Benthic Communities

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INTRODUCTION

This chapter focuses on the shallow water benthos surrounding the 10 emergent islands, reefs and atolls comprising the Northwestern Hawaiian Islands (NWHI). The composition and distribution of benthic communities in the subtropical NWHI reflect the interaction of numerous influences, including geographic isolation, latitude, exposure and the successional age of the islands they inhabit. This mosaic of habitats extend 1,200 nm northwest of the main Hawaiian Islands (MHI) and consist mostly of coral-dominated areas, stretches of hard-bottom algal-dominated meadows, and vast expanses of unconsolidated sediments such as sand and mud inhabited by few benthic infauna at shallower depths (<20 m). The benthic habitats at greater depths are relatively unknown, unexplored and are not covered here.

CORALS

Species Richness

The most recent published surveys of the NWHI revealed a total of 57 species of zooxanthellate stony corals (Maragos et al., 2004). However 2006 surveys at greater depths and in a wider variety of habitats have yielded a number of new morpho-species, most of which have yet to be collected and described. Appendix I lists of all coral and anemone species reported at 11 islands, banks, atolls and reefs in the NWHI as of October 2006. As was the case during earlier compilations, the larger atolls with diverse habitats and shelter from large northwest swell support the greatest number of species. Although these numbers are similar to the MHI, the Hawaiian coral fauna, as a whole, is depauperate relative to the Indo-West-Pacific, where up to 700 species have been reported (Veron, 1995). The most plausible cause is geographic isolation (Grigg, 1983) associated with the NWHI being located at the northeastern periphery of the Indo-Pacific biogeographic province.

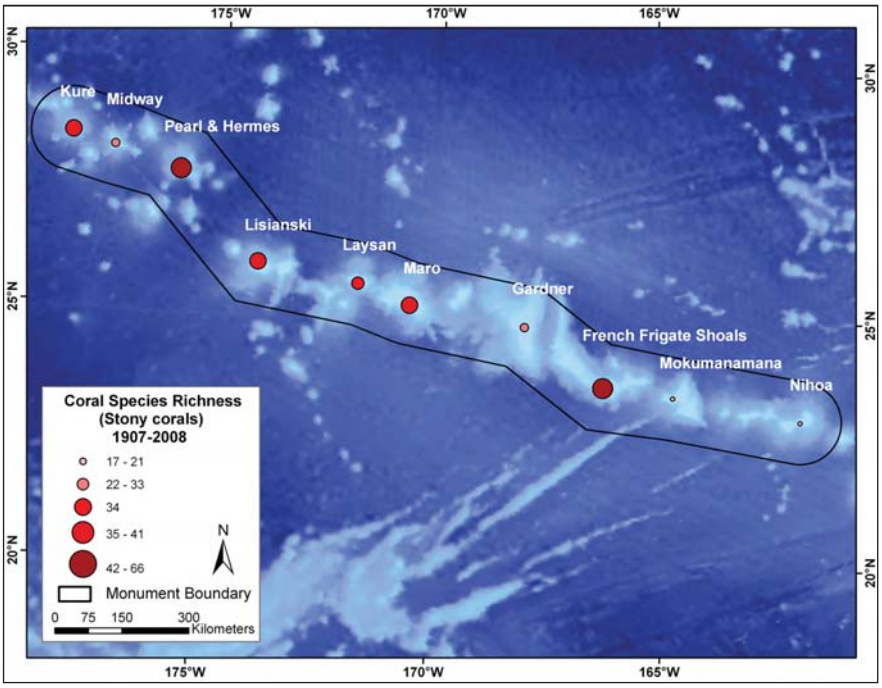

Figure 4.1. Total number of coral species reported in the NWHI between 1907 and 2006 compiled by Maragos from Dana (1846), Vaughan (1907), Dana (1971), Maragos et al. (2004) and unpublished records. Map: L. Wedding.

The distribution of coral species is related to geomorphology, size and age of the NWHI reefs (Grigg, 1997; Figure 4.1). There is a highly significant ($p < 0.001$) correlation between the number of coral taxa and the amount of reef area within 10 fathoms with French Frigate Shoals, Pearl and Hermes and Maro

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Reef having the highest richness of coral taxa (Table 4.1, Figure 4.2). Low coral species richness is found at the southern end among the small basalt islands of Nihoa, Mokumanamana and Gardner Pinnacles, which are openly exposed to severe wave events particularly during winter months (Maragos et al., 2004 ; Grigg et al., 2008). This area is dominated by robust species that are more tolerant of high wave action and soft corals such as *Sinularia* spp. and *Palythoa* spp. The large middle atolls (French Frigate Shoals and Maro) have some of the highest coral species richness reflecting optimal conditions in terms of both habitat (a large open atoll) and environmental conditions (wave shelter, temperature and low disturbance, as well as the high number of Acroporidae and Fungiidae species). Seven species of the genus *Acropora* are now known from the NWHI despite their almost complete absence in the MHI (Maragos et al., 2004), and several additional undescribed *Acropora* were photographed at French Frigate Shoals, Neva Shoal and Pearl and Hermes in 2006. Compared to French Frigate Shoals, Pearl and Hermes Atoll and Maro Reef, one-third fewer coral species are found at Mokumanamana and Nihoa islands. At the northern end of the chain, stony coral species decline is linked to lower winter water temperatures and lower average annual solar radiation (Grigg,1982), and coral development is limited by extensive sand shallows towards the eastern sides of the lagoons (Maragos et al., 2004). Moreover WWII era construction may have extirpated some corals from Midway's lagoon. Kure is the world's most northern atoll and is referred to as the Darwin Point, where coral growth and subsidence/erosion balance one another (Grigg,1982). However, there are at least 30 submerged and presumably drowning seamounts to the southeast of Kure and within the PMNM, and the "Darwin point" may be better characterized as a Darwin zone stretching from Nihoa to Kure.

Table 4.1. Least squares linear regression model for reef area less than 10 fathoms versus coral taxa richness. Source: Maragos, unpub. data.

SUMMARY OF FIT				
R^2	0.79859			
R^2 Adjusted	0.773414			
Root Mean Square Error	6.390495			
Mean of Response	35.7			
Observations (or Sum Wgts)	10			
ANALYSIS OF VARIANCE				
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	1	1295.393	1295.39	31.7199
Error	8	326.7074	40.84	**Prob > F**
C. Total	9	1622.1		0.0005
PARAMETER ESTIMATES				
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	24.88415	2.7878	8.93	<.0001
Reef area < 10 fathoms	0.072376	0.012851	5.63	0.0005

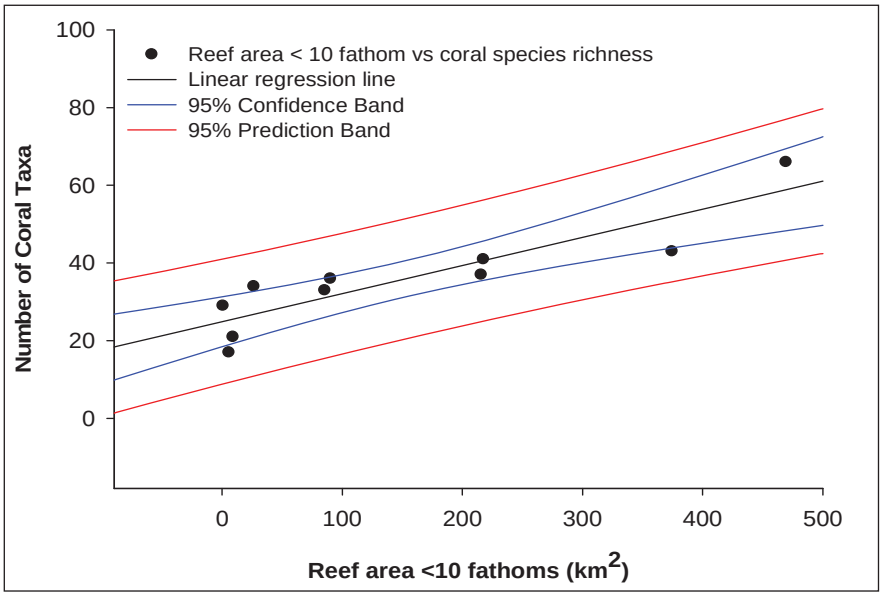


*Figure 4.2. Relationship between number of coral taxa and reef area within 10 fathoms (based on Rohman et al., 2005). Coral species richness = 24.88 + 0.072*Reef area <10 fathoms. Source: Maragos, unpub. data.*

Examination of reefs in ordination space based on presence-absence of coral taxa reveal two major clusters (Figure 4.3). High concordance exists among the basalt islands of Nihoa (NIH), Mokumanamana (MMM) and Gardner Pinnacles (GAR). These small islands are exposed to high wave energy from all directions and have low coral richness and cover. The reefs from Maro (MAR) north to Kure (KUR) cluster together in ordination space but the three most northern atolls (Midway [MID], Pearl and Hermes [PHR], and Kure [KUR]) show the highest concordance. The coral assemblage at French Frigate Shoals appears unique compared with all other locations likely due to the high proportion of acroporid species and possible connectivity with Johnston Atoll 830 km to the south (Grigg et al., 1981; Maragos and Jokiel, 1986).

Range Extensions and Possible New Coral Species

Recent scientific expeditions in the NWHI have yielded many new records and possibly many undescribed species of stony corals since the last compilation by Maragos et al. (2004; Table 4.2). One of the most exciting discoveries in 2006 was of the table coral *Acropora* off the southwest spur-and-groove habitat at Pearl and Hermes Atoll and off the shallow southeast fore reef at Neva Shoal. Additional dives confirmed the presence of *Acropora cytherea* and *A. cerealis-valida* at Pearl and Hermes, and *A. valida* at Neva Shoal, which led to other discoveries at Neva, a second *Acropora* sp.1 and three *Montipora* species that are all likely new to science.

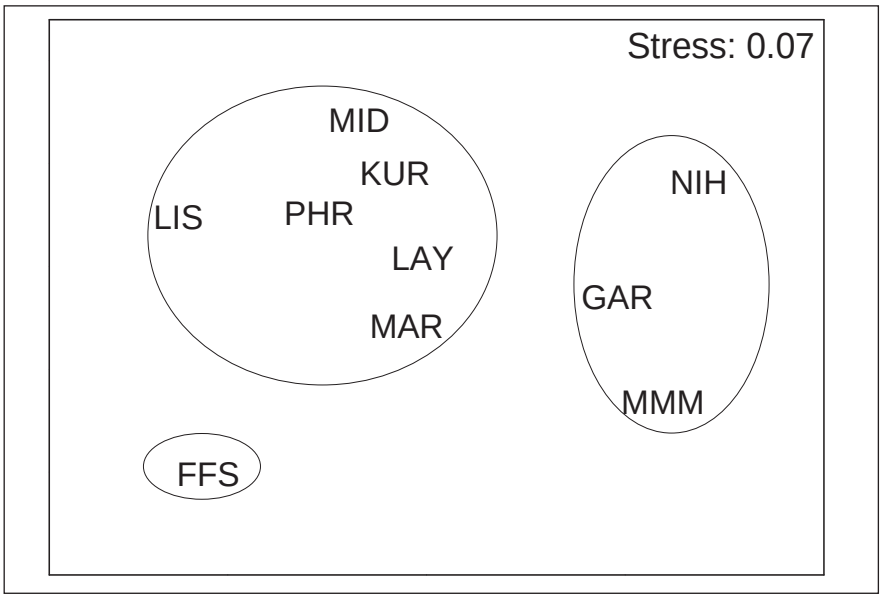


Figure 4.3. Spatial distribution of reefs in the PMNM based on presence-absence of coral species. Results of non-metric multidimensional scaling plot. Source: Maragos, unpub. data.

The Census of Marine Life (CoML) cruise to French Frigate Shoals in October 2006, led to additional sightings of rare species including *Diaseris distorta, Cycloseris tenuis*, *Leptoseris scabra* and *Acropora* sp.1. Another rare species, resembling *Leptoseris papyracea* was previously known only from dredge hauls by Vaughan (1907) in the MHI, and was reported for the first time in the NWHI off the southeast fore reef of French Frigate Shoals during CoML. An unidentified species, *Porites* sp. 15, was reported off a southwest pinnacle of French Frigate Shoals, and the first record of *Porites lutea* in the NWHI was reported off the northern reef crest. Many new records including several unidentified species of coral were reported during the CoML cruise. The 2006 investigations together have yielded possibly 11 new records for the NWHI most of which are likely to reveal new species. Towed-diver surveys contributed directly or indirectly to several of the new records and species, and exploratory dives in new habitats and sites contributed the rest. The Appendix at the end of the chapter lists all coral and anemone species reported at 11 islands, banks, atolls and reefs in NWHI as of October 2006. As was the case during earlier compilations, the larger atolls with diverse habitat and shelter from large northwest swell support the greatest number of species.

Table 4.2. A partial list of new records and possible new coral species from the NWHI. Source: Maragos, unpub. data.

SPECIES		LOCATION	YEAR	OBSERVERS
Leptoseris incrustans	New record	Pearl and Hermes	2006	Kenyon, PIFSC-CRED
Montipora	New species?	Pearl and Hermes	2006	Vargas, PIFSC-CRED
Acropora valida	New record	Laysan	2006	Kenyon, PIFSC-CRED
Pavona maldivensis	New record	Maro	2006	Kenyon, PIFSC-CRED
Diaseris distorta, Cycloseris vaughani, and *Cycloseris tenuis* and soft coral *Sinularia* sp	New record	Lisianski (30m)	2006	Maragos, Meyer, and Papastamatiou
Acropora cytherea and *A. cerealis-valida*	New record	Pearl and Hermes	2006	Asher and Zgliczynski
Acropora valida	New record	Neva Shoal	2006	Asher and Zgliczynski
Diaseris distorta, Cycloseris tenuis, Leptastrea scabra	New record	French Frigate Shoals	2006	CoML
Leptoseris papyracea??	New record	French Frigate Shoals	2006	CoML
Acropora sp.1	New species?	French Frigate Shoals	2006	CoML
Porites sp. 15	New species?	French Frigate Shoals	2006	CoML
Porites lutea	New record	French Frigate Shoals	2006	CoML
Unkown species	New species?	French Frigate Shoals	2006	CoML

Abbreviations: PIFSC-CRED: The Pacific Islands Fisheries Science Center Coral Reef Ecosystem Division; CoML=Census of Marine Life.

The most exciting coral discovery was of an unknown species that has not yet be identified to the genus and family (Figure 4.4). This coral may be a relict that was once common in the past and subsequently died out elsewhere but survived in Hawaii. The other possibility is that the coral may be a type previously restricted to deep water that evolved and subsequently adapted itself to shallow water habitats. Randall (2007) makes note of two fish that were previously characterized as relicts. Likewise it is possible for relict corals to have survived in Hawaii to this day. In order to confirm this, it will be necessary to collect this and other corals to determine their phylogenetic origin. So far coral experts have not been able to conclusively determine the family to which this coral belongs based on photographs alone. Marine life in the NWHI evolved for many millions of years in isolation from neighboring archipelagos and islands and it plausible that this, and perhaps other species, were able to survive and thrive without the threat of newer species displacing them as likely occurred in other archipelagos.

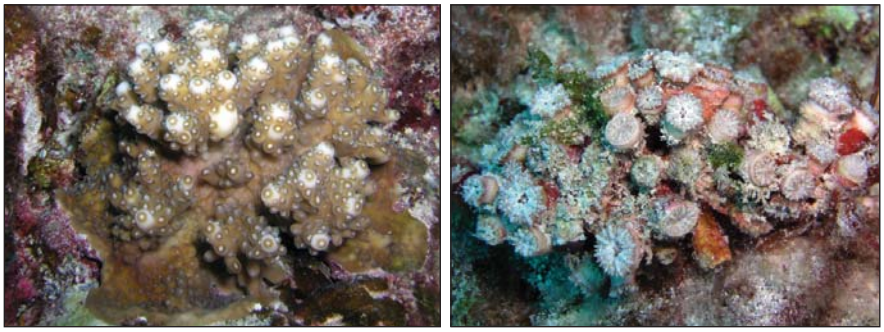


Figure 4.4. Potential new species of Acropora sp.1 from Lisianski-Neva Shoals and French Frigate Shoals (left). New, potential relict species yet undescribed from French Frigate Shoals. The genus and family are unknown (right). Both were discovered in 2006. Photo: J. Maragos.

French Frigate Shoals was chosen as the target for the first CoML cruise because of the potential of yielding new species of corals, other invertebrates and benthic algae and possibly extending the range of many other species. Eight more species of cnidarians have already been reported from the atoll, further cementing the atoll's status as the most diverse island or atoll for corals in Hawaii. The atoll is the closest of the Hawaiian chain to Johnston Atoll, some 450 nm to the southwest, and Johnston may be serving as a "stepping stone" for the dispersal of species to Hawaii from the Line Islands and other neighboring archipelagos south of Hawaii (Grigg, 1981; Maragos and Jokiel, 1986; Maragos et al,. 2004). This connection would explain why French Frigate Shoals has so many *Acropora* species which flourish at Johnston and why French Frigate Shoals has higher numbers of coral species compared to any of the other Hawaiian Islands.

Coral Endemism

The resumption of coral surveys to the NWHI in 2000-2006 were not focused on looking for new coral species because they were not expected to be there based on the Grigg and Dollar (1980) estimate of only 29 total species at 80 NWHI sites. Although endemic species and range extensions were encountered during the 2000-2006 surveys, most belonged to described species, although the totals nearly doubled the number of coral species (57) reported in the NWHI (Maragos et al., 2004). The exploratory and CoML expeditions of 2006 were both focused on looking for new species. However, scientists could only photograph and examine corals *in situ* because permission was not granted to collect corals.

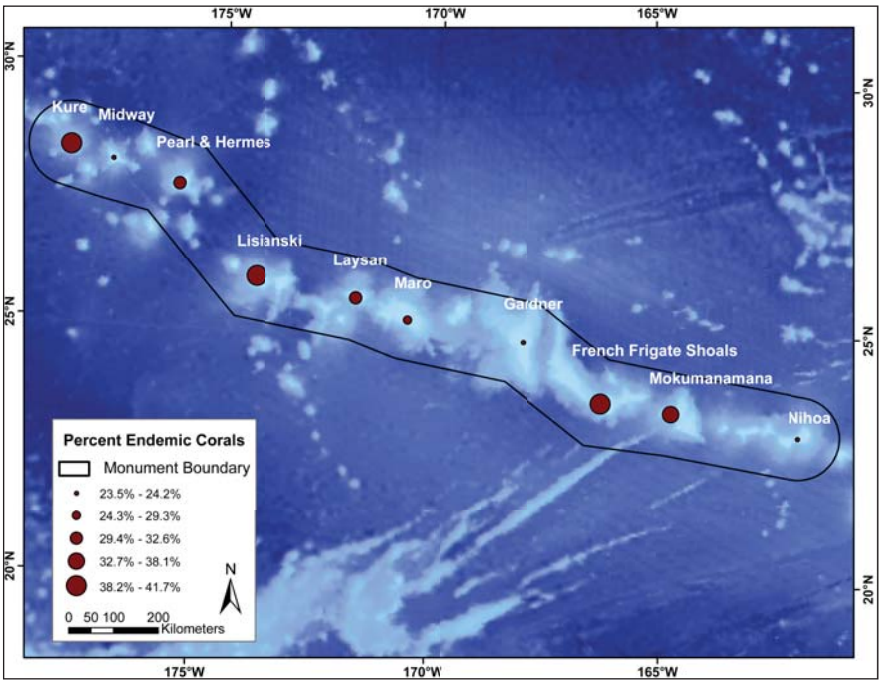


Figure 4.5. Percent endemic stony coral species at each reef in the NWHI during 1907-2006 compiled by Maragos from Dana (1846), Vaughan (1907), Dana (1971), Maragos et al. (2004) and unpublished records. Map: L. Wedding.

Based on all surveys to date (Figure 4.5; Table 4.3) , there are now approximately 80 morphologically distinct coral "species" in the NWHI, and about 35 are likely to be endemic. Perhaps an additional five species are similarly endemic, although other specialists (Veron, 2000) believe they are widespread Pacific species. More than 25 NWHI species are still undescribed or unidentified, and once type specimens are collected and examined morphologically and genetically, then final determinations can be made on which corals are new species and possible endemics. Notwithstanding efforts to date, NWHI explorations are still inadequate, and it is likely that additional undescribed coral species will be encountered in the future.

Table 4.3. Number of endemic and total stony coral taxa among major reefs in the PMNM. Source: Maragos, unpub. data.

ISLAND	TOTAL STONY CORAL SPECIES	NUMBER OF ENDEMIC	PERCENT ENDEMIC
Nihoa	17	4	23.5
Mokumanamana	21	8	38.1
French Frigate Shoals	66	27	40.9
Gardner	29	7	24.1
Maro	41	12	29.3
Laysan	34	11	32.3
Lisianski	37	15	40.5
Pearl and Hermes	43	14	32.6
Midway	33	8	24.2
Kure	36	15	41.7
Total	**80**	**35**	**44**

Table 4.4. Number of Rapid Ecological Assessments (REA) and Towed-diver Surveys (TDS) conducted by NWHI RAMP (2004 and 2006) and NWHI Ecosystem Reserve (2005). PHR = Pearl and Hermes. Source: NWHI RAMP, unpubl. data.

	2004		2005		2006	
	REA	TDS	REA	TDS	REA	TDS
Mokumanamana	3	0	3	0	2	4
French Frigate Shoals	11	17	6	0	10	19
Gardner	3	2	0	0	0	0
Maro	9	12	7	0	9	13
Laysan	3	5	0	0	3	6
Lisianski	9	12	0	0	9	12
PHR	14	21	9	0	13	26
Midway	9	15	6	0	9	15
Kure	9	13	6	0	9	13
Total	70	97	37	0	64	108

Coral Cover From Quantitative Surveys

Percent live coral cover was derived from towed-diver data and rapid ecological assessments (REAs; Kenyon et al,. 2006a; Table 4.4; Figures 4.6 and 4.7). Towed-divers observe a much greater expanse of benthic reef habitat (approximately 2 km in length/50 minute tow) than can be observed by free-swimming divers conducting REA surveys in a comparable time period and give a more widespread assessment of the total coral cover for each reef. Coral REA surveys were conducted at 70 sites in 2004, 37 sites in 2005 and 64 sites in 2006 (Table 4.4). As with percent cover data from 2002 surveys (which were calculated from size frequency data of colony counts within transects; Friedlander et al.; 2005), line-intercept data from surveys in all three years indicated coral cover varies greatly across the NWHI.

Based on towed-diver survey data, Lisianski (18.8%) and Maro (14.9%) have the highest coral cover, followed by French Frigate Shoals (Figure 4.6). Percent coral cover from the REAs is higher owing to the fact that they were conducted on hard bottom habitats only. However, the trends are strikingly simi-

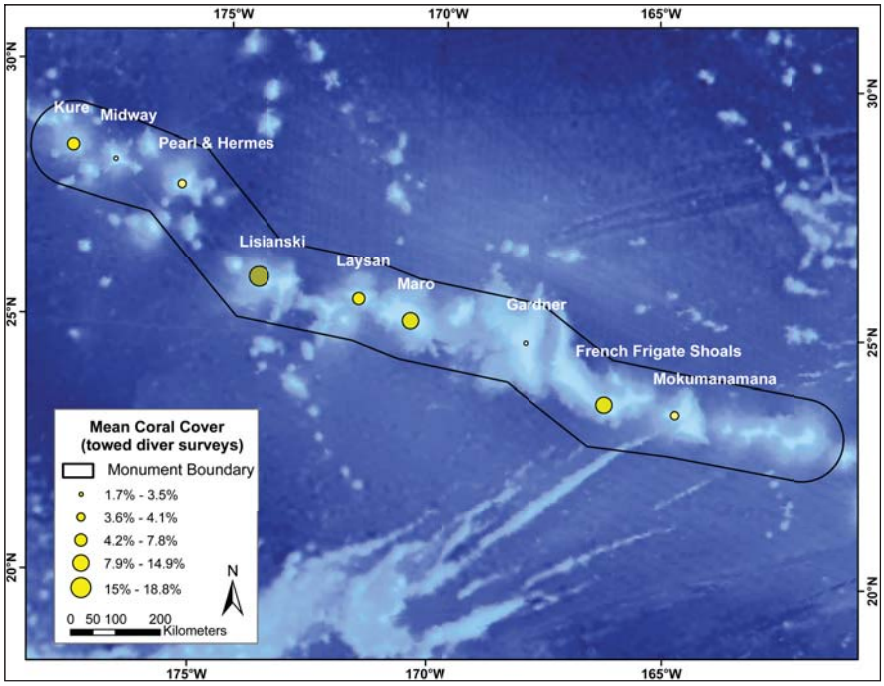


Figure 4.6. Percent live coral cover among reefs in the PMNM from towed-diver survey data, 2000-2002. Source: NWHI RAMP; map: L. Wedding

lar based on average estimates from 2004 to 2006, with the highest coral cover at Maro (39.0%), followed by Lisianski (37.5%) and French Frigate Shoals (26.0%; Figure 4.7). The lowest percent coral cover was recorded at Midway (1.7%), Gardner Pinnacles (3.5%), and Mokumanamana (4.1%). The lowest cover from the REA surveys was observed at Midway (10.1%), with Pearl and Hermes (12.1%) and Gardner Pinnacles (12.4%) also having low coral cover. Benthic REAs were not conducted at Mokumanamana from 2004 to 2006. Coral cover values determined from 2002 surveys also showed the highest coral cover values at Maro and Lisianski (Friedlander et al., 2005), though their magnitude (>60%) was greater than the values derived from the line-intercept method in 2004-2006.

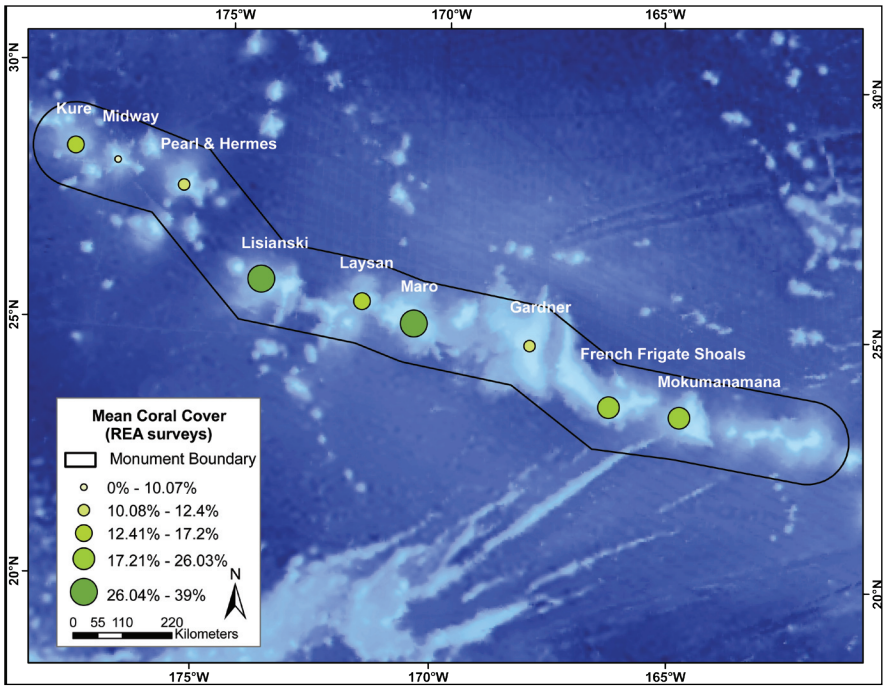


Figure 4.7. Live coral cover among reefs in the PMNM from REA data, 2004-2006. Source: NWHI RAMP; map: L. Wedding

Coral cover estimates for each reef from towed-divers and REAs compared with the mean coral cover for each method showed higher relative towed-diver survey values at Lisianski and French Frigate Shoals (Figure 4.8). This is likely due to the extensive deeper reefs that were not surveyed on the REAs, which are restricted to 15 m depth while towed-diver surveys operate down to 27 m. Higher relative coral cover estimates from REA were found at Nihoa, Midway, and Pearl and Hermes. The latter two locations have extensive back reef habitats that are not well surveyed by towed-divers due to the shallow depth.

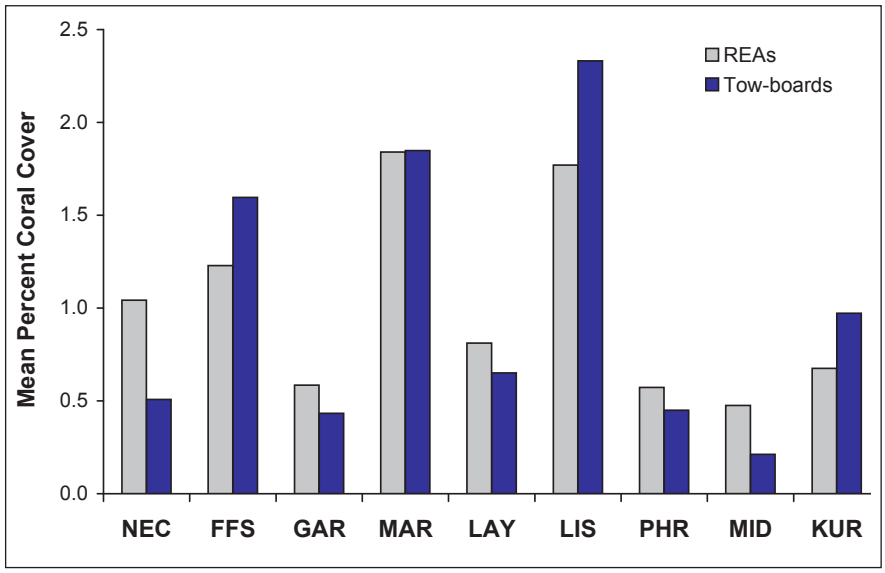


Figure 4.8. Comparisons of coral cover between towed-diver and REA estimates. Values are percent at each reef as a proportion of mean coral cover for that method. Source: NWHI RAMP, unpub. data.

Quantitative Estimates of Coral Genera and Species Abundance Among Reefs of the NWHI

Relative abundance of cnidarians was assessed by computing the proportion of colonies, by taxon, that occurred within belt transects (Table 4.5, Figure 4.9). Taxa comprising more than 10% of colony abundance in each location are highlighted in bold type. These 2006 data surveys exemplify some general patterns seen in all years. The relative abundance of corals varies among regions, though *Porites lobata* composes a majority of the fauna at numerous regions and is an important component of the fauna in all regions. *Acropora*, particularly *A. cytherea,* is an important component of the coral fauna at French Frigate Shoals, but less so in other regions where it occurs (Mokumanamana to Pearl and Hermes, inclusive). *Pocillopora meandrina* and *Montipora capitata* are both abundant in some regions but less common in others. Numerous taxa are represented throughout the NWHI at very low levels of abundance; although 57 species of stony corals have been documented in the NWHI (Maragos et al., 2004), many species occur at such low frequencies that they were not encountered within survey transects. Thus, relatively few coral species numerically dominate throughout the NWHI. When species are pooled by genus, *Porites*, *Pocillopora* and *Montipora* collectively emerge as the numerically dominant genera throughout the NWHI though their relative abundance varies by region (Figure 4.10).

Table 4.5. Relative abundance of cnidarian colonies in the NWHI based on REA surveys at 64 sites conducted by NWHI RAMP in 2006. All cnidarian taxa for which at least one colony was tallied in at least one location are listed. Source: Forsman and Maragos, unpub. data.

SPECIES	PERCENT OF CNIDARIAN FAUNA							
	MMM	FFS	MAR	LAY	LISI	PHR	MID	KUR
Acropora cytherea	0.0%	**10.7%**	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Acropora valida	0.0%	5.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Acropora humilis	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Montipora capitata	2.8%	2.6%	**15.1%**	9.4%	**17.7%**	6.3%	1.1%	2.7%
Montipora patula	2.5%	2.5%	5.2%	1.6%	6.8%	1.0%	0.1%	0.0%
Montipora flabellata	0.0%	0.0%	0.7%	0.0%	0.0%	0.5%	**13.6%**	1.9%
Montipora incrassata	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Pavona duerdeni	1.9%	2.5%	2.5%	3.8%	2.1%	0.3%	0.0%	0.0%
Pavona varians	0.1%	0.0%	0.0%	2.1%	0.1%	0.3%	0.4%	0.2%
Pavona maldivensis	0.0%	0.0%	0.0%	0.0%	1.1%	0.2%	0.0%	0.0%
Cyphastrea ocellina	0.0%	7.6%	4.8%	4.5%	**18.8%**	1.5%	0.9%	1.5%
Leptastrea purpurea	0.6%	1.0%	0.2%	0.2%	0.3%	7.3%	1.1%	3.6%
Fungia scutaria	0.0%	0.0%	0.5%	0.0%	0.9%	2.4%	0.0%	0.0%
Leptoseris incrustans	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
Pocillopora damicornis	0.0%	6.9%	0.7%	0.0%	6.4%	2.6%	8.5%	**13.4%**
Pocillopora eydouxi	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Pocillopora ligulata	0.7%	0.4%	1.2%	0.0%	0.6%	0.1%	0.2%	0.5%
Pocillopora meandrina	**28.9%**	8.1%	6.5%	**17.4%**	1.1%	**26.2%**	**11.3%**	**52.4%**
Porites brighami	0.6%	1.1%	0.3%	3.8%	0.6%	0.0%	0.0%	0.0%
Porites compressa	3.8%	**15.9%**	**39.8%**	1.9%	9.7%	8.5%	6.3%	5.4%
*Porites evermanni**	2.0%	1.5%	1.3%	0.2%	**11.9%**	0.0%	0.1%	0.1%
Porites lobata	**55.3%**	**32.2%**	**20.1%**	**54.9%**	**20.6%**	**37.1%**	**55.9%**	**16.3%**
Psammocora nierstraszi	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Psammocora stellata	0.0%	0.1%	0.0%	0.2%	1.3%	3.3%	0.2%	1.1%
Palythoa sp.	0.6%	1.3%	1.0%	0.0%	0.0%	2.3%	0.1%	0.8%
Total cnidarians counted	689	2,408	2,443	426	1,920	2,319	1,158	1,929
Area surveyed (m^2)	100	500	450	100	450	650	425	450

Island/Atoll abbreviations used throughout this chapter: MMM = Mokumanamana; FFS = French Frigate Shoals; and PHR = Pearl and Hermes Atoll; GAR = Gardner Pinnacles; MAR = Maro Reef; LAY = Laysan Island; LIS = Lisianski Island; MID = Midway Atoll; KUR = Kure Atoll; NIH = Nihoa Island.

***** *Porites evermanni* is considered to be *Porites lutea* by Fenner 2005, although recent molecular analyses have confirmed that *P. evermanni* is distinct from *P. lutea*.

Coral Density

Density, the number of cnidarian colonies per square meter, is another metric of community structure that reflects the degree of "packing" of individual colonies. Such indices are useful when considering processes that may be density-dependent, for example, the spreading of contagious diseases and fertilization by spawned gametes during sexual reproduction. Colony density should be considered in association with size frequency distributions in visualizing the nature of a population from graphed data, e.g., a high colony density accompanied by a right-skewed size frequency distribution indicates a large number of small colonies, while a low colony density accompanied by a left-skewed distribution indicates a small number of larger colonies. Density varies by taxon and by habitat, as demonstrated for Pearl and Hermes Atoll in Figure 4.11.

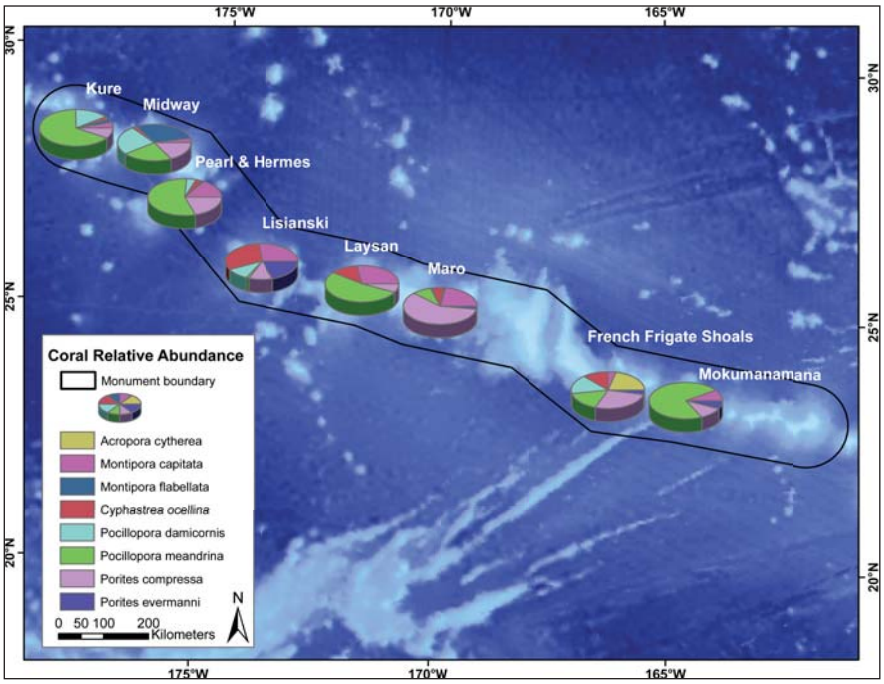


Figure 4.9. Relative abundance of coral species throughout the NWHI. Data are derived from colony counts within belt transects during 2006 surveys. Source: NWHI RAMP unpubl. data; map: L. Wedding.

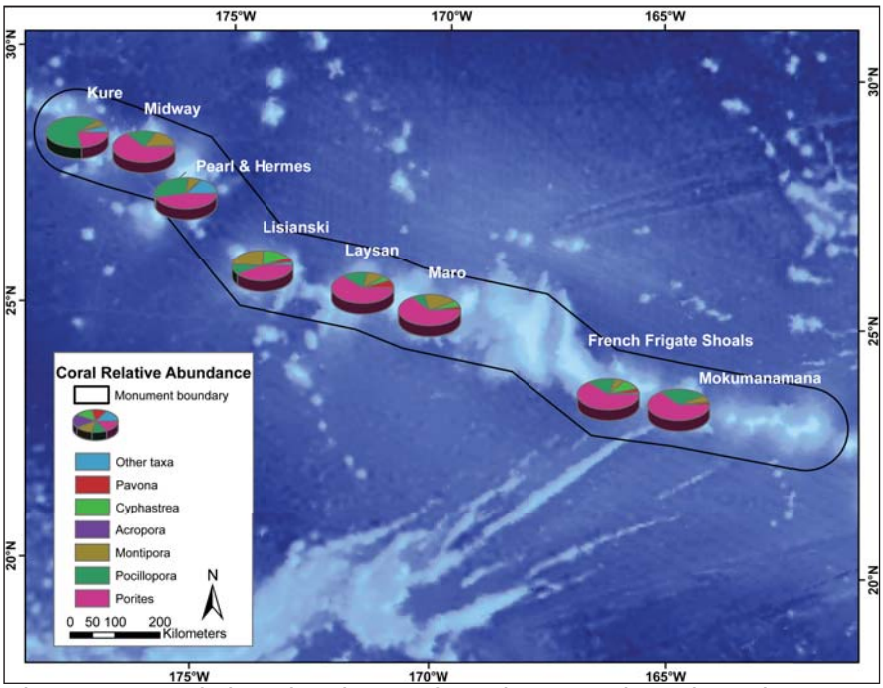


Figure 4.10. Relative abundance of coral genera throughout the NWHI. Data are derived from colony counts within belt transects during 2006 surveys. Source: NWHI RAMP unpubl. data; map: L. Wedding.

Habitat

Coral cover varies among reef geomorphologies and reef zones (Figure 4.12). Maro Reef has been described as a unique open atoll, as it lacks the emergent or very shallow perimeter reef around a deeper lagoon that characterizes a classic atoll. Instead, the innermost area of the reef complex, with characteristics of a protected lagoon, is separated from the open ocean by the surrounding mesh of reticulate, linear, and patch reefs. Average coral cover at Maro, as determined through quantitative analysis of benthic imagery recorded over extensive distances surveyed by towed divers between 2000 and 2002, was 14.0% (Kenyon et al., 2008a). Lisianski/Neva Shoal and French Frigate Shoals are also described as open atolls, the former with limited perimeter reef and the latter lacking perimeter reef to the west. Average coral cover at Lisianski was 19.7%, the highest average reef system value determined from extensive towed-diver surveys throughout the NWHI (Kenyon et al., 2007b). At French Frigate Shoals, coral cover was highest on the back reef (18.8%) and lowest in the lagoon (7.7%; Kenyon et al., 2006b). The most northern reef systems in the NWHI (Pearl and Hermes, Midway, and Kure) are described as classic atolls, as their perimeter reefs more completely surround a central lagoon. Quantitative analysis of benthic video images recorded over extensive distances by towed divers between 2000 and 2003 indicates that, in these classic atoll geomorphologies, coral cover is highest in the lagoon at Pearl and Hermes (19.1%) and at Kure (18.6%) and on

the back reef at Midway (6.4%; Kenyon et al., 2007a; 2008b). At all three locations, coral cover is lowest on the fore reef, ranging from 1.6% at Midway to 9.7% at Kure. Coral cover is low (5.3%) on the shallow (<30 m) bank surrounding Laysan (Kenyon et al., 2007b).

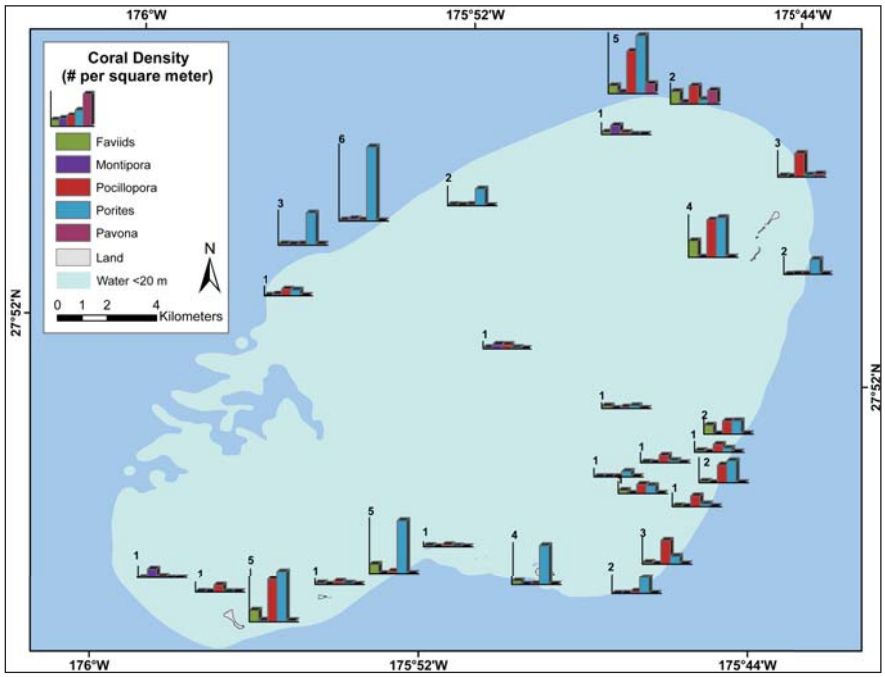


Figure 4.11. Colony density (n/m²) of five coral genera at Pearl and Hermes Atoll, NWHI. Number of colonies (n) was determined from belt transect surveys conducted in 2002. Source: NWHI RAMP; map, L. Wedding.

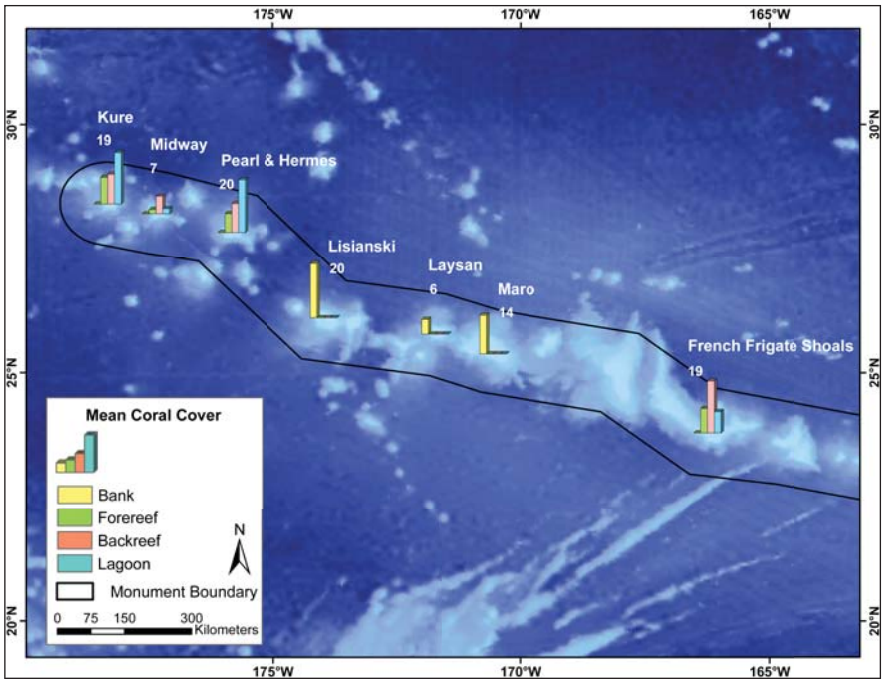


Figure 4.12. Differences in coral cover within different reef zones in the NWHI. Numbers represent the average coral cover: (%) + standard error. Coral cover calculated from size frequency data of colonies within transects. Data based on REA surveys in 2002. Not all habitats were sampled at all reefs. Source: NWHI RAMP, unpublished data; map: L. Wedding.

Wave exposure is a major determinant controlling the development of Hawaiian coral reefs, with moderate coral cover developing in areas directly exposed to winter wave regimes and high coral cover developing in sheltered embayments and areas protected from direct swells. In the NWHI, the greatest winter wave stress originates primarily from the northwest and secondarily from the northeast. At French Frigate Shoals, an open atoll lacking perimeter reef to the west, coral cover on the fore reef was highest in the northwest sector (approximately 26%; Kenyon et al., 2006b). At Pearl and Hermes Atoll, coral cover was highest on the fore reef in the northwest and north sectors (approximately 24–28%; Kenyon et al., 2007a). At Midway Atoll, coral cover on the fore reef was also highest on the north sector (J. Kenyon, unpubl. data). At Kure Atoll, coral cover on the fore reef was highest along the arc extending counterclockwise from north to west (approximately 11–16%; Kenyon et al., 2008b). At Laysan, coral cover was highest in the northwest sector (7.3%; Kenyon et al., 2007b). Reef-wide patterns of coral cover at Maro Reef and Lisianski vary from those at other locations in the NWHI with respect to wave exposure. At Maro Reef, an open atoll with no perimeter reef, the highest coral cover was along the northeast sector, closely followed by the southwest sector (Kenyon et al., 2008a). At Lisianski/Neva Shoal, an open atoll with limited perimeter reef, coral cover was highest in the southeast and southwest sectors (approximately 25–27%; Kenyon et al., 2007b). Both Lisianski/Neva Shoal and Maro Reef are classified as open atolls, but their complex structure of reticulate reef with little to no enclosure by perimeter reef likely generates a more complicated pattern of wave exposure than that experienced by atolls more clearly delineated by a perimeter reef, and accordingly they are characterized by different patterns of highest coral cover.

Wave Action

High – north and west sectors experience regular large to huge wave events, especially in winter months where waves can exceed more than 15 m in height. Primary benthic components on exposed reefs are energy tolerant species and growth forms such as crustose coralline algae, non-delicate fleshy algae and encrusting *Porites* corals.

Medium – east sectors experience nearly constant moderate wave action due to exposure from trade wind generated swells. Southern exposures receive occasional large swells generated by storms of tropical origin, especially in summer months.

Low – the southwesterly parts of the islands generally represent the most protected sectors of the islands, but this generally applies to larger islands/atolls where shelter from waves is more extensive. Areas of shelter are minimal for the smaller islands. Atoll lagoons are the most protected of all geomorphological zones of the NWHI.

Although early work in the NWHI assumed the best developed seaward reefs would occur off southwestern coasts (Grigg, 1983), analysis of imagery from more extensive and spatially comprehensive towed-diver surveys indicate coral cover on the fore reef is highest along the northwest, north, or northeast sectors at French Frigate Shoals, Maro Reef, Laysan, Pearl and Hermes Atoll, Midway Atoll, and Kure Atoll (Kenyon et al., 2006b; 2007a,b; 2008a,b). Only at Lisianski/Neva Shoal is coral cover highest along the southwest sector (Kenyon et al., 2007b) .

Effects of Temperature on Northwestern Hawaiian Island Corals

The coral reefs of the NWHI are in sub-tropical latitudes and exposed to large seasonal temperature fluctuations, particularly Kure, Midway and Pearl and Hermes Atolls, at the northwestern end of the archipelago. Sea surface temperature (SST) at these northerly atolls can fluctuate from less than 18°C in late winter (17°C in 1997) to highs exceeding 28°C in the late summer months (29°C in 2002). Compared with most reef ecosystems around the globe, the annual fluctuations of SST of 10°C at these northerly atolls is extremely high. The cooler winter temperatures are thought to reduce coral growth rates. While the summer temperatures are generally similar along the entire NWHI, the warmest summer temperatures tend to occur at the three northernmost atolls, presumably caused by reduced mixing due to weaker winds (situated closer to the center of the North Pacific high pressure ridge) and decreased circulation due to large shallow water lagoons (Brainard et al., 2004; Hoeke et al., 2005). Roughly two-thirds of the variability in growth rate across the archipelago can be explained by changes in temperature and light availability (Grigg, 1982). Growth rates for a representative species of coral *(P. lobata*) dominant throughout the chain vary from 3 mm/yr to 13 mm/yr (Grigg, 1982).

Siciliano (2005), however, reports that, while coral growth rates generally decline as a function of increasing latitude in the NWHI, as originally suggested by Grigg (1982), this decrease is habitat-specific. Coral colonies found in protected habitats throughout the NWHI chain (i.e., back reef and lagoon habitats on the atolls; embayments sheltered from wave action at the islands lacking lagoons) grow at similar rates regardless of latitude. This is may be explained by the microclimatic conditions experienced by corals growing in the shallower lagoon and back reef habitats, which are not closely related to offshore SST (Jokiel and Brown, 2004). Growth rates in these habitats may be influenced more by light and competition for space with other corals than by the relatively stable, and sometimes higher ambient temperatures afforded by these protected environments from solar heating in shallower lagoons. Conversely, corals growing in exposed habitats throughout the NWHI (i.e., fore reef of atolls or the reef slope of islands lacking a lagoon) experience temperatures more akin to offshore SST conditions, and therefore are more likely to respond to regional SST gradients, such as decreasing SST with increasing latitude, resulting in the measured latitudinal decrease in growth rates in these habitats.

The growth rates reported by Grigg (1982) may also be an under-estimate at Kure Atoll because of selective sampling. In his assessment of coral growth rate throughout the NWHI, Grigg (1982) sampled *Porites lobata* exclusively in 10 m depth from exposed southwest areas. Inspection of *Porites*' growth rates in three habitats at Kure atoll (Table 4.6, from Siciliano, 2005) reveals that the fore reef has the lowest growth rate

for this genus, among all sites sampled. Therefore exclusive sampling from this area is likely to underestimate average growth rates per atoll. Even so, *Porites*' growth rates from the fore reef habitat in Siciliano's study (4.5 mm/yr) are higher than those reported by Grigg for *Porites lobata* (3 mm/yr), even if the data for Porites exclude the faster growing, branching forms such as *P. compressa* (largely absent from Kure's fore reef). Encrusting and more massive growth forms of *P. lobata* and *P. evermanni*, important reef builders at Kure, were included in the more recent assessment.

Table 4.6. Mean linear growth rates (cm/yr) of five main reef-building coral genera in three habitats at Kure Atoll. Source: Siciliano, 2005.

GENUS	FORE REEF	BACK REEF	LAGOON
Porites	0.45	0.74	1.01
Pocillopora	1.69	1.72	1.69
Montipora	0.10	0.10	0.12
Pavona	1.63	0.76	0.63
Leptastrea	0.20	0.22	0.24

Inspection of Table 4.6 also indicates that if the *Porites* growth rates were adjusted to reflect those of other reef-building corals in the fore reef habitat using Grigg's approach (i.e., by averaging *Porites*' growth rates with those of other reef-building genera), the corals' growth rate would increase to 0.8 mm/yr, rather than decrease as suggested by Grigg (1982), who reported an adjusted growth rate of 0.2 mm/yr for Kure Atoll.

Monitoring Corals at Permanent Transect Sites in the Northwestern Hawaiian Islands: 2001-2006

This section focuses on the results of monitoring coral communities at 27 permanently marked transects established at seven of the 10 NWHI from 2001-2002 and resurveyed in September 2006, and account for most of the 42 permanent transects established in the NWHI from 2000-2002. Changes in percent coral cover per transect were compared between 2001-2002 and 2006 at permanent transects (Figure 4.13). Mean coral cover declined by 2% from 2001-2002 to 2006 but was not significantly different between these time periods (w= 53, p=0.51). Table 4.7 summarizes the results of the 2006 permanent transect resurveys and offers a comparisons to earlier surveys at the same sites. The changes in percent coral cover, mean diameter, number of coral genera and the density of all corals per transect are provided in the table. When pooling the data for all 27 sites, percent coral cover declined from 16.6 % to 14%, mean diameter declined from 22.7 to 15.5 cm, number of genera increased from 2.9 to 4.3, and coral densities increased from 4.8 to 6.7 corals m^2 at the same set of transect sites over the four to five year interval. These trends are significant for all categories except percent coral cover. Changes in the survey techniques between the two sets of surveys can explain some of these patterns. For one, *in situ* census of corals vis-à-vis analysis of photos would likely lead to detecting greater numbers and genera for smaller corals, leading to lower mean diameter values. However, the analysis of the individual sites over the time interval reveals that some of these trends can only be explained by *in situ* observations and site-specific data.

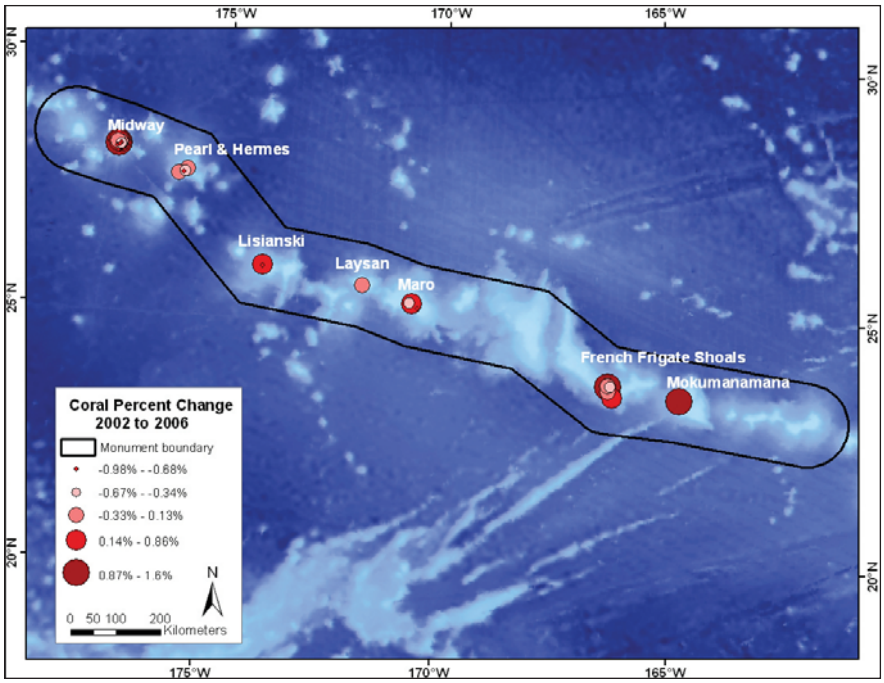


Figure 4.13. Percent change in coral cover between 2001-2002 and 2006 at permanent stations in the PMNM. Source: Maragos, unpub. data; map: L. Wedding.

Table 4.7. Percent coral cover, mean diameter, number of genera and frequency of all corals at each of 27 permanent transect sites surveyed in 2001-2002 and 2006. Bold numbers are the higher of two (earlier or later) values at each site.

SITE NUMBER	HABITAT	LOCALE	DATE	PERCENT CORAL COVER		MEAN DIAMETER CM		NUMBER GENERA/SITE		DENSITY (#/m²)	
				2001-2002	2006	2001-2002	2006	2001-2002	2006	2001-2002	2006
FFS- 5P	fore reef	NW	7/17/2001	**19.4**	16.8	11.6	**13.3**	**4**	3	**14.2**	11.7
FFS 3P	lagoon basalt	N cen.	7/16/2001	27.7	**28.8**	**19.9**	17.8	5	5	8.5	**11.5**
FFS 16P	Lagoon	N	9/15/2001	4.8	**9.5**	12.3	**15.1**	**5**	4	4.6	**7.8**
FFS 2P	reef crest	S	7/15/2001	27.2	**33.5**	**26.2**	20.1	**7**	6	5.3	**9.4**
FFS 11P	back reef	N	10/30/2002	**39.1**	22	**76.2**	21.3	3	**4**	1.6	**5.9**
LAY 1P	channel	S	9/17/2001	**5.9**	5.1	7.7	**10.9**	3	**6**	**9.5**	4.9
LAY 5P	reef pool	SE	9/18/2002	7.7	**8.7**	11	**14.6**	3	**4**	**5.6**	4.8
LIS 1P	reef crest	S cen.	9/30/2002	**5.3**	0.43	**14.5**	4.6	2	**4**	**3.8**	0.36
LIS 9P	pinnacle	E	10/2/2002	19.2	**24.9**	**22.9**	16.3	2	**4**	5.1	**9.8**
LIS 6P	fore reef	N	10/1/2002	27.9	**46.8**	**57.4**	40.6	1	**3**	1.8	**4**
MAR 4P	back reef	NW	9/16/2002	**52**	34.4	**36.4**	20.6	3	**7**	6.4	**11.4**
MAR 5P	Lagoon	center	9/21/2001	4.2	**5.9**	**10.9**	10.3	2	**5**	3.8	**5.1**
MAR 1P	fore reef	SE	9/15/2002	**32.4**	7.9	**29.6**	9.3	3	**7**	4.6	**8.2**
MID 7P	Lagoon	E	9/23/2002	**50**	1.1	**25**	7.6	4	4	nd.	3.2*
MID 16P	back reef	N	12/3/2002	24.3	**36**	**46.7**	29.7	3	3	2.1	**5.8**
MID 14P	lagoon pinnacle	center	9/24/2002	4.7	**12.2**	8	**12**	2	**3**	**12.2**	9.5
MID 18P	back reef	NE	12/4/2002	0.7	**1.3**	6.8	**7.4**	4	**5**	2.5	**3.5**
MID 19P	lagoon pinnacle	SW	12/5/2002	**5.1**	0.9	**14.7**	13.1	2	**3**	**2.77**	1.02
MID 20P	back reef	NW	12/6/2002	**22.3**	19.2	**48.7**	31	**3**	2	1.46	**2.7**
MID 1Pa	reef crest	E	12/3/2002	**3.3**	1.04	**17.6**	11.7	2	**4**	1.73	**2.46**
MID 2P	back reef	NE	9/21/2002	13.8	13.8	**22.6**	21.3	4	4	2.8	2.8
MID 17P	back reef	E	12/4/2002	**9**	3.5	10.4	**20**	2	**4**	**4.6**	1
MMM 1P	basalt fore reef	S	9/9/2002	6	**14.6**	8.4	**10.6**	2	**4**	9.1	**18.4**
PHR 6P	lagoon pinnacle	S	9/19/2002	**2.53**	1.53	**11.7**	7.6	2	**4**	1.8	**4.8**
PHR 7P	lagoon patch reef	center	9/27/2002	**24**	20.7	**25.6**	10.1	1	**3**	**4.64**	19.8
PHR 9P	Pass	S	9/28/2002	**1.69**	0.23	**14.4**	9.5	2	**4**	**1.07**	0.4
PHR12P	fore reef	SW	9/29/2002	**8.95**	7.11	**15.5**	11.1	3	**6**	3.15	**6.48**
TOTALS	**27**		**MEANS**	**16.64**	14	**22.69**	15.46	2.9	**4.3**	4.8	**6.7**

Mokumanamana

Permanently marked transect NEC-1P is located in a semi-sheltered recessed bay or bight off the southwest side of Mokumanamana and is the only permanent transect established to date. The site was re-surveyed on September 3, 2006. All coral population parameters increased during the four year period between the two surveys. Mean diameter increased from 8.4 cm to 10.6 cm. Coral densities increased from 9.1 to 18.4/m^2, generic diversity increased from two to five genera, and coral cover more than doubled to 14.6%. All four of the smaller size classes for total corals increased substantially during the four year period although there were only a few corals represented at the higher size classes for each survey period (Figures 4.14 and 4.15). Overall, all smaller size classes increased and the larger stayed the same. Severe exposure to waves from any direction and the large winter swell from the northwest may prevent development of large, high profile corals. The lobe coral (*Porites lobata)* followed by the rose/cauliflower coral (*Pocillopora meandrina)* continue to dominate the coral fauna, although the zoanthid soft coral (*Palythoa tuberculosa)* has emerged as a common coral on the transect in 2006, even though absent in 2002. The number of *Porites* corals doubled for the all four smaller size classes while *Pocillopora* also increased dramatically in all size classes. Despite the exposed and scoured environment at the site, corals have increased dramatically at NEC-1P over the four year period.

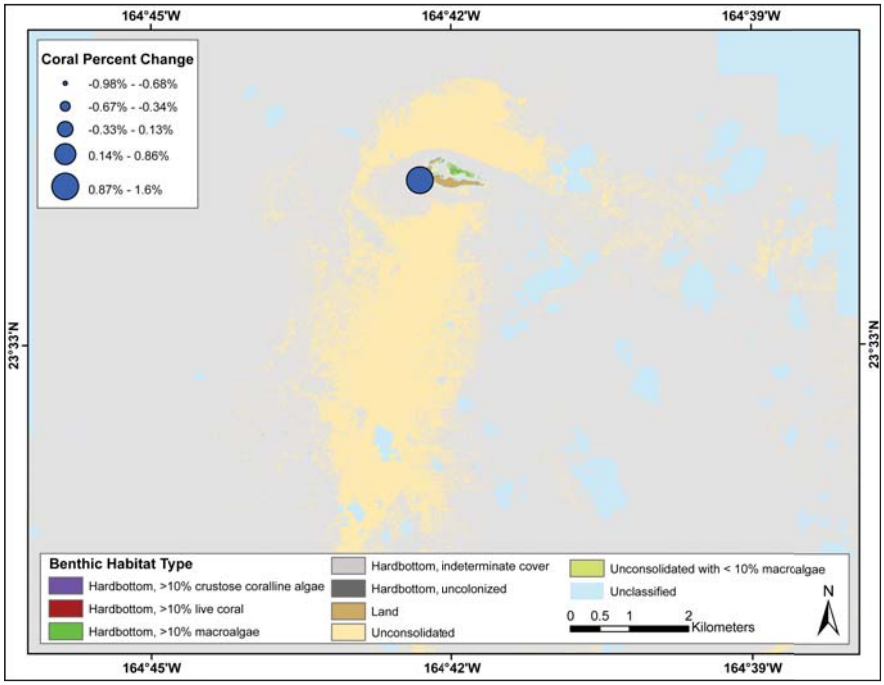


Figure 4.14. Percent change in coral cover at Mokumanamana between 2002 and 2006. Source: Maragos, unpub. data; map: L. Wedding.

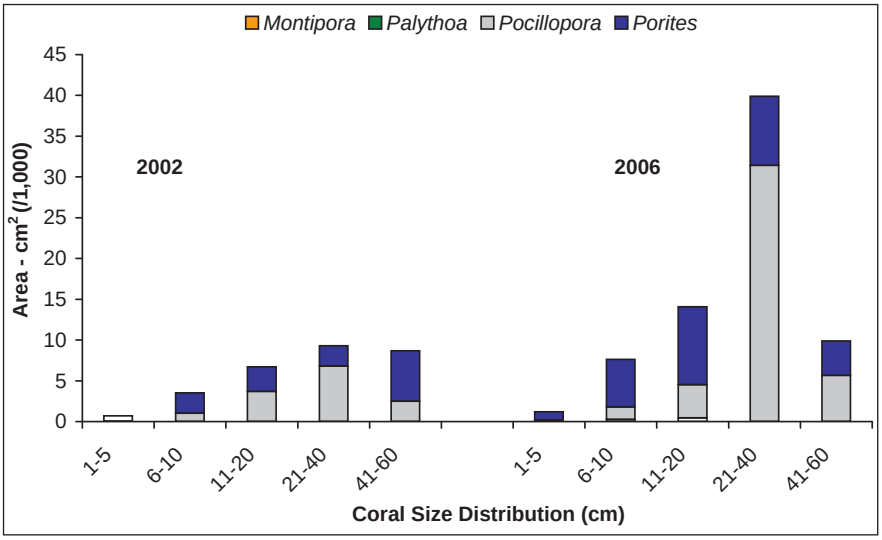


Figure 4.15. Changes in the proportion of each genus, size distribution and cover for corals reported at Mokumanamana Island permanent sites between 2001-2002 and 2006 permanent site 1P. Source: Maragos, unpub. data.

French Frigate Shoals

Eleven permanent monitoring transects for corals were established at French Frigate Shoals from 2001-2002, with four resurveyed in September 2006. These are: Serendipity Hollow (site FFS 11P) on the northern back reef; site FFS 16P at the CREWS buoy site in the northern lagoon; site FFS 3P off the north side of La Perouse Pinnacle in the north central lagoon; and site FFS 2P just west of Disappearing Island off the south reef crest of the atoll. Large northerly swell and limited time during the visit prevented safe access to and survey of the remaining seven sites.

All sites showed increases in coral density (number of corals/m^2) and most showed increases in coral cover and generic diversity (Figures 4.16 and 4.17). The northern lagoon site (FFS-16P) showed increases in mean coral diameter and dramatic increases in the other coral parameters between 2001 and 2006, although the three smallest size classes peaked in 2002. The Serendipity Hollow (FFS 11P) site appears to have ex-

perienced wave damage in the recent past, based upon broken and overturned corals observed at the site in 2006, but coral populations continued to maintain high values and post modest increases in all size classes except the largest two. The La Perouse site (FFS 3P) posted increases in generic richness, with the addition of *Acropora, Montipora and Psammocora*, although there were slight decreases in the abundance of *Pocillopora* and *Porites.* Corals at the Disappearing Island, site (FFS 2P) showed consistent gains in the four smallest size classes and dramatic increases in the number of genera over the five year period. Moreover, six coral genera noticeably increased in abundance (*Acropora, Pocillopora, Porites, Palythoa, Pavona, Psammocora*) with *Montipora* showing a modest decline.

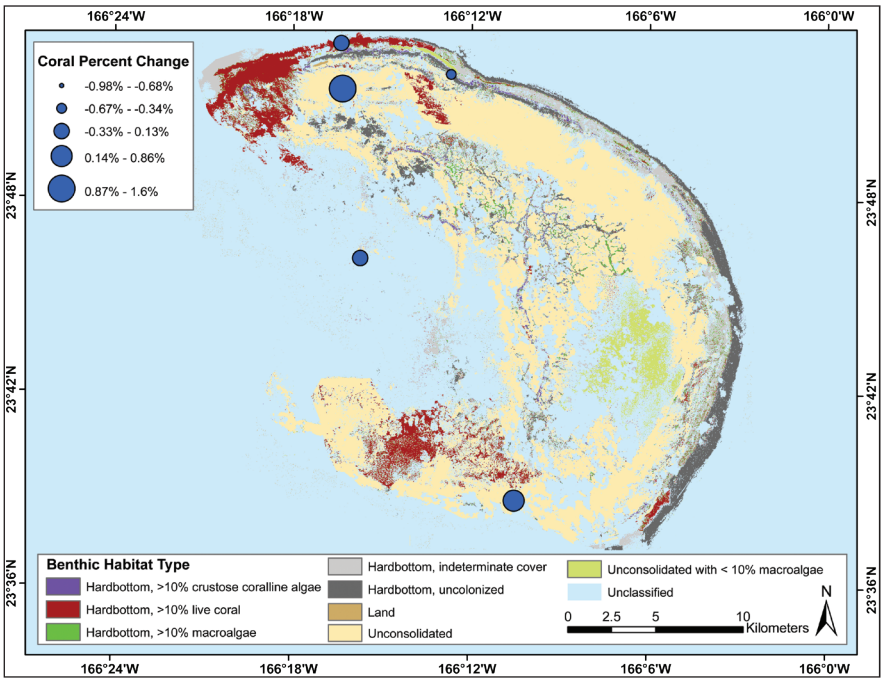


Figure 4.16. Percent change in coral cover at French Frigate Shoals between 2002 and 2006. Source: Maragos unpub. data; map: L. Wedding.

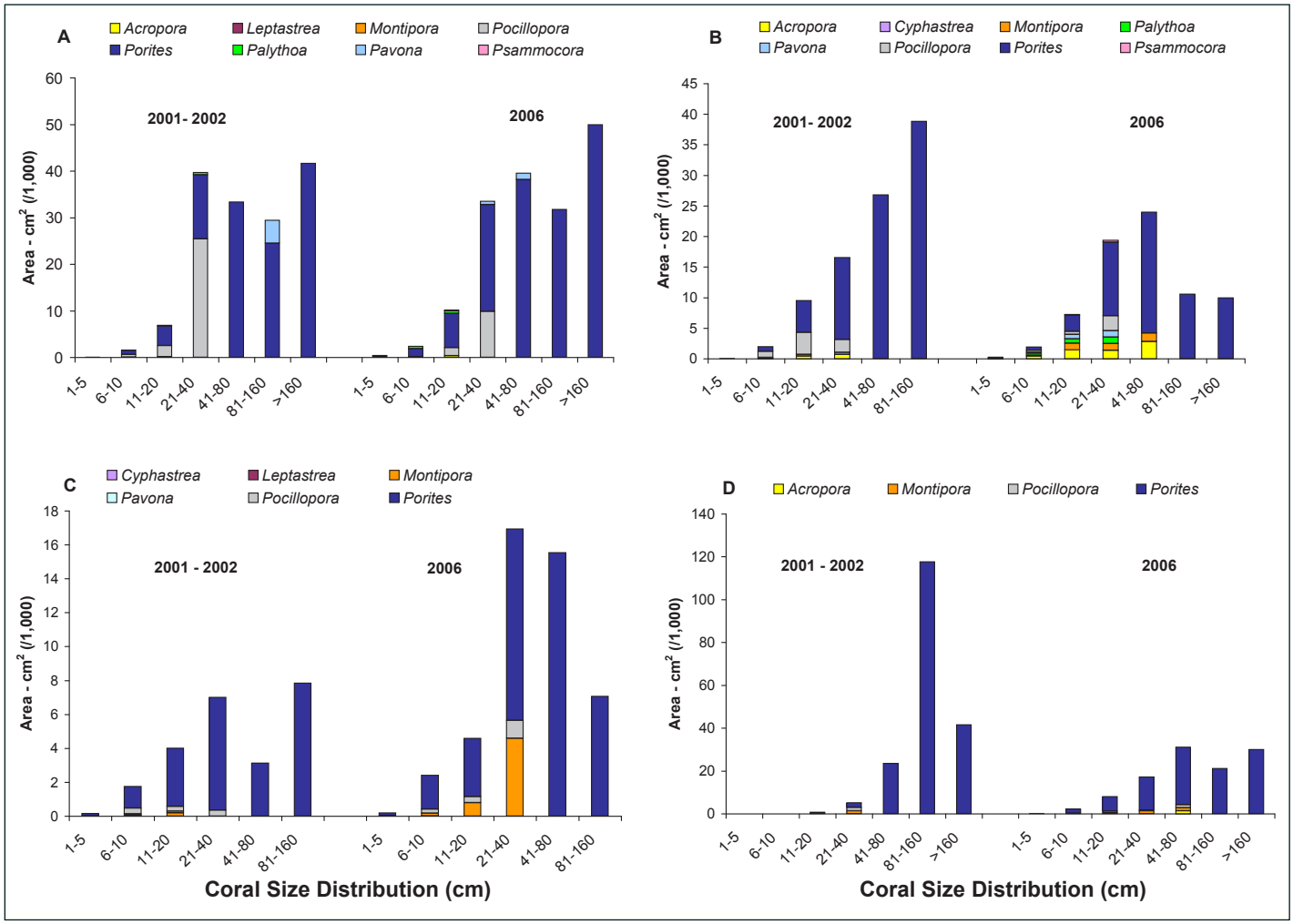


Figure 4.17. Changes in the proportion of each genus, size distribution and cover for corals reported at French Frigate Shoals permanent sites between 2001-2002 and 2006: a) 2P, b) 3P, c) 16P and d) 11P. Source: Maragos, unpub. data.

Maro Reef

Three permanent transect sites were established at Maro Reef between September 2001 and September 2002 (Figures 4.18 and 4.19). Site MAR 1P is located on a southeast facing fore reef of a patch reef. Site MAR 4P is located at the far northwest end of Maro, on a south-facing leeward fore reef. MAR 15P is near the middle of these two extremes in the central shallow protected lagoon 20 m north of the NOAA CREWS buoy. All sites were resurveyed on 7-9 September 2006. Wave exposure varies considerably among the three, with the southeast site most exposed, the central site least exposed, and the northwest subjected to intermediate wave but stronger current exposure.

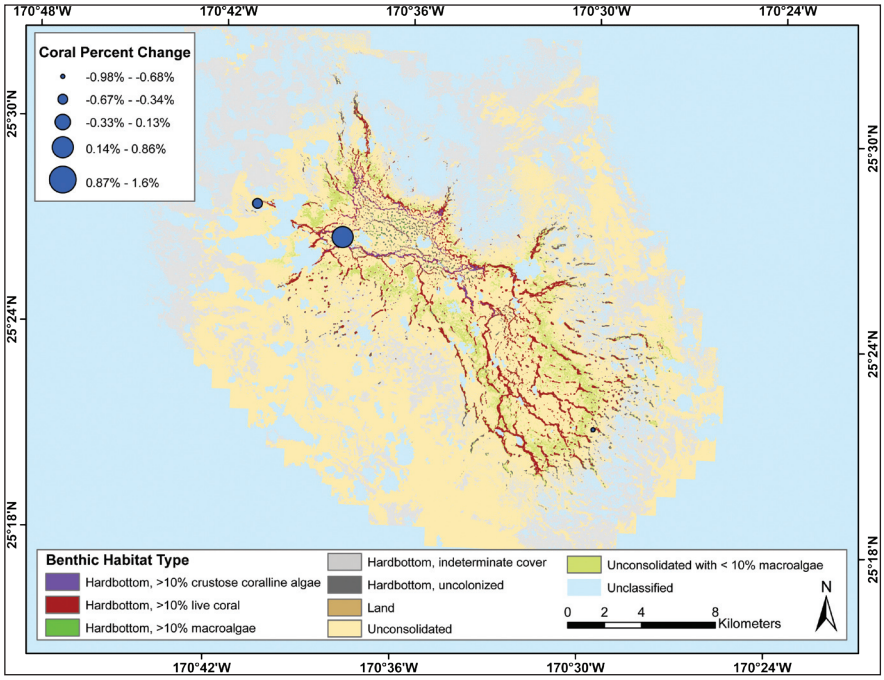


Figure 4.18. Percent change in coral cover at Maro Reef between 2002 and 2006. Source: Maragos, unpub. data; map: L. Wedding.

Coral populations showed mixed trends over the four to five year period. The number of genera increased from 2-3 per site in 2001-2002 and to 6-7 per site in 2006. The dominant corals at all three transects were the lobe coral (*Porites lobata)* and the rose coral (*Pocillopora meandrina).* Other common coral genera were *Pavona* and *Montipora,* the latter absent at the southeast site in 2001 (MAR 1P), but more abundant at all three in 2006. The encrusting brain coral (*Leptastrea pruinosa)* was absent at all three sites in 2001-2002 but emerged as a common species at the northeast site (MAR 4P).

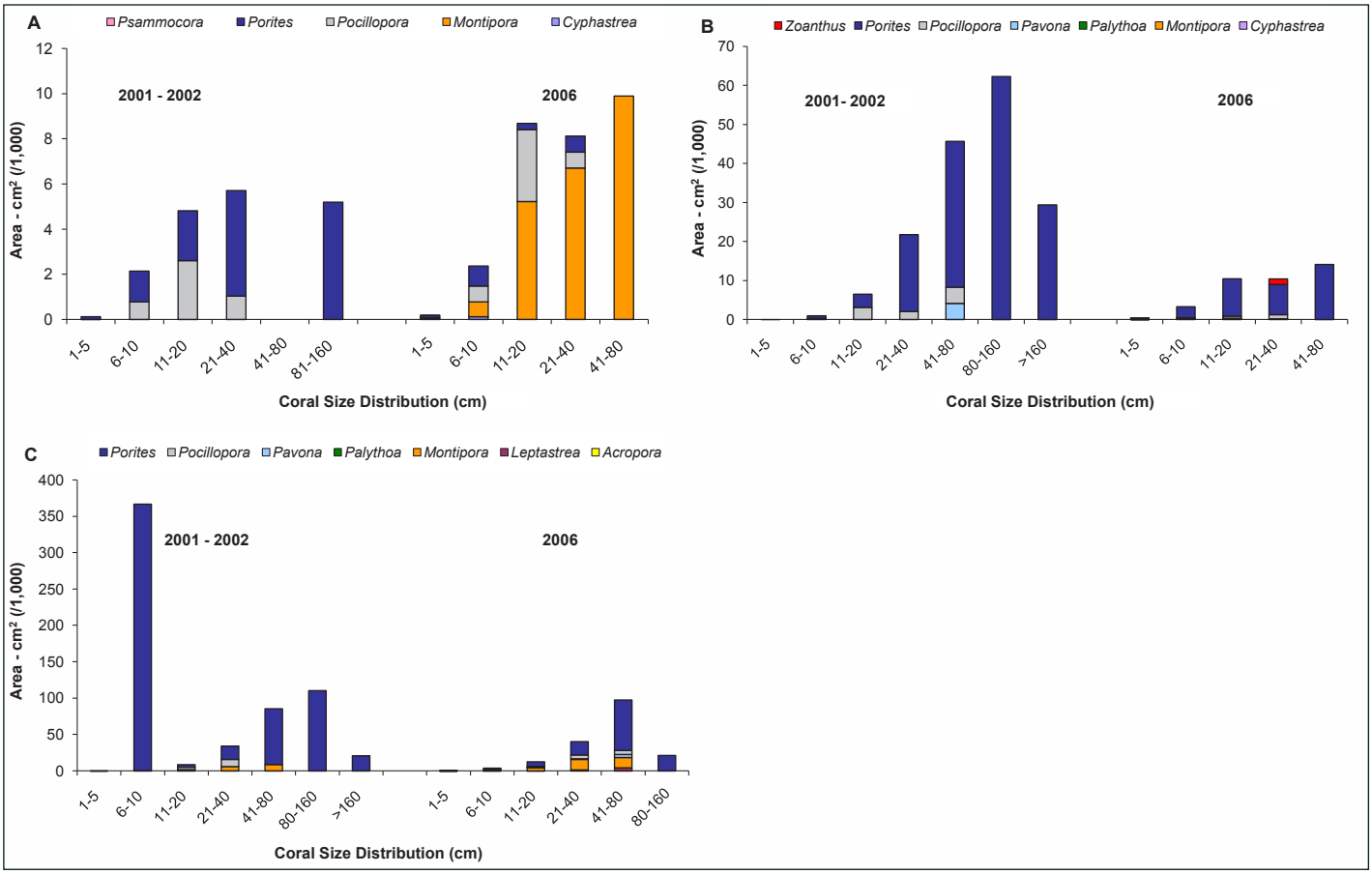


Figure 4.19. Changes in the proportion of each genus, size distribution and cover for corals reported at Maro Reef permanent sites between 2001-2002 and 2006: A) 15P, B) 1P and C) 4P. Source: Maragos, unpub. data.

Mean diameters decreased at all sites, from 10.9, 29.6 and 36.5 cm in 2001-2002 to 10.3, 9.3 and 20.6 in 2006 at sites MAR 1P, MAR 4P and MAR 15P, respectively. However, coral densities (number of corals/m^2) increased at all sites over the same period from 3.8, 4.7 and 6.4 to 5.1, 8.4 and 11.2 corals in 2006 at the same respective sites. Coral cover decreased at MAR 4P and 1P and increased at MAR 15P. At site MAR 15P the numbers of smaller corals generally increased, but at the southeast site (MAR-1P) and the northwest site (MAR 4P) the numbers for all size classes decreased. Many larger corals appeared to show signs of fragmentation to smaller sized corals at the two more exposed sites (MAR-1P, MAR-4P) that could explain the observed shifts in size.

Laysan Island

Two permanent transect sites were established at Laysan Island in September 2002 and resurveyed in September 2006. Site LAY-1P is located along the north side of the sand channel in the southwest embayment (Figures 4.20 and 4.21). Site LAY-5P is located on the shallow southwest reef crest, just south of the embayment and west of the NOAA monitoring buoy. Both transects are sheltered from heavy winter swells from the northwest Pacific that strike the NWHI during the winter months.

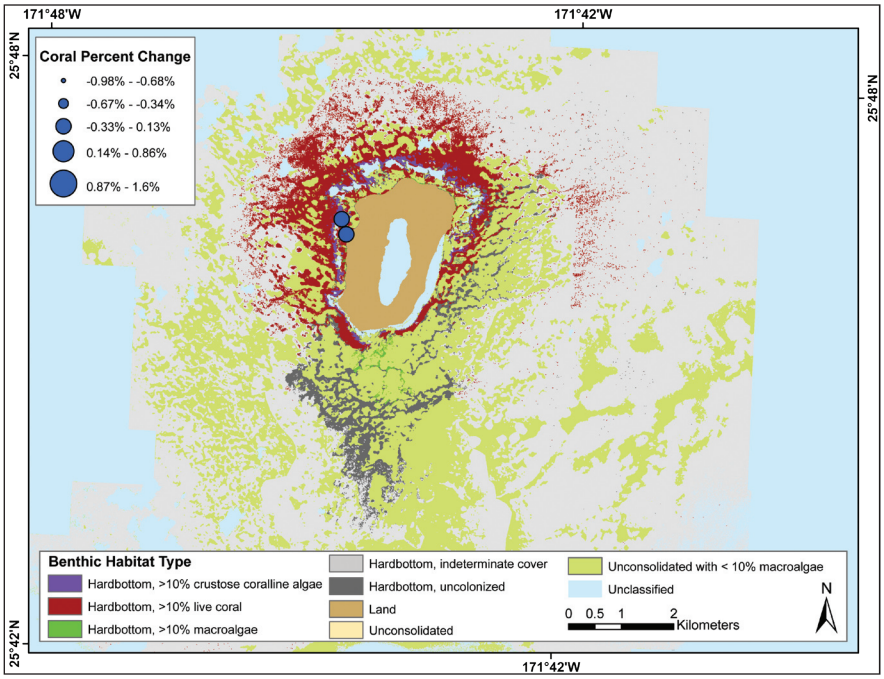
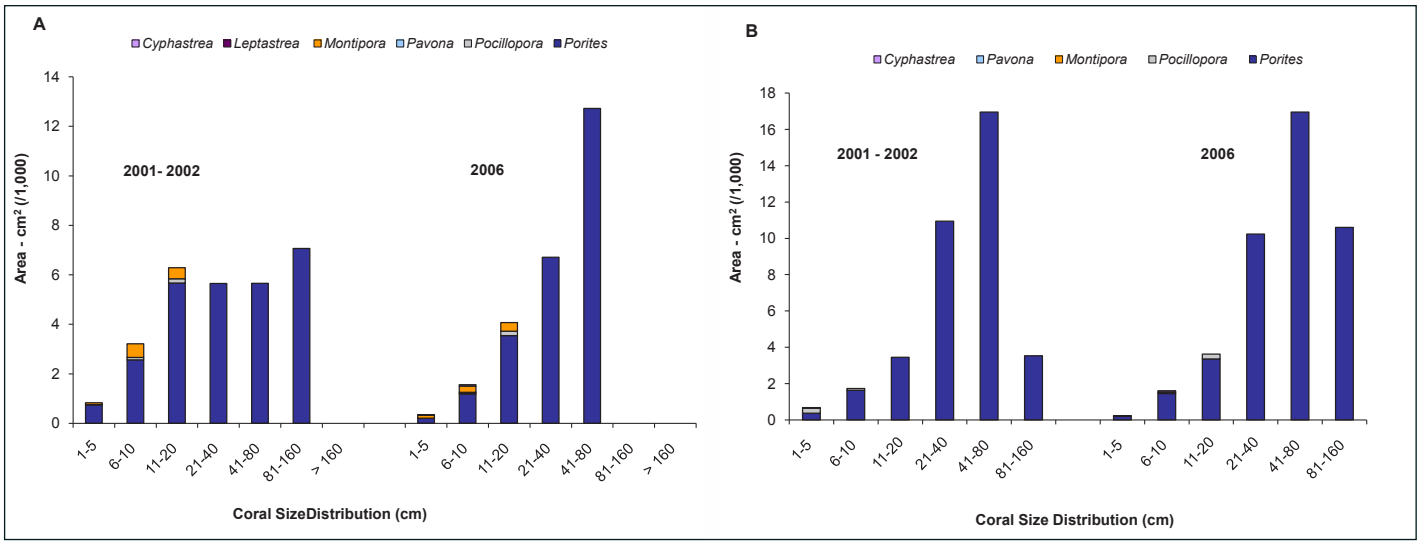


Figure 4.20. Percent change in coral cover at Laysan Island between 2002 and 2006. Source: Maragos, unpub. data; map: L. Wedding.

Coral population parameters showed mixed trends over the four-year period. Generic richness increased from three to four genera at sites LAY-1P and LAY-5P from 2002-2006. Mean diameters also increased at both sites, from 7.7 cm to 10.9 cm at LAY-1P and from 11 cm to 14.7 cm at LAY-5. However, coral densities dropped at both sites, dramatically at LAY-1P from 9.5 to 4.9, and less so at LAY-5P from 5.6 to 4.8 over the four- ear period. About 10% of the corals, mostly *Porites lobata,* at LAY-1P appeared sick or dying, and overall coral health at this site appears less than reported there in 2002, including a 50% decrease in coral cover. There were few sick or dying corals at the reef crest site LAY-5P although coral cover declined slightly.



Figures 4.21. Changes in the proportion of each genus, size distribution, and cover for corals reported at Laysan Island permanent sites between 2001-2002 and 2006: A) 1P B) 5P. Source: Maragos, unpub. data.

Laysan's smaller oval shape renders it vulnerable to severe exposure to waves from the west to northeast, and the large winter swell from the northwest may prevent development of large, high profile corals at shallow depths. Although not measured during the 2006 surveys, benthic algal cover appeared especially high at the west channel site LAY-1P, and algae is prolific at other sites (J. Maragos, per. obs.). Aside from its small size, Laysan Island supports over a million breeding seabirds and significant monk seal and sea turtle populations. Together with seepage from its high nutrient-laden hypersaline lake, Laysan Island may be subsidizing substantial localized productivity from local nutrients which in turn may favor the growth of algae over corals in most shallow reef habitats.

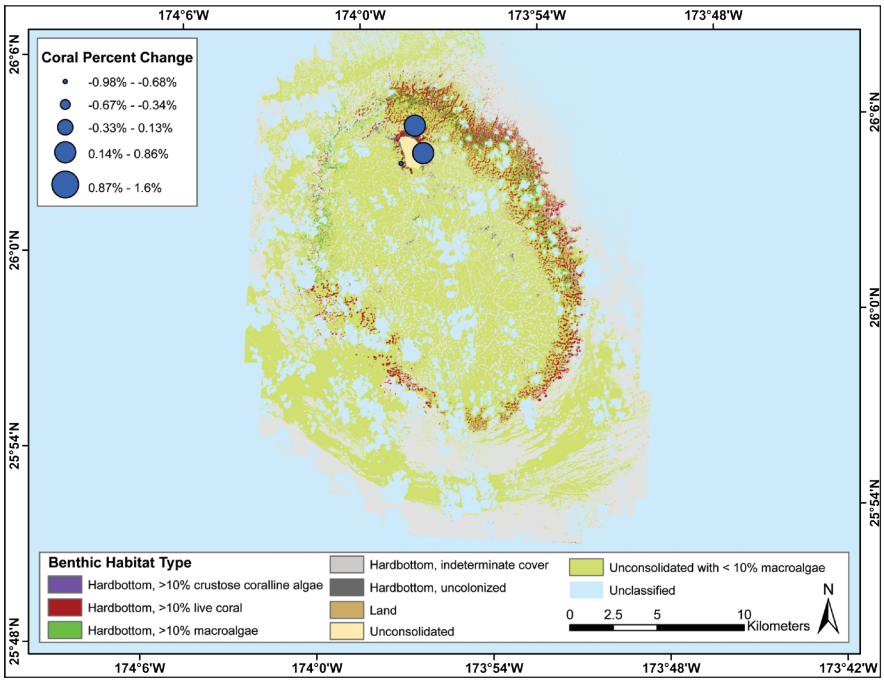


Figure 4.22. Percent change in coral cover at Lisianaski-Neva Shoals between 2002 and 2006. Source: Maragos, unpub. data; map: L. Wedding.

Lisianski Island

Three permanent 50 m long transects were established in shallow water near Lisianski Island in September-October 2002 and all three were resurveyed in September 2006 (Figures 4.22 and 4.23). Site LIS 1P was established on the shallow southwest fore reef at depths of 1.2 to 4.6 m. Site LIS 6P was established near the opposite, east side of the island at similar depths along the fore reef-reef crest margin. The third site LIS 9P was established off the northern fore reef slope of the island at depths of 7.3-14.9 m. Water visibility, wave action and currents are notably stronger at the latter two sites (LIS 6P and 9P) located windward of the island. Site LIS 1P is down-drift of the island and in the direct path of current and water flow from the island.

In 2002 coral coverage was estimated at 5.3%, coral density at 3.8 corals/m^2, and mean diameter at 14.5 cm at the southwest site LIS-1P. Corals there were primarily plates of *Montipora* corals intermixed with green algal growths of *Neomeris* and *Microdictyon.* On the opposite, eastern site, LIS-6P, large plates of the same coral *Montipora* cf.

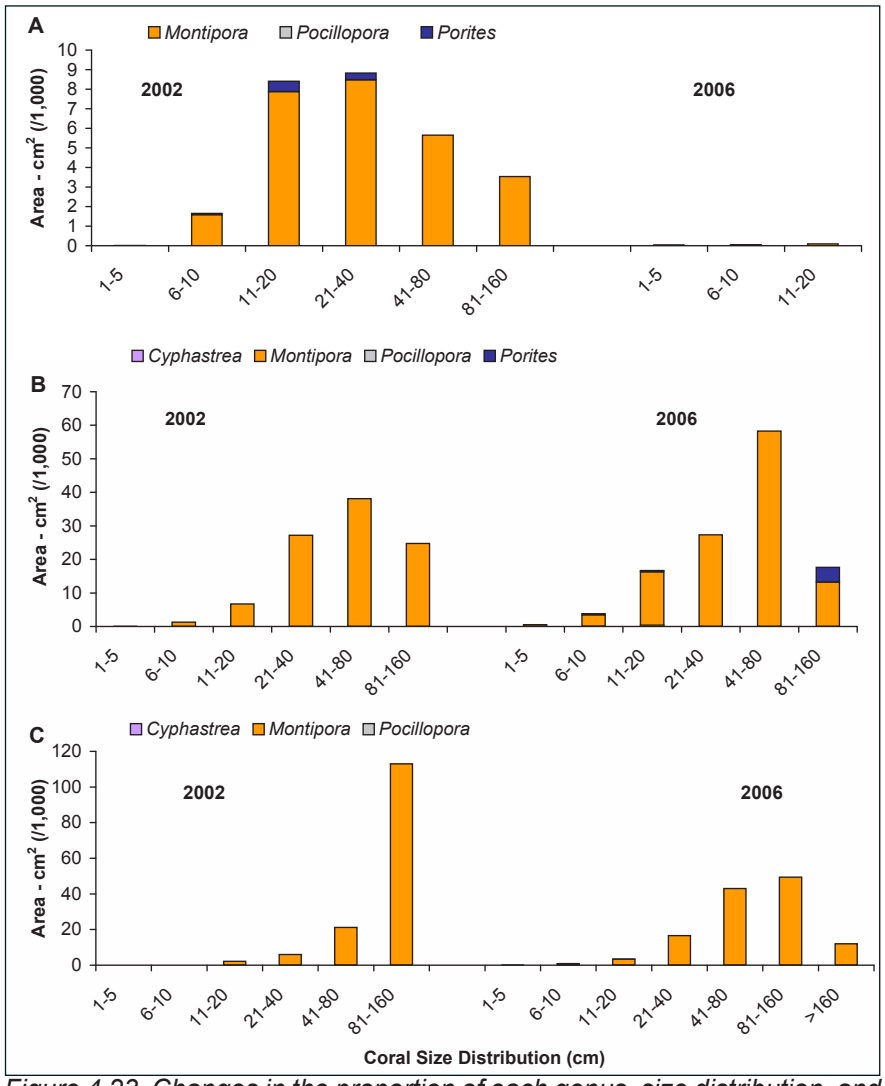


Figure 4.23. Changes in the proportion of each genus, size distribution, and cover for corals reported at Lisianski-Neva Shoals between 2002 and 2006: A) 1P, B) 9P and C) 6P. Source: Maragos, unpub. data.

turgescens dominated the bottom, averaging 27.9% coral cover, 1.8 corals/m^2, and with an average diameter of 57 cm in 2002. The north, offshore site consisted of hard bottom covered with encrusting *Montipora corals* at shallow (6-7.6 m) depths and transitioned to larger, widely spaced colonies of *Porites* lobe corals and *Pocillopora* rose corals over a rubble sand bottom at depths of 9.1-15.2 m. Coral coverage was 19.2% with a mean diameter of 23 cm and frequency 5.06 corals/m^2 in 2002.

Four years later, resurveys yielded a near total collapse of corals at site LIS-1P. Coral cover was estimated at 0.43%, mean diameter at 4.56 cm, and coral density at 0.36 corals/m^2, translating to only 17 corals in the three smallest size classes for the entire transect. In great contrast, the two windward sites fared much better over the four years with coral cover higher at both in 2006. Mean diameter at site LIS-6P was less but still substantial at 40.6 cm. Likewise site LIS-9P showed smaller mean diameter for corals at 16.3 cm, but coral frequencies nearly doubled at both windward sites, with 2006 values at 4.00 and 9.84 corals/m^2 respectively. The small brain coral *Cyphastrea* appeared at all three sites for the first time in 2006, and *Pocillopora* increased in size and numbers at all three sites. The plate coral *Montipora* nearly disappeared by 2006 at site LIS-1P with only 10 small colonies remaining from 184 mostly larger colonies in 2002. At the other two sites *Montipora* plate coral increased dramatically for smaller to middle sized corals. The lobe coral *Porites* also declined at the southwest site LIS-1P, but increased modestly at the northern site LIS-9P. Figure 24 illustrates the changes in size distribution for all corals over the four year period at the three sites.

The collapse of the coral community at southwest site LIS-1P may have been caused by a coral bleaching event followed by the overgrowth of algae, the latter perhaps stimulated by plentiful nutrients leaching from the island and derived by extensive guano production generated by the large resident seabird populations at Lisianski. Ambient water temperature was higher at the site during the 2006 survey and may have a longer residence time in shallow depths where solar heating would be higher. Also, the waters to the southwest were noticeably greener due to higher phytoplankton productivity. In contrast, water clarity was better, water motion stronger and temperatures cooler at the two windward sites that showed increased coral development.

Pearl and Hermes Atoll

Eight permanent coral transects were established at Pearl and Hermes prior to the September 2006 visit. Four of these were established at the site of the 2000 grounding of the fishing vessel *Swordman I.* The 2006 REA team did survey one or more of the back reef sites but these data are currently not available. The remaining four permanent transects established in 2002 consist of site PHR 6P, a shallow south lagoon pinnacle slope; PHR 7P, a central lagoon patch reef in the finger coral gardens; PHR 9P on the floor of the main south pass of the atoll; and PHR-12P off the southwest fore reef of the atoll (Figures 4.24 and 4.25).

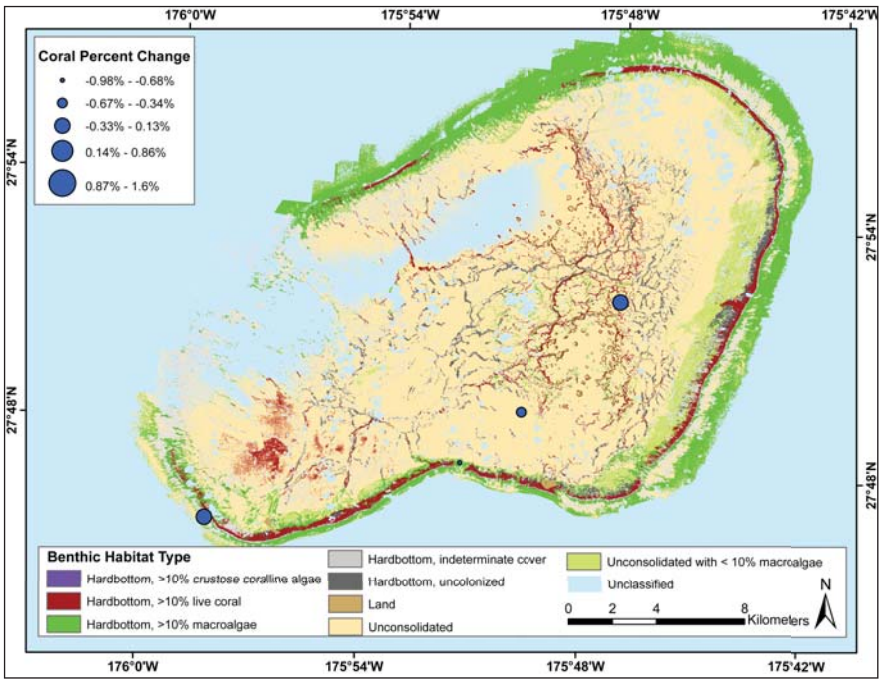


Figure 4.24. Percent change in coral cover at Pearl and Hermes Atoll between 2002 and 2006. Source: Maragos, unpub. data; map: L. Wedding.

Coral populations showed smaller mean diameters (7.6 to 11.1 cm) in 2006 compared to their corresponding 2002 values (11.7 to 25.7 cm) at all sites. However, all sites showed higher generic diversity levels in 2006 (three to six genera/transect) compared to corresponding 2002 values (one to three genera). The 2006 coral populations also showed larger densities at all sites except PHR-9P, varying from 0.4 to19.8 corals/m^2, compared to 2002 levels (1.07 to 4.64 corals/m^2). The

small brain coral (*Cyphastrea ocellina)* was reported on three transects for the first time in 2006, and *Palythoa, Pavona* and *Psammocora* were all reported for the first time on one transect each.

The three smallest size classes dominated the coral numbers at all 2006 sites except the south pass site (PHR-9P). Coral populations in the pass were much diminished from their 2002 levels at all size classes. During both the 2002 and 2006 surveys, currents ranged from 2 to 3 knots in the pass, with considerable suspended sediments. Scour and periodic wave action may be controlling coral development in the south pass. At the fingercoral garden site (PHR-7P), corals in the three smallest size classes were an order of magnitude more abundant in 2006 compared to 2002 levels for *Porites compressa*, although there was no substantial difference in the larger four size classes. In general, all corals combined were more numerous at the larger size classes at all four sites in 2002, Figure 4.25 compares size distributions for all corals in 2002 and 2006 at the four permanent coral transect sites.

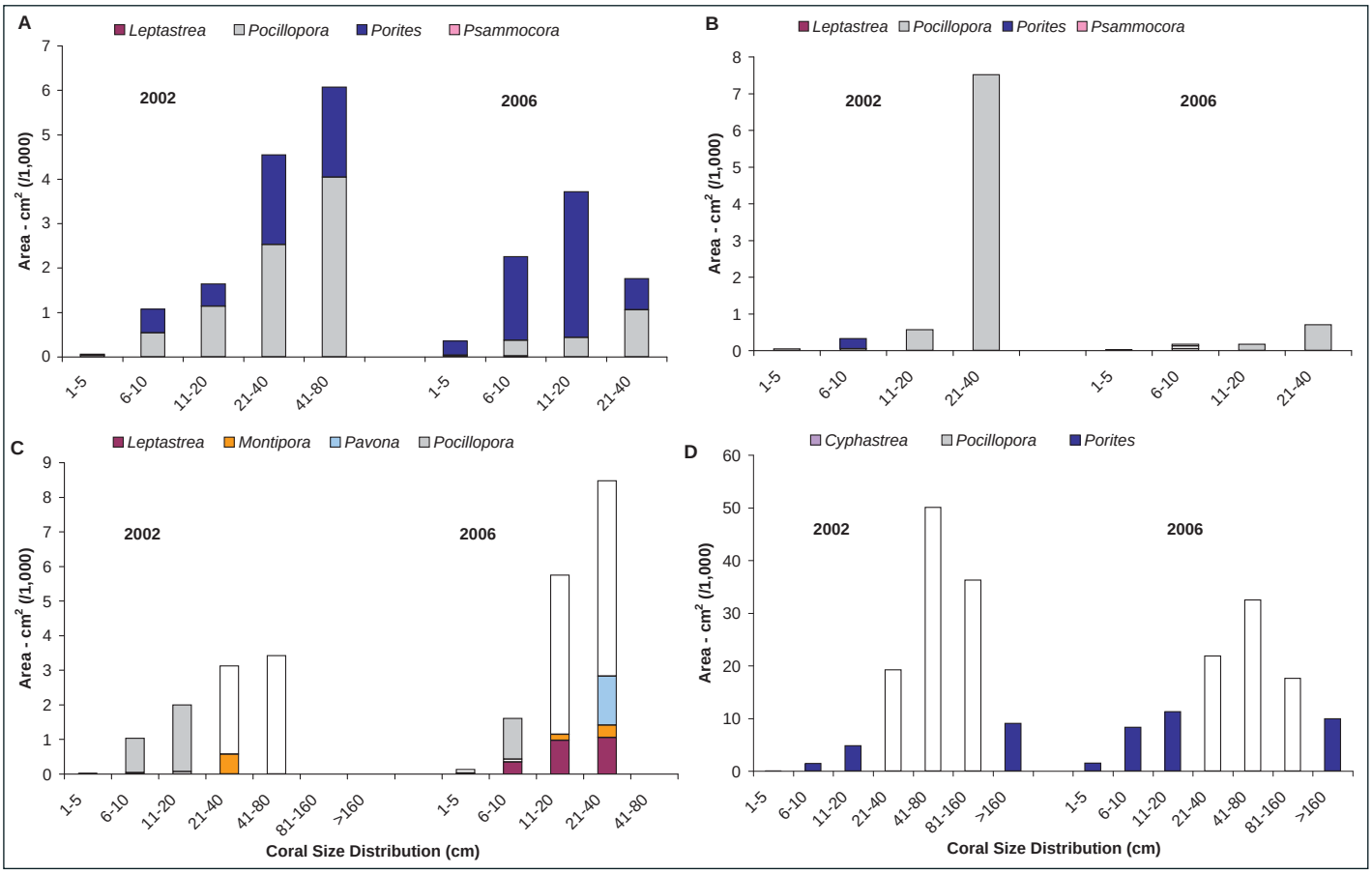


Figure 4.25. Changes in the proportion of each genus, size distribution, and cover for corals reported at Pearl and Hermes permanent sites 6P, 9P, 12P and 7P from 2002 and 2006. Source: Maragos, unpub. data.

Midway Atoll

Eleven permanently marked transects were established at Midway Atoll National Wildlife Refuge between 2000-2002. Eight sites were resurveyed in September 2006 and are shown in Figures 4.26 and 4.27. Five of the resurveyed sites are situated on the northern and eastern back reefs (MID 1Pa, 2P, 7P and 17P), two on the NW back reef (MID 18P, 20P), one near the southwest reef crest (MID 19P) and one on a central lagoon patch reef (MID 14P).

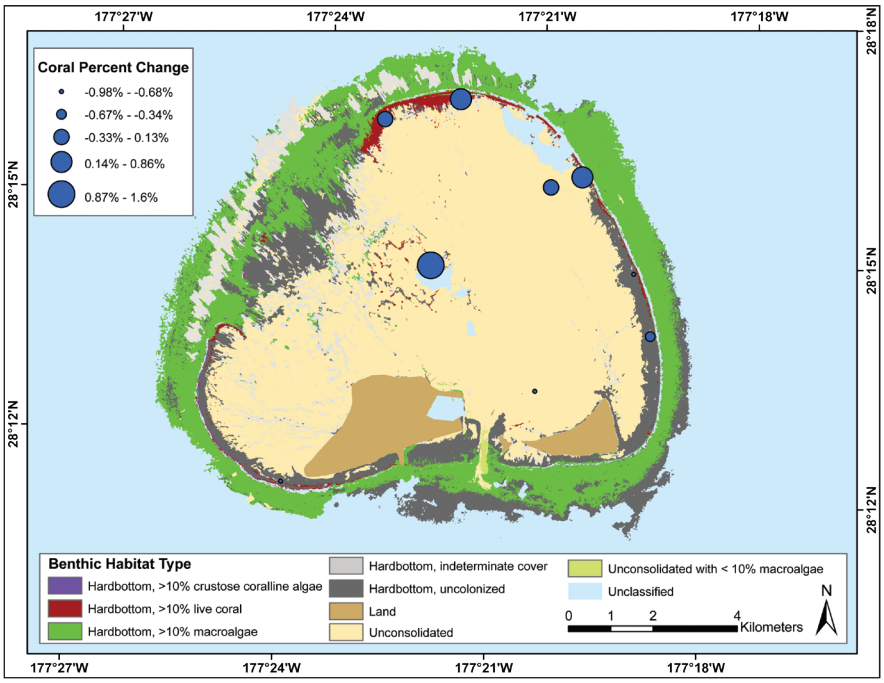


Figure 4.26. Percent change in coral cover at Midway Atoll between 2002 and 2006. Source: Maragos, unpub. data; map: L. Wedding.

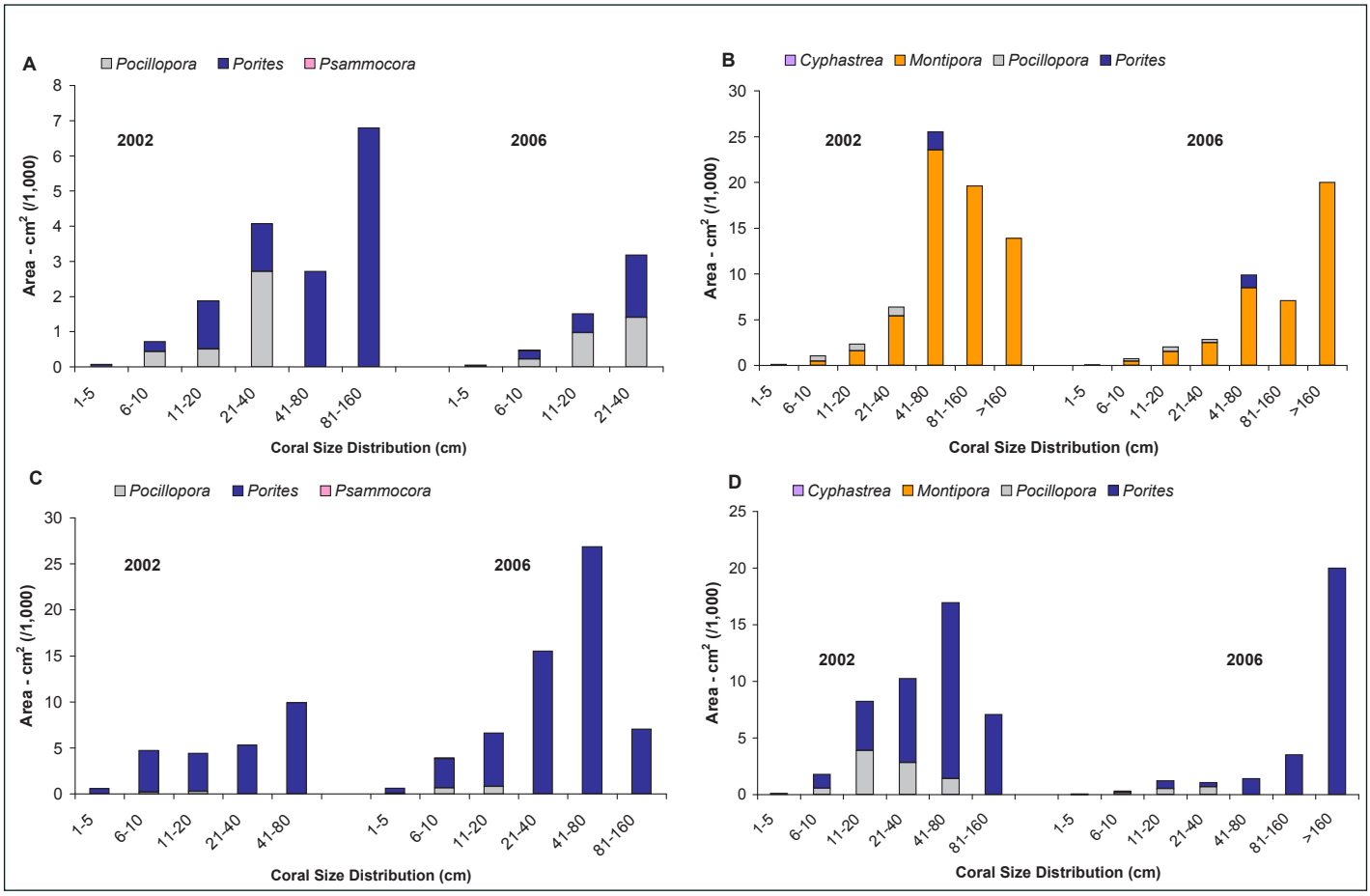


Figure 4.27. Changes in the proportion of each genus, size distribution, and cover for corals reported at 7 permanent sites at Midway: A) MID 1Pa, B) 2P, C) 14P, D) 17P, E) 18P, F) 19P and G) 20P. Source: Maragos, unpub. data.

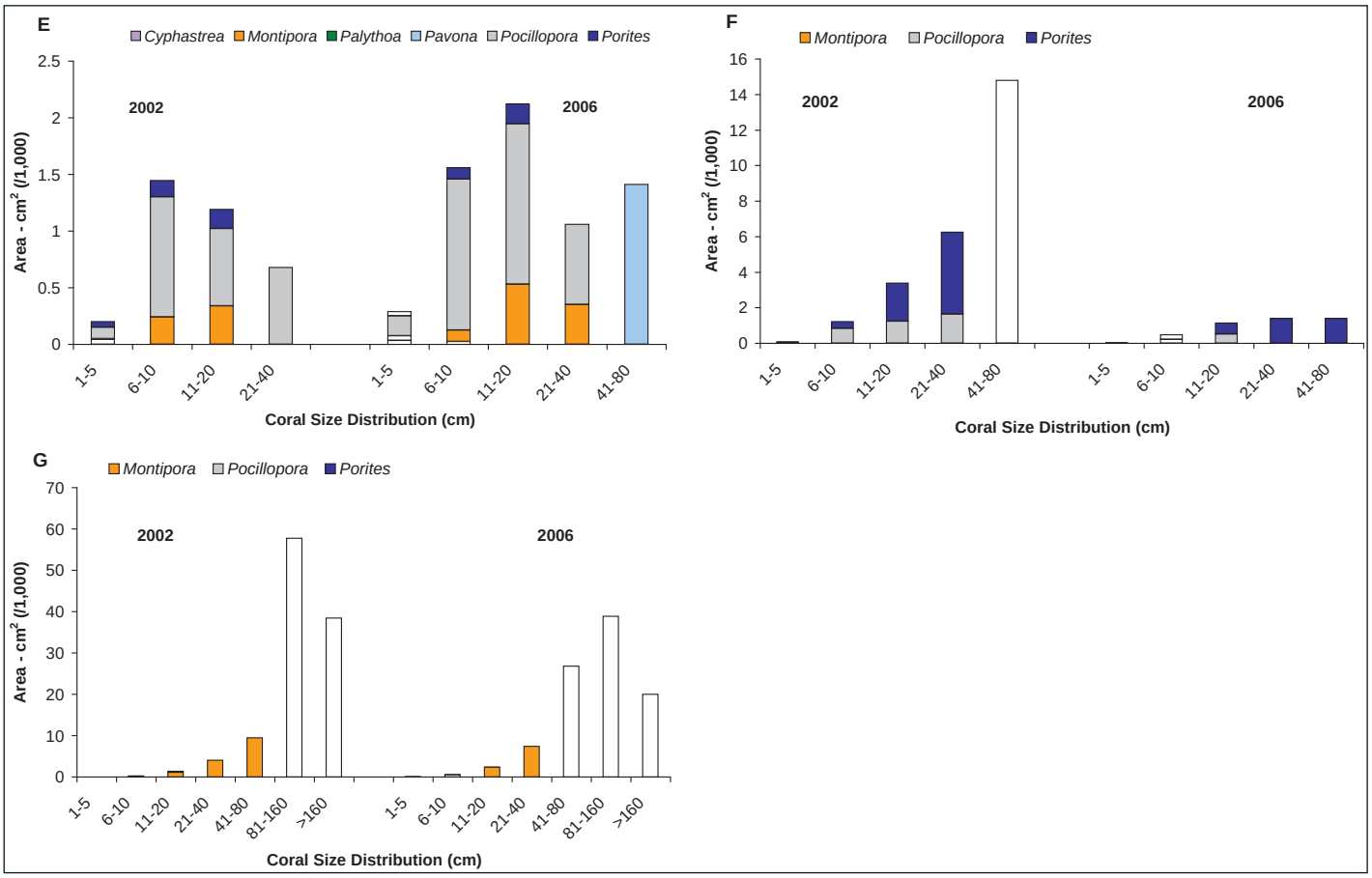


Figure 4.27 (continued). Changes in the proportion of each genus, size distribution, and cover for corals reported at 7 permanent sites at Midway: E) 18P, F) 19P and G) 20P. Source: Maragos, unpub. data.

Overall, coral populations showed mixed trends during the four year period. The abundance and numbers of *Porites lobata* and *P. compressa* decreased slightly. The rose coral *Pocillopora* spp showed no clear trend, and the abundance of *Montipora capitata* and *M.* cf. *turgescens* generally increased from 2002-2006. The small brain coral (*Cyphastrea ocellina)* and small branching coral (*Psammocora stellata)* were reported for the first time at several transects in 2006 (Figure 4.28). Overall there were no trends for coral mean diameter or frequencies over the four year period, although generic diversity per transect increased at most sites.

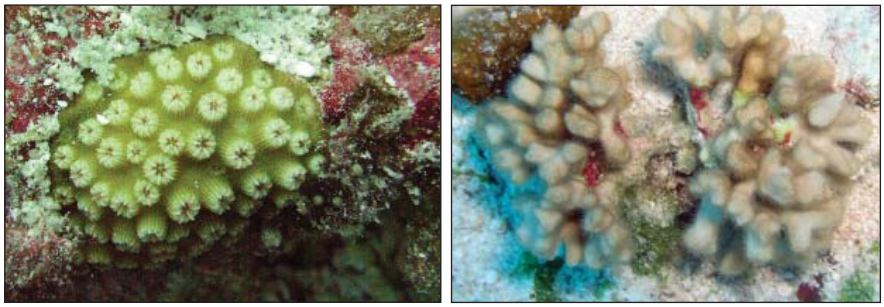


Figure 4.28. In 2006 both Cyphastrea ocellina *(left) and* Psammocora stellata *(right) were reported for the first time at Midway Atoll. Photos: J. Maragos.*

The eastern back reef site MID-1Pa showed increases at smaller size classes but declines in larger corals. The neighboring east back reef site 17P showed major declines in all size classes and genera. Finger coral (*Porites compressa*) at the southeast lagoon site MID-7P were abundant in 2002, but in 2006 were all dead but still standing. The southwest reef crest/back reef site MID-19P also showed catastrophic declines in all corals. In contrast, the two northern back reef sites MID-20P and MID-18P dominated by *Montipora* showed major increases over the four year period. In 2002, *Montipora* at these sites were especially hit hard by coral bleaching, but now have rebounded to levels comparable if not higher than those reported earlier. The reasons for the major coral declines at sites MID-7P, -1P and -17P are not clear but warrant continued monitoring. The declines may be related to the residual effects of WWII and post WWII military construction at Midway, which resulted in the dredging of a deep channel between the lagoon and ocean and the likely change in lagoon circulation and water levels.

Descriptive Statistics for Corals from 2006 Rapid Ecological Assessment Data

Mokumanamana

In 2006 only two stations were sampled at Mokumanamana Island (Table 4.8, Figure 4.29). Average coral species richness ($\bar{x}$ = 11.5, SD ± 2.1) ranked the highest among all reefs surveyed. Percent live coral cover was 22.1% (SD ± 15.9) and ranked forth overall. Density of coral colonies (number/m^{-2}) also ranked first among all locations sampled in 2006 with a mean density of 6.9 colonies m^{-2}.

Table 4.8. Descriptive statistics for corals from 2006 REA data at Mokumanamana Island. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	2	11.5	2.12	1.5	-7.56	30.56
Coral cover (%)	2	22.06	15.94	11.28	-121.2	165.32
Density (no. m^{-2})	2	6.89	0.55	0.39	1.93	11.85

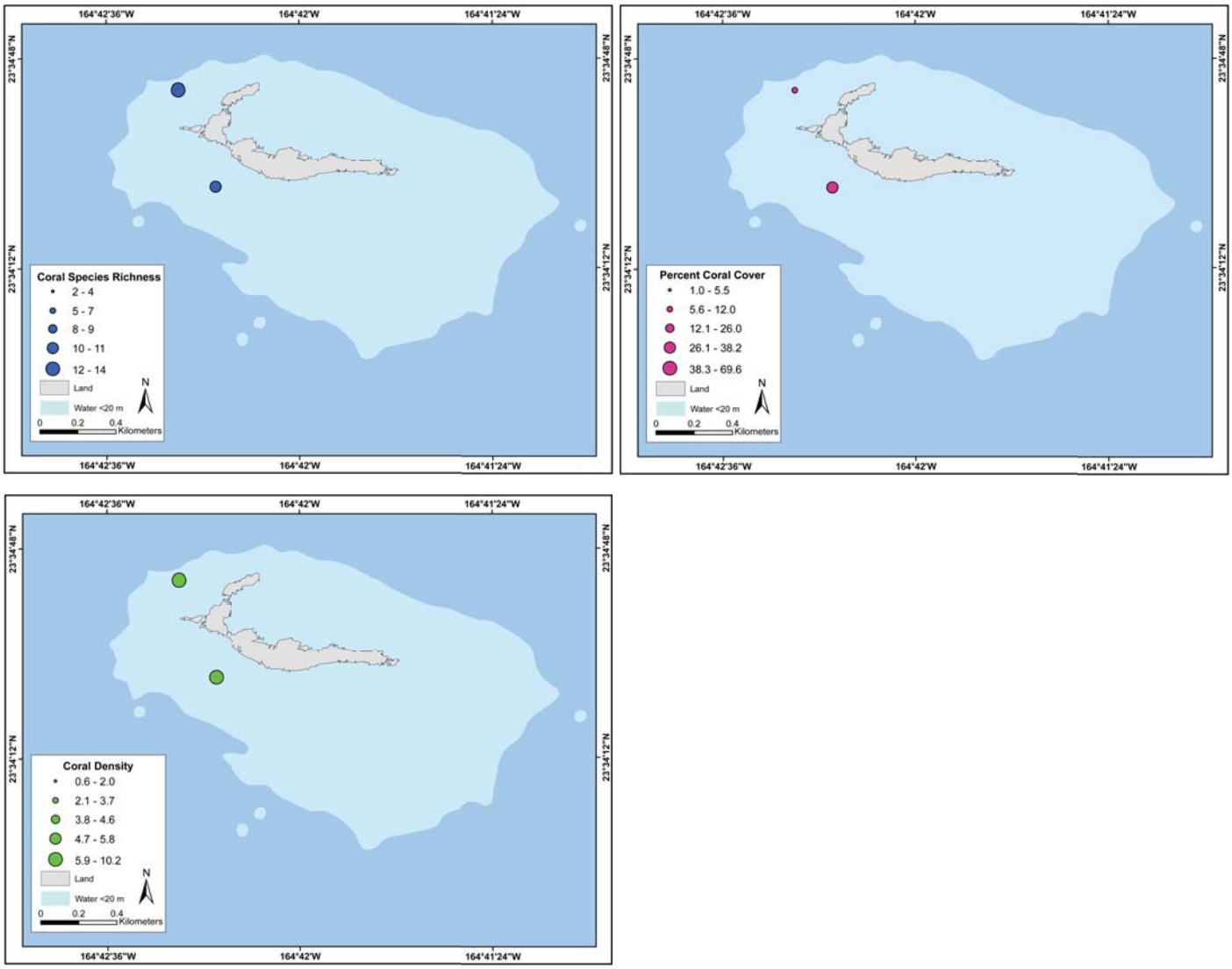


Figure 4.29. Mokumanamana coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

French Frigate Shoals

French Frigate Shoals ranked third overall in coral species richness with an average of 9.9 coral species per transect (Table 4.9, Figure 4.30). Percent live coral cover was 29.7% and also ranked third among all locations surveyed in 2006. Coral colony density was 4.82 m^{-2} and again ranked third among locations.

Table 4.9. Descriptive statistics for corals from 2006 REA data at French Frigate Shoals. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	10	9.9	3.07	0.97	7.7	12.1
Coral cover (%)	10	29.71	18.68	5.91	16.3	43.07
Density (no. m^{-2})	10	4.82	2.37	0.75	3.12	6.52

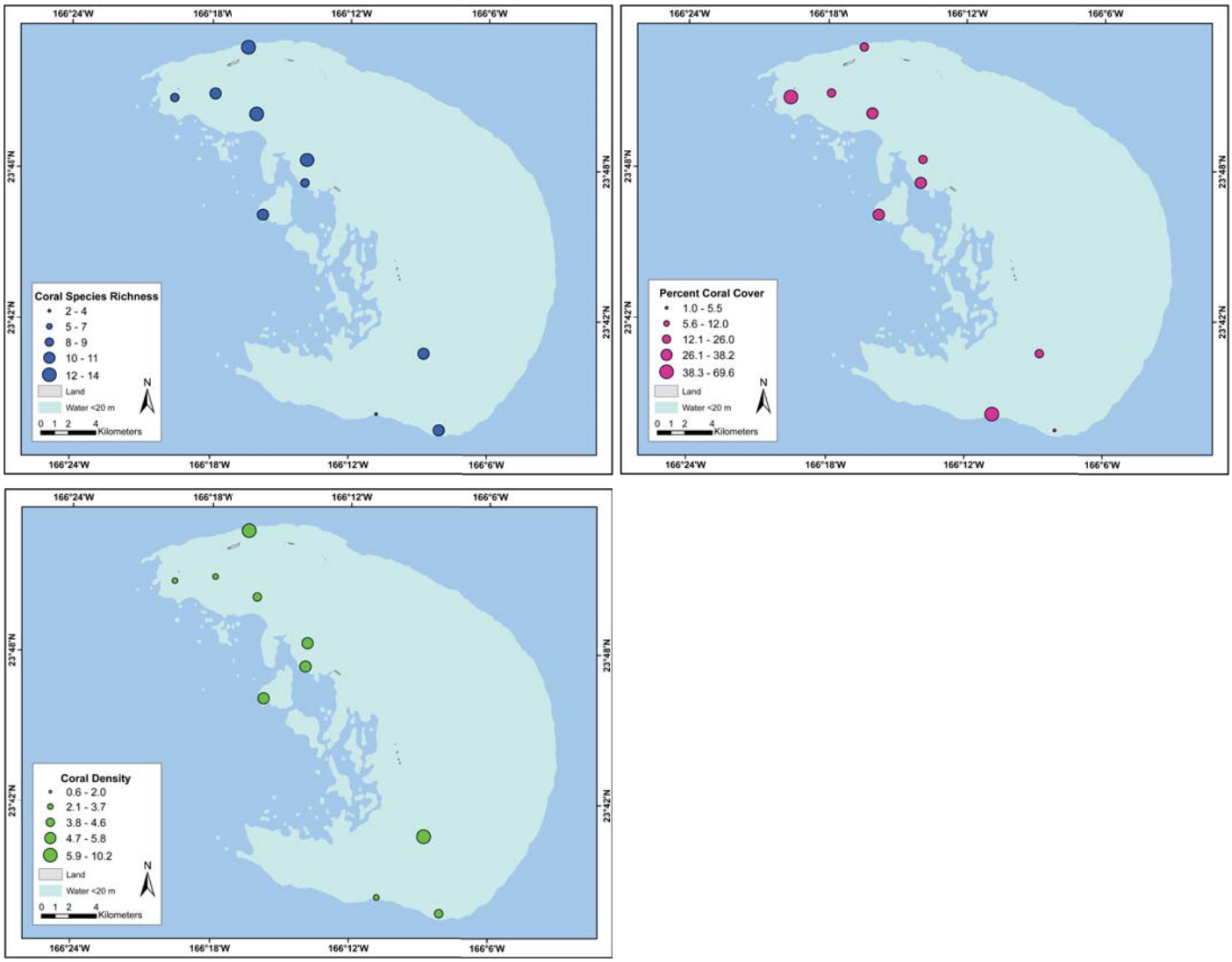


Figure 4.30. French Frigate Shoals coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Maro Reef

Species richness at Maro Reef was 9.1 per transect and ranked fourth overall (Table 4.10, Figure 4.31). Coral cover was high ($\bar{x}$ = 33.3, SD ± 17.8) and ranked second overall. Density was the second highest among all sites and averaged 5.43 colonies/m^{-2}.

Table 4.10. Descriptive statistics for corals from 2006 REA data at Maro Reef. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	9	9.11	1.45	0.48	7.99	10.23
Coral cover (%)	9	33.29	17.85	5.95	19.6	47.01
Density (no. m^{-2})	9	5.43	1.47	0.49	4.3	6.56

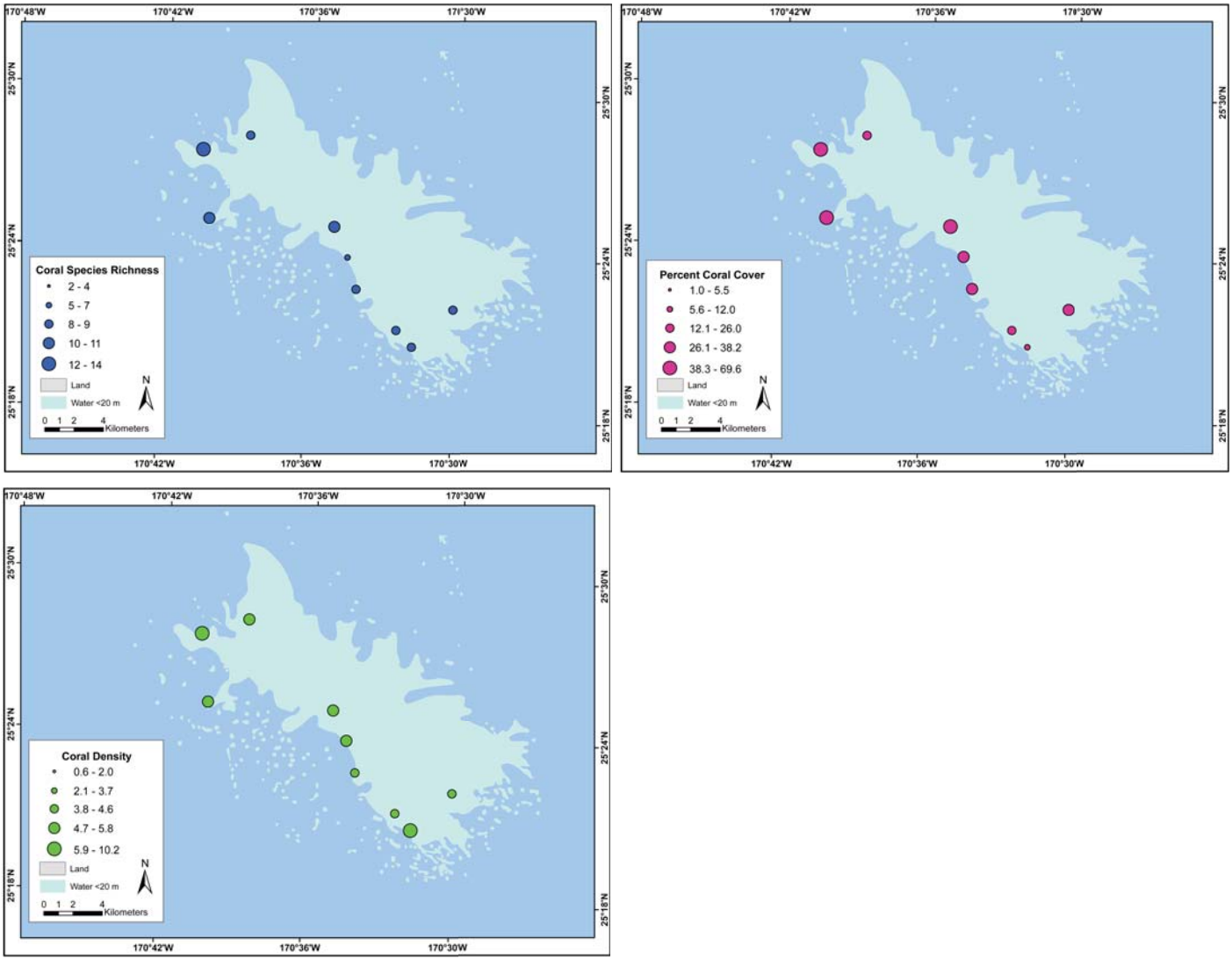


Figure 4.31. Maro reef coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Laysan Island

Lasyan Island had limited sampling effort in 2006 (Table 4.11; Figure 4.32). There were an average of 8.0 species recorded from transects, ranking fifth overall. Coral cover was also intermediate (fifth in rank) with an average cover of 17.7%. The density of coral colonies was low (seventh in overall rank) with an average of 2.8 coral colonies/m^{-2}.

Table 4.11. Descriptive statistics for corals from 2006 REA data at Laysan Island. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	3	8	1	0.58	5.52	10.48
Coral cover (%)	3	17.65	12.86	7.42	-14.3	49.59
Density (no. m^{-2})	3	2.84	1.06	0.61	0.2	5.48

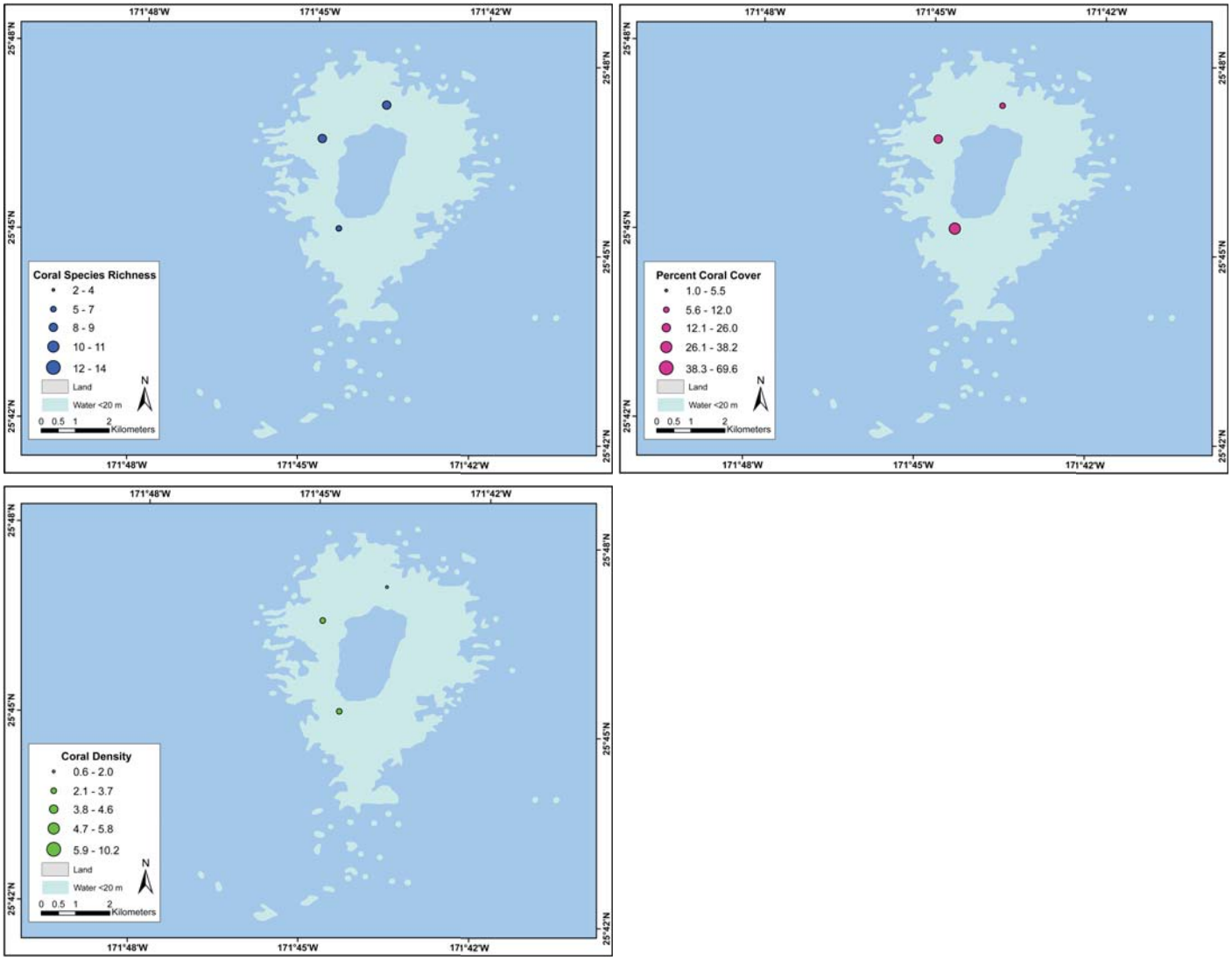


Figure 4.32. Laysan Island coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Lisianski-Neva Shoals

Lisianski-Neva Shoals averaged 10.8 coral species per transect and ranked second overall (Table 4.12, Figure 4.33). It ranked first in coral cover with an average of 36.7%. Density of coral colonies was intermediate with 4.3 colonies/m^{-2}.

Table 4.12. Descriptive statistics for corals from 2006 REA data at Lisianski. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	9	10.78	2.28	0.76	9.03	12.53
Coral cover (%)	9	36.74	20.77	6.93	20.8	52.71
Density (no. m^{-2})	9	4.27	1.54	0.51	3.08	5.45

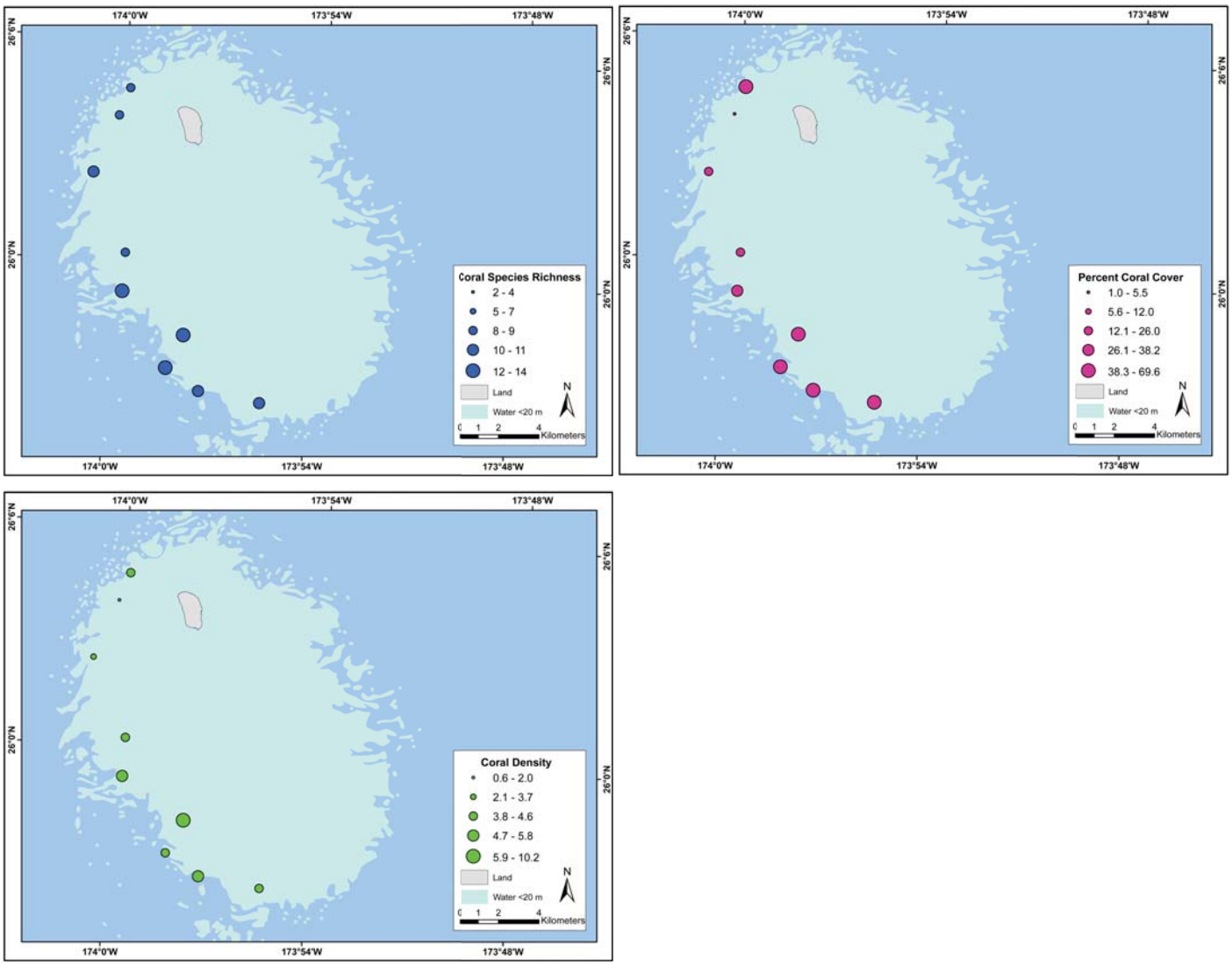


Figure 4.33. Lisianski-Neva Shoals coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Midway Atoll

Species richness of corals at Midway was the lowest of any reef surveyed in 2006 with an average of four species per transect (Table 4.13, Figure 4.34). Coral cover was 13.8% and ranked sixth overall. The density of coral colonies was 2.7/m^{-2}, which was also the lowest among all location.

Table 4.13. Descriptive statistics for corals from 2006 REA data at Lisianski. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	9	4.44	1.24	0.41	3.49	5.4
Coral cover (%)	9	13.81	17.74	5.91	0.17	27.44
Density (no. m^{-2})	9	2.68	1.98	0.66	1.15	4.2

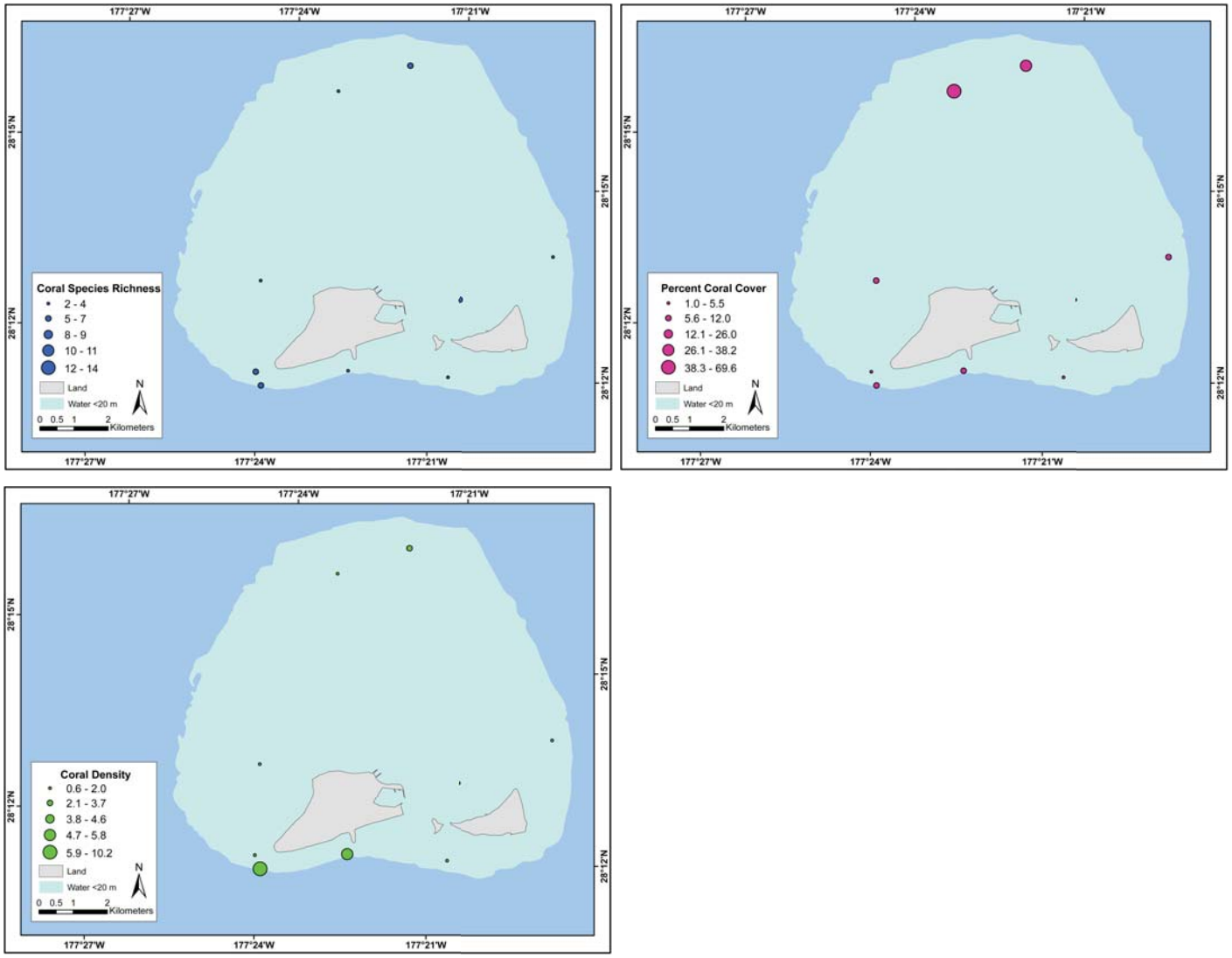


Figure 4.34. Midway Atoll coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Kure Atoll

Kure had the second lowest coral species richness with an average of six species per transect (Table 4.14, Figure 4.35). Coral cover was second lowest after Midway at 13.7%. Colony density was intermediate at 4.3 colonies/m^{-2} and ranked fourth overall.

Table 4.14. Descriptive statistics for corals from 2006 REA data at Kure Atoll. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	9	6	2.24	0.75	4.28	7.72
Coral cover (%)	9	13.67	9.34	3.11	6.5	20.85
Density (no. m^{-2})	9	4.29	2.54	0.85	2.33	6.24

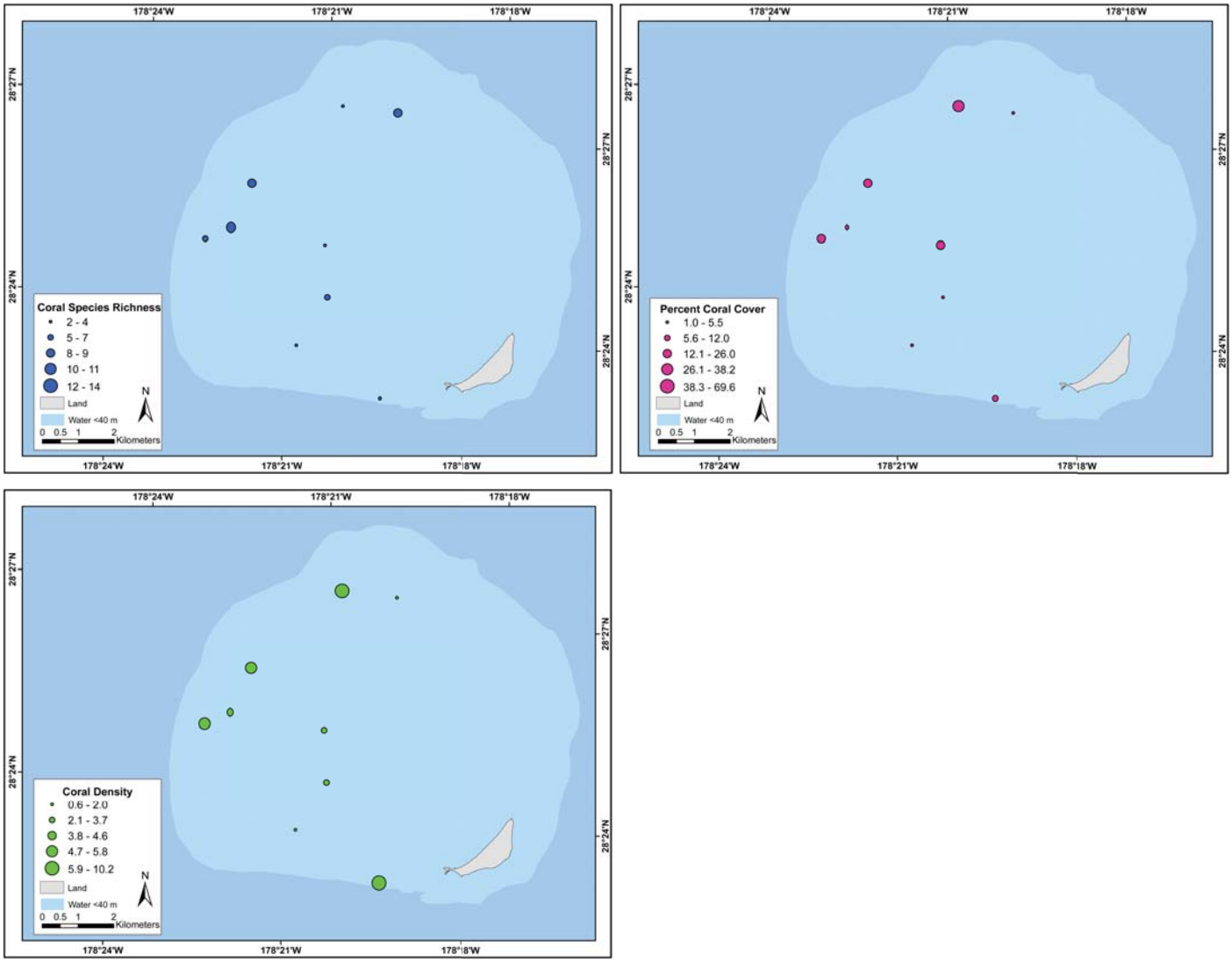


Figure 4.35. Kure Atoll coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Changes In Coral Cover Over Time From Rapid Ecological Assessment Data

Most regions have low coral cover (<20%), with higher values at Maro, Lisianski and French Frigate Shoals. Coral cover values determined from REA surveys showed the highest coral cover values at Maro and Lisianski though their magnitude (>60%) was greater than the values derived from the line-intercept method in 2004-2006 (Figure 4.36). At each region, the coral cover values computed from the different survey years (2004, 2005 and 2006) are highly similar, indicating little change overall in each region.

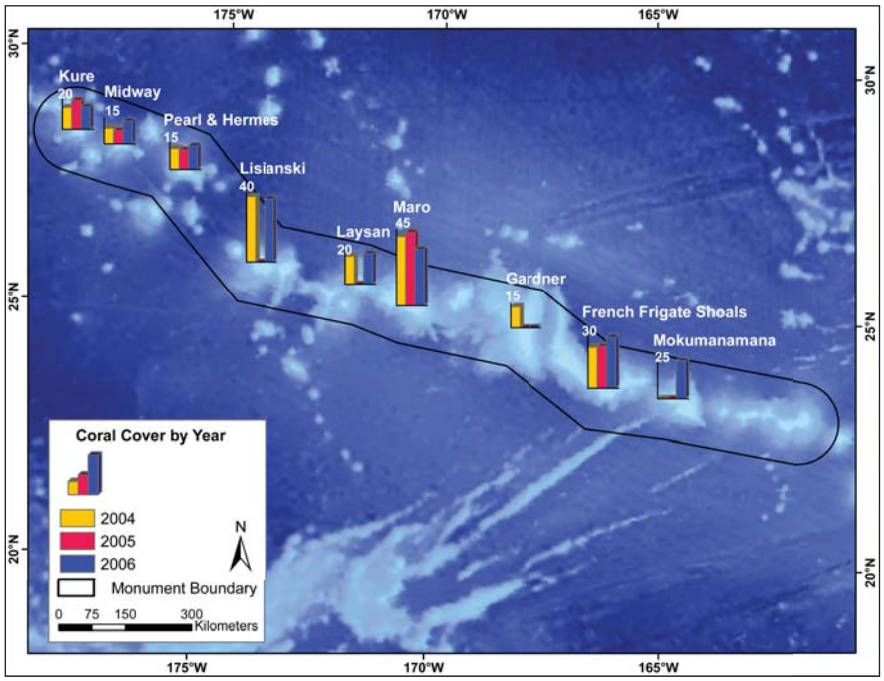


Figure 4.36. Differences in coral cover among regions within the NWHI. Not all regions were surveyed in all three years. Coral cover was calculated from the line-intercept method at 0.5 m intervals. Data are mean and standard error. Source: NWHI RAMP, unpublished data; map: L. Wedding.

Coral Settlement and Recruitment

In fall 2001 an array of recruitment plates was attached to the base of CREWS moorings at French Frigate Shoals, Maro, Lisianski, Pearl and Hermes, Midway and Kure to assess larval recruitment. The plates were collected in fall 2002 and fresh arrays were deployed which, in turn were collected in 2003. Coral recruits present on the plates were counted and measured with the use of a dissecting microscope. While the second cohort of plates were in the water for a shorter time period than the first cohort of recruitment plates that had been deployed between 2001 and 2002 (293 versus 376 days, respectively), the number of recruits was higher in 2003 (382) than in 2002 (Figure 4.37). Plates at Maro showed the highest number of recruits in both years. Nearly all juvenile recruits were from the family Pocilloporidae, though members of the families Acroporidae and Poritidae were also found on plates from French Frigate Shoals and Maro.

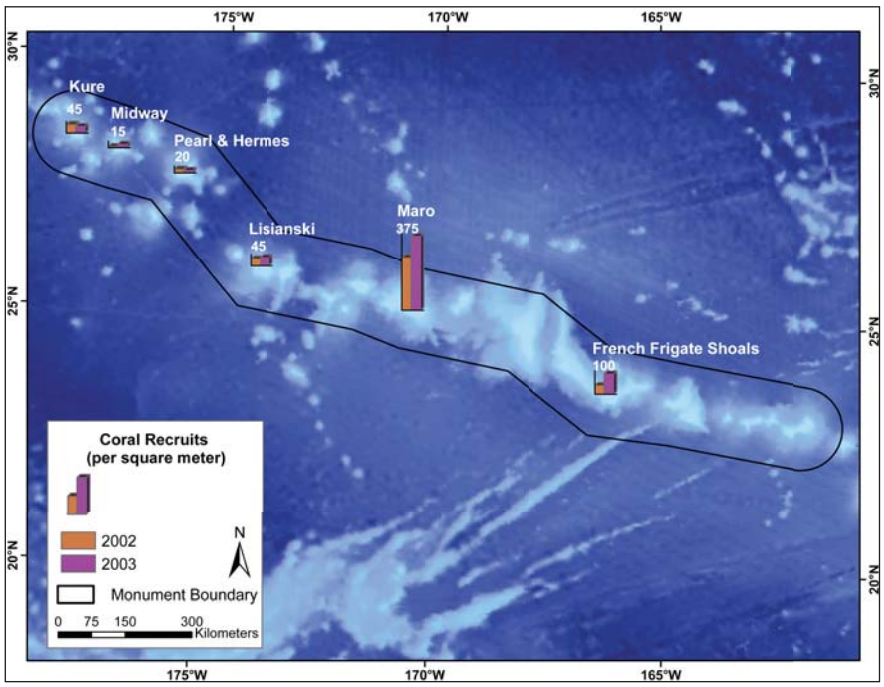


Figure 4.37. Density of coral recruits on plates deployed at six locations in the NWHI in 2002 and 2003. Source: NWHI RAMP; map: L. Wedding.

Coral Bleaching

Mass coral bleaching affected numerous shallow reefs through the NWHI in 2002 and 2004 (Figure 4.38). In both years, the incidence of bleaching was greater at the three northern atolls (Pearl and Hermes, Midway and Kure) than at Lisianski and farther south. At the three northern atolls, bleaching was most severe in shallow back reef and lagoon habitats. In both years, colonies in the genus *Montipora* and *Pocillopora* sustained the highest levels of bleaching (Kenyon et al., 2006; Kenyon and Brainard, 2006). In comparison, only low levels of bleaching were observed during 2006 surveys (Figure 4.38), which were conducted at the same time of year (September) as those in 2002 and 2004. Colonies in the genus *Montipora* were again most affected by bleaching in 2006.

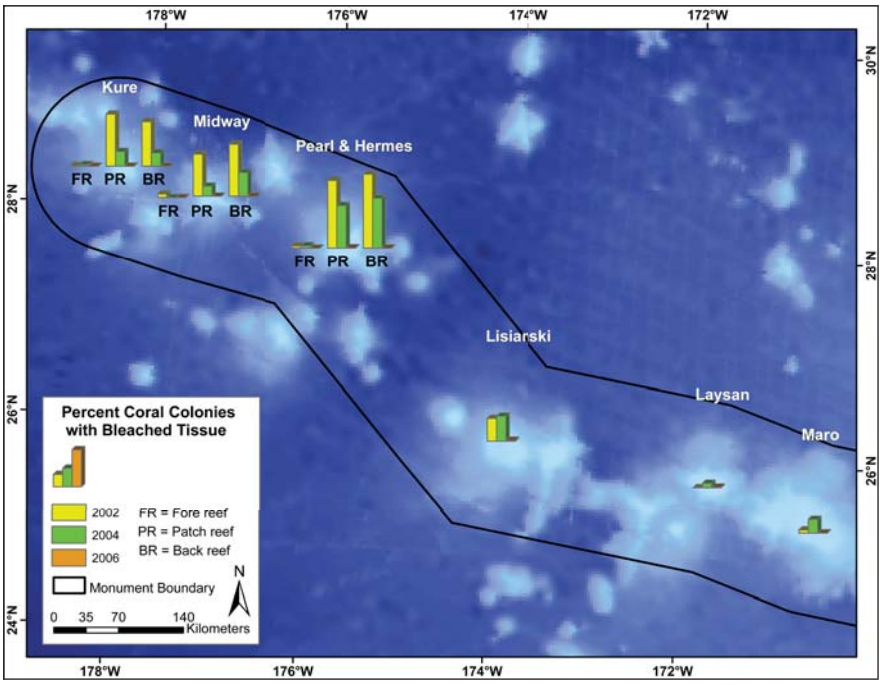


Figure 4.38. Percentage of colonies with bleached tissue within belt transects surveyed in 2002, 2004 and 2006. Minimal bleaching was seen at Gardner Pinnacles and French Frigate Shoals, which are not shown to reduce the complexity of the figure. Source: NWHI RAMP; map: L. Wedding.

In 2004, visual estimates of mortality and algal overgrowth of *Montipora capitata* and *M. cf. turgescens* at back reef sites at the three northern atolls conservatively exceeded 50%, with nearly complete mortality of surface-facing portions of colonies at numerous sites. The shallow crest of a large central patch reef system at Kure Atoll, previously referred to as "the coral gardens" due to its luxuriant growth of montiporids and pocilloporids, was heavily bleached in 2002. In 2004, only a few branches of *Porites compressa* remained alive and the dead coral skeletons were thickly covered in turf and macroalgae. Little change was seen in this reef's condition in 2006. A striking shift occurred at this location from a system dominated by coral in 2001 to a system dominated by algae in 2004 (Figure 4.39).

Figure 4.39. Phase shift on a patch reef at Kure Atoll from a benthos dominated by coral to one dominated by algae after a bleaching event in 2002. Photos: J. Kenyon.

Distribution of Coral Disease

Coral disease has emerged as a serious threat to coral reefs worldwide and a major cause of reef deterioration (Weil et al., 2006). The numbers of diseases and coral species affected, as well as the distribution of diseases, have all increased dramatically within the last decade (Porter et al., 2001; Green and Bruckner, 2000; Sutherland et al., 2004; Weil, 2004). Changing climatic conditions as well as local anthropogenic stressors have been implicated in increased disease levels but our ability to fully understand recent disease outbreaks is hampered by the paucity of baseline and epidemiological information on the normal disease levels in the ocean (Harvell et al., 1999, 2002). The NWHI is considered to be one of the last relatively pristine large coral

reef ecosystems remaining in the world. As such, it provides the unique opportunity to document the normal levels of disease in a coral reef system exposed to limited human influence and the potential of understanding disease dynamics in response to changing climatic conditions.

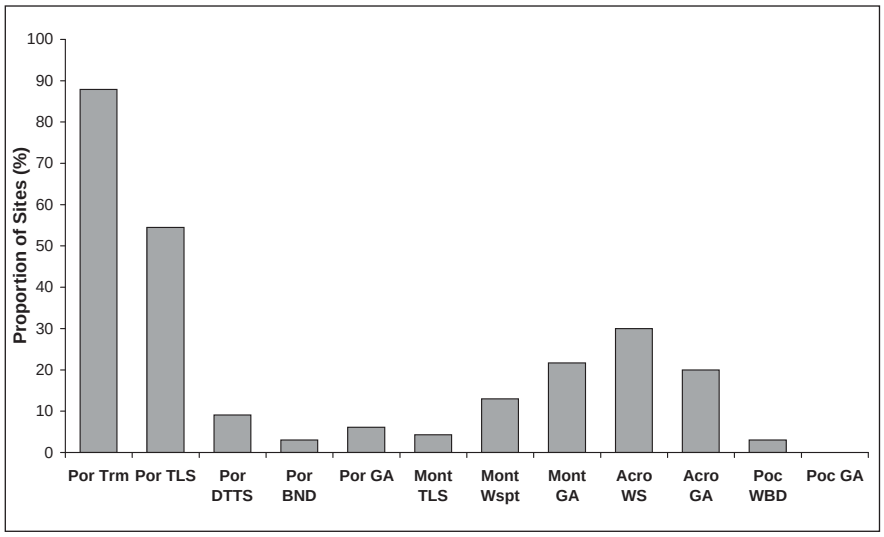


Figure 4.40. Frequency of occurrence of different coral diseases within the NWHI. Data based on 33 REA surveys conducted in 2005. Source: NWHI RAMP, unpub. data.

Table 4.15. Distribution on of twelve coral diseases based on REA surveys conducted between 2002-2005. Source: Aeby, unpub. data.

	MMM	FFS	GAR	MAR	LAY	LIS	PHR	MID	KUR
Por TRM	X	X	X	X	X	X	X	X	X
Por TLS		X		X	X	X	X	X	X
Por DTTS		X		X	X	X	X	X	X
Por BND						X	X		
Por GA				X			X		X
Mont WS				X	X	X	X	X	X
Mont MFTL				X				X	X
Mont GA		X		X	X		X		
Acroporid WS		X							
Acro GA		X							
Poc WB							X		X
Poc GA	X								
Total # Diseases	**2**	**6**	**1**	**7**	**5**	**5**	**8**	**5**	**7**

Coral disease abbreviations: Por = *Porites,* Mont = *Montipora,* Acro =*Acropora,* Poc = *Pocillopora,* TRM = trematodiasis, WS = white syndrome, WB = white band,TS = tissue loss syndrome, DTTS = discolored tissue thinning syndrome, BND = brown necrotising disease, GA = growth anomaly, MFTL = multifocal tissue loss

During a multi-agency cruise conducted in September 2002, disease investigation was incorporated into the protocol and a characterization of coral diseases was initiated. In 2003, baseline coral disease surveys were conducted at 73 permanent monitoring sites throughout the NWHI and have since been surveyed annually. Twelve disease states have now been documented in the four major genera of coral (*Porites, Montipora, Pocillopora and Acropora*) on the reefs of the NWHI (Figure 4.40). The distribution and frequency of occurrence of the different coral diseases varied widely within the nine islands/atolls of the NWHI (Table 4.15; Figure 4.41). The most common disease is *Porites* trematodiasis (Figure 4.42) caused by the digenetic trematode, *Podocotyloides stenometra* (Aeby, 1998*).* This disease is widespread (69.8% of the sites in 2003) and is known to exclusively affect *Porites* sp. coral (Aeby, 2006). Other diseases are less common, such as *Porites* brown necrotizing disease, which only occurred at only 3.2% of the sites in 2003 (Aeby, 2006). Patterns in disease prevalence among the coral genera suggest *Acropora* is highly susceptible to disease and *Pocillopora* appears to be very resistant. *Acropora* comprised only 2.2% of the overall coral community along transects, yet showed high overall prevalence of disease (Aeby, 2006). In contrast, pocilloporids are a common coral in the NWHI (21.1% of the overall coral community along transects) yet seldom showed signs of disease (Aeby, 2006). In contrast, Willis et al. (2004) found pocilloporids on the Great Barrier Reef to have the highest prevalence of disease among all coral families surveyed despite pocilloporids having the lowest coral cover.

Although coral disease was found to be widespread on the reefs of the NWHI, disease prevalence (proportion of colonies affected) for most coral diseases, with the exception of *Porites* trematodiasis, was found to be low in a healthy ecosystem (2005: average prevalence = 0.43% SE ± 0.1%; n = 37 sites surveyed; Figure 4.43). In contrast, the average prevalence of *Porites* trematodiasis in 2005 was 12.5% (SE ± 3.2%; n=36 sites surveyed). *Porites* trematodiasis is an unusual coral disease, in that, it is caused by a larval trematode, which is transmitted through the food chain and requires multiple hosts (coral, mollusk, fish) for completion of its life cycle (Aeby, 1998). In contrast, most coral diseases are caused by bacteria or viruses that can be transmitted directly (host to host) or through the water column. For *Porites* trematodiasis, prevalence of the disease is de-

pendent upon and thus reflective of the abundance of its three hosts. Hence it is not surprising to find high prevalence of this disease on the pristine reefs of the NWHI where host abundance is high. Similarly, Aeby (2007) examined the prevalence of *Porites* trematodiasis in Kaneohe Bay, Oahu which has a distinct north-south gradient in rural to urbanized watersheds. Most of the human population in surrounding watersheds is concentrated in the southern sector and so the south Bay has been most affected by impacts of urbanization (Maragos et al., 1985; Hunter and Evans, 1995). Aeby (unpub. data) found disease levels to be higher in the north Bay than in the south Bay and concluded that host abundance, not environmental stressors, was the primary factor affecting prevalence of *Porites* trematodiasis in Kaneohe Bay. Prevalence of disease varied among islands (Figure 4.44) and differed among coral genera at each island. In 2005, Maro had the highest prevalence of montiporid disease whereas Kure had the highest level of poritid disease. It is not yet clear why differences in disease prevalence occur among islands. Understanding patterns of disease occurrence will require much more information on disease epizootiology such as etiology and mode of transmission.

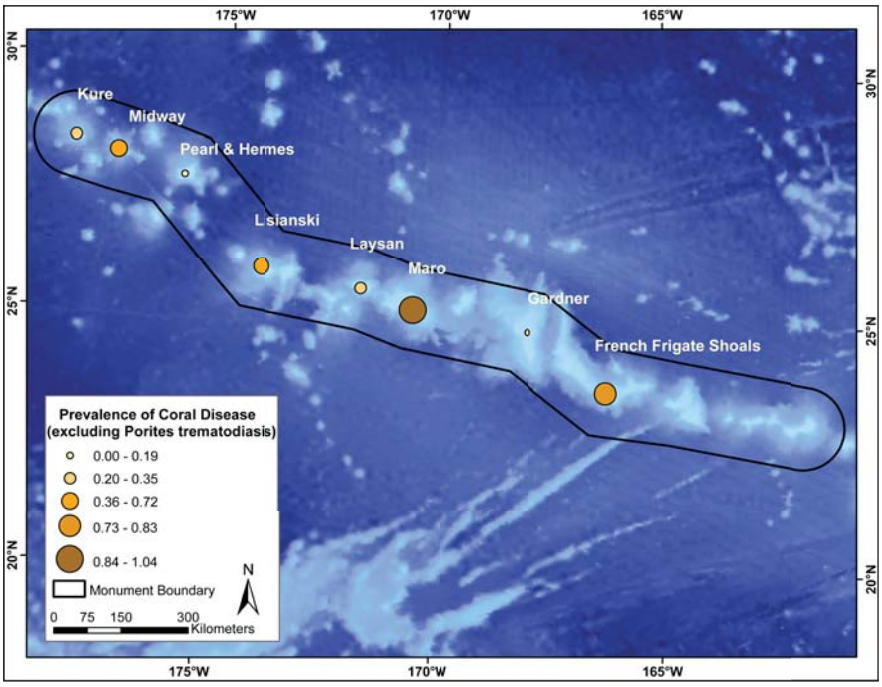


Figure 4.41. Frequency of occurrence of different coral diseases within the NWHI. Data based on 33 REA surveys conducted in 2005. Source: Aeby; unpub. data; map: L. Wedding.

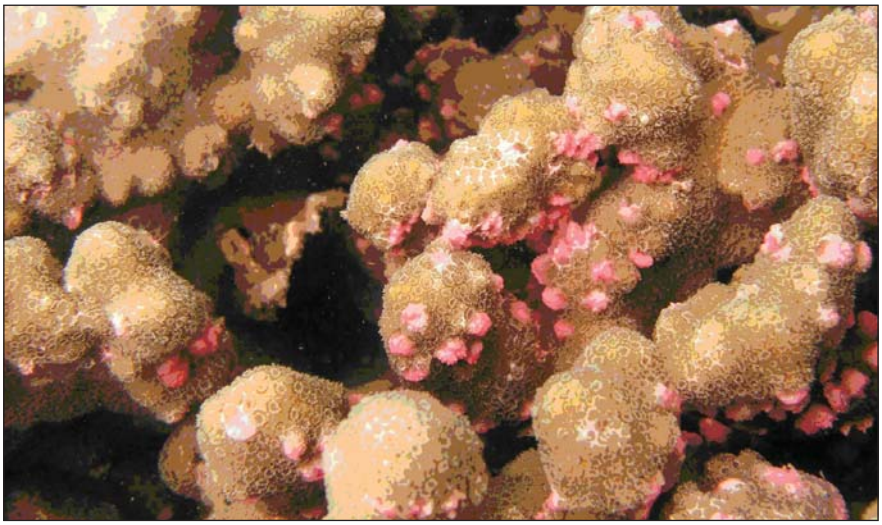


Figure 4.42. Porites trematodiasis *is caused by a larval trematode, which is transmitted through the food chain and requires multiple hosts (coral, mollusk, fish) for completion of its lifecycle. Photo: G. Aeby.*

Prevalence of the disease is dependent upon and thus reflective of the abundance of its three hosts. Hence it is not surprising to find high prevalence of this disease on the pristine reefs of the NWHI where host abundance would also be high. One exception to the pattern of healthy levels of coral disease on the reefs of the NWHI is an outbreak of *Acropora* white syndrome (AWS) that was first documented at French Frigate Shoals in 2003 (Aeby, 2006b). AWS has caused significant coral loss on reefs at French Frigate Shoals (Aeby, unpub. data), as well as in other areas of the Indo-Pacific (Willis et al., 2004; Jacobson, 2006). As of 2006, studies found the disease to have spread to seven reefs within French Frigate Shoals. Acroporids have also been greatly affected by disease in Australia (Willis et al., 2004) and the Marshall Islands (Jacobson, 2006) and have been decimated by disease in the Caribbean (Green and Bruckner, 2000; Porter et al., 2001; Patterson et al., 2004; Weil, 2004). Acroporids were one of the major frame-building corals in the Florida Keys, but losses of acroporids are now averaging 87% or greater (Miller et al., 2002; Patterson et al., 2002). Research is desperately needed to understand disease processes to prevent the acroporid reefs of the Monument and neighboring Johnston Atoll National Wildlife Refuge from following the same path as the acroporid reefs of the Florida Keys. More research is also needed to understand disease transmission dynamics across Indo-Pacific and the impact climate change will have on the health of coral reef ecosystems.

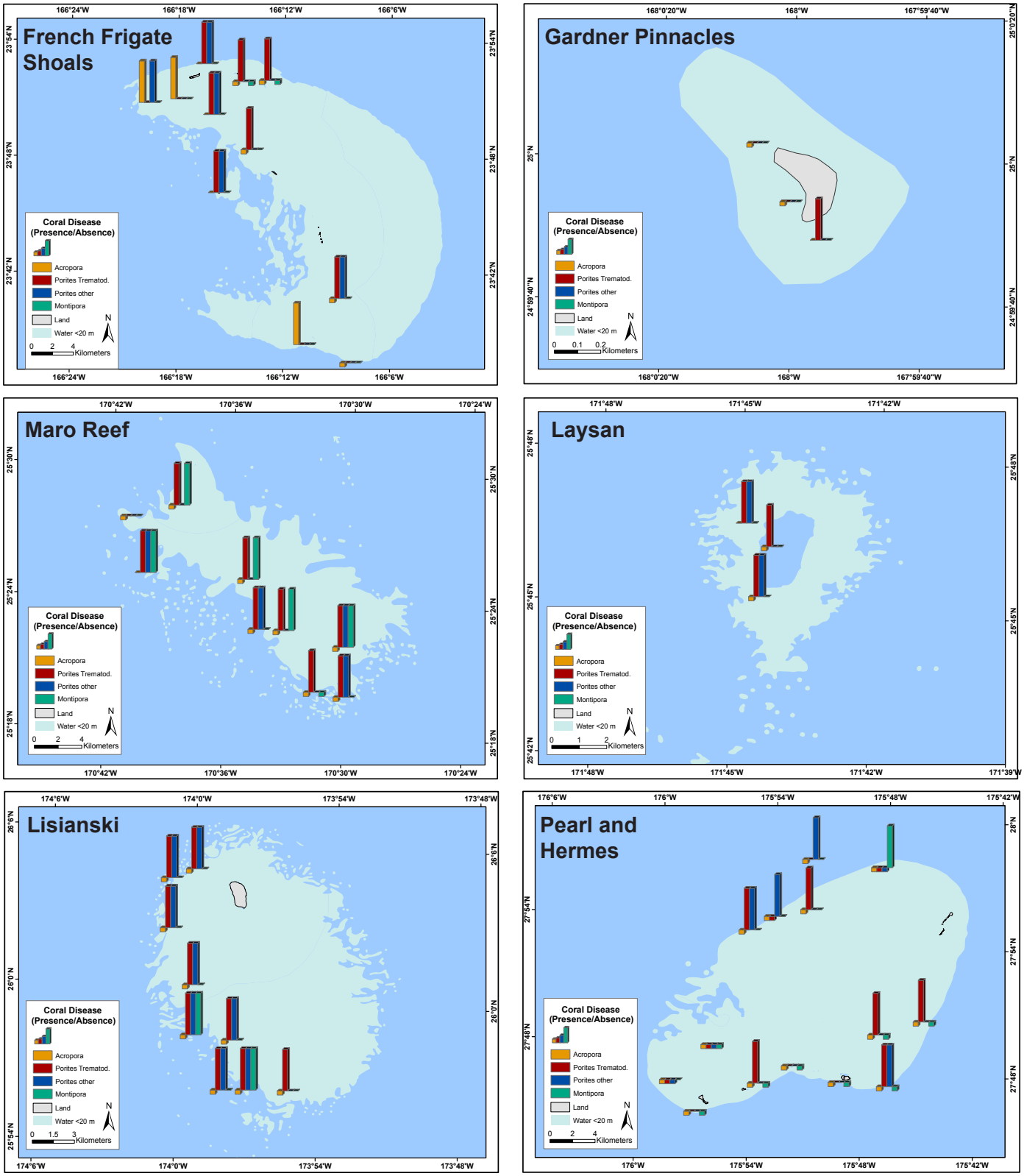


Figure 4.43. Coral disease for French Frigate Shoals, Gardner Pinnacles, Maro Reef, Laysan, Lisianski and Pearl and Hermes. Source: Aeby, unpub. data; maps: L. Wedding.

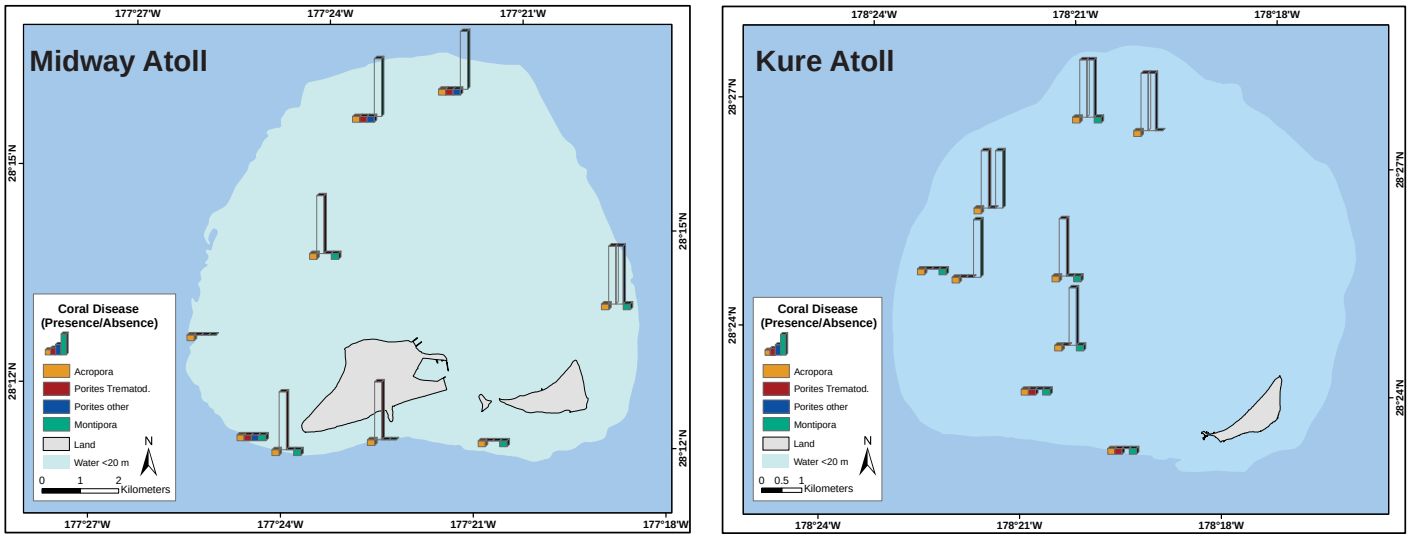


Figure 4.43 (continued). Coral disease at Midway and Kure atolls. Source: Aeby, unpub. data; maps: L. Wedding.

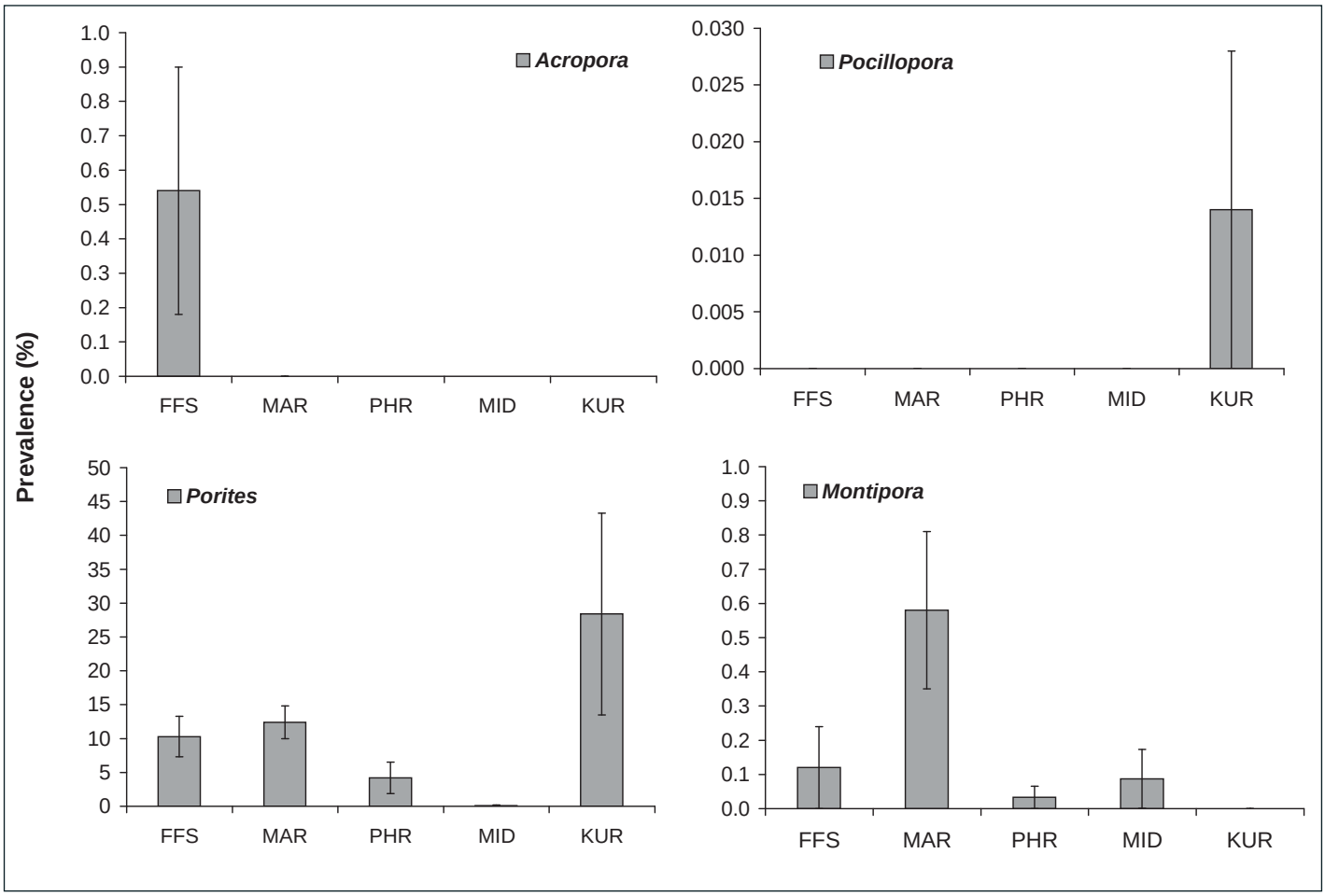


Figure 4.44. Prevalence of coral disease among locations by major coral genera. Note the differences in y-axis among genera. Source: G. Aeby, unpub. data.

Coral Predators

The Crown-of-thorns starfish (COTS; *Acanthaster planci*; Figure 4.45) and Drupellid snails (*Drupella* sp.) are both corallivores that have caused significant coral damage in other areas of the Indo-Pacific, and were monitored on the reefs of the NWHI during benthic (COTS and Drupellid snails) and towed-diver surveys (COTS). Towed-diver surveys report COTS to be present on the reefs of the NWHI but to occur at low levels (average=0.65 COTS/km; NWHI Reef Assessment and Monitoring Program or RAMP, unpub. data). During annual benthic monitoring surveys it was found that the frequency of occurrence (the number of sites with animals

or feeding scars/total sites surveyed) for *Drupella* sp. was low (3% in 2004, 15.4% in 2005) (Aeby, unpub. data). *Drupella* were usually found feeding at the base of branches of cauliflower coral (*Pocillopora meandrina)*. For COTS, frequency of occurrence was also low with reports of COTS observed at 4.5% of the monitoring sites in 2004 and 28.2% in 2005 (Aeby, unpub. data). COTS were usually found as single animals.

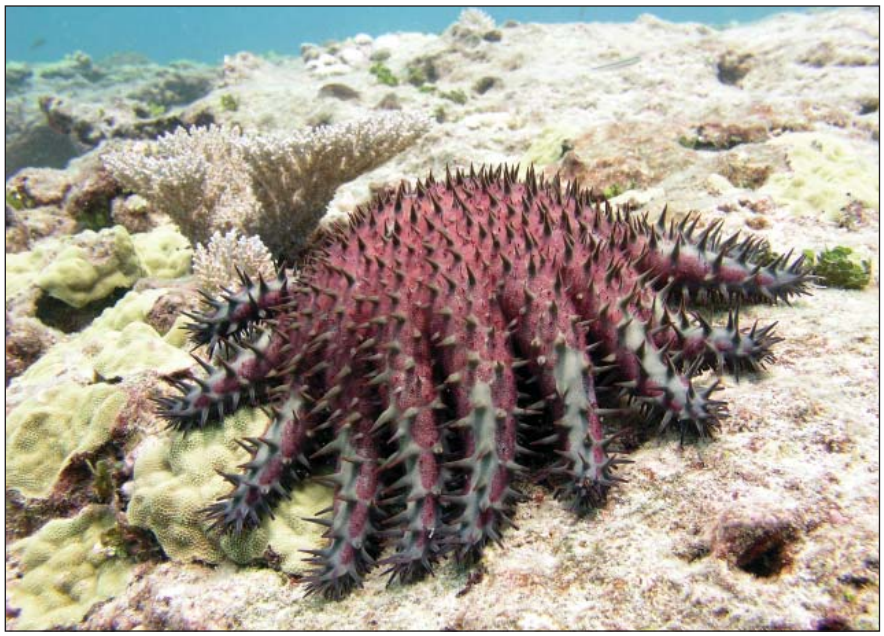
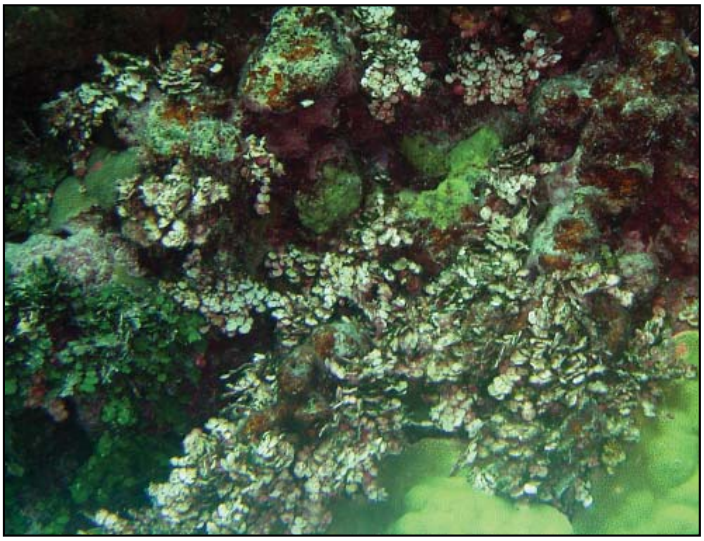


Figure 4.45. Crown-of-thorns sea star in the NWHI. Photo: J. Kenyon.

ALGAE

Although the NWHI represent one of the last relatively intact tropical reef ecosystems in the world, macroalgal community dynamics of the 10 atolls, islands, and reefs situated in the NWHI Marine National Monument remain poorly understood. A study published in conjunction with the Northwestern Hawaiian Islands' third Scientific Symposium (Vroom and Page, 2006) was the first to provide distributional maps of common algal species, statistically compare sites from differing habitats and islands based on relative abundance of macroalgae and look for temporal differences in macroalgal populations. Findings revealed that the abundance of most macroalgal genera was low across the archipelago, but that members of certain green algal genera including *Halimeda* and *Microdictyon* (Figure 4.46) can be extremely common and in some cases form dense monotypic meadows on the reef, especially in fore reef areas (*Microdictyon*) and lagoons (*Halimeda*). Other genera, such as the brown algae *Stypopodium* and *Lobophora*, and the red alga *Laurencia*, become increasingly prevalent in the three northwestern-most atolls of the Hawaiian archipelago (Kure, Midway, and Pearl and Hermes). Relative abundance of macroalgae across the NWHI chain as a whole remained relatively static for the years surveyed; however, slight changes occurred at Kure and Midway atolls where coral bleaching events were documented in 2002 and 2004.



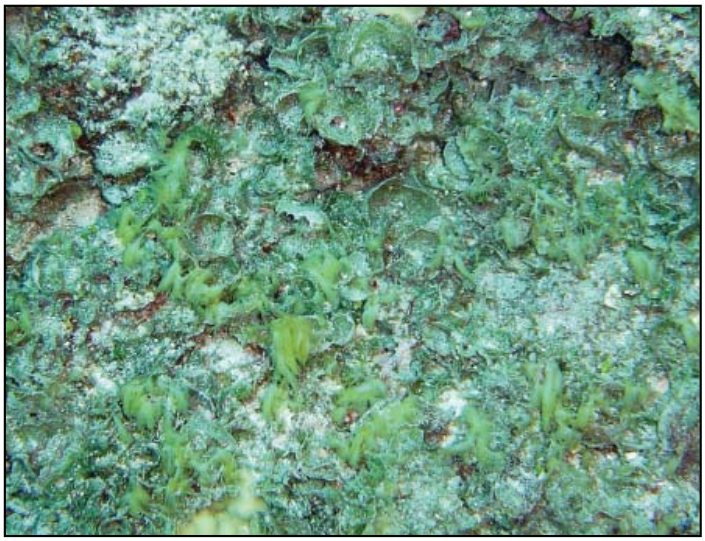


Figure 4.46. Halimeda velasquezii *at Maro Reef (left).* H. velasquezii *is the most common species of* Halimeda *in the NWHI.* Microdictyon *is also very common in some regions of the NWHI. A close-up photo of a* Microdictyon setchellianum *(right) field at Gardner Pinnacles. Photos: P. Vroom.*

A study recently completed at Pearl and Hermes Atoll (Page, 2006) used detailed species-level percent cover analyses coupled with environmental variables to better understand the mechanisms that determine distributional patterns of organisms, particularly algae. Benthic community composition was examined along a wave exposure gradient using multivariate statistical analyses with the hypothesis that sites with similar levels of wave exposure would exhibit similar benthic communities. Species richness of coral and macroalgae were also compared to determine if sites with intermediate levels of wave exposure would contain the highest diversity of benthic organisms. To test these hypotheses, percent cover of benthic organisms was determined at 34 sites in four wave exposure categories: high, intermediate-high, intermediate-low and low. Multivariate statistical analyses revealed that sites from each wave exposure category differed significantly, and a non-metric multi-dimensional scaling ordination (nMDS) and cluster diagram grouped sites from low, high, and intermediate-high wave disturbance areas into three relatively discrete clusters. However, sites experiencing intermediate-low wave exposure did not group together in the nMDS ordination or cluster diagram, suggesting variability in benthic compositions among these sites. Coral and macroalgal species richness was significantly higher at sites with intermediate-high and intermediate-low levels of wave exposure than at sites with low wave exposure, although not significantly higher than sites with high wave exposure.

An article appearing in *American Scientist* magazine (Vroom et al., 2006) compared percent cover of macroalgal, turf algal, crustose coralline algal and coral populations at eight islands across the Pacific Ocean basin, including two from the NWHI. The NWHI are documented to contain the highest percent cover of algal species when compared to other geographic locations, and the lowest percent cover of living coral. This is likely due to the subtropical location of the NWHI and cool SSTs that bathe biological communities during winter months. Despite high algal populations, the NWHI remain healthy and thriving marine ecosystems that are dominated by top predators and high fish populations.

Algal diversity appears similar across the NWHI chain even though brown algae tend to be more abundant at Midway and Kure atolls when compared to most other islands (Figure 4.47). The lower abundance of green algae at Midway may be tied to lower apex predator biomass and higher herbivorous fish densities at this atoll system, suggesting possible top-down control of the benthic habitat (DeMartini and Friedlander, 2004, 2006).

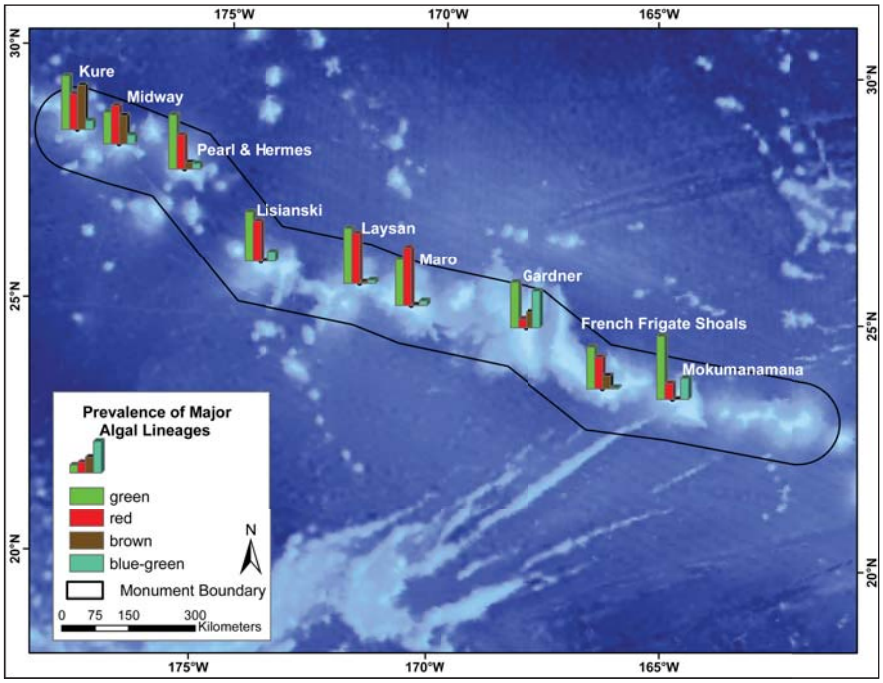


Figure 4.47. Prevalence of major algal lineages in the Northwestern Hawaiian Islands. Bars represent standard deviation. Source: NWHI RAMP, unpub. data; map: L. Wedding.

Although the mix of macroalgal species is relatively similar throughout the NWHI chain, certain species (e.g., *Stypopodium flabelliforme*, *Laurencia galtsoffii*) are more abundant in the northwesternmost atolls where SSTs experience the greatest annual fluctuation. While *S. flabelliforme* is a major component of shallow reef systems at Kure Atoll, it is a minor component of reefs at most other islands and atolls in the NWHI. Because brown algae are known to predominate over other algal lineages in cool, temperate environments (Cheney, 1977), it is possible that the cooler SSTs found at Kure and Midway atolls during winter months may favor a higher abundance of brown algal species (Figure 4.47).

Algae Data: 2006

Mokumanamana

Only two stations were assessed for algae at Mokumanamana in 2006 (Figure 4.48; located on pages 144-145). It is a composite of maps illustrating the percent frequency of occurrence of major algae by island). Four algal groups were present with *Halimeda* occurring in 100% of the samples, followed by *Laurencia* (91.7%), crustose coralline red algae (12.5%) and *Jania* (8.3%; Table 4.16).

Table 4.16. Summary statistics for algal groups at Mokumanamana Island in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	0	0	0	0.00%
Halimeda	100	0	2	100.00%
Microdictyon	0	0	0	0.00%
Neomeris	0	0	0	0.00%
Jania	8.33	11.79	1	50.00%
Laurencia	91.67	11.79	2	100.00%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	12.5	17.68	1	50.00%
Lobophora	0	0	0	0.00%
Padina	0	0	0	0.00%

French Frigate Shoals

Ten stations were sampled in 2006 at French Frigate Shoals with seven algal groups present on quantitative surveys (Table 4.17, Figure 4.48). *Laurencia* was present all stations and found, on average, in 77% of quadrats. *Halimeda* was present at 90% of the stations and found, on average, in 62% of the quadrats. *Jania* was found at half the stations but on occurred in 9% of the quadrats, on average.

Table 4.17. Summary statistics for algal groups at French Frigate Shoals in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	1.67	5.27	1	10.00%
Halimeda	62.5	38.14	9	90.00%
Microdictyon	15.83	21.68	4	40.00%
Neomeris	0	0	0	0.00%
Jania	9.17	15.44	5	50.00%
Laurencia	76.67	20.71	10	100.00%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	0	0	0	0.00%
Lobophora	30	32.68	8	80.00%
Padina	2.5	7.91	1	10.00%

Maro Reef

Nine stations were sampled at Maro Reef in 2006 with six algal groups present (Table 4.18, Figure 4.48). *Halimeda* was present at all stations and found, on average, in 91% on the quadrats. *Laurencia* was also found at all stations and occurred in 75% of the quadrats. Crustose coralline red algae were found at three-quarters of the stations surveyed and appeared an average of 34% of the quadrats.

Table 4.18. Summary statistics for algal groups at Maro Reef in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	5.56	8.33	4	44.44%
Halimeda	90.74	6.51	9	100.00%
Microdictyon	0	0	0	0.00%
Neomeris	0	0	0	0.00%
Jania	12.96	19.59	4	44.44%
Laurencia	75	19.09	9	100.00%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	34.26	36.43	6	66.67%
Lobophora	27.78	30.33	6	66.67%
Padina	0	0	0	0.00%

Laysan Island

Three stations were surveyed at Lasyan Island in 2006 with eight algal groups observed in these surveys (Table 4.19, Figure 4.48). *Halimeda* and *Laurencia* were found at all stations and were the dominant groups being found, on average, in 89% and 86% of all quadrats, respectively. Crustose coralline red algae occurred at two of the three stations and were present in 44% of the quadrats, on average.

Table 4.19. Summary statistics for algal groups at Laysan Island in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	0	0	0	0.00%
Halimeda	88.89	19.25	3	100.00%
Microdictyon	19.44	33.68	1	33.33%
Neomeris	2.78	4.81	1	33.33%
Jania	8.33	14.43	1	33.33%
Laurencia	86.11	17.35	3	100.00%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	44.44	38.49	2	66.67%
Lobophora	19.44	4.81	3	100.00%
Padina	5.56	9.62	1	33.33%

Lisianski-Neva Shoals

Eight stations were sampled at Lisianski-Neva Shoals in 2006 with eight algal groups present in those surveys (Table 4.20, Figure 4.48). *Halimeda* occurred at all stations and in nearly all quadrats (94%). Other important genera included *Laurenica*, which was present in 78% of the quadrats, and *Jania*, which occurred in 42% of the quadrats. Both genera were present at 89% of the stations surveyed.

Table 4.20. Summary statistics for algal groups at Lisianski-Neva Shoals in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	12.96	13.89	6	66.67%
Halimeda	93.52	8.1	9	100.00%
Microdictyon	25	33.59	5	55.56%
Neomeris	10.19	11.62	5	55.56%
Jania	42.59	33.19	8	88.89%
Laurencia	77.78	31.18	8	88.89%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	1.85	5.56	1	11.11%
Lobophora	25	16.14	8	88.89%

Pearl and Hermes Atoll

A total of 12 stations were sampled at Pearl and Hermes in 2006 with nine algal groups present in those surveys (Table 4.21; Figure 4.48). *Laurencia* occurred at the greatest number of stations (92%), followed by *Halimeda* (75%), *Microdictyon* (67%), *Dictyosphaeria* (67%) and *Lobophora* (58%). On average *Halimeda* was present in 49% of quadrats, followed by *Microdictyon* with 42%, and *Laurencia* with 40%. Although *Dictyosphaeria* had a high frequency of occurrence, it was only present in 12% of the quadrats, on average.

Table 4.21. Summary statistics for algal groups at Pearl and Hermes Atoll in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	11.81	12.54	8	66.67%
Halimeda	49.31	39.64	9	75.00%
Microdictyon	41.67	44.1	8	66.67%
Neomeris	4.86	10.33	3	25.00%
Jania	20.14	23.15	6	50.00%
Laurencia	40.28	31.15	11	91.67%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	18.75	32.4	4	33.33%
Lobophora	29.86	36.66	7	58.33%
Padina	10.42	26.38	3	25.00%

Midway Atoll

Sampling at Midway Atoll in 2006 included six stations with eight algal groups present (Table 4.22, Figure 4.48). Laurencia was found at all stations and 39% of the quadrats. *Lobophora* was found at 83% of the stations and occurred in 47% of the quadrats, on average. Microdicyton was found at half the stations and occurred in 22% of the quadrats. Padina was present at two-thirds of the stations (19% of the quadrats).

Table 4.22. Summary statistics for algal groups at Midway Atoll in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	6.94	13.35	2	33.33%
Halimeda	11.11	16.39	3	50.00%
Microdictyon	22.22	32.77	3	50.00%
Neomeris	0	0	0	0.00%
Jania	1.39	3.4	1	16.67%
Laurencia	38.89	19.48	6	100.00%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	12.5	16.46	3	50.00%
Lobophora	47.22	24.53	5	83.33%
Padina	19.44	21.52	4	66.67%

Kure Atoll

Eight stations were sampled at Kure Atoll in 2006 with eight algal groups present (Table 4.23, Figure 4.48). *Microdictyon* was the most abundant genera, occurring at all stations and in 62% of all quadrats. *Halimeda* also was present at all stations but in a lower percentage of quadrats (25%). *Jania* and *Lobophora* were both present at 87% of the stations.

Table 4.23. Summary statistics for algal groups at Kure Atoll in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	10.42	19.8	4	50.00%
Halimeda	25	23.15	8	100.00%
Microdictyon	62.5	26.35	8	100.00%
Neomeris	0	0	0	0.00%
Jania	20.83	15.43	7	87.50%
Laurencia	43.75	37.73	6	75.00%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	31.25	36.39	4	50.00%
Lobophora	30.21	27.44	7	87.50%
Padina	6.25	11.57	3	37.50%

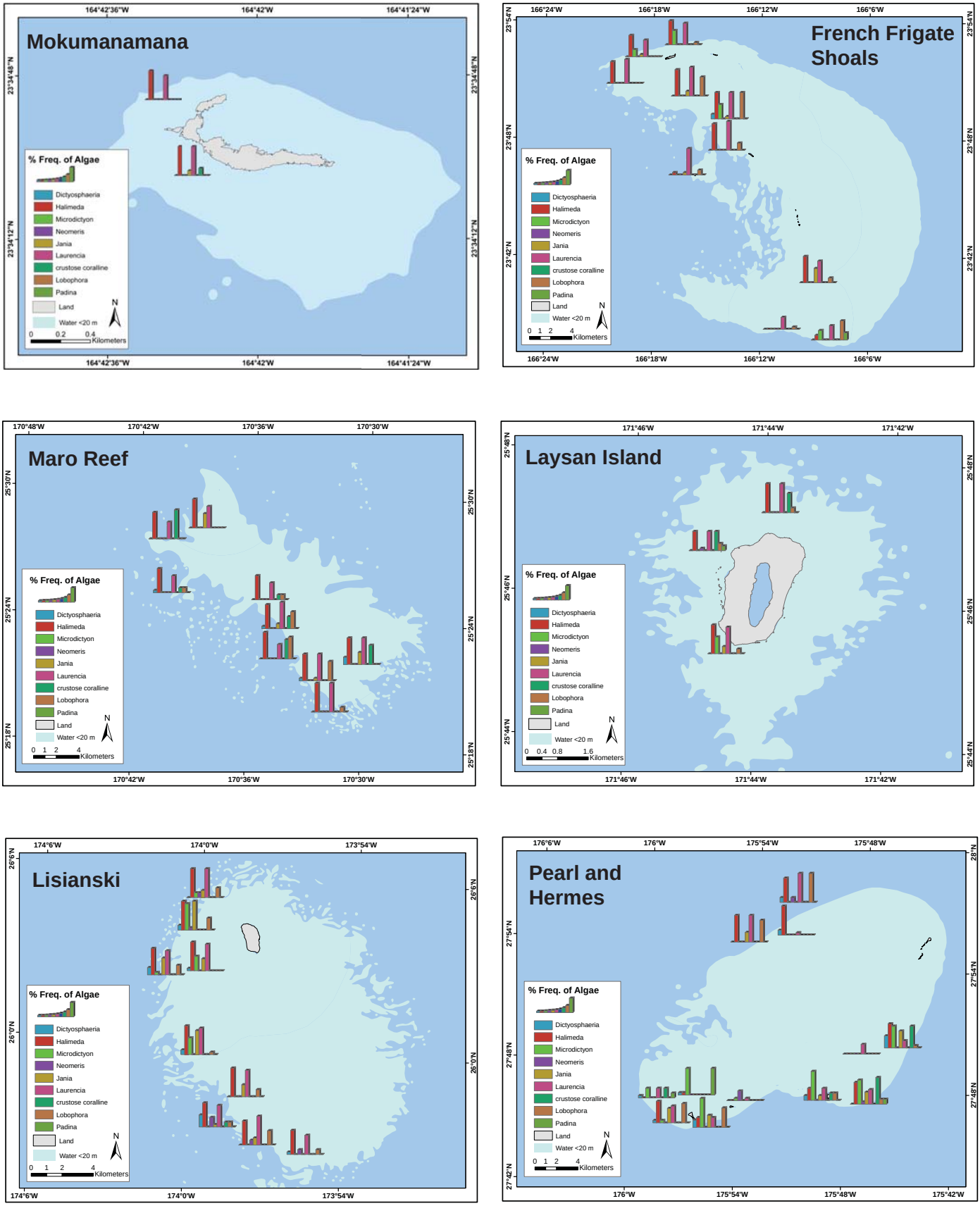


Figure 4.48. Percent frequency of occurrence of major algal groups by island in 2006. Source: NWHI RAMP, unpub. data; maps: L. Wedding.

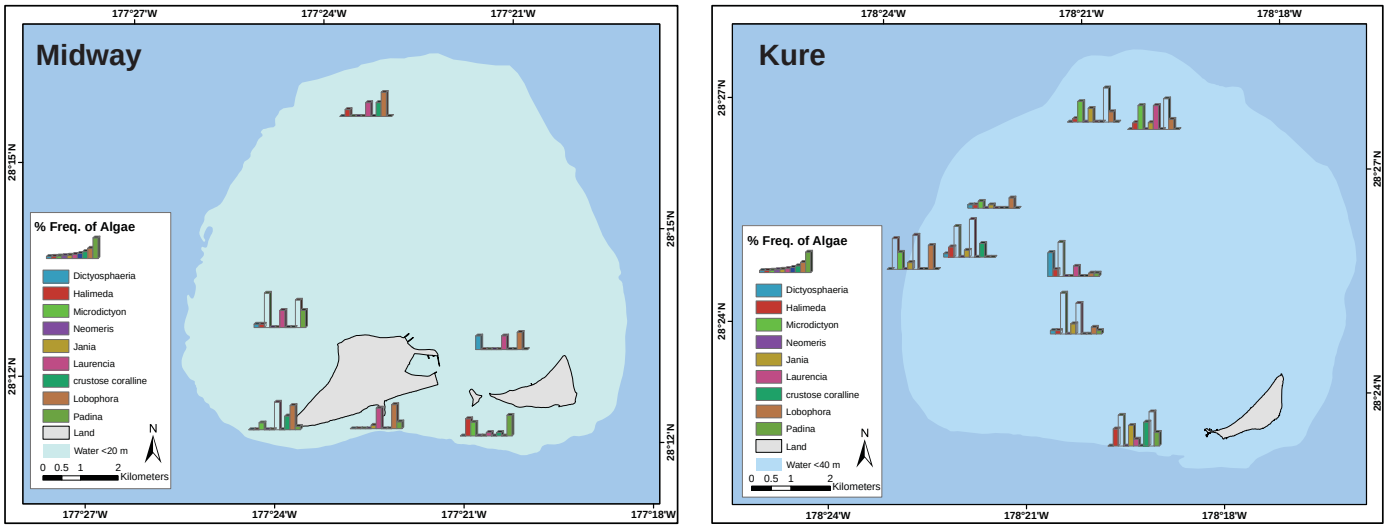


Figure 4.48 (continued). Percent frequency of occurrence of major algal groups by island in 2006. Source: NWHI RAMP, unpub. data; maps: L. Wedding.

INVERTEBRATES

Census of Coral Reef Ecosystems (CReefs)

The international CoML is a global effort to assess the diversity, distribution and abundance of ocean life and explain how it changes over time. Over 1,700 scientists from 73 countries are pooling their findings to create a comprehensive and authoritative portrait of life in the oceans today, yesterday and tomorrow. As one of 17 projects of the CoML, the goals of the CReefs are to increase tropical taxonomic expertise, conduct a taxonomically-diversified global census of coral reef ecosystems, and improve access to and unify coral reef ecosystem information scattered throughout the world.

As part of the CReefs effort, NOAA's Pacific Islands Fisheries Science Center Coral Reef Ecosystem Division led a multi-institutional team of international taxonomists on a 23-day research expedition in October 2006 to explore the biodiversity of small, understudied, or lesser known invertebrate, algal and microbial species at French Frigate Shoals. In an effort to maximize the ability to document biodiversity, surveys were conducted at over 50 different sites representing 14 habitat types using 12 diverse sampling methods (including baited traps, rubble brushing, rubble extraction, underwater vacuuming with gentle suction, plankton tows, light traps, sediment and water sampling) specifically designed to minimize habitat impacts while maximizing the number of ecological niches sampled.

During the three week cruise, scientists documented more than 1,000 species at French Frigate Shoals. For comparison, this corresponds to around 20% of the Hawaiian marine invertebrate fauna documented over the past 200 years. These new findings indicate just how little is known about tropical marine invertebrates in general and especially within the NWHI, and may offer clues to the extent of undiscovered diversity at French Frigate Shoals. Collected species were photo-documented for future study. Many species had never been photographed, fresh or alive, and thus represent the first documentation of their living color and appearance. DNA samples were also collected to facilitate DNA-based identification of Hawaiian and tropical Pacific invertebrates in the future.

Thorough taxonomic identifications and molecular analyses of the samples collected are still being analyzed and will take many years to complete. However, preliminary findings suggested that approximately 2,300 unique morpho-species were collected and photographed during the 16 days of sampling (Figure 4.50). To improve the long-term ability to monitor biodiversity, tissue samples for molecular barcoding were collected from about 60% of the unique morpho-species. An estimated 30-50 collected specimens are thought to be new species to science, including new species of crabs, corals, sea cucumbers, sea quirts, worms, sea stars, snails and clams. From this expedition, well over a hundred new species records from sponges, corals, anemones, flatworms, segmented worms, hermit crabs, crabs, sea slugs, bivalves, gastropods, octopus, sea cucumbers,

sea stars and sea squirts, will likely be identified for French Frigate Shoals. The highest sampled diversities at French Frigate Shoals were in the phylums Anthropoda and Mollusca. By habitat type, lagoon patch reefs, La Perouse Pinnacle (basalt), back reef and deep fore reefs had the highest diversity. Due to the high level of taxonomic expertise available on the cruise, hand collection was the most effective sampling methodology, following by rubble extraction, rubble brushing and use of baited traps.

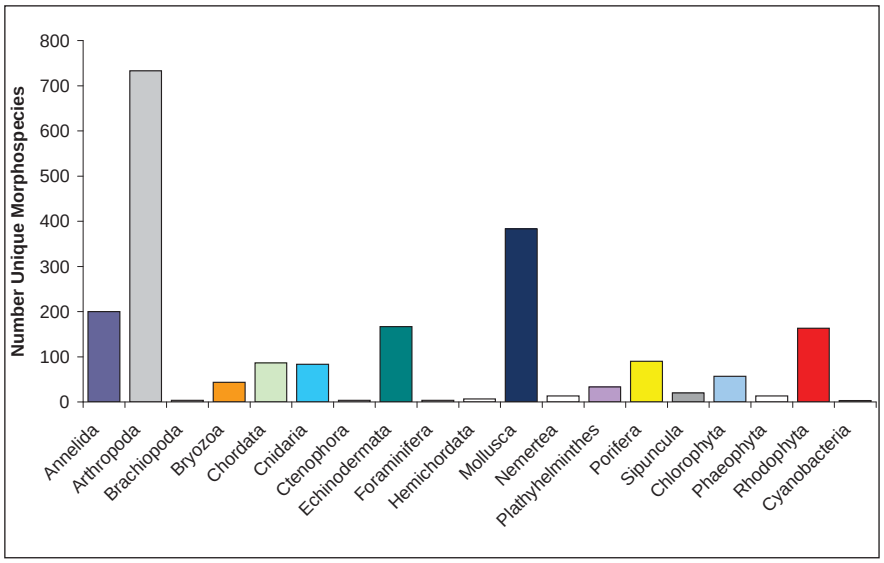


Figure 4.49. Unique morphospecies collected at French Frigate Shoals by phylum from CReefs cruise. Source: CoML, unpub. data.

Some anecdotal figures indicate the degree of novelty. For example, of the six specimens of octopus collected three species may be new to science (Figure 4.50). In comparison, 15 species of octopus were previously known from the Hawaiian Islands. Additionally, there were at least 25 species of sea cucumbers documented; three are new species and two are new records for Hawaiian fauna (Figure 4.50). Previously, about 30 species of shallow water holothurians have been documented from Hawaiian waters.

Figure 4.50. Six species of octopus (left) were collected during the mission, three of which maybe new to science. The right photo shows a newly discovered species of sea cucumber. Photos: G. Paulay.

Though relatively high diversity was found for sponges, bryozoans, eulimid gastropods, hermit crabs, echinoderms, ascidians and other invertebrates (including corallimorph anemones, galatheid squat lobsters, porcellanid crabs, pea crabs and coral barnacles), had strikingly low diversity or were absent. Interestingly, about one third of all invertebrate morphospecies collected were either found only once or found at only one site. A possible new family of ascidian for the NWHI, Mogulidae, was collected. Likewise, a new species of coral that could not even be identified to family level was found and photographed, since coral collections were not authorized under this permit. An estimated 48 new species records of Opisthobranch molluscs for French Frigate Shoals were collected, 27 of which appear to be new records for the NWHI.

Other Invertebrate Surveys

Recent efforts to quantify the non-coral invertebrate populations in the NWHI included two broad-scale towed-diver surveys conducted in 2004 and 2006 (Figure 4.51) and a REA survey conducted in 2005. Surveys were focused on collecting information on three target classes of invertebrates: Echinoidea, Holothuroidea and Asteroidea. Towed-diver surveys found densities of echinoids and holothuroids to be highest at the northernmost

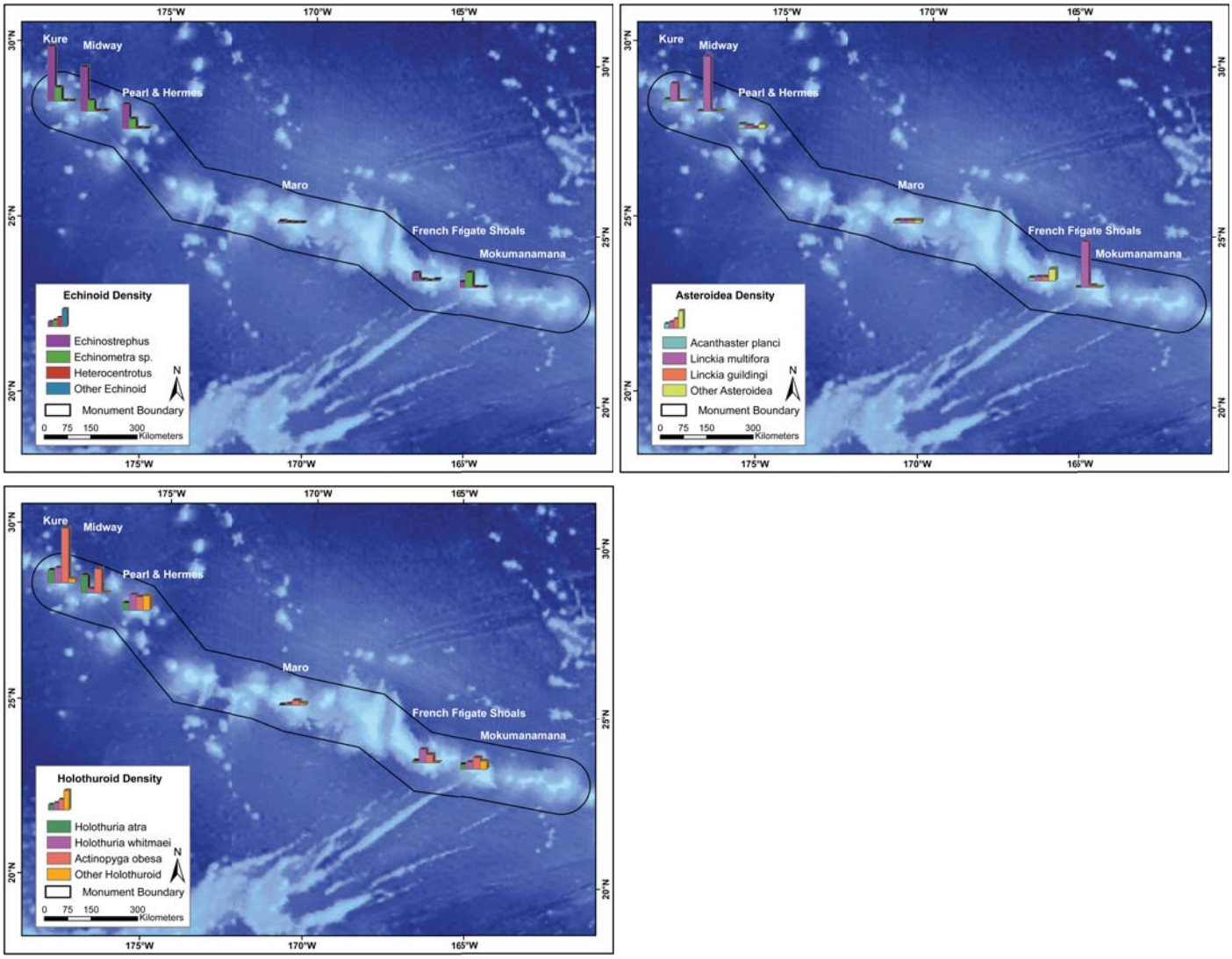


Figure 4.51 Mean density of Echinoids, Asteriods and Holothuroids per m² from towed diver surveys. Sources: NWHI RAMP, Brainard et al., in prep.; maps: L. Wedding.

islands/atolls. Sea urchins were the most common invertebrate observed during these surveys, with Kure (2004 and 2006) and Midway (2006) reporting the highest densities in the island chain (>1,600 urchins/ha). Sea cucumbers were present at all islands but in low densities, with the exception of the northern atolls. The highest sea cucumber density was recorded at Kure in 2006. COTS were in relatively low abundance throughout the archipelago with the highest density recorded in 2004 at Pearl and Hermes. Though abundance of COTS was relatively low in comparison with reported infestation levels in higher coral cover areas, such as the Great Barrier Reef, the impacts of these abundances could be significant due to the relatively low coral cover found throughout much of the NWHI.

Data collected during REA surveys included species level information on the three target classes of invertebrates and followed the general patterns of the towed-diver data. The most common echinoid throughout the NWHI was the burrowing sea urchin, *Echinostrephus* sp., with the highest densities recorded at Midway and Kure (>12 individuals/m²). As in towed-diver surveys, sea cucumbers were present at all islands/atolls but in low densities. The most common sea cucumber was *Actinopyga obesa*, with a density of .03 individuals/ m² at Kure. The most common sea-star was *Linckia multifora*.

EXISTING DATA GAPS

Effective management decisions are based on reliable information on the biological characteristics of the organisms, their ecological relationships and understanding of the natural temporal variations that characterize their ecosystems. Overall there is a need for basic information on all living resources at the NWHI. Taxonomy studies should provide knowledge of all species presents to develop a baseline and facilitate identification of new species records and which ones are endemic, rare and worthy of special attention. Life history studies are needed to provide information on essential habitat requirements (reproduction, recruitment and feeding) for all life stages, environmental tolerance, larval dispersal mechanisms and other parameters (age structure, growth, mortality, etc.) for key native species. Specific research opportunities include:

- Developing a comprehensive catalog of native species that include: ecological requirements, georeferenced habitat use during different life stages, life history metrics (population age/size distributions, growth rates, size/age of maturity, mortality rates, etc.);
- Comparing native species habitats and ecological requirements to a catalog of anthropogenic threats in order to identify native species vulnerable to anthropogenic stress;
- Developing comparative life history studies between NWHI and MHI to determine anthropogenic effects on growth, maturation, and reproductive success of native species;
- Documenting the trophic dynamics of key native species;
- Developing a comprehensive species list of algal taxa for the NWHI;
- Determining habitat distribution/availability, especially that essential to reproduction, recruitment, and feeding;
- Characterizing the genetic structure of specific populations; and
- Determining the functional ecological roles of native species.

Monitoring programs require research to determine priority parameters and indicators to be measured for changes to ecosystems and ecological processes. Research also needs to indicate the scale, resolution and frequency of sampling that will contribute to meaningful monitoring, and the kinds of tools and technology that can best obtain the desired data. There are key gaps in the development and implementation of monitoring programs, including the need to determine:

- The variables, scale and the spatial and temporal resolution at which ecological processes and connectivity can be monitored to support management needs;
- The existing parameters and indicators of existing monitoring programs and identify gaps as the basis for more comprehensive monitoring of ecosystem change; and
- The spatial and temporal basis of ecological processes to identify ecological boundaries between subregions.

There are also key research issues that have been identified as important for monitoring and modeling, including:

- Which environmental conditions, e.g., temperature, flow, geomorphology, have a mitigating influence on survival in a changed environment;
- To what extent the reduction or expansion of one or more segments of the community assemblage result in competitive top down pressure or an increase in bottom up production;
- How ecosystem acclimation to change varies among taxa and in relation to both survival and the ability to effectively reproduce;
- The degree to which variability in an ecosystem may determine its capacity for resilience;

- How the rebound of an ecosystem depends on maintenance of established pathways of energy flow, which provide the system a stable means of recovery rather than risk a transition to a different state of equilibrium;
- To what extent reducing fish populations of the ecosystem undermine or realign energy flow and trophic stability;
- The other key aspects that affect ecosystem stability and resilience need to be identified, e.g., rates of energy flow, oceanographic conditions, nutrient levels and recruitment;
- The spatial and temporal patterns of plankton and larval dispersal, sources and sinks and
- The size, location and effectiveness of closed areas, e.g., MPAs.

As with monitoring of ecosystems and ecological processes, there is a need for research on the parameters and indicators most appropriate and practical for measuring changes to species populations and habitats. Research needs to address both marine terrestrial biodiversity and communities and seek to identify the scale, resolution and frequency of sampling that will contribute to meaningful monitoring of flora and fauna, as well as the most useful tools and technology for gathering the data. Important gaps in the development and implementation of monitoring programs include the need to determine:

- The variables, scale and the spatial and temporal resolution at which biodiversity and habitats should be monitored to support management needs;
- The existing parameters and indicators of existing monitoring programs and identify gaps as the basis for more comprehensive monitoring; and
- What spatial and temporal parameters distinguish sub-populations of species or differentiate habitats in the NWHI.

There are also specific research issues that have been identified as important for monitoring biodiversity and habitats, including the need to:

- Determine the priority species for monitoring in relation to anticipated short-term impacts, including from management actions, and long-term change;
- Document ‘hot spots’ of adult population abundance;
- Determine the movement of key species into the NWHI and within the NWHI;
- Assess priority species populations as a basis for monitoring and developing recovery models and projections of future population levels;
- Undertake life history studies for all priority species to provide information on essential habitat requirements (reproduction, recruitment and feeding) for all life stages;
- Determine essential habitat and ecological requirements of protected species to minimize anthropogenic threats and the effect of catastrophic events;
- Determine which likely effects of climate change on protected species are priorities for monitoring, e.g., the effect of sea level rise on nesting site of the green sea turtle and Hawaiian monk seal; and
- Evaluate exiting and potential diseases affecting priority species and habitats of the NHWI and develop appropriate methods to monitor the presence and impact of these on terrestrial and marine biodiversity.

APPENDIX

Distribution of corals and anemones reported in the NWHI during 1907-2006 compiled by Maragos from Dana (1846), Vaughan (1907), Dana (1971), Maragos et al. (2004), and the unpublished records of G. Aeby, J. Asher, J. Kenyon, J. Maragos, B. Vargas and B. Zgliczynski. Endemics in bold and asterisks (*) indicate undescribed species.

STONY CORALS	NIH	NEC	FFS	GAR	MAR	LAY	LIS	PHR	MID	KUR	N
*Coral unid., seen first by J. Starmer, sp.18			x								**1**
Acropora cerealis			x	x	x						**3**
A. cytherea		x		x	x	x		x			**5**
A. gemmifera			x	x							**2**
A. humilis			x	x	x						**3**
A. nasuta			x		x	x					**3**
A. paniculata			x								**1**
***A. sp.1 (prostrate)**			x				x				**2**
A. sp.28 cf. *retusa			x								**1**
A. valida			x		x	x	x	x			**5**
***A. sp.29 (table)**			x								**1**
A. sp.30 cf. *palmerae			x								**1**
A. sp. 20 (neoplasia/tumor?)			x								**1**
A. sp.26 cf. *loripes*			x								**1**
Montipora capitata	x	x	x	x	x	x	x	x	x	x	**11**
M. flabellata		x	x	x	x	x	x	x	x	x	**9**
M. patula	x	x	x	x	x	x	x	x	x	x	**10**
M.* sp.4 cf. *incrassata		x	x		x					x	**4**
M. dilatata						x	x				**2**
M.* sp.6 cf. *dilatata					x						**1**
***M.* sp.7 (foliaceous)**			x				x	x	x		**4**
***M.* sp.2 (ridges)**								x		x	**2**
***M.* sp.5 (branching)**							x				**1**
***M.* sp.14 (nodular) first** seen by B. Vargas								x			**1**
M. tuberculosa			x		x	x	x	x	x	x	**7**
***M.* sp.24 (irregular)**			x								**1**
M.* sp.3 cf. *turgescens					x	x	x	x	x	x	**6**
M. verrilli			x		x	x	x	x	x	x	**7**
Gardineroseris planulata									x		**1**
Leptoseris hawaiiensis			x			x					**2**
L. incrustans			x					x	x	x	**4**
L. sp.22 cf. incrustans			x								**1**
L. mycetoseroides			x								**1**
***L.* cf. *papyracea* sp19**			x								**1**
***L.* cf. *scabra* sp17**			x				x				**2**
Pavona clavus								x	x	x	**3**
P. duerdeni	x	x	x	x	x	x	x	x	x	x	**10**
P. maldivensis			x		x		x	x	x	x	**6**
P. varians	x	x	x	x	x	x	x	x	x	x	**10**
**Balanophyllia* sp. (pink)			x		x					x	**3**
Cladopsammia eguchii			x	x	x	x		x	x	x	**7**
Tubastraea coccinea	x		x	x	x	x		x	x	x	**9**
Cyphastrea ocellina	x	x	x	x	x	x	x	x	x	x	**10**
Leptastrea agassizi			x		x				x		**3**
L. bewickensis			x				x	x			**3**
L. purpurea	x	x	x	x	x	x		x	x	x	**9**
L. pruinosa		x	x	x	x						**4**
L. sp.8 cf. *F. hawaiiensis		x	x		x		x			x	**5**
**Cycloseris tenuis*			x	x			x	x			**4**
**C. vaughani*			x				x	x	x		**4**
Diaseris distorta			x				x				**2**

Continued from previous page, distribution of corals and anemones reported in the NWHI during 1907-2006 compiled by Maragos from Dana (1846), Vaughan (1907), Dana (1971), Maragos et al. (2004), and the unpublished records of G. Aeby, J. Asher, J. Kenyon, J. Maragos, B. Vargas and B. Zgliczynski. Endemics in bold and asterisks (*) indicate undescribed species.

STONY CORALS	NIH	NEC	FFS	GAR	MAR	LAY	LIS	PHR	MID	KUR	N
Fungia scutaria	x		x	x	x	x	x	x	x	x	**9**
F. granulose					x	x		x			**3**
Pocillopora damicornis			x		x	x	x	x	x	x	**8**
P. eydouxi	x	x	x	x	x	x	x	x	x		**9**
P.* sp.10 cf. *laysanensis			x			x				x	**4**
P. ligulata	x	x	x	x	x	x	x	x	x	x	**11**
P. meandrina	x	x	x	x	x	x	x	x	x	x	**10**
P. molokensis	x		x	x	x	x	x	x		x	**9**
P.* sp.32 cf. *verrucosa			x				x	x			**3**
P. sp.33 cf. *zelli*			x								**1**
**P.* sp.11 cf. *capitata*			x		x	x	x	x	x	x	**8**
Porites* sp.12 cf. *annae							x	x		x	**3**
***P.* sp. 15 (paliform lobes)**			x								**1**
Porites brighami	x	x	x	x	x	x	x	x		x	**9**
P. compressa	x	x	x	x	x	x	x	x	x	x	**11**
***P.* sp.23 (arthritic fingers)**			x								**1**
P. duerdeni		x	x	x	x			x		x	**6**
P. evermanni	x	x	x	x	x	x	x	x	x	x	**10**
P. hawaiiensis		x	x		x	x	x	x	x	x	**8**
P. lobata	x	x	x	x	x	x	x	x	x	x	**10**
P.* sp. 21 cf. *lobata			x								**1**
P.* sp.16 cf. *lutea			x								**1**
P. rus					x						**1**
***P.* sp.27 (columns)**			x								**1**
P.* sp.13 cf. *solida			x	x		x		x	x	x	**6**
Psammocora explanulata				x							**1**
P. nierstraszi		x	x	x	x	x	x	x	x		**8**
P. stellata	x		x	x	x	x	x	x	x	x	**10**
P. verrilli								x	x	x	**3**
Total	**17**	**21**	**66**	**29**	**41**	**34**	**37**	**43**	**33**	**36**	
Endemic	**4**	**8**	**27**	**7**	**12**	**11**	**15**	**14**	**8**	**15**	**Mean**
Percent endemic	**23.5**	**38.1**	**40.9**	**24.1**	**29.3**	**32.3**	**40.5**	**32.6**	**24.2**	**41.7**	**32.8**

Non-stony corals and anemones.

Non-Stony Corals & Anemones	NIH	MMM	FFS	GAR	MAR	LAY	LIS	PHR	MID	KUR
Palythoa tuberculosa	x	x	x	x	x	x	x	x	x	x
P. sp.			x							
Zoanthus pacificus			x		x			x		x
Zoanthus sp (Kure)										x
Zoanthus sp ("B")	x	x	x		x		x			
**Sinularia* sp (yellow)	x	x	x	x			x			
**Sinularia* (purple)				x						x
**Sinularia* (brown)			x							
**Sinularia* (pink)								x		
Acabaria bicolor			x							x
Cirrhipathes sp	x		x							
Heteractis malu			x	x	x	x				x
Total Species Per Island	**4**	**3**	**9**	**4**	**4**	**2**	**3**	**3**	**1**	**6**

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PERSONAL COMMUNICATIONS

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