitment was more than threefold higher than the shallow stations.

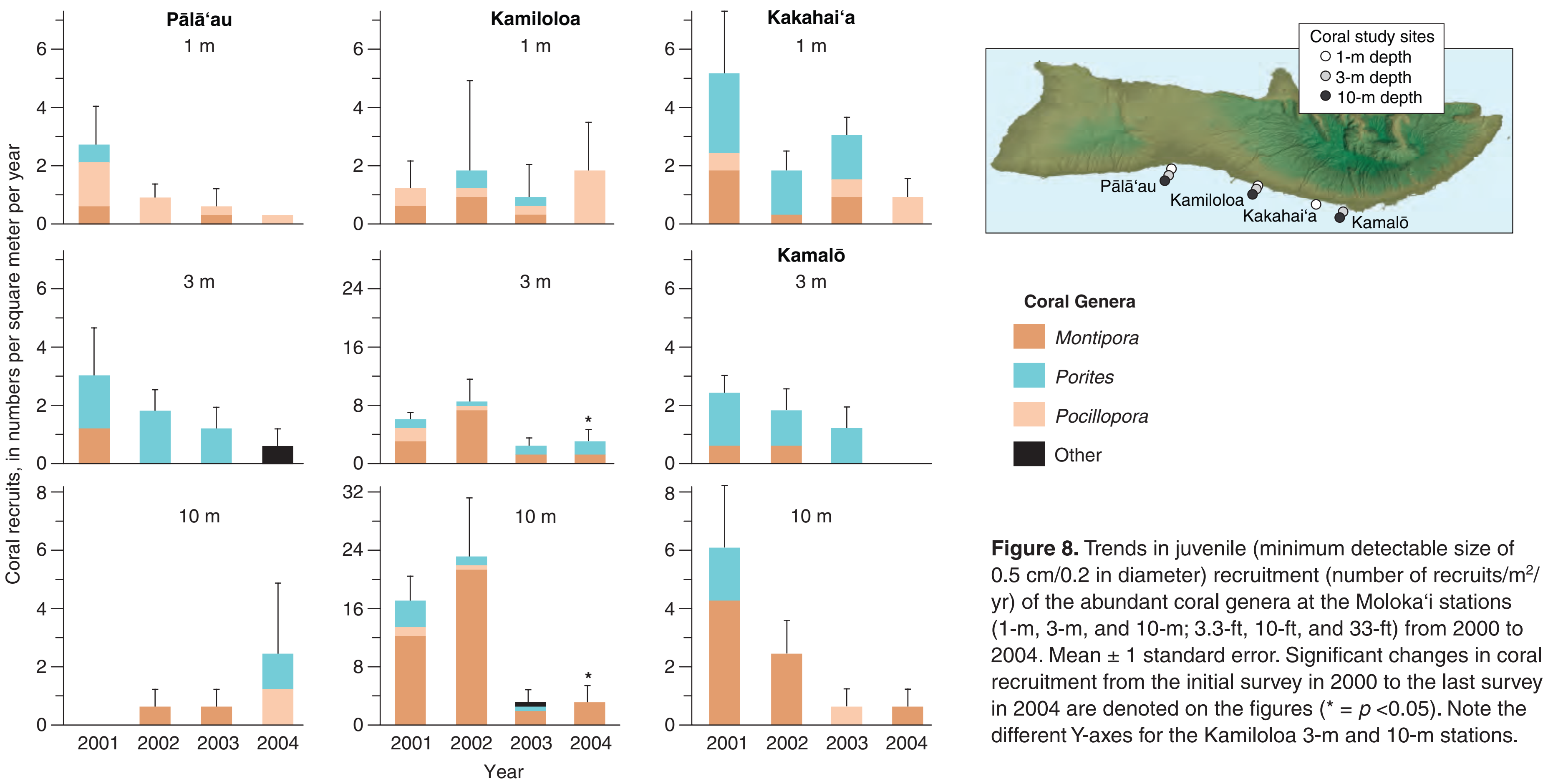

Figure 8. Trends in juvenile (minimum detectable size of 0.5 cm/0.2 in diameter) recruitment (number of recruits/m^2/yr) of the abundant coral genera at the Moloka‘i stations (1-m, 3-m, and 10-m; 3.3-ft, 10-ft, and 33-ft) from 2000 to 2004. Mean ± 1 standard error. Significant changes in coral recruitment from the initial survey in 2000 to the last survey in 2004 are denoted on the figures (* = $p < 0.05$). Note the different Y-axes for the Kamiloloa 3-m and 10-m stations.

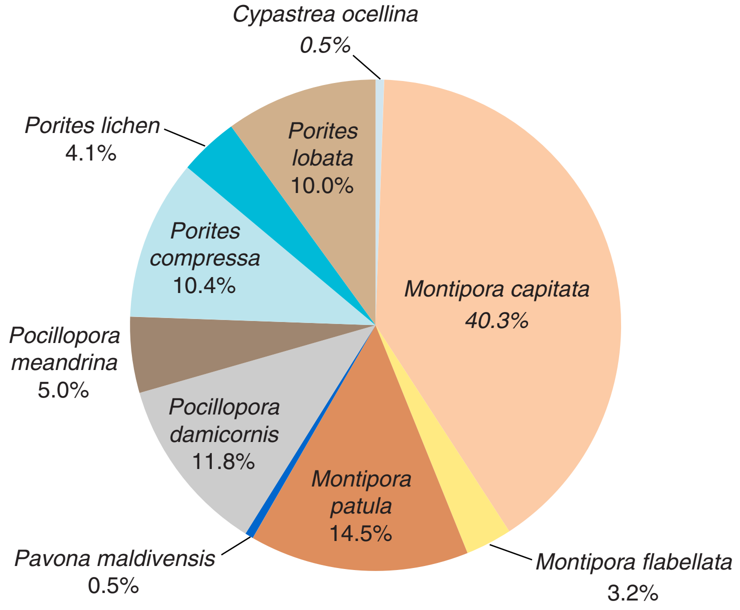

Figure 7. Chart showing percentage of new coral recruits by species among all nine of the stations off south Moloka‘i from 2000 to 2004. See table 1 for data and list of common names.

Discussion

Trends in Coral Cover

Analysis of long-term monitoring data at stations along the south shore of Moloka‘i over the past 5 years has documented patterns of reef decline, recovery, and stability. Stations spanning a distance >20 km, such as the Pālā‘au 10-m, Kamiloloa 3-m, and Kamalō 3-m and 10-m stations, all experienced declines in coral cover since 2000, although the Kamalō 3-m station appeared to be recovering (fig. 6). In contrast, coral cover at the centrally located Kamiloloa 10-m station was increasing, while less than 200 m away at the 3-m station it decreased. In addition, the Pālā‘au 3-m station, which is only 250 m from the 10-m station, appears to be holding steady compared to the declining 10-m station. What explains these differences in community trends over varying distances?

Coral community structure at each of the stations reflects the influence of natural and anthropogenic factors along the fringing reef tract. The principal natural factors on the south shore of Moloka‘i, discussed separately in other chapters in this volume and elsewhere, include wave exposure (Storlazzi and others, this vol., chap. 11), tidal cycle (Storlazzi and others, 2004), wind patterns (Storlazzi and others, this vol., chap 11), freshwater intrusion (Grossman and others, this vol., chap. 13), and natural erosion from land (Roberts and Field, this vol., chap. 15). Wave disturbance has been proposed as the primary factor shaping coral reef communities in Hawai‘i (Grigg, 1983; Jokiel and others, 2004). The long-term trends in coral cover on Moloka‘i suggest that stations within a site at a scale of several hundred meters are influenced differently by wave events. Indeed, Connell and others (1997) observed that reefs in close proximity (30-300 m) at Heron Island in the Great Barrier Reef varied in their response to natural disturbances such as cyclones over a 30-year period. Edmunds (2002) also found contrasting patterns in long-term (12 yr) cover data from two sites in the U.S. Virgin Islands separated by <1 km. He attributed this pattern to the different depths and the coastal features that protected one reef from the impact of Hurricane Hugo in 1989.

In the present study at Moloka‘i, it appears that depth may also play a role in producing differential trends in coral cover, but the trends were not the same at a given depth. Disturbances (for example, waves, flooding, coastal development) over the past 5 years may have been of sufficient magnitude to alter coral community structure between stations within a site. For example, the cooler average water temperatures at the shallow Kamalō and

Kakahaiʻa stations suggests that freshwater intrusion has been higher than at deeper stations and stations further west (E. K. Brown, written commun., 2004). Spatial patterns in historical precipitation levels on Molokaʻi support this observation (Giambelluca and Schroeder, 1998). Heavy rainfall in Hawaiʻi has been known to result in reef "kills" caused by freshwater intrusion at the surface on shallow reef areas (Jokiel and others, 1993). This may explain the sudden decline in coral cover from 2000 to 2001 at the Kamalō stations. Precipitation levels during this time period, however, were not abnormally high (National Climatic Data Center, v://www.ncdc.noaa.gov/oa/ncdc.html, accessed August 31, 2007), so this scenario does not appear likely. Biological factors such as predation, parasitism, disease, competition, and bioerosion can also play a role and add to the dynamic changes that occur on reefs.

The primary anthropogenic factor on Molokaʻi appears to be sedimentation from erosion (Roberts, 2001) and the subsequent resuspension of the sediment along the reef flat (Ogston and others, 2004; Storlazzi and others, 2004; Presto and others, 2006). Initial site selection for this study was based on a perceived sediment stress gradient from Pālāʻau, which was believed to be the most heavily impacted site, to the more easterly Kamalō, with relatively little sediment influx. Roberts (2001) reported that cattle ranching in western and central Molokaʻi in the mid-to-late 1800s and early 1900s resulted in a severe loss of native vegetation, producing upland erosion and subsequent deposition at Pālāʻau. Parts of the shoreline at Pālāʻau have prograded approximately 200 m since the late 1800s (see D'Iorio, this vol., chap. 16, for a further discussion of historical shoreline changes). Consequently, it was hypothesized that the sediment influx would have detrimental impacts on the adjacent reef. Clearly this was not the case at Pālāʻau, where moderate to high coral cover has been coupled with the relatively steady state in community structure. It appears that the introduction of the mangroves in 1902 (Roberts, 2001), coupled with the reduction in cattle grazing, served to retain upland sediment close to shore and reduce sediment influx onto the reef. Kamiloloa farther east was the depauperate site, with some of the lowest coral cover in the state (Jokiel and others, 2004). Surveys of coral cover at 1-km intervals along the 10-m isobath indicated that coral reefs at Kamiloloa are situated in a pocket of low (<5 percent) coral cover surrounded by regions of extremely high (>60 percent) coral cover (Storlazzi and others, 2005). Thus, it appears that most of the anthropogenic stress is now focused on the region between Kawela and Kamiloloa because of the sediment influx and resuspension (Storlazzi and others, 2004).

An important point to consider in the development of a coral reef is the coral community structure at the initial observation. The Pālāʻau 10-m and Kamalō 3-m and 10-m stations all had high coral cover >50 percent in 2000. Consequently, it is much more likely that coral cover would decline rather than increase (Hughes, 1993). In comparison, the Kamiloloa stations had <5 percent coral cover, so the probability of coral cover increasing is much greater. Therefore, long-term trends must be interpreted with caution.

Recruitment Patterns

Biological processes such as recruitment could explain coral-cover temporal patterns at stations in close proximity. Recent evidence suggests that many marine populations of corals, fish, molluscs, and crustaceans once considered open to larval input at a large spatial scale are in fact relying more on self-recruitment than on outside sources (Kingsford and others, 2002; Sponaugle and others, 2002; Swearer and others, 2002; Warner and Cowen, 2002). Perhaps the coral populations in this study are self-seeding and therefore heavily influenced by the local adult community. Harriott (1992) hypothesized this relationship at an isolated subtropical reef (Lord Howe Island), but in that case the coral recruits came from brooding corals rather than the broadcast spawners documented in this study. Brooding corals have exhibited a shorter time to competency (Harriott, 1992) and a larger dispersal potential than broadcast spawners (Richmond, 1988), which would facilitate self-seeding. Consequently, it is not directly apparent in this study that self-seeding is occurring, but genetic analysis of the coral recruits and surrounding adult population may help resolve this question. Supply-side considerations indicate that a decline in living tissue would subsequently reduce reproduction and ultimately recruitment (see, for example, Hughes and others, 2000). The lag time, however, between the decline in coral cover and the subsequent reduction in local recruitment may not be evident in the short time frame of this study.

Spatial patterns in recruitment rates at the Molokaʻi stations generally corresponded to trends in coral cover. For example, the Kamiloloa 10-m station had the highest annual recruitment rate among the 9 stations (fig. 8), and this was the only station that experienced an increase in coral cover. This increase was attributed to the high initial recruitment of *Montipora* spp. in 2001 and 2002, which also most likely resulted in the abundance of this genus in the community structure (fig. 6). Other examples included the low recruitment rate at the Pālāʻau 10-m station coupled with the declining coral cover at this same station. Some recruitment patterns, however, did not match the trend in coral cover. An example is the high annual recruitment at the Kamiloloa 3-m station (fig. 8) and the low coral cover that was actually decreasing (fig. 6). This pattern suggests that high water motion and the resulting sediment stress (Storlazzi and others, 2004) are limiting recruitment success at this station. Other possibilities exist to explain the poor relationship between recruitment and coral cover trends at certain stations. Perhaps the source of recruitment is from nearby reefs outside the sampling area, or maybe differential mortality is occurring at the stations for all age classes.

Temporal patterns in recruitment are more difficult to interpret because of the highly variable nature of recruitment (Hughes and others, 1999a; Brown, 2004) and the short time frame of this study. For example, the higher initial recruitment at each of the stations may simply be an episodic recruitment pulse rather than a high, sustained level of recruitment along the Molokaʻi coastline followed by a subsequent decline. Therefore, understanding temporal patterns in recruitment probably requires monitoring over time scales commensurate with coral reproductive patterns (that is, decades).

In general, recruitment rates for similar species and genera were lower in this study compared to other studies around the globe (table 2). Higher rates were documented by Smith (1992) for *Porites astreoides* (12.1 recruits/m^2/yr) in Bermuda and by McClanahan (2000) for *Porites* spp. (3.3 recruits/m^2/yr) in the Maldives (table 2). Connell (1973) and Connell and others (1997) reported recruitment rates averaging 5 recruits/m^2/yr for all coral taxa on recovering reefs subjected to periodic cyclones in the Great Barrier Reef. In their study, the highest recruitment rates (mean 8 to 13 recruits/m^2/yr) occurred at reefs that experienced the greatest absolute declines in percent coral cover (Connell and others, 1997). Smith (1992), however, observed similar recruitment rates at both damaged (12 recruits/m^2/yr) and control (13 recruits/m^2/yr) reefs in Bermuda. In addition, Loch and others (2002) documented recruitment rates of 12 recruits/m^2/yr at reefs in the Maldives that had experienced severe bleaching during the 1998 El Niño event. Consequently, high recruitment rates associated with various disturbance events imply either that larval sources are not necessarily local or that adult fecundity was unaffected by the storms, at least within the spatial scale (100 m) of the sampled adult community.

Perhaps the coral communities on Molokaʻi, with low coral recruitment in comparison to other areas, have not experienced disturbances of sufficient magnitude to open up suitable substrate for new recruits. Indeed, the highest recruitment rates were observed at stations (Kamiloloa 3-m and 10-m) with the lowest coral cover. If these Kamiloloa stations had experienced a recent disturbance, then substrate could have become available for settlement from adjacent coral communities with high cover. Larger scale qualitative surveys have documented coral-rich communities east and west of Kamiloloa (Storlazzi and others, 2005) that could easily have accounted for the high recruitment seen at these stations. It is important to note, however, that disturbance events are not necessarily associated with wave phenomena and do not necessarily promote recruitment. For example, sediment stress, either acute or chronic, might actually reduce the amount of available substrate for recruitment (Rogers, 1990; Fabricius, 2005). Given the high recruitment levels at the two Kamiloloa fore reef stations coupled with high sediment accumulation (Storlazzi and others, 2004) and resuspension (Ogston and others, 2004), it appears that sediment may not influence recruitment rates as much as other factors such as adult fecundity (Hughes and others, 2000). Lack of sediment data at the other stations, however, limits any spatial and temporal conclusions regarding disturbance type and recruitment.

In Hawai‘i, other studies of juvenile recruits (>0.5 cm in diameter) on natural substrates have included Polacheck (1978) on O‘ahu and Brown (2004) on Maui. Polacheck (1978) found no *Montipora* spp. or *Porites* spp. recruits and lower *Pocillopora meandrina* recruitment rates (0.18 recruits/m^2/yr) in comparison to this study (mean 0.26 recruits/m^2/yr) (table 2). His study sites off Waikīkī may not have been conducive for good recruitment because of large areas of unconsolidated sediment (Coyne and others, 2003), which can inhibit survival of new recruits (Fabricius, 2005). Polacheck’s study was also 1 year in duration and may not have detected episodic recruitment events. In contrast, Brown (2004) documented high recruitment rates for all species at his west Maui sites (table 2). The difference in recruitment rates between these studies can possibly also be explained by the lower coral cover, and thus more available substrate, at the west Maui stations (Brown, 2004). It should be noted, however, that areas existed on both islands with plenty of available space but low recruitment. Thus, other factors (for example, sedimentation stress, larval availability) must also be contributing to the low recruitment observed in these photoquadrats.

Table 2. Average coral recruitment on natural substrates for juveniles (minimum detectable size of 0.5 cm/0.2 in diameter and no previous settlement record) of coral species and genera in the Caribbean, Pacific, and Indian Oceans.
[Recruitment rates for Moloka‘i are averaged across all nine stations for the four years 2001–2004.]

Site	Region	Genus/Species	Common Name[1]	Recruitment (number of recruits/m^2/yr)	Reference
O‘ahu, Hawai‘i	Pacific	*Montipora capitata*	Rice coral	0	Polacheck (1978)
Maui, Hawai‘i	Pacific	*Montipora capitata*	Rice coral	4.5	Brown (2004)
Moloka‘i, Hawai‘i	Pacific	*Montipora capitata*	Rice coral	1.4	Brown and others, this study
Maui, Hawai‘i	Pacific	*Montipora flabellata*	Blue rice coral	0.3	Brown (2004)
Moloka‘i, Hawai‘i	Pacific	*Montipora flabellata*	Blue rice coral	0.1	Brown and others, this study
Great Barrier Reef	Pacific	*Montipora foliosa*	*	0.3	Connell (1973)
Great Barrier Reef	Pacific	*Montipora hispida*	*	0.3	Connell (1973)
Maui, Hawai‘i	Pacific	*Montipora patula*	Sandpaper rice coral	1.0	Brown (2004)
Moloka‘i, Hawai‘i	Pacific	*Montipora patula*	Sandpaper rice coral	0.5	Brown and others, this study
Maldives	Indian	*Montipora* spp.		0.4	McClanahan (2000)
Great Barrier Reef	Pacific	*Pocillopora damicornis*	Lace coral	0.7	Connell (1973)
Moloka‘i, Hawai‘i	Pacific	*Pocillopora damicornis*	Lace coral	0.2	Brown and others, this study
O‘ahu, Hawai‘i	Pacific	*Pocillopora meandrina*	Cauliflower coral	0.2	Polacheck (1978)
Maui, Hawai‘i	Pacific	*Pocillopora meandrina*	Cauliflower coral	1.0	Brown (2004)
Moloka‘i, Hawai‘i	Pacific	*Pocillopora meandrina*	Cauliflower coral	0.2	Brown and others, this study
Maldives	Indian	*Pocillopora* spp.		0.1	McClanahan (2000)
Great Barrier Reef	Pacific	*Porites annae*	Nodule coral	0.7	Connell (1973)
Bermuda	Caribbean	*Porites astreoides*	Mustard hill coral	12.1	Smith (1992)
Florida	Caribbean	*Porites astreoides*	Mustard hill coral	1.3	Miller and others (2000)
O‘ahu, Hawai‘i	Pacific	*Porites compressa*	Finger coral	0	Polacheck (1978)
Maui, Hawai‘i	Pacific	*Porites compressa*	Finger coral	1.7	Brown (2004)
Moloka‘i, Hawai‘i	Pacific	*Porites compressa*	Finger coral	0.3	Brown and others, this study
Maui, Hawai‘i	Pacific	*Porites lobata*	Lobe coral	1.1	Brown (2004)
Moloka‘i, Hawai‘i	Pacific	*Porites lobata*	Lobe coral	0.3	Brown and others, this study
Great Barrier Reef	Pacific	*Porites lutea*	Mound coral	0.9	Connell (1973)
Florida	Caribbean	*Porites porites*	Finger coral	0.4	Miller and others (2000)
Maldives	Indian	*Porites* spp.		3.3	McClanahan (2000)

[1] Common names are from Fenner (2005) for Pacific species and Humann (1993) for Caribbean species. Species denoted with an * have no documented common name.

Statewide and Global Comparisons of Reef Condition

Spatial patterns in coral cover indicate that reefs along the south shore of Moloka‘i have both some of the highest levels and some of the lowest levels of coral cover found in Hawai‘i (Jokiel and others, 2004). Sections of the reef around Kamalō contain some of the most densely packed coral communities in the State. Temporal patterns, however, reveal that the Moloka‘i sites may not be faring as well as other sites in Hawai‘i. From 2000 to 2002, the six CRAMP stations on Moloka‘i discussed here experienced the largest decline (by island) compared to the other 54 CRAMP stations on Kaua‘i, O‘ahu, Kaho‘olawe, Maui, and Hawai‘i (Jokiel and others, 2004) (fig. 9). The decline was not statistically different from those stations on O‘ahu and Maui, but declines in coral cover on O‘ahu and Maui corresponded to high human populations. In contrast, Moloka‘i has a small population relative to land area (Juvik and Juvik, 1998), so causal mechanisms have focused on poor land-use management, attempted coastal development (Roberts, 2001), and the subsequent sediment influx and resuspension on the reef (Ogston and others, 2004). Efforts are currently underway on Moloka‘i to control feral ungulates and revegetate upland areas.

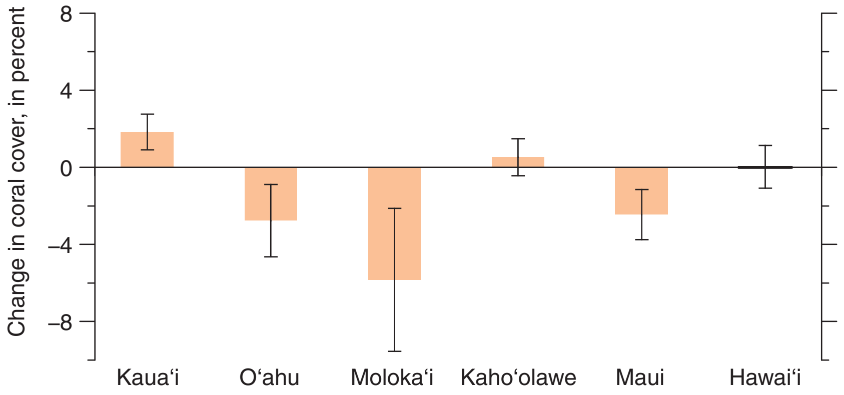

Figure 9. Mean percent change (±1 standard error) in coral cover by island at sites across the state of Hawai‘i from 1999 to 2002 (from Jokiel and others, 2004).

Reefs in the Hawaiian archipelago appear to be doing better than reefs in other parts of the world. Of the 20 regions examined in the latest biennial review, "Status of Coral Reefs of the World: 2004," the Hawaiʻi region had the highest percentage of reefs (93 percent) at low or no threat level (Wilkinson, 2004). Only 1 percent of the reef area in the region is considered destroyed (Waikīkī) compared to a high of 65 percent in the Persian Gulf (Wilkinson, 2004). The south shore of Molokaʻi, however, was included in the 5 percent of Hawaiʻi's reefs at the threatened stage. Local residents are taking steps to reverse this pattern by changing upslope land-use patterns and limiting coastal development. These proactive measures may not be enough to protect near-shore reefs, because changes in global climate are elevating water temperatures in Hawaiʻi above critical thresholds for corals (Jokiel and Brown, 2004). If annual water temperatures continue to increase with extended durations of seasonal high temperature anomalies, then reefs along the south shore of Molokaʻi may not recover. In addition, long residence time and resuspension of sediment may compound the problem (Ogston and others, 2004; Presto and others, 2006). The reefs in decline may already be responding to these chronic disturbances, which could lead to the demise of the Molokaʻi reefs. Coral reef ecosystems, however, operate in a cyclical fashion over time (Karlson, 1999), and therefore the decline we are currently witnessing may simply represent the downward portion of the community cycle before the upswing. Indeed, one station (Kamalō 3-m) is already showing signs of recovery.

Conclusions

Temporal trends in coral cover indicate that four of the six CRAMP stations on Molokaʻi (Pālāʻau 10-m, Kamiloloa 3-m, and Kamalō 3-m and 10-m) experienced a statistically significant drop in coral cover from 2000 to 2004. In contrast, the Pālāʻau 3-m station appeared to be holding steady, while coral cover at the centrally located Kamiloloa 10-m station increased significantly. Temporal patterns reveal that Molokaʻi may not be faring as well as other sites in Hawaiʻi, but from a global perspective the reefs along this coastline are better off than elsewhere. Spatial patterns in recruitment rates at the Molokaʻi stations generally correspond to trends in coral cover but there are exceptions (for example, the Kamiloloa 3-m station). Recruitment rates of comparable coral species and genera are generally lower along the south shore of Molokaʻi than at other sites around the State and globally.

Molokaʻi has the longest contiguous reef tract in the main Hawaiian Islands, but there are signs that the reef community along the south shore may be experiencing a difficult period in its evolution. Coral recruitment patterns and anthropogenic stressors will need to be closely monitored to see if the reef ecosystem can continue to sustain itself. Projected changes in climate and sea level will further exacerbate an already tenuous situation along this coastline and could lead to the demise of an outstanding fringing reef area.

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