AN ASSESSMENT OF THE CONDITION OF CORAL REEFS OFF THE FORMER NAVY BOMBING RANGES AT ISLA DE CULEBRA AND ISLA DE VIEQUES, PUERTO RICO

FINAL REPORT

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EXECUTIVE SUMMARY

The impact of military exercises at insular bombing ranges on adjacent coral reefs has not been convincingly established. Some investigators imply widespread and catastrophic damage to reef organisms from errant ordnance, while others suggest that military zones create a *de facto* sanctuary from deleterious human activities such as coastal development, deforestation, and overfishing. This study documents the condition of fringing coral reefs in military and non-military areas, using the Puerto Rican islands of Culebra and Vieques as models.

Historical records of military training and civilian use were reviewed in order to designate study sites as one of three types: civilian, military target, and military non-target. A total of 18 study sites were evaluated for biotic and environmental parameters. Proxy indicators of reef condition included percent coral cover, coral species richness, juvenile coral abundance, topographic complexity, fish species richness, fish abundance, herbivorous fish abundance, echinoid abundance, macroalgae cover, turf algae cover, incidence of coral diseases, and incidence of coral bleaching. To examine the relative condition of fringing reefs at Culebra and Vieques, we combined a Bray-Curtis distance measure with an Unweighted Pair Group Method with Arithmetic Averages (UPGMA) linkage method to perform a cluster analysis of the proxy indicators and to generate associated dendrograms (Sneath and Sokal 1973; McCune and Mefford 1999).

The UPMGA analyses produced clusters deviating from *a priori* expectations (i.e., that site types would cluster together). Resulting dendrograms showed that sites cluster roughly by island (i.e., Culebra sites are more similar to each other than to Vieques sites) and that the sites with the lowest reef condition score were the Vieques military target sites. Overall, the Culebra sites we surveyed appeared to be in better condition than the Vieques fringing reefs when considering the sum of the proxy indicators of reef condition. Yet, the Culebra sites contained more incidences of coral maladies (coral diseases, bleaching, and fish predation) than the Vieques sites. The UPMGA analyses on similarity matrices consisting of proxy indicators of reef condition suggest that the reefs of Culebra and Vieques are different types of reefs or reef environments. Turbidity was the only environmental parameter that was consistently higher at Vieques during the course of our survey. More turbidity data from Vieques and Culebra would be needed to verify that Vieques fringing reefs are consistently bathed by water that is naturally more turbid than at Culebra. Although reefs can function under turbid conditions, turbidity negatively affects their level of development (e.g., Kleypas 1996). Sedimentation rates on Vieques nearshore reefs (fringing and crest) are significantly greater than in deeper reefs (18 meters (m) [59 feet (ft)] water depth) (DON 2003b). Further, sedimentation rates on nearshore reefs at Vieques do not differ between the live impact area (LIA) and the Eastern Maneuver Area (EMA), and do not differ between the north and south sides of the island (DON 2003b). One possible explanation for the differences in turbidity levels we observed between Culebra and Vieques may be due to differences in nearshore circulation (tidal currents) as it affects fine sediment resuspension.

This study shows that despite decades of military training exercises on Vieques and Culebra, the condition of fringing reefs around the military portions of these islands appears to be similar to civilian sectors. Negative impacts from military exercises, especially live-fire exercises, have probably been concentrated in areas adjacent to bombing targets of the LIA (e.g., Bahia Salina del Sur, Vieques). Because the areal extent of the former military lands greatly exceeded the area of the LIAs, much more shoreline and adjacent reefs and seagrass meadows were probably spared and protected than were impacted. Although not expressly forbidden in waters adjacent to military lands, deleterious human activities (e.g., fishing, diving, and anchoring) may have been diluted or excluded by the presence of the military and the schedule of military exercises. Also, the existence of the military base necessarily precluded civilian coastal development on military lands. On other islands in the Caribbean (e.g., mainland Puerto Rico), extensive coastal development (e.g., commercial, residential, and recreational) has triggered a cascade of environmental degradation and ecological disasters (Gardner et al. 2003).

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ACRONYMS AND ABBREVIATIONS

°C	Degrees Celsius
°F	Degrees Fahrenheit
ac	Acre(s)
AFWTF	Atlantic Fleet Weapons Training Facility
ASP	Aspergillosis
ATG	Air-to-ground
ATSDR	Agency for Toxic Substances and Disease Registry
BBD	Black-band Disease
C	Civilian
CFR	Code of Federal Regulations
cm	Centimeter
cm/s	Centimeters per Second
Culebra	Isla de Culebra
DGPS	Differential Global Positioning System
DNER	Department of Natural and Environmental Resources
DSD	Dark-spots Disease
EFH	Essential Fish Habitat
EMA	Eastern Maneuver Area
ENE	East-Northeast
EOD	Explosive Ordnance Disposal
ft	Feet
GMI	Geo-Marine, Inc.
GPS	Global Positioning System
ha	Hectare(s)
in	Inch(es)
in/s	Inches per Second
kg	Kilogram(s)
km	Kilometer(s)
km^2	Square Kilometer(s)
kt	Knots
lb(s)	Pound(s)
LIA	Live Impact Area
LPI	Linear Point Intercept
m	Meter(s)
mi	Mile(s)
mm	Millimeter(s)
MPA	Marine Protected Area
MSL	Mean Sea Level
MyaBP	Millions of Years Before Present
Navy	U.S. Navy
NASD	Naval Ammunition Support Detachment
NSFS	Naval Surface Fire Support
ppt	Parts per Thousand
PR	Puerto Rico
PRVI	Puerto Rico Virgin Islands
PVC	Polyvinyl Chloride
RBD	Red-band Disease
SACEX	Supporting Arms Coordination Exercise
SAV	Submerged Aquatic Vegetation
SD	Standard Deviation
UPGMA	Unweighted Pair Group Method with Arithmetic Averages
U.S.	United States
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service

ACRONYMS AND ABBREVIATIONS
(Continued)

Vieques	Isla de Vieques
WBD	White-band Disease
WP	White Plague
yd	Yard(s)

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1.0 INTRODUCTION

1.1 ENVIRONMENTAL SETTING–CULEBRA AND VIEQUES

Isla de Culebra (Culebra) and Isla de Vieques (Vieques) are located in the Caribbean Sea (**Figure 1**). Culebra is 32 kilometers (km) (20 miles [mi]) east of mainland Puerto Rico. Culebra and its 20 cays have a total land area of approximately 29.5 square kilometers (km^2) (7,300 acres [ac]). From east to west, Culebra measures roughly 10.5 km (6.5 mi) and from north to south, it measures 8.5 km (5.3 mi). Vieques is located approximately 11 km (6.9 mi) southeast of mainland Puerto Rico. Vieques covers a 133.5 km^2 (33,000 ac) area, and is approximately 35 km (21.7mi) long (east to west) and 7.2 km (4.5 mi) wide (north to south). Hence, Vieques is 3.3 times longer (east to west) than Culebra and covers 4.5 times more land area. Culebra and Vieques are separated by the "Sonda de Vieques" which is approximately 26 meters (m) (84 feet [ft]) deep. Within 4.8 km (3 mi) from the shoreline, water depths at Culebra range from 1 to 53 m (3 to 174 ft), and at Vieques they range from 1 to 800 m (3 to 2,556 ft) (Waterproof Chart Inc. 1998).

1.1.1 Physical Setting

Vieques and Culebra are emergent parts of the southern edge of the Hispaniola-Puerto Rico microplate, bounded by deep trenches to the north and south (Puerto Rico Trench and Muertos Trench, respectively) (van Gestel et al. 1999). Rock outcroppings of Culebra and Vieques upon which reefs formed are continuous of those found on the main island of Puerto Rico. Three tectonic phases shaped Culebra and Vieques. From the Cretaceous to the Eocene (135 to 38 million years before present [MyaBP]), a forearc basin was formed on the Puerto Rico Trench side and then filled in. At that time, the Greater Antilles Arc was still intact and formed a subduction zone. During the second phase (middle Oligocene to early Pliocene, 30 to 5 MyaBP), the Puerto Rico Virgin Islands (PRVI) platform was formed and a carbonate sedimentary structure covered much of the platform. Finally, during the third phase (Pliocene to Holocene, 5 MyaBP to the last 11,000 years), the PRVI platform was tilted and Puerto Rico (including Culebra and Vieques) was uplifted, which led to the erosion of the carbonate cover and outcropping of the arc basement (van Gestel et al. 1999). The general geological profile for Vieques (and probably also for Culebra) is granitic volcanic rock (Late Cretaceous-aged andesite) and marine sedimentary rocks overlain by alluvial sediments (DON 2001).

Culebra and its surrounding cays all have sandy beaches, a rugged coastline, and gentle to steep hills (USACE 1995). Culebra also has lagoons, coastal wetlands, steep mountains (90% of the island is mountainous; the highest point is Mt. Resaca, 192 meters (m) [630 feet (ft)] above mean sea level [MSL]), and narrow valleys. Vegetation on undeveloped parts of Culebra and on the larger cays is moderate to extremely dense (USACE 1995). The topography of Vieques can be characterized as a series of rolling hills and peaks, with narrow, low-lying costal zones (DON 2001). The hills of the eastern end of the island are more rugged and angular in appearance, and have more exposed rock surfaces than hills of the central and western parts of the island. The largest low-lying coastal areas include the northwestern corner of the island and the area near the eastern end of Vieques (north of Bahia del Sur). The highest peak, Monte Pirata (299 m [984 ft] above MSL) is located at the western end of the island. In the undeveloped coastal areas of Vieques there are mangrove swamps, lagoons, coconut plain flats, and salt-sand flats. There are also bioluminescent bays, evergreen scrub, upland forest, and lowland forest. Thorn scrub communities are common on Vieques and are interspersed with forested ravines (quebradas) and other upland forest types (DON 2001).

1.1.2 Climate

Culebra and Vieques have a tropical marine climate. August is the warmest month (27.8 degrees Celsius [°C]; 82 degrees Fahrenheit [°F]) and February the coldest month (23.9°C; 75°F) (NLMOC 2000). As with the rest of the Caribbean, the dominant climate force in Culebra and Vieques is the warm, moist northeast trade winds. Because of the trade winds, the wind direction is almost always out of the east or east-northeast (ENE) year-round. From November through January, winds out of the ENE average 7 to 9 knots (kt), with gusts reaching 40 to 47 kt. From February to October, winds out of the east average 6 to 8

Figure 1. Location of Isla de Culebra and Isla de Vieques, Puerto Rico.

kt, with gusts ranging 35 to 76 kt. A typical daily weather pattern in Puerto Rico may include scattered showers, heavy at times, but passing. The showers usually occur in the morning or late afternoon. The showers are strongest in the mountains. Culebra and Vieques do not have the elevation of mainland Puerto Rico and consequently do not have the dramatic gradient of elevation versus rainfall. There are two weather patterns that produce significant amounts of rainfall. From May through November, the "easterly waves" will blow every five to seven days accompanied by increasing thunderstorm activity. From November through April, cold fronts occur every seven to ten days, resulting in one to two days of showers and overcast skies (NLMOC 2000).

Rainfall varies on a monthly basis. At Culebra and Vieques, the driest months are usually January through April. The lowest amount of rainfall occurs in February, averaging about 6.4 centimeters (cm) (2.5 inches [in]). Thereafter, amounts of monthly rainfall increase to peak in October with about 19.1 cm (7.5 in). May, with an average rainfall of 19.1 cm (7.5 in), is the exception to this gradual increase in rainfall. The mean annual rainfall on Vieques is 115 cm (45.3 in) (DON 1996) and 91 cm (36 in) on Culebra (USACE 1995). The eastern end of Vieques receives on average 64 cm (25 in) of rainfall per year, and the western end 125 cm (49 in) per year (DON 1996).

Hurricane season is June through November, and the most active months are August through October. From 1946 through 1999, 39 cyclones passed close to Naval Station Roosevelt Roads. Eleven of the cyclones occurred in August, and 19 in September (NLMOC 2000). From 1996 to 1999, nine tropical storms affected Puerto Rico (NLMOC 2000). These tropical storms invariably moved close to Culebra and Vieques. Severe hurricanes occur every 10 to 20 years (Rodriguez et al. 1994; NLMOC 2000). From 1886 to 2002, many hurricanes and tropical storms hit Vieques and Culebra. The average recurrence period for hurricanes is just over six years, while for hurricanes and/or tropical storms it is just under six years. The range of recurrence for two consecutive hurricanes or two consecutive hurricanes and/or tropical storms was one to 33 years. A lull in storm disturbance occurred from 1956 through 1989.

Two hurricanes in 1916, hurricanes David and Frederic in 1979, and Hurricane Hugo in 1989 were violent hurricanes that severely impacted coral reefs of Vieques and Culebra. Hurricanes David and Frederic broke and caused the mortality of *Acropora palmata* stands along the south side of Vieques (Raymond and Dodge 1980). From records of nearby islands, Hurricane Hugo, with wind gusts of up to 104 kt (NLMOC 2000), must have caused tremendous damage on the south side of the Vieques since the eye of the hurricane passed over the eastern half of Vieques (Rodriguez et al. 1994). Then, in 1999, Hurricane Lenny must also have impacted the eastern end of Vieques. Since the late 1970s, some of the recent changes in the shallow-water coral communities of Vieques and Culebra were probably related to the hurricane and/or tropical storm disturbances. One significant change in the composition of coral populations at Vieques since the 1970s is the abrupt decline in the abundance of *A. palmata*. Recently observed rubble and rubble ridges of *A. palmata* skeletons at Vieques were typical of hurricane disturbance (Blanchon and Jones 1997; Riegl 2001).

1.1.3 Hydrography

Sea surface transport (surface and down to 15 m [49 ft] water depth) around Culebra and Vieques is driven mainly by the prevailing trade winds (east and ENE) (NLMOC 2000). Diurnal tidal currents secondarily modify wind-driven currents. Prevailing surface currents at the eastern end of Vieques flow east to west at approximately 10 centimeters per second (cm/s) (3.9 inches per second [in/s])along the north and south coastlines. Flood tidal surface currents (26 to 67 cm/s, 10 to 26 in/s) intensify the flow to the west along the north coast. Ebb tidal surface currents (26 to 62 cm/s, 10 to 24 in/s)) intensify the flow to the northwest along the southwest coast. There are strong southwest currents and riptides along the northwest corner of Vieques. The tidal range in Culebra and Vieques is 12 to 40 cm (4.7 to 15.7 in) (NLMOC 2000).

Wave heights in the Pasaje de Vieques (Vieques Passage/Channel) between Vieques and mainland Puerto Rico vary slightly by season (NLMOC 2000). From January through September, wave heights are 1.2 to 1.5 m (4 to 5 ft), while from October through December wave heights are 0.9 to 1.2 m (3 to 4 ft). From January through March, 10 to 20% of the waves were greater than 2.4 m (8 ft) in height, while from

April through December 10% of the waves were above 2.4 m (8 ft) in height. Throughout the year, less than 5% of waves in the Vieques Passage/Channel were higher than 3.7 m (12 ft) (NLMOC 2000).

As with air temperature, sea surface temperature at Culebra and Vieques varies slightly by season (NLMOC 2000). The coldest water sea surface temperature is usually measured from December through February and ranges from 25.5 to 26.7°C (78 to 80°F). The warmest water temperature (June through September) ranges from 27.8 to 28.9°C (82 to 84°F) (NLMOC 2000).

1.2 MOTIVATION FOR THIS STUDY

This study was designed to document the condition of coral reefs in military and non-military areas, using Culebra and Vieques as models. Can differences between reefs be detected? Can generalizations be made about the types of reefs that differ from one another? Do military activities confer additional protection to natural resources, or do they contribute to the environmental degradation of the resources? Given the sociological and environmental impacts of military activities, it is important to objectively document these impacts. Scientific evidence can then be used by natural resource managers to provide better stewardship of the environment, by politicians for informed policy decisions, and by the general public to better understand the facts of the issues.

1.3 HISTORY OF MILITARY TRAINING AT CULEBRA AND VIEQUES

The history of military training operations at Culebra and Vieques was examined (DOD 1972, 2001; Langhorne 1987; USACE 1995; DON 2001, 2002). This information was used to better understand the nature and geographical extent of military activities, as well as to select appropriate study site locations.

1.3.1 Culebra

From 1901 through 1975, United States (U.S.) and foreign military forces used Culebra for pre-deployment training and preparation (combat readiness). Included in the training area were portions of Culebra Island, surrounding cays and waters, and the former Naval Defense Sea Area (delimited from the high water mark to three miles offshore) (**Figure 2**). The U.S. Navy (Navy) officially had title to 2,660 acres on Culebra, including 1,980 ac (803 hectares [ha]) on Culebra Island, 266 ac (108 ha) on Culebrita, 343 ac (139 ha) on Cayo Luis Peña, 7 ac (2.8 ha) on Cayo del Agua, and 64 ac (26 ha) on other cays (USACE 1995). Culebra was part of the Atlantic Fleet Weapons Ranges system, including an "Inner Range" target complex for shore bombardment, air to ground bombing, strafing, and rocket and missile firing, and an "Outer Range" for fleet exercises including mine laying, missile firing, and occasional shore bombardment and strafing (DOD 1972). As military training requirements increased in the 1950s and 1960s, the eastern end of Vieques was made part of the Inner Range. Airspace was restricted above Culebra and the Naval Defense Sea Area up to an elevation of 15,152 m (50,000 ft) when military aircraft exercises were taking place. There also was a Danger Area and Warning Area that overlapped and extended beyond the 4.8 km (3 mi) boundary of the Naval Defense Sea Area.

The military presence on Culebra began in 1901 with the establishment of a military base camp near Dewey (then San Idelfonso). From 1903 through 1943, extensive amphibious landings, ground maneuver training, and large fleet exercises took place at Culebra (**Figure 3A**). Large fleet exercises included one that took place from December 1923 through February 1924 when a huge fleet was at anchor west of Culebra and 3,300 Marines of the 5th Marine Regiment participated in amphibious training. The last amphibious exercise at Culebra took place in February 1941 (1st Marine Brigade, Army 1st Infantry Division, Marine air support, and naval gunfire). Primary landing areas were on Culebrita, Cayo Norte, and Cayo Luis Peña. Aerial strafing, bombing, and naval gunnery training on Culebra began in 1936 and ended on 30 September 1975. The Flamenco Peninsula, Los Gemelos, and Alcarraza were prominent aircraft bombing targets until the early 1960s. The Flamenco Peninsula was a main target area for Naval gunfire support training, with white painted tanks, trucks, drums, rocks, and panels placed as targets (**Figure 3B**; USACE 1995). War reserve ordnance was stocked on the island during military training.

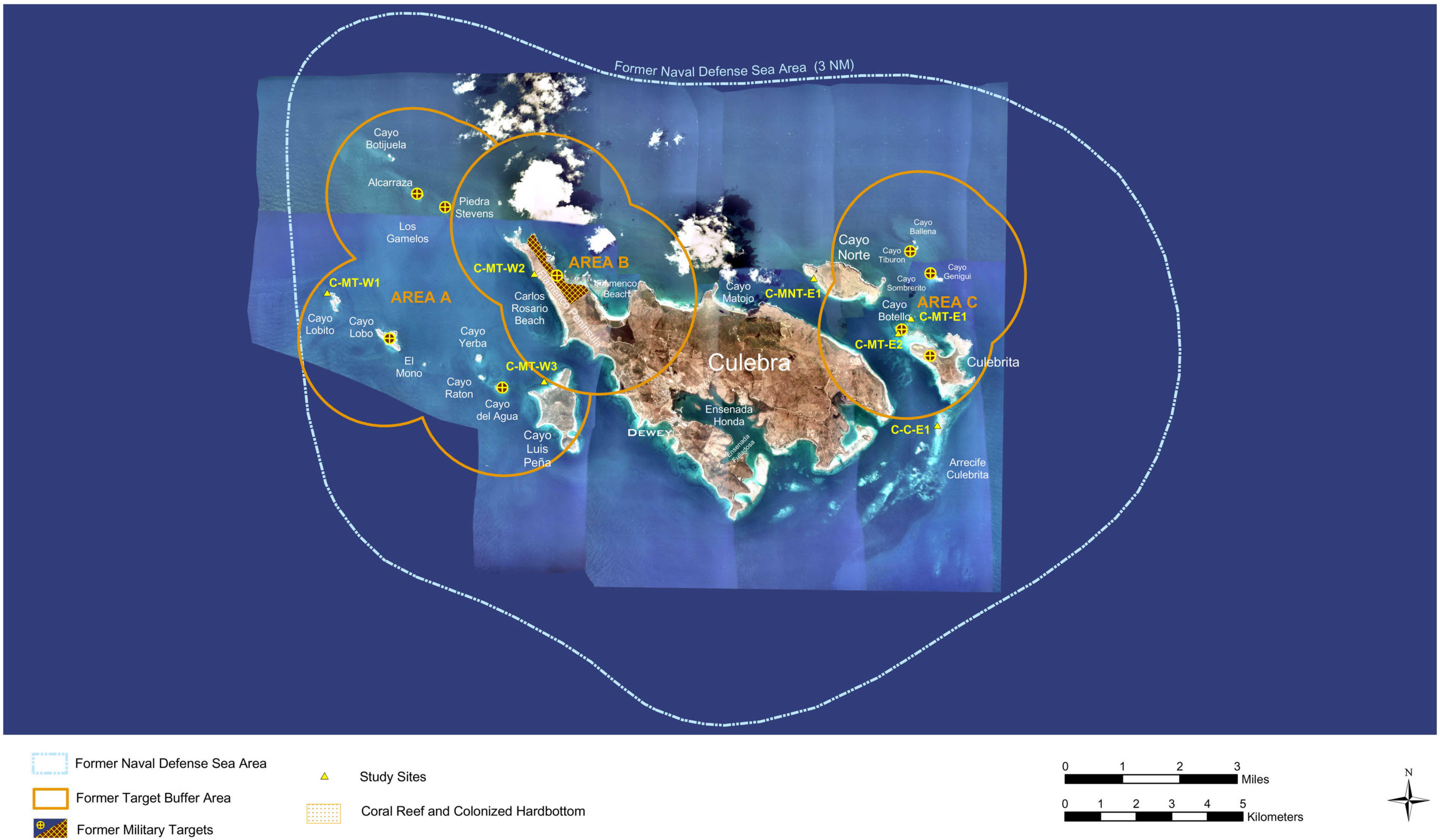

Figure 2. Isla de Culebra and cays showing the former Naval Defense Sea Area, bombing targets in the Culebra Inner Range, and locations of the study sites.

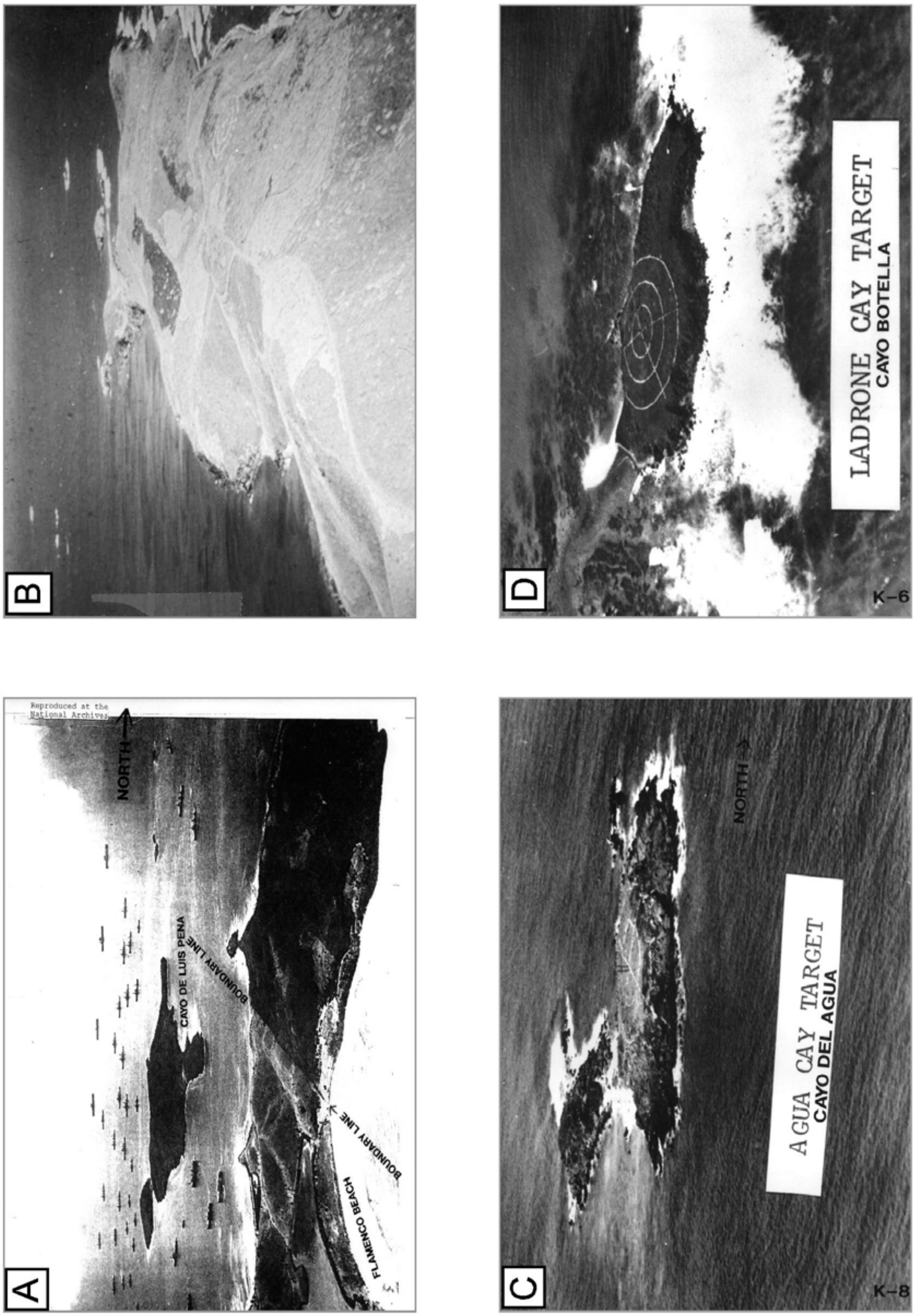

Figure 3. (A) U.S. Fleet at anchor near Cayo Luis Peña, March 1939 (from USACE 1995); (B) Bull's-eye target on northwest Peninsula of Flamenco (U.S. Army Engineering and Support Center, Huntsville, Alabama); (C) Bull's-eye target on Cayo del Agua circa 1971 (from USACE 1995); (D) Bull's-eye target on Cayo Botella circa 1968 (from USACE 1995).

With increased needs for military training during the Vietnam conflict, bombing target areas were expanded to include eastern and western cays of Culebra. The Flamenco Peninsula and Isla Culebrita were used as aircraft strafing targets. Aircraft bombing and rocket targets were placed on Alcarraza, Los Gemelos, Cayo del Agua, Cayo Tiburon, Cayos Geniqui, and Cayo Botella (**Figures 3C** and **3D**). Live ordnance was used primarily on Alcarraza, Cayo Tiburon, and Cayos Geniqui targets. From 1942 through 1968, a total of 320,000 units of aerial ordnance were fired at targets at Culebra (USACE 1995). In addition to ordnance shot from surface ships and aircraft, torpedoes were fired from submarines at coastal targets. For example, in November 1959, Submarine Squadron II fired fourteen live torpedoes at Cayos Geniqui from a range of 914 m (1,000 yards [yd]). Other submarines fired torpedoes at Marc Point (the northeast corner of Isla Culebrita). Torpedo firing ceased in 1969 (USACE 1995).

The peak of bombing practice at Culebra took place in 1969 during which various live and practice rockets and bombs (up to 907 kilograms [kg], 2,000 pounds [lbs]) were used. During that year, 207 ships fired at Flamenco Peninsula for a total of 973 daylight exercises (1,331 hours) and 177 night exercises (290 hours) (DOD 1972). Bombing, rocket fire, and strafing exercises on Flamenco Peninsula ended after 1969, a year in which an estimated 750,000 rounds of ordnance were shot at the peninsula (80% were 12.7 cm [5 in] rounds; 10% were 7.6 cm [3 in], 15.2 cm [6 in], and 20.3 cm [8 in] rounds; and 10% were mortar, howitzer, and 40.6 cm [16-in] rounds).

The Navy defined an area of impact on Culebra as “the zone around a target in which ordnance aimed at the target is likely to fall, except in the rare cases of gross error, plus an allowance for the distance to which explosive effects of live ordnance and scattering of debris from inert ordnance could extend from the point of impact.” Bombs and rockets had a 2.4 km (1.5 mi) radius impact area for inert ordnance and a 4.8 km (3 mi) radius impact area for live ordnance (DOD 1972). For live ordnance, the inner 2.4 km (1.5 mi) was the target area and the outer 2.4 km (1.5 mi) was the fragment distance. Records of ordnance misses from 1965 through 1969 include four cases of ship to shore bombing when ordnance (7.6 cm or 12.7 cm, 3 in or 5 in) aimed at Flamenco Peninsula hit Cayo Luis Peña or hit south of Cayo del Agua. Two other cases involve Marine aircraft that missed Culebrita and Cayo del Agua and hit instead eastern Culebra and Culebra Harbor, respectively (USACE 1995).

There were three main impact areas (i.e., target buffer areas) used for bombing practice in the Culebra Inner Range. These were known as Areas A, B, and C (**Figure 2**; USACE 1995):

- Area A included Isla Culebrita, Cayo Botella, Cayos Geniqui, Cayo Tiburon, Cayo Ballena, Cayo Sombrerito, and the eastern shore of Cayo Norte. Area A was used from 1960 through 1970 for aerial bombing and rockets, torpedo targets, and strafing.
- Area B included Cayo de Luis Peña, Cayo del Agua, Cayo Yerba, Cayo Raton, El Mono, Cayo Lobo, Cayo Lobito, Alcarraza, Los Gemelos, and Cayo Botijuela. Area B was used from 1935 through 1975 for aerial bombing and rockets, Naval gunnery, loft and over-the-shoulder bombing, and air to ground missiles.
- Area C included Flamenco Peninsula, Piedra Stevens, Carlos Rosario Beach, and Flamenco Beach. Area C was used from 1903 through 1975 for Naval gunnery, aerial bombing and rockets, and strafing.

There were 13 other military training areas: a mortar range (Area D); the airfield rifle and pistol range (Area E; 1913-1934); the southern peninsula rifle range (Area F); the lower camp (Areas G and H; 1905); Cayo Matojo located east of Punta Resaca (Area I); Navy gun positions – coastal defense artillery (Area J); “mining west” – mines dropped from aircraft in open water (Area K; 1967-1969); open water minefields, mine laying, and mine sweeping exercises (Area L); a shallow water area known as “confirmed water” located between Punta Tamarindo and Punta Melones, south of Playa Sardinas (Area M); “all other water” (Area N); “all other land” (Area O); and Flamenco Point (Area P) (USACE 1995).

Unexploded ordnance at or near the ground surface or exposed on the seafloor was periodically removed from Culebra target areas (DOD 1972). A systematic underwater cleanup of ordnance began in December 1970 (USACE 1995). Because the cleanup by demolition was destroying coral reef resources (corals and fishes), the cleanup was stopped by a court injunction. In 1976 and 1978, the Navy Explosive

Ordnance Disposal (EOD) disposed of unexploded ordnance collected at Flamenco Beach. In 1983, EOD recovered a MK27 torpedo east of Cayos Geniqui, two 227 kg (500 lb) bombs west of Cayos Geniqui, and one 227 kg (500 lb) bomb west of Cayo Ballena (USACE 1995). In 1985, the Puerto Rico Army National Guard cleared some of the unexploded ordnance on land (USACE 1995). The most recent clearing of unexploded ordnance on land took place in December 2002, when the U.S. Army Corps of Engineers (USACE) cleared 73 ac (30 ha) on Flamenco Peninsula (66 ac [27 ha] of the National Wildlife Refuge and 7 ac [3 ha] of the adjoining Puerto Rico Department of Natural and Environmental Resources [DNER] and U.S. Fish and Wildlife Service [USFWS] property) (Teresa Tallevast, personal communication).

All Navy property, except for an observation post on the northern end of Culebra (Flamenco Point OP), was transferred to local (private landowners, the municipality of Culebra, the Puerto Rico DNER) and federal (USFWS) owners from 1975 through 1982 (USACE 1995).

1.3.2 Vieques

During the 1940s, the Navy acquired approximately 25,000 ac (10,143 ha) of land on Vieques: 10,000 ac (4,057 ha) on the western end and 15,000 ac (6,086 ha) on the eastern end (**Figure 4**). The Navy, U.S. Marine Corps, the Puerto Rican Army National Guard, and allied forces used the facilities at Vieques for pre-deployment training and preparation (DOD 2001; DON 2001). Navy lands on the western end were used mainly for munitions storage as part of the Naval Ammunition Support Detachment (NASD). The eastern third of the island (except for the Punta Este Conservation Zone at the very eastern tip of Vieques) included the Eastern Maneuver Area (EMA; 11,000 ac, 4,463 ha) and the Atlantic Fleet Weapons Training Facility (AFWTF; 3,600 ac, 1,461 ha) (**Figure 4**). Within the AFWTF, the Live Impact Area (LIA) was where bombing took place as part of naval gunfire support and air-to-ground (ATG) ordnance training (from the 1940s until 1 May 2003). The EMA and the AFWTF together constituted the Vieques Inner Range. A buffer zone extended four nautical miles seaward of the Inner Range. This buffer zone included a “Danger Zone” on either side of the LIA and two minefield-training areas (**Figure 4**). During military training, all people other than military personnel were restricted from the Inner Range. A 16 km (10 mi) wide swath of Navy-owned lands separated the LIA from civilian areas (DOD 2001; DON 2001).

On Vieques, the EMA was where most of the amphibious operations training, all of the small arms training, and part of Special Operations amphibious training took place (DOD 2001; DON 2001; **Figure 5**). The remainder of the amphibious and special operations training took place within the LIA. Red Beach and Blue Beach on the south side of the EMA were the most frequently used sites for amphibious landings. Ordnance was fired from the EMA into the LIA during exercises such as the Supporting Arms Coordination Exercise (SACEX), a firing exercise conducted during the most advanced level of training, the Joint Task Force Exercise. The SACEX was designed to test communications and the combined firing of arms to support a Marine amphibious assault (DOD 2001; DON 2001). During the SACEX, training included high and low altitude air strikes using bombs and strafing rounds and the firing of ordnance from a ship. During the late 1960s, the Navy anchored the hulk of a WW II destroyer, the ex-USS Killen, in Bahia Salina del Sur as a target (DON 2003a; Naval Historical Center 2002; Haze Gray & Underway 2003) (**Figure 6**). The ex-USS Killen was sunk in Bahia Salina del Sur and ceased to be operational as a target in 1975 (Naval Historical Center 2002; Haze Gray & Underway 2003). Land targets in the LIA included six targets for NSFS training (on the south side of the LIA); 26 targets for ATG training – including two mock surface-to-air missile launching pads, a simulated military airstrip and fuel farm, an artillery target area, a mock railroad tunnel entrance, and a mock military convoy; and an ATG strafing target and bull’s-eye target (**Figure 6**) (DON 1996).

From 1983 through 1999, military forces conducted between 159 to 228 days of training per year at Vieques and used on average 1,862 tons of live ordnance per year. Starting in January 2000, military training exercises at Vieques were limited to 90 days per year and to the use of inert ordnance by the Presidential Directive, Isla Vieques. As part of normal operations and periodical LIA range refurbishment efforts, EOD conducted on-land clearing of unexploded ordnance (DOD 2001; DON 2001).

During each military exercise, some bombs missed their targets and landed in the water (water hits) or skipped off the ground into the water (skips) (DON 2002). Underwater surveys of ordnance at Vieques conducted prior to 1986 found that less than 1% of the reefs adjacent to the Inner Range contained ordnance (DON 1986). Yet, bombing did have adverse impacts on specific reef areas off the LIA including the fringing reef surrounding Roca Alcatraz at the entrance of Bahia Salina del Sur; a large patch reef in Bahia Salina del Sur; fringing reefs along the northern shoreline of Bahia Salina del Sur; and reefs off Bahia Icacos, Punta Icacos, Punta Gato, Punta Fosil, Isla Yalis, and Puerto Diabolo (DON 1980) (**Figure 6**).

Because coral reefs and submerged aquatic vegetation (SAV) are integral parts of Essential Fish Habitat (EFH) and Habitats of Particular Concern, we use the term “adverse impact” in the same manner as defined in the Magnuson-Stevens Fishery Conservation and Management Act: “any impact which reduces quality and/or quantity of [coral reef or seagrass resources]. Adverse effects may include direct (e.g., contamination or physical disruption), indirect (e.g., loss of prey, reduction in species’ fecundity), site-specific or habitat-wide impacts, including individual, cumulative, or synergistic consequences of actions” (50 Code of Federal Regulations [CFR] 600.910).

Skips from Naval Surface Fire Support (NSFS) rounds were more frequent than those of ATG rounds because ATG rounds hit the ground at greater angles. For example, in 2001, 303 NSFS rounds (12% of all NSFS rounds) were skips. Another 35 rounds (1.4% of all NSFS rounds) missed targets (misses) and landed in the water (DON 2002). In general, most of the in-water hits probably originated from ship gunnery. Records of in-water hits from 1989 through 1999 show that 85% were from ships, 14% were from aircraft, and 1% were from other sources (DON 2002). A plot of the locations of in-water ordnance hits (DOD 1999), skips, and misses (DON 2002) in the LIA, superimposed on a map of the coral reef and SAV habitats at Vieques (NOAA 2001), suggests two probable areas of impacts (i.e., “concentrated ordnance locations”): the eastern side of Bahia Salina del Sur between targets T3 and T6 (in-water ordnance hits) and a relatively large area off the north shore of the LIA between Punta Gato and Punta Salinas (**Figure 6**).

NSFS skips and water hits that entered areas populated by coral reefs or SAV probably caused adverse impacts such as scouring of SAV and crushing of corals (DON 2002). ATG rounds, although less likely to hit in-water or skip, probably had greater adverse impacts on coral reefs and SAV since ATG ordnance was larger and heavier (up to 907 kg [2,000 lbs]) and struck at greater angles. In particular, direct ATG hits and ensuing shock waves may have caused extensive scouring, shearing, breaking, fracturing, and crushing of reef substrates (Rogers et al. 1978; DON 2002). Fragmented reef substrate and rubble produced by ATG hits exacerbates subsequent abrasion and smothering of corals and SAV (Rogers et al. 1978). Furthermore, unexploded or inert ordnance that is not lodged in the seafloor can be a source of abrasion as the ordnance is rocked, shifted, or dragged through the reef or SAV by wave action and storm surge (Rogers et al. 1978). Examples of such “loose” ordnance were witnessed during the course of this study along the north shore of the LIA. We also observed reef substrate in the northern end of Bahia Salina del Sur entangled with the shroud lines and canopy of a parachute flare (possibly U.S. flare, air-craft, parachute MK 45 Mod 0) used for illumination during nighttime operations.

On 30 April 2001, the majority of Navy lands on the western end (8,100 ac, 3,286 ha) were transferred to the municipality of Vieques, the Puerto Rico Conservation Trust, and the USFWS Vieques National Wildlife Refuge (EPA 2004). On 1 May 2003, Navy lands on the eastern end of Vieques were transferred to the USFWS to also become part of the Vieques National Wildlife Refuge. These recently transferred lands to the USFWS constitute the largest national wildlife refuge in the Caribbean (EPA 2004).

2.0 METHODS

2.1 METHODOLOGICAL CONSIDERATIONS

Ecological field studies, especially in the marine environment, are confounded by at least the following three factors:

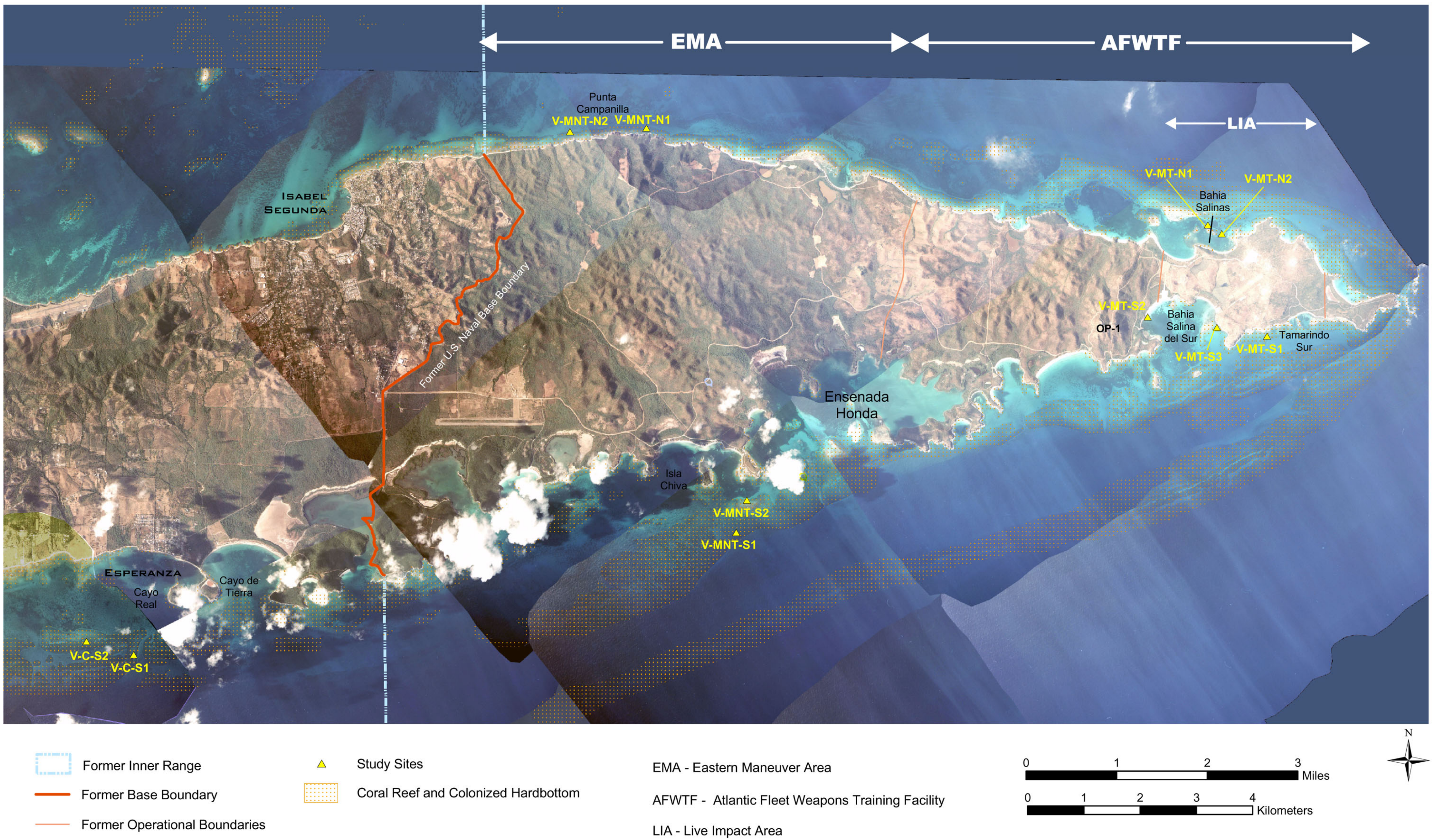

Figure 4. Former Navy lands on eastern Vieques including Eastern Maneuver Area (EMA), Atlantic Fleet Weapons Training Facility (AFWTF), and Live Impact Area (LIA).

Figure 5. Landing craft (LCM-8) returning to USS Shreveport (LPD-12) after landing troops on Vieques in March 1972. USS Grant County (LST-1174) is in the background.

1. Spatial considerations: When selecting sites for monitoring, some sites are considered ecologically equivalent and are lumped together as “replicate” sites (e.g., Gust et al. 2001). By having multiple replicate sites, it is felt that the theoretical and statistical rigor of the study is improved. Other sites, considered ecologically dissimilar, are selected for comparison purposes. For example, some sites might be considered “impacted” sites, while others might be denoted as “non-impacted” sites. In reality, such designations are arbitrary. However, because ecological field studies are not conducted under laboratory-controlled conditions (where all variables can be exactly manipulated or standardized), this arbitrariness is necessary, and best-judgment efforts must be made to select study sites that conform to the experimental design.

2. Temporal considerations: Many of the questions asked by field ecologists involve time frameworks on the order of decades, centuries, or even geological time. Typically, the first sampling event is defined as the “baseline,” which fails to take into account the environmental history of a site prior to the first observations. This methodological problem has been dubbed the “shifting baseline syndrome” (Pauly 1995; Sheppard 1995; Jackson 1997). The baseline conditions are often assumed to be the most natural conditions (especially in the context of subsequent impacts), but most places on earth have already experienced hundreds, if not thousands, of years of human impact. The ideal, but unrealistic, solution is to observe specific sites over long time scales, from pre-human contact through current time and into the future.

Therefore, contemporary sites must be selected which approximate the temporal sequence of interest.

3. Multi-variability: Coral reefs are extremely complex ecosystems. The physical structure of a given reef, along with the associated biodiversity, is subject to a tremendous number of variables, both natural and anthropogenic. No two reefs are the same. Before human contact, all reefs were heterogeneous. Natural factors that affect the physical structure, species diversity, and biomass of a reef include depth, salinity, turbidity, exposure to wave action, freshwater and sediment inputs, periodic storms, tectonic events, reproductive/ population cycles, diseases, predation, bioerosion, competition, and changes on a geological time scale (e.g., continental drift, subsidence of islands, climate change). The intermediate disturbance hypothesis suggests that the greatest biodiversity on a reef may be maintained by a moderate amount of disturbance (Connell 1978; Aronson and Precht 2001). Anthropogenic impacts to a reef include mechanical damage (e.g., from anchors, divers, and ship groundings), increased siltation (e.g., due to deforestation and coastal development), overfishing, pollution (e.g., oil, sewage, pesticides), accelerated climate change from human activities, and increased susceptibility to diseases and bleaching due to the other impacts. Each reef is affected by these variables to different degrees, such that it is extremely difficult to establish cause and effect scenarios when monitoring changes on a reef or when comparing two or more reefs. Research approaches are required that can isolate effects of particular activities from non-human sources of natural variation as well as background variation caused by other anthropogenic events (Osenberg and Schmitt 1996; Osenberg et al. 1996).

2.2 STUDY DESIGN

To formulate this study we posed the following question: “Are there presently any between-site differences in abundance and/or diversity in coral and fish populations in civilian and former-military reef sites of Vieques and Culebra?” This question led us to state the research hypothesis “the condition of reefs in the civilian sites is different from that at the military sites.” The following parameters were used as proxy indicators of reef “condition”: percent coral cover, coral species richness, juvenile coral abundance, topographic complexity, fish species richness, fish abundance, herbivorous fish abundance, echinoid abundance, macroalgae cover, turf algae cover, incidence of coral diseases, and incidence of coral bleaching (i.e., coral and fish parameters were emphasized). We tested the null hypothesis (H_O) “the condition of reefs at civilian sites is identical to that at military sites.”

From historical land use information for Vieques and Culebra we established three categories of study sites: civilian (C), military target (MT), and military non-target (MNT). Eighteen study sites were then assigned to appropriate locations. The prefixes “V” and “C” were used to designate Vieques and Culebra, respectively (e.g., V-C = Vieques civilian, C-MT = Culebra military target). Suffixes were used to designate replicate sites for each site category (e.g., C-MT-E2 = Culebra military target east 2, V-MNT-S1 = Vieques military non-target south 1). Civilian sites are those that have no history of military activity and are potentially subject to civilian impacts (e.g., fishing, diving, anchoring, impacts from coastal development). Military target sites are reefs adjacent to shoreline targets and in areas of known ordnance water hits and skips. Military non-target areas are those that were overseen by the military, but were not within live impact areas. At Vieques we selected two civilian sites, both on the south side of the island (V-C-S1, V-C-S2); four military non-target sites, two along the north shore (V-MNT-N1, V-MNT-N2) and two on the south shore (V-MNT-S1, V-MNT-S2); and five military target sites, two on the north side (V-MT-N1, V-MT-N2) and three on the south side (V-MT-S1, V-MT-S2, V-MT-S3) (**Figures 4** and **7**). At Culebra we chose one civilian site (C-C-E1); one military non-target site on the eastern side (C-MNT-E1), and five military target sites, two on the eastern side (C-MT-E1, C-MT-E2) and three on the western side (C-MT-W1, C-MT-W2, C-MT-W3) (**Figures 2** and **7**). Data from Garrison et al.’s (2000) site D (Dewey) was qualitatively useful as an additional civilian site (**Figure 2**). To facilitate comparisons (both intra- and inter-island) between the various reefs of Vieques and Culebra, fringing reefs were selected (whenever possible) as the standard study site habitat. Depths of study sites ranged between 2.9 and 12.8 m (9.6 and 42.2 ft), and average 5.9 m (19 ft) (±2.8 standard deviation [*SD*]).

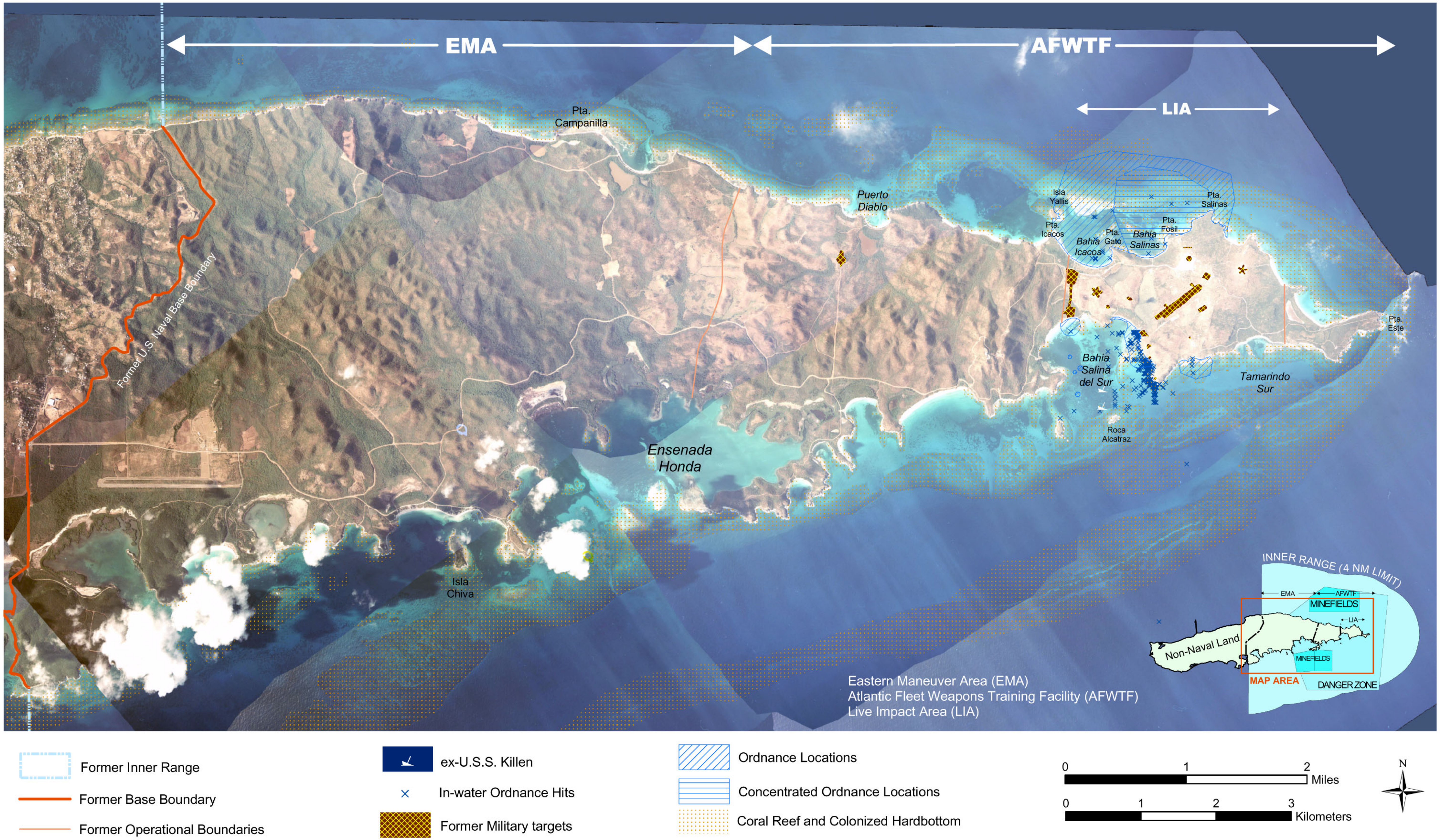

Figure 6. Eastern Vieques, showing locations of targets and areas of ordnance hits.

Figure 7. Orthophotographs of all 18 study sites around Culebra and Vieques (NOAA 2001).

Because of the complexity of natural ecosystems, it is extremely difficult to compare one study site with another (or, more specifically, to lump various sites that are deemed "ecologically similar"). To remove the arbitrary nature of such *a priori* decisions, all study sites were treated as independent samples and were compared with one another in pairwise analyses. Various conclusions were then made as to how certain sites were similar (or dissimilar) to one another in the context of "perceived site category" (i.e., target, military non-target, and civilian). Further statistical analyses were then carried out to detect the significance of potential differences between sites.

Fieldwork was conducted from 18 June through 28 June 2003. All study sites were reached by boat (the 7.9 m [26 ft] *GMI Explorer*). The study sites were examined by scuba divers employing typical scientific diving techniques (Heine 2001).

Navigation was facilitated by nautical charts, aerial photographs, a hand-held global positioning system (GPS) unit, local knowledge, and triangulation. Each study site was geo-referenced using a Trimble® ProXRS differential GPS (DGPS) unit (Trimble Navigation Ltd., Sunnyvale, CA) running Assess Surveyor 4.0. The OmniSTAR (Caribbean/South American Service) real-time DGPS correction service was used to ensure accuracies of +/- 1.0 m (3.3 ft) (OmniSTAR, Inc. 2003). The DGPS positioning data were downloaded using Pathfinder Office 2.70 and exported into ESRI ArcGIS 8.2 Geodatabase data layers.

Three sampling stations were established at each study site. Although the stations were not permanently marked, the DGPS positions obtained at each station were precise enough to allow the stations to be located on future visits. The stations were marked by buoys that were placed in a roughly linear array parallel to shore. Those study sites most distant from shore had buoys arranged more in a triangular array (**Figure 2**). The maximum width of the entire 3-buoy array ranged from 33.8 m (111.5 ft) (site VS3) to 120.3 m (397 ft) (VC2) (mean = 82 m [271 ft]). The number and location of stations within a study site were intended to account for variation when characterizing a given study site. Actual surveys usually took place within 20 m (66 ft)of each buoy. Therefore, the total sampled area for a given study site was potentially as much as 3,770 m^2 (40,580 ft^2) (i.e., three circular areas of 20 m [66 ft] radius each).

Surveys were conducted during late June when sea surface temperature in Puerto Rico averages 28.5°C (84°F) (i.e., is within 0.5°C [33°F] of the mean annual maximum of 29°C [84.2°F]; Winter et al. 1998). Algae growth rates are likely to be high in June due to the maximum day lengths and elevated insolation (NASA 2003; The Weather Underground, Inc. 2003). Such conditions are optimal for increased photosynthetic rates, uptake of nutrients, and algal growth (Valiela 1984). Therefore, we assumed that algal cover (macroalgae and algal turfs, sensu Steneck 1988) was probably high during our surveys and may have influenced coral cover estimates (Aronson et al. 1994).

The following parameters were the focus of our data collection efforts: hard corals (percent cover and diversity), topographic complexity, echinoids, and juvenile corals, coral maladies, reef fishes (abundance, diversity, and length), herbivore density, and water quality. These parameters were chosen for several reasons: 1. the taxa are from well-known groups and are readily recognizable (for the most part) to both field biologists and the general public; 2. the techniques used to assess these parameters are relatively low-tech, inexpensive, and non-labor-intensive; and 3. the data collected are readily comparable to those of other studies, in which similar techniques were employed to collect similar data. Sampling techniques were selected to be the most effort effective (i.e., rapid) while still accounting for the biodiversity of a study site. The rapidity of the assessment was important, but not at the cost of accurately characterizing a site. The biota of the study sites was assessed using the following techniques.

2.2.1 Benthic Surveys

Coral reef benthic surveys were conducted to compare the condition of reefs between study sites. The condition of a reef was determined using hard coral percent cover and diversity (Porter and Meier 1992; Aronson et al. 1994; Aronson et al. 2002), topographic complexity (Aronson et al. 1994), the abundance of juvenile corals (Edmunds and Carpenter 2001), the abundance of echinoids (Aronson et al. 1994; Edmunds and Carpenter 2001), and an assessment of diseased and dead corals (Porter and Meier 1992; Santavy et al. 2001; Bruckner 2002).

Hard Corals—Percent Cover and Diversity. The percent cover and diversity of hard corals (Scleractinia and Milleporina) and associated sessile organisms (octocorals, sponges, macroalgae, algal turfs, crustose coralline algae, zoanthids) were determined. Because of the short 11-day fieldwork period, the time-efficient Linear Point Intercept (LPI) transect method (Liddell and Ohlhorst 1987; Ohlhorst et al. 1988; Aronson and Precht 1995; Rogers et al. 1994) was used. Despite best efforts to select comparable fringing reef habitats for each study site, there was noticeable within- and between-site heterogeneity (both in live benthic coverage and topographic complexity).

Six LPI transects were conducted at each of the study sites (three sampling stations per study site; two LPI transects per sampling station). An LPI transect consisted of a 10 m (33 ft) long surveyor's fiberglass measuring tape (marked at 1 cm [0.4 in] intervals) loosely draped over the top surface of the reef. Each end of the tape was weighted down using a 0.45 kg [1 lb] lead ball. The replicate LPI transects were located haphazardly about the fringing reef immediately surrounding the sampling stations. A single observer recorded the identity of the sessile organism/substrate found immediately beneath every 20 cm (7.9 in) mark of the transect tape for a total of 50 observations per transect. The percent cover of a given organism/substrate (PC_i) in a transect was equal to the ratio of the sum of observations for that particular organism/substrate (OB_i) and the total number of observations per transect (50).

$$PC_i = \frac{OB_i}{50}$$

LPI sample size adequacy for each site was evaluated by examining the cumulative number of coral species recorded versus the number of transects ("see species richness (*S*) below"). Identification of species was focused on hard corals. Other taxa included octocorals (mostly gorgonians), sponges, algal turfs (mostly filamentous algae, less than 10 millimeters (mm) (0.4 in) in height; Steneck 1988), and macroalgae. When possible, macroalgae were identified to the genus level. Species were identified using Littler et al. (1989), Humann (1992, 1993), and Littler and Littler (2000).

Once the LPI survey was complete, the observer swam twice above the transect tape and listed all hard coral and echinoid species occurring within 1 m (3.3 ft) on side of and at the end of the LPI transect (i.e., 23 m^2 [248 ft^2] surveyed for each transect). Hard coral diversity was then estimated using both the incidence of hard coral species along LPI transects and the list of hard corals occurring immediately around the transect tape. Species diversity was expressed as both the Shannon-Wiener diversity index (*H*') and as species richness (*S*). Echinoid data were used in an analysis of herbivory.

The Shannon-Wiener diversity index (*H'*) is calculated as:

$$H' = -\sum_{i=1}^{k} p_i \log p_i$$

where k is the number of species present and p_i is the proportion (n_i/N) of the ith species. As recommended by Aronson et al. (1994), *H'* is based on coral cover and not on coral colony counts since coral colonies could not be consistently identified.

Species richness (*S*) was estimated as the asymptotic value of the species-area curve formed by the number of coral species against the number of LPI transects (e.g., Valiela 1984). Not only did *S* provide a measure of diversity, but also the calculation allowed us to validate the number of LPI replicates in our methodology.

Topographic Complexity. Topographic complexity (i.e., reef three-dimensionality) was examined as a measure of total disturbance (i.e., the sum of all natural and anthropogenic disturbances having affected the reef) (Aronson et al. 1994; Aronson and Precht 1995). A high level of topographic/structural complexity is indicative of a low level of disturbance, and vice versa. Coral growth and active cementing of the reef framework by crustose algae help maintain reef structure (Barnes and Chalker 1990).

Topographic complexity can be decreased by single destructive events (e.g., hurricanes) and/or recurring disturbances (e.g., mechanical damage, polluted runoff, and overfishing), particularly when exacerbated by bioerosion (Woodley et al. 1981; Rogers et al. 1982, 1991; Hutchings 1986; Bak 1987; Carpenter 1990). Also, increased macroalgae abundance can negatively affect reef structural integrity by decreasing colonization sites for crustose algae (Lewis 1986). Along each LPI transect, we carefully conformed a 5 m (16.5 ft) chain (17 mm [0.67] in links) to the surface of the reef. Topographic complexity was calculated as:

$$C = 1 - \frac{d}{l}$$

where *d* was the horizontal distance in meters covered by the chain on the reef, and *l* was the length of the chain (5 m, 16.5 ft). Maximal topographic complexity would be observed when *C* = 1, and a flat reef substrate would be represented by *C* = 0.

Juvenile Corals. Densities of juvenile corals were measured using a quadrat method (0.25 m^2 [2.7 ft^2] plot). The quadrat was made of 21 mm (0.83 in) diameter polyvinyl chloride (PVC) pipe covered in black electrical tape and weighted with two 1 lb weights. Quadrats were haphazardly placed in 15 locations at each station, for a total of 45 plots per study site. Each plot was both photographed and carefully examined (Edmunds et al. 1998). Juvenile corals (i.e., ≤5 mm [0.2 in] at greatest diameter) and echinoids (i.e., sea urchins) were counted and identified (Aronson et al. 2002). Adult corals (i.e., >5mm [0.2 in] diameter) were identified and the percent cover of all live corals was estimated for the plot. Identification of corals was based on Humann (2002). The echinoid data were used in an analysis of herbivory.

Coral Maladies. Incidences of coral diseases and other maladies (including fish bites and bleaching) that occurred within each of the juvenile coral quadrats were identified, counted, and photographed. Other diseased corals occurring between quadrats were also identified and photographed as encountered (Santavy et al. 2001; Bruckner 2002). No samples of coral tissue or disease mats were taken. Diseases were identified with the aid of laminated underwater photographic identification cards of coral syndromes (Bruckner and Bruckner 1999).

2.2.2 Reef Fish Censuses

Reef fishes were assessed using a stationary visual census technique (Bohnsack and Bannerot 1986) and a roving diver technique (Schmitt et al. 2002). Three stationary counts (one count per station) and one roving diver survey were conducted at each study site. For each stationary census, we recorded all fish species observed in five minutes within an imaginary cylinder with a radius of 7.5 m (25 ft) from the observer. Immediately following the initial five minutes, additional time was used to record abundance (number of individuals per species) and total length (cm) (minimum, maximum, and average) of the species observed during the first five minutes. A T-shaped device referred to as a “fish stick” was used as a size reference when estimating fish lengths. The fish stick consisted of a 30 cm (12 in) section of PVC tubing (1/2” gauge) attached perpendicularly to a 1 m (3.3 ft) long section of PVC tubing (1/2” gauge). Black electrical tape was used to mark the PVC tubing at 10 cm (4 in) intervals. During roving diver surveys, the diver recorded species and an abundance estimate during a swim-through of the study site. Fish abundance categories during roving diver surveys were single (one fish), few (2 to 10 fishes), many (11 to 100 fishes), and abundant (>100 fishes) (Schmitt et al. 2002). Species were identified using Humann (1994) and Humann and DeLoach (2002).

The species composition of reef fish assemblages was expressed as species richness, diversity, and evenness. Richness was represented by the average number of species per sampling station. Diversity was calculated using the Shannon-Wiener diversity index (*H*’):

$$H' = -\sum_{i=1}^{k} p_i \log p_i$$

where k is the number of species present and p_i is the proportion (n_i/N) of the ith species.

Evenness (J') was calculated as:

$$J' = \frac{H'}{H'_{\max}}$$

where H'_{max} = log k (Zar 1984). k is the maximum number of species observed per site.

2.2.3 Herbivore Abundance

Herbivores in Caribbean reef environments include parrotfishes (family Scaridae), surgeonfishes (Acanthuridae), certain damselfishes (Pomacentridae) and blennies (Blenniidae), certain sea urchins, some gastropods and chitons, amphipods, and polychaetes (Hatcher 1983; Lewis and Wainwright 1985; Steneck 1988; Choat 1991). There are potentially more than 60 species of herbivores on a Caribbean coral reef (Carpenter 1986). Parrotfishes, urchins, some gastropods, and chitons are "scraping" (i.e., deep grazing) herbivores and cause the greatest grazing impact on the abundance and distribution of benthic algae (Hatcher 1983; Steneck 1988). These herbivores feed on a wide range of algae and use specialized teeth or buccal musculatures to bite into the reef (Ogden and Lobel 1978; Steneck 1988). In large enough numbers, other herbivores, including surgeonfishes, damselfishes, blennies, and some gastropods, can denude a reef of fleshy algae (e.g., *Sargassum*, *Lobophora*, *Dictyota*, and *Halimeda*) and thus are called "denuding" herbivores (Hatcher 1983). Our study followed the AGRRA methodology (Kramer and Lang 2003) by including parrotfishes ("scrapers"), surgeonfishes ("browsers"), and the yellowtail damselfish (a pomacentrid "browser") in our analysis of herbivory. Quantifying herbivore density is necessary to assess the overall functioning of reefs (Lewis 1986). Indeed, the recent catastrophic decline of corals on Jamaican reefs clearly showed the vital importance of herbivorous fish and echinoids in preventing a shift to an algal phase (Hughes 1994). Furthermore, herbivores are essential in maintaining benthic species diversity and biomass (Lewis 1986).

Herbivore abundance was determined by combining results from our censuses of echinoids and fishes. The abundance of sea urchins was recorded within a one-meter distance of each of the six LPI transects per site (139 m^2/site [1,496 ft^2/site]) and within each of the 45 0.25 m^2 (2.7 ft^2) quadrats per site used to survey juvenile corals (11.25 m^2/site [121 ft^2/site]). LPI transects and juvenile coral quadrats were haphazardly located within the fringing reef habitat. Because these surveys were conducted during daylight hours, we probably underestimated the actual sea urchin populations since sea urchins are more active at night (e.g., Lewis 1986). The abundance and size of herbivorous fishes were extracted from our fish census data.

2.2.4 Water Quality

Water quality parameters were measured using a Hydrolab Datasonde 4a Multiprobe equipped with the Surveyor 4a waterproof display and Hydrolab Profiler software. The multiprobe was calibrated using required calibration standards and techniques. The sensor probe was suspended off the bow of the anchored research vessel at each study site. The boat was usually anchored just offshore of the central buoy in the three-buoy sampling station array. The probe was lowered close to but above the bottom. Selected parameters (i.e., temperature, specific conductivity, salinity, dissolved oxygen, pH, depth of the probe, and turbidity) were measured every 20 minutes during the roughly two hours spent at each study site. Each evening, data were downloaded from the Hydrolab handheld data logger to a laptop computer using Hyper Terminal serial cable connection software.

2.2.5 Statistical Analyses

Between-site comparisons were done on data of hard corals (percent cover, species diversity, species richness), topographic complexity, juvenile corals (abundance, number of genera), and echinoids (abundance) using a one-way, Model II ANOVA (single factor analysis of variance for a random effects model; Zar 1984). Differences between sites were further analyzed using the Tukey test (Zar 1984). To allow the valid application of parametric analyses of variance, data were transformed to make them normal, homoscedastic, and additive (Zar 1984; Aronson et al. 1994; Edmunds and Carpenter 2001). The coral percent cover and topographic complexity data were arcsine transformed, and the abundances of juvenile corals were logarithmically transformed (Zar 1984; Aronson et al. 1994). Species diversity (*H'*) data were not transformed because *H'* values were normally distributed (D'Agostino's test of departure from normality; Zar 1984).

Fish census data included species composition, abundance, mean length, and number of herbivore species. The fish abundance data were logarithmically transformed (for normality, homoscedasdicity, and additivity) to insure a valid application of parametric analyses of variance (Zar 1984; Schmitt et al. 1998, 2002) using the following transformation:

$$X' = \log_{10}\left(X + 1\right)$$

where *X* is the fish abundance (i.e., total fish count) (Zar 1984).

Abundance, richness, mean length, and number of herbivore species were compared between sites using the one-way, Model II ANOVA (single factor analysis of variance for a random effects model; Zar 1984). Differences between sites were further analyzed using the Tukey test (Zar 1984).

3.0 RESULTS

3.1 BENTHIC SURVEYS

3.1.1 Hard Corals and Associated Taxa – Percent Cover and Diversity

Linear Point Intercept transects—A total of 5,300 individual points were evaluated for taxonomic composition (50 points per transect, six transects per study site for 17 sites, four transects at site V-MT-S2). The resulting taxa were categorized into ten groups, eight of which comprised the "live cover" of the reef ("rock" and "sand" were the two non-living categories). The three greatest contributors to live cover were turf algae, macroalgae, and hard corals (**Table 1**).

Table 1. Mean percent cover of ten benthic categories at 18 study sites around Culebra and Vieques as determined from LPI transects.

Categories	Mean	SD	Minimum	Maximum
Hard Corals	11.5	8.0	2.3	27.7
Gorgonians	7.9	5.1	0.0	17.0
Zoanthids	0.9	1.7	0.0	5.7
Sponges	2.0	1.9	0.0	6.3
Echinoids	0.1	0.4	0.0	1.5
Turf Algae	41.1	11.1	22.0	57.3
Macroalgae	28.5	14.9	2.7	50.0
Crustose Algae	5.2	8.4	0.0	26.0
Rock	0.1	0.2	0.0	0.7
Sand	2.6	2.9	0.0	11.7

Each study site had a unique assemblage of sessile organisms (**Table 2** and **Figure 8**). The percent cover of hard corals varied between sites. Some groups of organisms (e.g., gorgonians, zoanthids, sponges, and crustose algae) were present at some sites and absent at others.

The percent cover of **hard corals** varied widely between some study sites, from a high of 27.7% at site C-C-E1, to a low of 2.3% at site V-MT-S3 (**Figure 9**). Some sites, despite their physical proximity to one another and their exposure to similar impacts, differed dramatically in their hard coral cover, illustrating the patchy nature of coral distribution. For example, sites V-MT-S3 and V-MT-S2, both located in Bahía

Table 2. Percent cover of sessile benthos at 18 study sites around Culebra (C) and Vieques (V) as determined from LPI transects (mean ± standard deviation, *n* = 300 points for each site, except *n* = 200 points for study site V-MT-S2).

Site	Hard Corals	Gorgonians	Zoanthids	Sponges	Turf Algae	Macroalgae	Crustose Algae	Total*
C-C-E1	27.7	8.0	0.0	0.0	51.7	5.7	0.0	93.0
SD	*±12.1*	*±11.4*			*±16.0*	*±5.3*		
C-MNT-E1	14.3	14.0	0.0	0.7	35.7	30.7	3.0	98.3
SD	*±8.3*	*±6.3*		*±1.0*	*±18.0*	*±13.9*	*±2.1*	
C-MT-E1	5.7	5.0	0.0	1.0	34.3	50.0	1.0	97.0
SD	*±3.7*	*±6.8*		*±1.1*	*±2.7*	*±8.6*	*±1.1*	
C-MT-E2	9.0	12.7	0.0	0.0	57.3	15.7	2.0	96.7
SD	*±10.3*	*±9.2*			*±14.6*	*±10.6*	*±4.0*	
C-MT-W1	10.3	14.0	1.7	6.3	45.3	2.7	19.0	99.3
SD	*±5.6*	*±2.5*	*±2.3*	*±4.3*	*±14.7*	*±2.1*	*±11.6*	
C-MT-W2	27.0	6.3	0.7	2.3	51.0	8.0	3.7	99.0
SD	*±6.3*	*±2.9*	*±1.6*	*±2.0*	*±9.0*	*±4.4*	*±2.7*	
C-MT-W3	12.0	7.7	0.0	5.0	33.3	39.0	0.0	97.0
SD	*±6.4*	*±4.6*		*±3.7*	*±10.9*	*±10.6*		
V-C-S1	4.0	5.7	0.0	4.0	55.7	26.7	0.3	96.3
SD	*±1.3*	*±1.5*		*±2.2*	*±7.9*	*±9.9*	*±0.8*	
V-C-S2	11.7	12.3	2.7	0.3	53.3	17.0	0.3	97.7
SD	*±8.2*	*±6.3*	*±3.9*	*±0.8*	*±19.0*	*±16.4*	*±0.8*	
V-MNT-N1	10.3	12.0	4.0	3.3	34.7	33.0	2.0	99.3
SD	*±6.0*	*±9.5*	*±3.3*	*±3.5*	*±15.7*	*±9.0*	*±1.3*	
V-MNT-N2	12.7	17.0	5.7	3.7	32.0	28.7	0.3	100.0
SD	*±5.5*	*±7.0*	*±2.9*	*±2.9*	*±9.1*	*±8.3*	*±0.8*	
V-MNT-S1	6.3	6.0	0.0	1.7	43.7	36.7	1.0	95.3
SD	*±3.7*	*±2.8*		*±1.5*	*±14.3*	*±14.7*	*±1.1*	
V-MNT-S2	18.3	12.3	2.0	0.0	49.0	16.0	0.0	97.7
SD	*±12.2*	*±8.3*	*±2.2*		*±9.5*	*±4.6*		
V-MT-N1	2.7	2.0	0.0	0.7	27.3	47.3	18.3	98.3
SD	*±3.7*	*±1.8*		*±1.6*	*±14.0*	*±20.6*	*±10.4*	
V-MT-N2	5.0	4.0	0.0	1.7	30.0	31.7	26.0	99.0
SD	*±4.3*	*±3.8*		*±4.1*	*±8.4*	*±18.6*	*±22.0*	
V-MT-S1	4.3	4.0	0.0	0.0	31.0	43.0	16.3	98.7
SD	*±5.3*	*±3.6*			*±16.5*	*±14.9*	*±5.0*	
V-MT-S2	23.5	0.0	0.0	3.5	22.0	49.5	0.0	100.0
SD	*±16.7*			*±4.1*	*±15.1*	*±7.7*		
V-MT-S3	2.3	0.0	0.0	1.7	53.3	31.0	0.0	88.3
SD	*±2.0*			*±2.0*	*±19.7*	*±19.8*		

* The total percent cover does not include echinoids (mean percent cover by site = 0.1 %; percent cover range = 0-1.5 %), bare rock (mean percent cover by site = 0.1 %; percent cover range = 0-0.7 %), and sand (mean percent cover by site = 2.6 %; percent cover range = 0-11.7 %).

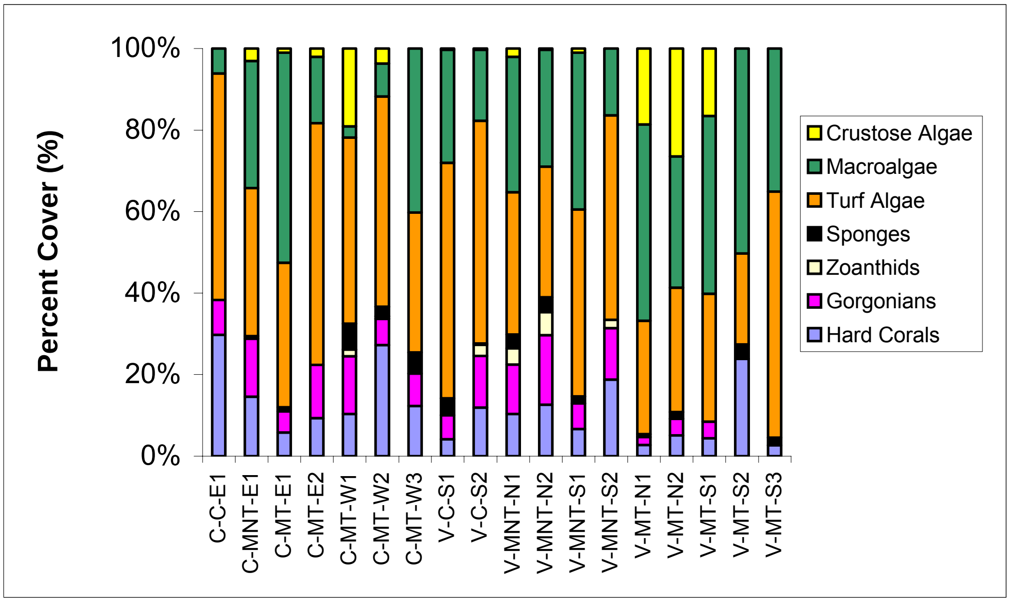

Figure 8. Percent cover of sessile benthos at 18 study sites around Culebra (C) and Vieques (V) as determined from LPI transects (*n* = 6 transects for each site, except *n* = 4 for site V-MT-S2).

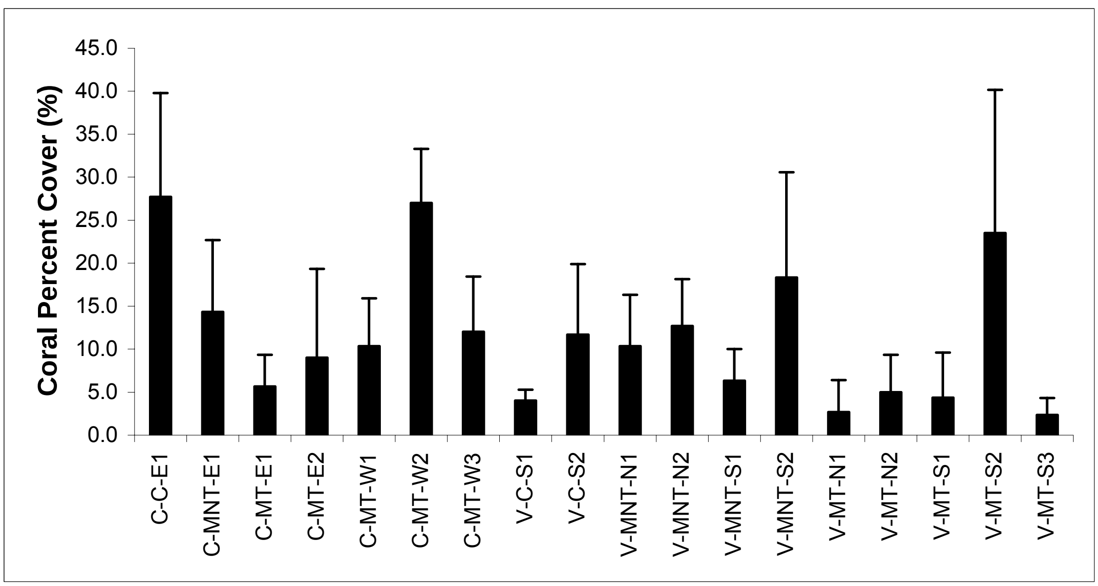

Figure 9. Percent cover of hard corals at 18 study sites around Culebra (C) and Vieques (V) as determined from LPI transects (mean ± standard deviation, *n* = 6 transects for each site, except *n* = 4 for site V-MT-S2).

Salina del Sur near the LIA of Vieques had hard coral covers of 2.3% and 23.5% respectively. Use of the Tukey test resulted in multiple cases of statistical significance between the sites with the most percent hard coral cover and the sites with the least cover (**Table 3**). Sites with the significantly highest amount of hard coral cover were C-C-E1, C-MT-W2, V-MT-S2, V-MNT-S2, C-MNT-E1, V-MNT-N2, and C-MT-W3 (in decreasing order of cover: 27.7% - 12.0%). Garrison et al. (2000) found coral cover of 8.9% at civilian site Dewey.

Table 3. Tukey test comparisons of the percent cover of hard corals at 18 study sites around Culebra (C) and Vieques (V).

Site	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S1	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
C-C-E1																		
C-MNT-E1	ns																	
C-MT-E1	P<0.05	ns																
C-MT-E2	P<0.05	ns	ns															
C-MT-W1	P<0.05	ns	ns	ns														
C-MT-W2	ns	ns	P<0.05	P<0.05	P<0.05													
C-MT-W3	ns	ns	ns	ns	ns	ns												
V-C-S1	P<0.05	ns	ns	ns	ns	P<0.05	ns											
V-C-S2	P<0.05	ns	ns	ns	ns	ns	ns	ns										
V-MNT-N1	P<0.05	ns	ns	ns	ns	P<0.05	ns	ns	ns									
V-MNT-N2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns								
V-MNT-S1	P<0.05	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns							
V-MNT-S2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns						
V-MT-N1	P<0.05	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns	ns					
V-MT-N2	P<0.05	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns				
V-MT-S1	P<0.05	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns			
V-MT-S2	ns	ns	P<0.05	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	P<0.05	P<0.05	P<0.05		
V-MT-S3	P<0.05	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns	P<0.05	ns	ns	ns	P<0.05	

Legend:

ns = no significant difference between the two sites

The percent cover of **macroalgae** varied widely between some study sites, from a high of 31.0% at site C-MT-E1 to a low of 2.3% at site C-MT-W1 (**Figure 10**). Use of the Tukey test resulted in multiple cases of statistical significance between the sites with the greatest percent macroalgae cover and the sites with the least cover (**Table 4**). Sites with the significantly lowest amount of macroalgae cover were C-MT-W1, C-C-E1, C-MT-W2, C-MT-E2, V-MNT-S2, and V-C-S2 (in increasing amount of cover: 2.7% - 17.0%). Site Dewey had a macroalgae cover of 17.0% (Garrison et al. 2000).

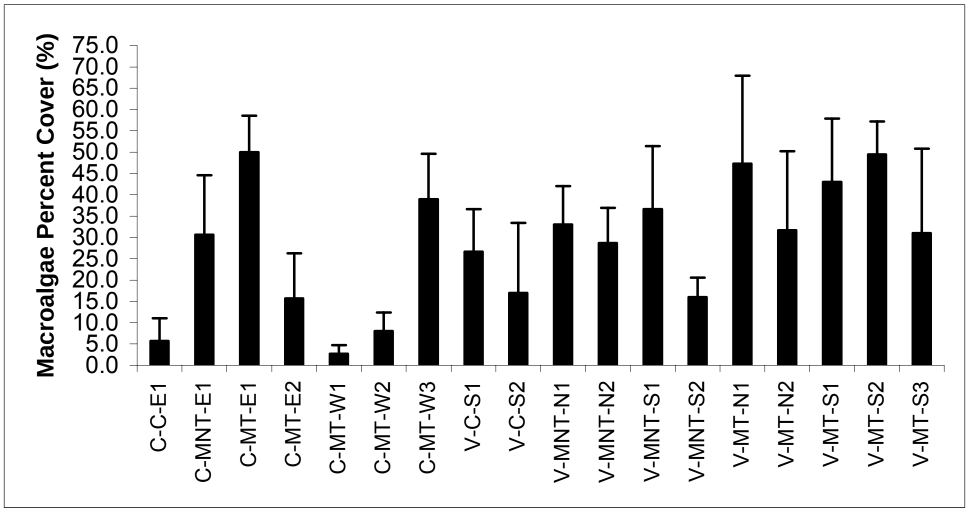

Figure 10. Percent cover of macroalgae at 18 study sites around Culebra (C) and Vieques (V) as determined from LPI transects (mean ± standard deviation, *n* = 6 transects for each site, except *n* = 4 for site V-MT-S2).

The percent cover of **turf algae** varied between some study sites, from a high of 57.3% at site C-MT-E2 to a low of 22.0% at site V-MT-S2 (**Figure 11**). Use of the Tukey test resulted in only two cases of statistical significance (P<0.05) between the site with the most percent turf algae cover and the sites with the least cover (**Table 5**). Sites V-MT-S2 and V-MT-N1 had the significantly lowest amount of turf algae cover (22.0% and 27.3%, respectively).

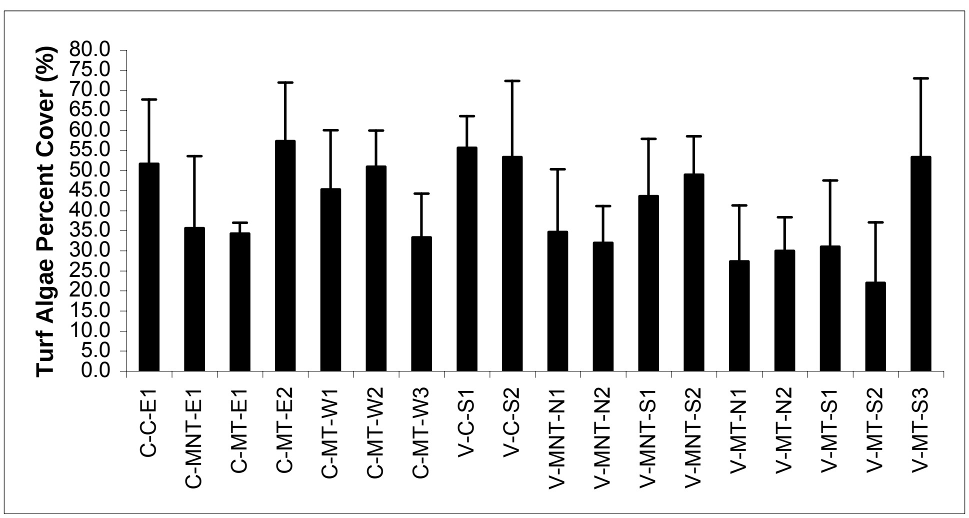

Figure 11. Percent cover of turf algae at 18 study sites around Culebra (C) and Vieques (V) as determined from LPI transects (mean ± standard deviation, *n* = 6 transects for each site, except *n* = 4 for site V-MT-S2).

Table 4. Tukey test comparisons of the percent cover of macroalgae at 18 study sites around Culebra (C) and Vieques (V).

Site	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S1	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
C-C-E1																		
C-MNT-E1	ns																	
C-MT-E1	P<0.05	ns																
C-MT-E2	ns	ns	P<0.05															
C-MT-W1	ns	P<0.05	P<0.05	ns														
C-MT-W2	ns	ns	P<0.05	ns	ns													
C-MT-W3	P<0.05	ns	ns	ns	P<0.05	P<0.05												
V-C-S1	ns	ns	ns	ns	ns	ns	ns											
V-C-S2	ns	ns	P<0.05	ns	ns	ns	ns	ns										
V-MNT-N1	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns									
V-MNT-N2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns								
V-MNT-S1	P<0.05	ns	ns	P<0.05	P<0.05	P<0.05	ns	ns	ns	ns	ns							
V-MNT-S2	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns						
V-MT-N1	P<0.05	ns	ns	P<0.05	P<0.05	P<0.05	ns	ns	P<0.05	ns	ns	ns	P<0.05					
V-MT-N2	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns				
V-MT-S1	P<0.05	ns	ns	P<0.05	P<0.05	P<0.05	ns	ns	ns	ns	ns	ns	P<0.05	ns	ns			
V-MT-S2	P<0.05	ns	ns	P<0.05	P<0.05	P<0.05	ns	ns	P<0.05	ns	ns	ns	P<0.05	ns	ns	ns		
V-MT-S3	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	

Legend:

ns = no significant difference between the two sites

Table 5. Tukey test comparisons of the percent cover of turf algae at 18 study sites around Culebra (C) and Vieques (V).

Site	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S1	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
C-C-E1																		
C-MNT-E1	ns																	
C-MT-E1	ns	ns																
C-MT-E2	ns	ns	ns															
C-MT-W1	ns	ns	ns	ns														
C-MT-W2	ns	ns	ns	ns	ns													
C-MT-W3	ns	ns	ns	ns	ns	ns												
V-C-S1	ns	ns	ns	ns	ns	ns	ns											
V-C-S2	ns	ns	ns	ns	ns	ns	ns	ns										
V-MNT-N1	ns	ns	ns	ns	ns	ns	ns	ns	ns									
V-MNT-N2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns								
V-MNT-S1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns							
V-MNT-S2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns						
V-MT-N1	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns					
V-MT-N2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns				
V-MT-S1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns			
V-MT-S2	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns		
V-MT-S3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	

Legend:

ns = no significant difference between the two sites

The percent cover of **gorgonians** varied widely between some study sites, from a high of 17.0% at site V-MNT-N2 to a low of 0% at two sites (**Figure 12**). Use of the Tukey test revealed that site V-MNT-N2 had

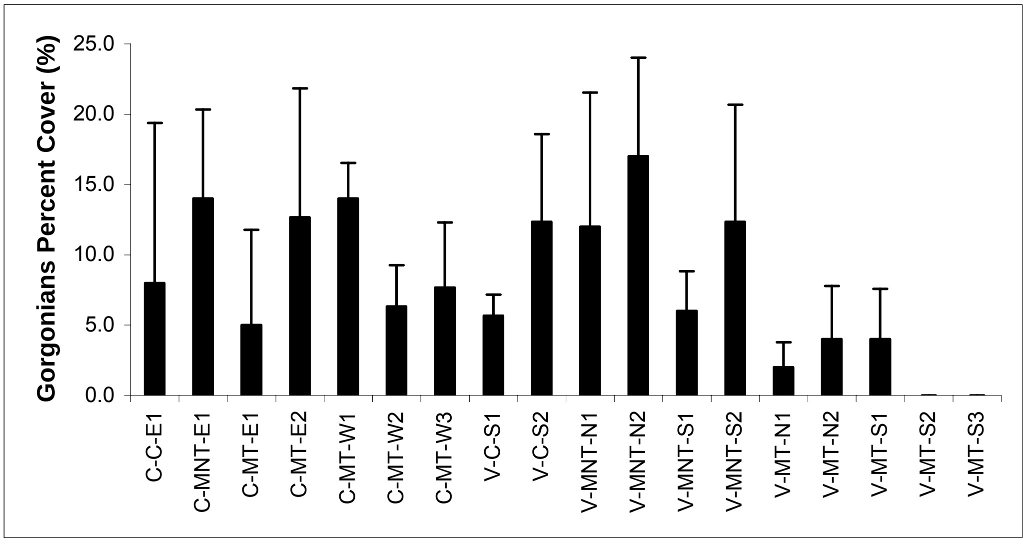

Figure 12. Percent cover of gorgonians at 18 study sites around Culebra (C) and Vieques (V) as determined from LPI transects (mean ± standard deviation, *n* = 6 transects for each site, except *n* = 4 for site V-MT-S2).

statistically (P<0.05) more gorgonian percent cover than the five sites with the lowest percent cover (V-MT-S2, V-MT-S3, V-MT-N1, V-MT-N2, and V-MT-S1) (**Table 6**). Site Dewey had a gorgonian cover of approximately 1% (Garrison et al. 2000).

Table 6. **Tukey test comparisons of the percent cover of gorgonians at 18 study sites around Culebra (C) and Vieques (V).**

Site	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S1	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
C-C-E1																		
C-MNT-E1	ns																	
C-MT-E1	ns	ns																
C-MT-E2	ns	ns	ns															
C-MT-W1	ns	ns	ns	ns														
C-MT-W2	ns	ns	ns	ns	ns													
C-MT-W3	ns	ns	ns	ns	ns	ns												
V-C-S1	ns	ns	ns	ns	ns	ns	ns											
V-C-S2	ns	ns	ns	ns	ns	ns	ns	ns										
V-MNT-N1	ns	ns	ns	ns	ns	ns	ns	ns	ns									
V-MNT-N2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns								
V-MNT-S1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns							
V-MNT-S2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns						
V-MT-N1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	P<0.05	ns	ns					
V-MT-N2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	P<0.05	ns	ns	ns				
V-MT-S1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns			
V-MT-S2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns		
V-MT-S3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns	

Legend:

“ns” = “not significant” (i.e., no significant difference between the two sites

The abundance of **echinoids** varied between some study sites, from a high of 17.3 echinoids at site V-MT-S2 to a low of 0 echinoids at four sites (V-C-S1, V-C-S2, V-MNT-S1, and V-MNT-S2) (**Figure 13**). Despite the disparity in abundance between some sites, use of the Tukey test revealed that there were no statistical differences between sites. This result was primarily due to high intra-site variability between sampling stations.

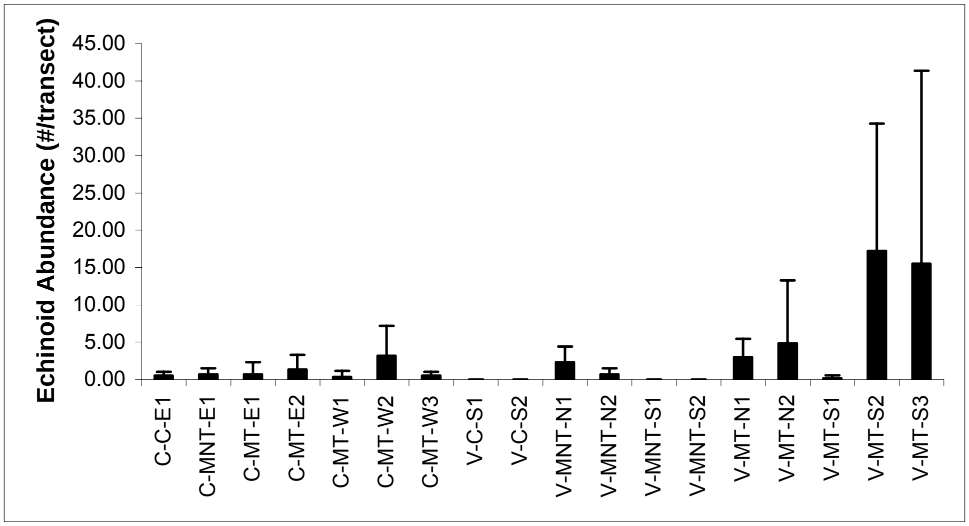

Figure 13. Echinoid abundance at 18 study sites around Culebra (C) and Vieques (V) as determined from LPI transects (mean ± standard deviation, *n* = 6 transects for each site, except *n* = 4 for site V-MT-S2).

Coral species richness was assessed quantitatively by counting coral colonies (by species) beneath the LPI transects, as well as qualitatively by listing coral species adjacent to the LPI transects. Overall, at least 30 species were observed at Culebra study sites (**Table 7**), while at least 27 species were observed at Vieques sites (**Table 8**). An evaluation of the cumulative coral species richness versus the number of transects revealed that the asymptote was reached after approximately three transects (**Figure 14**). Statistical analyses showed multiple significant differences between the sites with the greatest richness and the sites with the lowest richness (**Table 9**). In particular, each Vieques military target site and the Vieques military non-target site V-MNT-S2 had a mean species richness that was significantly different from all other sites (all Culebra sites and five remaining Vieques sites) ($F_{0.05(2),\ 17,\ 88}$ = 12.80, P<0.001; Tukey test, α = 0.05). Coral species diversity, expressed as the Shannon-Wiener index (*H'*), was calculated using the LPI dataset (i.e., observations of corals found beneath the transect line) (**Table 10**). Statistical analyses showed multiple significant differences between the sites with the greatest diversity and the sites with the lowest diversity (**Table 11**). The most abundant hard coral taxa at the Culebra sites were *A. cervicornis*, *M. annularis*, *Agaricia* spp., *P. astreoides*, and *Millepora* spp. (in decreasing order of mean occurrence) (**Table 7**). Coral taxa present in at least six of the seven Culebra sites were *A. cervicornis*, *Agaricia* spp., *C. natans*, *D. stokesii*, *D. labyrinthiformis*, *D. strigosa*, *Millepora* spp., *M. annularis*, *M. cavernosa*, *M. franksi*, *P. astreoides*, *S. radians*, and *S. michelini* (**Table 7**). The most abundant coral species at site Dewey was *Montastraea annularis* (Garrison et al. 2000).

The most abundant hard coral taxa at the Vieques sites were *M. annularis*, *Millepora* spp., *D. labyrinthiformis*, and *P. porites* (in decreasing order of mean occurrence) (**Table 8**). Coral taxa present in at least nine of the 11 Vieques sites were *Agaricia* spp., *D. strigosa*, *Millepora* spp., *M. annularis*, *M. faveolata*, *P. astreoides*, *P. porites*, and *S. radians* (**Table 8**).

Table 7. Total number of observations of hard coral taxa found under LPI transects at seven study sites around Culebra (six transects and 300 total observations per site).

Taxa	C-C-E1	C-MNT-E1	C-MT-E1	C-MT-E2	C-MT-W1	C-MT-W2	C-MT-W3
Acropora cervicornis	41	29	4	*	1	7	0
Acropora palmata	0	0	*	0	0	0	0
***Agaricia* spp.**	3	7	1	2	3	10	6
Colpophyllia natans	*	*	*	*	0	1	1
Dendrogyra cylindrus	0	0	0	0	*	0	*
Dichocoenia stokesii	*	*	*	*	*	*	*
Diploria clivosa	0	0	*	*	0	0	0
Diploria labyrinthiformis	0	*	1	*	*	9	3
Diploria strigosa	*	1	5	1	1	3	*
Eusmilia fastigiata	*	0	0	0	*	0	0
Favia fragum	*	0	*	0	*	0	0
Isophyllastrea rigida	1	0	*	*	0	0	0
Isophyllia sinuosa	*	0	0	0	0	0	0
Meandrina meandrites	*	0	0	0	*	*	*
***Millepora* spp.**	1	*	4	*	2	12	5
Montastraea annularis	26	2	*	16	3	15	6
Montastraea cavernosa	0	*	*	*	8	*	3
Montastraea faveolata	3	1	0	2	0	5	0
Montastraea franksi	*	*	0	1	*	1	3
Mussa angulosa	*	*	0	0	0	0	0
Mycetophyllia danaana	0	0	0	0	*	0	0
Mycetophyllia ferox	*	0	0	0	0	0	0
Mycetophyllia lamarkiana	0	0	0	0	*	0	0
***Mycetophyllia* spp.**	0	*	0	0	0	0	0
Porites astreoides	1	1	1	1	9	7	7
Porites porites	7	2	*	3	1	5	1
***Scolymia* spp.**	0	*	0	0	0	0	*
Siderastrea radians	0	*	*	*	*	2	1
Siderastrea siderea	0	0	1	*	2	3	*
Stephanocoenia michelini	*	0	*	1	1	1	*
Total taxa	18	17	17	18	20	17	17
Total LPI observations	83	43	17	27	31	81	36

Legend:

***** = taxa observed adjacent to, but not under, the LPI transect line.

Table 8. **Total number of observations of hard coral taxa found under LPI transects at 11 study sites around Vieques (six transects and 300 total observations per site, except site V-MT-S2 with four transects and 200 total observations).**

Taxon	V-C-S1	V-C-S2	V-MNT-N1	V-MNT-N2	V-MNT-S1	V-MNT-S2	V-MT-N1	V-MT-N2	V-MT-S1	V-MT-S2	V-MT-S3
Acropora cervicornis	0	*	2	*	*	*	0	0	0	0	0
Acropora palmata	0	*	0	*	0	0	0	0	0	*	0
Agaricia spp.	*	2	1	1	3	4	0	*	*	*	*
Colpophyllia natans	*	*	*	0	*	1	0	*	0	0	0
Dendrogyra cylindrus	*	0	0	0	0	0	0	0	0	0	0
Dichocoenia stokesii	1	*	1	*	3	0	0	0	1	*	*
Diploria clivosa	0	1	*	0	*	0	*	0	0	5	0
Diploria labyrinthiformis	*	2	0	*	*	0	0	0	1	22	0
Diploria strigosa	2	3	3	5	*	1	*	0	*	6	*
Eusmilia fastigiata	0	1	0	*	0	0	0	*	0	0	1
Favia fragum	0	0	0	0	0	0	0	*	*	0	*
Isophyllastrea rigida	*	0	*	*	*	0	0	0	0	0	0
Macracis spp.	0	0	*	*	0	0	0	0	0	0	0
Meandrina meandrites	*	*	*	*	*	0	*	0	0	*	0
Millepora spp.	*	6	8	11	2	*	3	6	6	0	2
Montastraea annularis	*	1	*	*	*	44	*	*	0	0	*
Montastraea cavernosa	5	2	3	7	3	*	*	0	*	0	0
Montastraea faveolata	*	8	1	3	*	*	*	6	*	*	0
Montastraea franksi	*	*	4	1	4	0	0	0	0	0	0
Occulina diffusa	0	0	0	*	0	0	0	0	0	0	0
Porites astreoides	2	7	6	2	1	*	1	*	1	0	0
Porites porites	1	*	*	2	*	3	4	1	1	11	2
Scolymia spp.	0	0	0	0	0	*	0	0	0	0	0
Siderastrea radians	*	1	1	3	1	2	*	2	1	0	0
Siderastrea siderea	1	1	1	3	2	*	0	0	2	0	0
Siderastrea spp.	0	0	0	0	0	0	0	0	0	3	2
Stephanocoenia michellini	*	*	*	*	*	*	0	0	0	0	0
Total taxa	18	20	19	21	19	14	10	10	12	10	9
Total LPI observations	12	35	31	38	19	55	8	15	13	47	7

Legend:

* = taxa observed adjacent to, but not under, the LPI transect line.

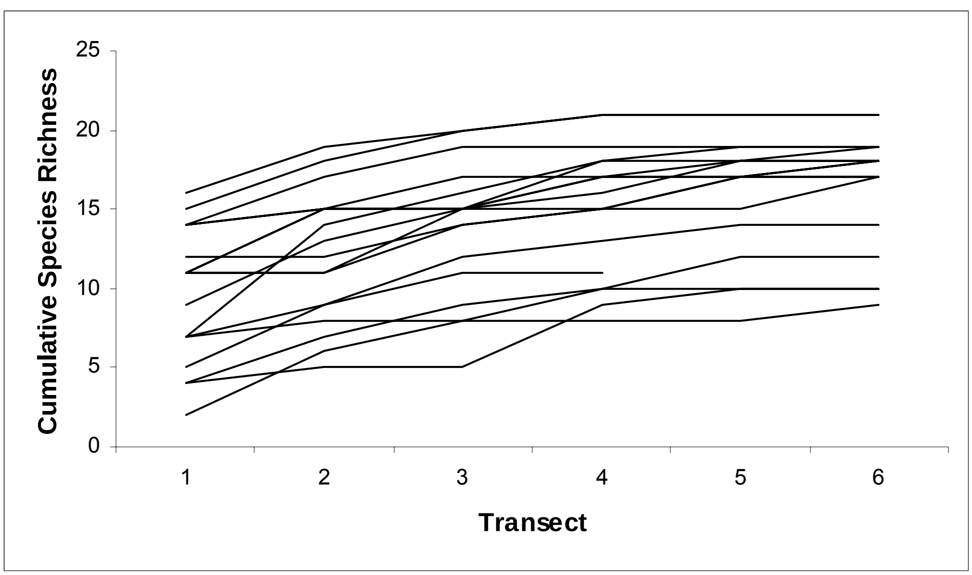

Figure 14. Cumulative coral species richness at 18 study sites around Culebra and Vieques (6 transects per site, except 4 for site V-MT-S2). Note: overlap of data results in less than 18 visible lines.

Table 9. **Tukey test comparisons of coral species richness at 18 study sites around Culebra (C) and Vieques (V).**

Site	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S1	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
C-C-E1																		
C-MNT-E1	ns																	
C-MT-E1	ns	ns																
C-MT-E2	ns	ns	ns															
C-MT-W1	ns	P<0.05	ns															
C-MT-W2	ns	ns	ns	ns	ns													
C-MT-W3	ns	ns	ns	ns	ns	ns												
V-C-S1	ns	ns	ns	ns	ns	ns	ns											
V-C-S2	ns	ns	ns	ns	ns	ns	ns	ns										
V-MNT-N1	ns	ns	ns	ns	ns	ns	ns	ns	ns									
V-MNT-N2	ns	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns								
V-MNT-S1	ns	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns							
V-MNT-S2	ns	ns	P<0.05	ns	P<0.05	P<0.05	P<0.05	P<0.05	ns	ns	P<0.05	P<0.05						
V-MT-N1	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	ns					
V-MT-N2	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	ns	ns				
V-MT-S1	ns	ns	P<0.05	ns	P<0.05	P<0.05	ns	ns	ns	ns	P<0.05	P<0.05	ns	P<0.05	ns			
V-MT-S2	P<0.05	ns	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	ns	ns	ns	ns		
V-MT-S3	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	ns	ns	ns	ns	ns	

Legend:

“ns” = “not significant” (i.e., no significant difference between the two sites

Table 10. **Species diversity (Shannon-Wiener index, *H’*) of hard coral taxa found under LPI transects at 18 study sites around Culebra (C) and Vieques (V) (six transects and 300 total observations per site, except site V-MT-S2 with four transects and 200 total observations).**

Site	H’	Site	H’
C-MT-W2	1.0262	**V-C-S1**	0.6876
V-C-S2	0.9427	**V-MT-S2**	0.6659
V-MNT-N1	0.9182	**C-MT-E2**	0.6202
C-MT-W3	0.9162	**C-C-E1**	0.5884
V-MNT-N2	0.8860	**V-MT-S3**	0.5871
V-MNT-S1	0.8626	**V-MT-N2**	0.5134
C-MT-W1	0.8501	**C-MNT-E1**	0.4816
C-MT-E1	0.7415	**V-MT-N1**	0.4231
V-MT-S1	0.7085	**V-MNT-S2**	0.3448

Table 11. Results of t test comparisons of coral diversity at 18 study sites around Culebra (C) and Vieques (V).

Site	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S1	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
C-C-E1	x																	
C-MNT-E1	ns	x																
C-MT-E1	ns	ns	x															
C-MT-E2	ns	ns	ns	x														
C-MT-W1	ns	ns	ns	ns	x													
C-MT-W2	ns	ns	ns	ns	ns	x												
C-MT-W3	ns	ns	ns	ns	ns	ns	x											
V-C-S1	ns	ns	ns	ns	ns	ns	ns	x										
V-C-S2	ns	ns	ns	ns	ns	ns	ns	ns	x									
V-MNT-N1	ns	ns	ns	ns	ns	ns	ns	ns	ns	x								
V-MNT-N2	ns	ns	ns	ns	ns	P<0.005	ns	ns	ns	ns	x							
V-MNT-S1	ns	ns	ns	ns	ns	P<0.001	ns	ns	ns	ns	ns	x						
V-MNT-S2	P<0.005	ns	P<0.0005	P<0.005	P<0.0005	P<0.0005	P<0.0005	P<0.001	P<0.0005	P<0.0005	P<0.0005	P<0.0005	x					
V-MT-N1	ns	ns	P<0.001	ns	P<0.0005	P<0.0005	P<0.0005	P<0.01	P<0.0005	P<0.0005	P<0.0005	P<0.0005	ns	x				
V-MT-N2	ns	ns	P<0.005	ns	P<0.0005	P<0.0005	P<0.0005	ns	P<0.0005	P<0.0005	P<0.0005	P<0.0005	ns	ns	x			
V-MT-S1	ns	ns	ns	ns	ns	P<0.0025	ns	ns	ns	ns	ns		ns	ns	ns	x		
V-MT-S2	ns	ns	ns	ns	P<0.01	P<0.0005	P<0.0005	ns	P<0.0005	P<0.0005	P<0.0005	P<0.001	ns	ns	ns	ns	x	
V-MT-S3	ns	ns	ns	ns	P<0.0005	P<0.0005	P<0.0005	ns	ns	P<0.0005	P<0.0005	P<0.0005	ns	ns	ns	ns	ns	x

Legend:

"ns" = "not significant" (i.e., no significant difference between the two sites

3.1.2 Topographic Complexity

Topographic complexity, expressed as a dimensionless ratio from zero to one, varied widely between some study sites, from a high of 0.54 at site C-C-E1 to a low of 0.19 at site V-C-S1 (**Figure 15**). Use of the Tukey test revealed multiple cases in which the sites with the most topographical complexity were statistically different (P<0.05) from the sites with the least topographical complexity (**Table 12**). Sites with the significantly highest topographic complexity were C-C-E1, V-MNT-S2, C-MNT-E1, V-MT-N2, V-MT-N1, C-MT-E2, C-MT-W2, C-MT-W1, C-MT-W3, and V-MT-S2 (in decreasing order of mean topographic complexity). Site Dewey had the lowest spatial complexity of the three sites examined by Garrison et al. (2000).

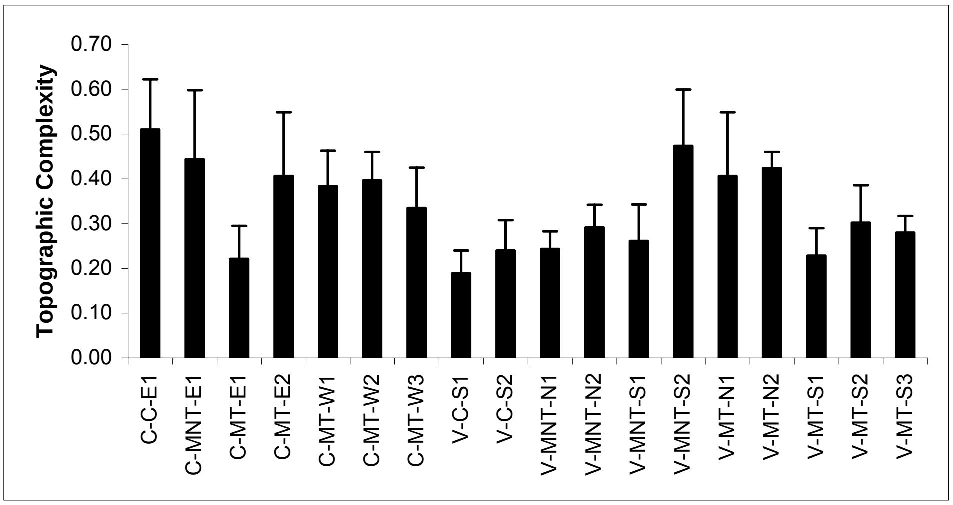

Figure 15. Topographic complexity of reefs at 18 study sites around Culebra (C) and Vieques (V) as determined from LPI transects (mean ± standard deviation, *n* = 6 assessments per site, except *n* = 4 for site V-MT-S2).

Table 12. Tukey test comparisons of topographic complexity at 18 study sites around Culebra (C) and Vieques (V).

Site	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S1	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
C-C-E1																		
C-MNT-E1	ns																	
C-MT-E1	P<0.05	P<0.05																
C-MT-E2	ns	ns	ns															
C-MT-W1	ns	ns	ns	ns														
C-MT-W2	ns	ns	ns	ns	ns													
C-MT-W3	ns	ns	ns	ns	ns	ns												
V-C-S1	P<0.05	P<0.05	ns	P<0.05	ns	P<0.05	ns											
V-C-S2	P<0.05	P<0.05	ns	ns	ns	ns	ns	ns										
V-MNT-N1	P<0.05	P<0.05	ns	ns	ns	ns	ns	ns	ns									
V-MNT-N2	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns								
V-MNT-S1	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns							
V-MNT-S2	ns	ns	P<0.05	ns	ns	ns	ns	P<0.05	P<0.05	P<0.05	ns	P<0.05						
V-MT-N1	ns	ns	ns	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns					
V-MT-N2	ns	ns	P<0.05	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns				
V-MT-S1	P<0.05	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	P<0.05	ns	ns			
V-MT-S2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns		
V-MT-S3	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	

Legend:

"ns" = "not significant" (i.e., no significant difference between the two sites

3.1.3 Juvenile Corals

The mean number of juvenile corals per quadrat (0.25 m^2, 2.7 ft^2) and per site was highly variable and ranged from 0.04 to 1.22 **(Figure 16)**. There were no significant differences (P>0.05) in the abundance of juvenile corals per quadrat between site types (civilian, military non-target, and military target) at either Culebra or Vieques. There were, however, significant differences in the mean number of juvenile corals per quadrat between site types when islands were combined ($F_{0.05(2), 17, 252}$ = 2.059, P<0.02). A Tukey test showed that the Culebra military target and civilian sites had significantly greater abundances of juvenile corals per quadrats compared with Culebra military non-target, and Vieques civilian, military non-target, and military target sites (α = 0.05). We also found that there were significant between site differences in the mean number of juvenile corals per quadrat ($F_{0.05(2), 17, 777}$ = 8.48, P<0.001). A Tukey test showed that Culebra site C-MT-W2 (Peninsula Flamenco) contained significantly more juvenile corals per quadrat than any other site (α = 0.05) (**Table 13**). Further the same Tukey test revealed a grouping of ten sites containing significantly more juvenile corals per quadrat than the remaining sites (one Culebra and three Vieques military non-target sites and three Vieques military target sites): C-MT-W1, C-MT-W3, V-MT-S3, V-MT-S2, V-MNT-S1, C-MT-E1, C-C-E1, C-MT-E2, V-C-S2, and V-C-S1 (in decreasing order of mean number of corals per quadrat).

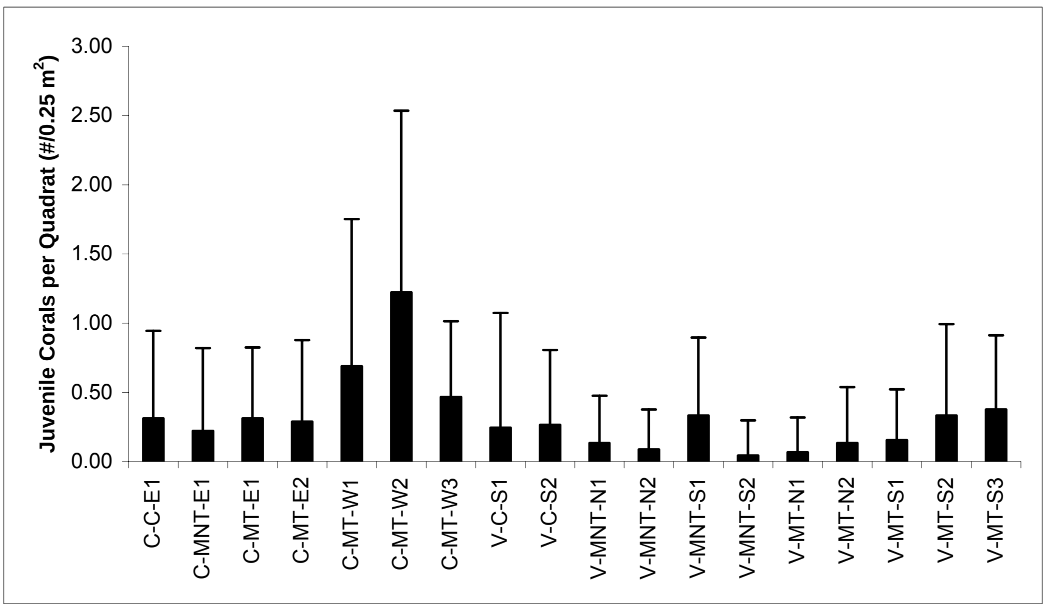

Figure 16. Mean number of juvenile corals per quadrat (0.25 m^2) at 18 study sites around Culebra (C) and Vieques (V) (mean ± standard deviation, n = 45 quadrats per site, except n = 30 for site V-MT-S2).

Juvenile corals in quadrats were identified to the genus level. A total of 12 genera of juvenile hard corals were found at the Culebra and Vieques sites. There were on average 4.2 (± 1.8 *SD*) coral genera per site (1.27 coral genera/m^2 ± 1.09 *SD*). The Culebra site C-MT-W2 contained significantly more juvenile coral genera per quadrat compared with all other sites ($F_{0.05(2), 17, 777}$ = 9.52, P < 0.001; Tukey test, α = 0.05). Further, the Vieques sites V-MNT-S2, V-MT-N1, and V-MNT-S1 contained significantly less juvenile coral genera than site C-MT-W1. In total, site C-MT-W2 contained eight juvenile coral genera. Nine of the sites, including all of the Culebra sites, each contained five or more coral genera (5-8 genera/site). sites The most common and abundant genera of juvenile corals were *Porites* and *Montastraea* **(Table 14)**. The least common genera were *Colpophyllia* and *Stephanocoenia*. *Porites* juveniles occurred in 17 of the 18 sites and the mean number of *Porites* juveniles per quadrat (0.25 m^2, 2.7 ft^2) ranged from 0.02 to 0.49. *Montastraea* juveniles occurred in 12 of the 18 sites and the mean number of *Montastraea* juveniles per quadrat ranged from 0.02 to 0.29.

Table 13. Tukey test comparisons of the mean number of juvenile corals at 18 study sites around Culebra (C) and Vieques (V).

	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S1	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
C-C-E1																		
C-MNT-E1	ns																	
C-MT-E1	ns	ns																
C-MT-E2	ns	ns	ns															
C-MT-W1	ns	P<0.05	ns	ns														
C-MT-W2	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05													
C-MT-W3	ns	ns	ns	ns	ns	P<0.05												
V-C-S1	ns	ns	ns	ns	ns	P<0.05	ns											
V-C-S2	ns	ns	ns	ns	ns	P<0.05	ns	ns										
V-MNT-N1	ns	ns	ns	ns	P<0.05	P<0.05	ns	ns	ns									
V-MNT-N2	ns	ns	ns	ns	P<0.05	P<0.05	ns	ns	ns	ns								
V-MNT-S1	ns	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns							
V-MNT-S2	ns	ns	ns	ns	P<0.05	P<0.05	ns	ns	ns	ns	ns	ns						
V-MT-N1	ns	ns	ns	ns	P<0.05	P<0.05	ns	ns	ns	ns	ns	ns	ns					
V-MT-N2	ns	ns	ns	ns	P<0.05	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns				
V-MT-S1	ns	ns	ns	ns	P<0.05	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns			
V-MT-S2	ns	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns		
V-MT-S3	ns	ns	ns	ns	ns	P<0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	

Legend:

"ns" = "not significant" (i.e., no significant difference between the two sites

Table 14. **Mean number of juvenile corals per quadrat (0.25 m^2) and per hard coral genus at 18 study sites around Culebra (C) and Vieques (V) (mean ± standard deviation, *n* = 45 quadrats per site, except *n* = 30 for site V-MT-S2).**

	C-C-E1	C-MNT-E1	C-MT-E1	C-MT-E2	C-MT-W1	C-MT-W2	C-MT-W3	V-C-S1	V-C-S2	V-MNT-N1	V-MNT-N2	V-MNT-S1	V-MNT-S2	V-MT-N1	V-MT-N2	V-MT-S1	V-MT-S2	V-MT-S3
Acropora		0.02	0.02	0.02		0.02				0.02	0.04							
SD		*0.15*	*0.15*	*0.15*		*0.15*				*0.15*	*0.21*							
Agaricia	0.16		0.04	0.07		0.09	0.04		0.02		0.02	0.07						
SD	*0.37*		*0.21*	*0.25*		*0.29*	*0.21*		*0.15*		*0.15*	*0.25*						
Colpophyllia									0.02									
SD									*0.15*									
Dichocoenia	0.02		0.04	0.02	0.07	0.09	0.04									0.04		
SD	*0.15*		*0.21*	*0.15*	*0.33*	*0.29*	*0.21*									*0.21*		
Diploria		0.02						0.02				0.04						0.02
SD		*0.15*						*0.15*				*0.21*						*0.15*
Eusmilia	0.04																	
SD	*0.30*																	
Meandrina			0.13		0.09	0.21	0.09			0.13		0.19		0.09				0.09
SD			*0.12*		*0.09*	*0.15*	*0.09*			*0.12*		*0.14*		*0.09*				*0.09*
Millepora		0.02		0.07	0.04	0.07	0.02	0.02	0.04							0.02		
SD		*0.15*		*0.33*	*0.21*	*0.25*	*0.15*	*0.15*	*0.21*							*0.15*		
Montastraea	0.07	0.04			0.04	0.29	0.11	0.02	0.13			0.02	0.07		0.04		0.17	0.16
SD	*0.25*	*0.21*			*0.21*	*0.46*	*0.32*	*0.15*	*0.40*			*0.15*	*0.25*		*0.21*		*0.38*	*0.37*
Porites	0.02	0.11	0.16	0.11	0.49	0.47	0.22	0.18	0.04	0.02	0.02	0.09		0.04	0.09	0.09	0.13	0.16
SD	*0.15*	*0.32*	*0.42*	*0.32*	*0.82*	*0.63*	*0.42*	*0.78*	*0.21*	*0.15*	*0.15*	*0.29*		*0.21*	*0.29*	*0.29*	*0.43*	*0.37*
Siderastrea						0.09				0.02		0.02						
SD						*0.29*				*0.15*		*0.15*						
Stephanocoenia					0.02													
SD					*0.15*													
Unknown			0.04		0.02	0.11	0.02			0.04		0.09		0.02				0.02
SD			*0.21*		*0.15*	*0.32*	*0.15*			*0.21*		*0.29*		*0.15*				*0.15*

Legend:

SD – Standard Deviation

3.1.4 Coral Maladies

At least one type of malady (coral disease, bleaching, or fish bites) was observed in each of the sites. Coral bleaching (partial bleaching of coral colonies) was the prevalent malady accounting for more than 78% of malady observations (**Tables 15**). A few quadrats contained diseases unknown to the observer (**Table 16**). Site C-MT-W3 had almost twice as much bleaching (incidence per quadrat) compared with all other sites and had a significantly higher incidence of bleaching compared with nine other sites where the least amount of bleaching was observed ($F_{0.05(2), 17, 777} = 2.485$, $P < 0.001$; Tukey test, α = 0.05) (C-C-E1, V-MNT-N2, V-MT-N2, V-MT-S1, C-MNT-E1, C-MT-E1, V-MT-S3, V-MT-S2, and V-C-S1) (**Tables 15** and **17**). Six different types of coral diseases were encountered at Culebra and Vieques: Aspergillosis (ASP), black-band disease (BBD), dark-spots disease (DSD), red-band disease (RBD), white-band disease (WBD), and white-plague (WP) (**Table 15**). Sites that had significantly fewer incidences of diseases were C-MT-W1, V-MT-N1, V-MT-S2, V-MT-N2, and V-MT-S1 ($F_{0.05(2), 17, 777} = 2.330$, $P < 0.002$; Tukey test, α = 0.05). Culebra sites, and in particular site C-MNT-E1, had more types and incidences of coral diseases than any of the Vieques sites. We observed fish bites in six of the sites (civilian, military non-target, and military target site). Site C-MT-E2 contained the greatest number of fish bites. There were no fish bites observed in our quadrats in three out of seven Culebra sites and nine of the 11 Vieques sites. Among the coral diseases observed at site Dewey were ASP, WP, and BBD (Garrison et al. 2000).

Table 15. **Total occurrences of coral maladies (coral diseases, bleaching, and fish bites) and density of occurrence (incidences/m^2; reported in italics below the number of incidences) at 18 study sites around Culebra (C) and Vieques (V) as determined from juvenile coral quadrats (0.25 m^2/quadrat; *n* = 45 quadrats per site, except *n* = 30 for site V-MT-S2).**

Site	ASP	BBD	DSD	RBD	WP	WBD	UNK	BLCH	FB
C-C-E1	1	0	1	0	0	1	x	2	1
(#/m^2)	*0.09*		*0.09*			*0.09*		*0.18*	
C-MNT-E1	4	1	1	0	0	4	0	4	0
(#/m^2)	*0.36*	*0.09*	*0.09*			*0.36*		*0.36*	
C-MT-E1	1	0	0	0	0	0	x	4	1
(#/m^2)	*0.09*							*0.36*	
C-MT-E2	0	0	0	0	0	2	0	10	4
(#/m^2)						*0.18*			
C-MT-W1	0	0	0	0	0	0	0	11	0
(#/m^2)								*0.98*	
C-MT-W2	1	0	0	0	0	1	0	9	0
(#/m^2)	*0.09*					*0.09*		*0.80*	
C-MT-W3	0	0	0	0	1	0	x	18	2
(#/m^2)					*0.09*			*1.60*	
V-C-S1	1	0	0	0	0	0	x	6	0
(#/m^2)	*0.09*							*0.53*	
V-C-S2	0	0	0	0	0	0	x	6	0
(#/m^2)								*0.53*	
V-MNT-N1	0	0	0	1	0	0	x	6	0
(#/m^2)				*0.09*				*0.53*	
V-MNT-N2	0	0	0	0	0	0	x	3	0
(#/m^2)								*0.27*	
V-MNT-S1	0	1	0	0	0	0	0	10	2
(#/m^2)		*0.09*						*0.89*	
V-MNT-S2	0	0	0	0	0	2	0	9	1
(#/m^2)						*0.18*		*0.80*	
V-MT-N1	0	0	0	0	0	0	0	6	0
(#/m^2)								*0.53*	
V-MT-N2	0	0	0	0	0	1	0	3	0
(#/m^2)						*0.09*		*0.27*	
V-MT-S1	0	1	0	0	0	0	0	3	0
(#/m^2)		*0.09*						*0.27*	
V-MT-S2	0	0	0	0	0	0	0	3	0
(#/m^2)								*0.27*	
V-MT-S3	0	1	0	0	0	0	x	4	0
(#/m^2)		*0.09*						*0.36*	

Legend:

ASP – Aspergillosis
BLCH – bleaching
FB – fish bite
WP – white-plague
UNK – unknown
BBD – black-band disease
DSD – dark-spots disease
RBD – red-band disease
WBD – white-band disease

Table 16. Description of unidentified coral diseases by study site, the number of incidences, and the density of occurrence (incidences/m^2; reported in italics below the number of incidences) at six study sites around Culebra (C) and Vieques (V) as determined from juvenile coral quadrats (0.25 m^2/quadrat; *n* = 45 quadrats per site).

Site	Disease Description	Affected Species	Number of Incidences Incidences/m^2
C-MT-E1	"Paling" (light bleaching?) of live tissue	*Diploria clivosa*	1 *0.09*
C-MT-W3	Red filamentous cover (1-cm long filaments) and tissue loss to the skeleton	*Dendrogyra cylindrus*	1 *0.09*
V-C-S2	"Paling" (light bleaching?) of live tissue	*Porites astreoides*	2 *0.18*
V-MNT-N2	Black fuzzy material (fungus?) similar to black-band but not in a band	*Millepora* spp.	2 *0.18*
V-MNT-N2	Black, "burnt" aspect	*Millepora* spp.	1 *0.09*
V-MT-S3	Tissue loss, down to the skeleton	*Porites porites*	1 *0.09*

Table 17. Total occurrences of bleaching by coral species at 18 sites around Culebra (C) and Vieques (V) as determined from juvenile coral quadrats (0.25 m^2/quadrat; *n* = 45 quadrats per site, except *n* = 30 for site V-MT-S2).

Species	C-C-E1	C-MNT-E1	C-MT-E1	C-MT-E2	C-MT-W1	C-MT-W2	C-MT-W3	V-C-S1	V-C-S2	V-MNT-N1	V-MNT-N2	V-MNT-S1	V-MNT-S2	V-MT-N1	V-MT-N2	V-MT-S1	V-MT-S2	V-MT-S3
Acropora cervicornis	1	1	1	4		1												
Agaricia agaricites							1											
Agaricia spp.							2					2						
Colpophyllia natans	1																	
Dichocoenia stokesii							1	2										
Diploria clivosa																	1	
Diploria labyrinthiformis							3											
Diploria strigosa		1	1	1						1								
Favia fragum																	2	
Millepora spp.														1				
Montastraea annularis				3		1	3					1						
Montastraea cavernosa													1					
Montastraea faveolata							2											
Montastraea sp.			1	1	11	5	3	4	4	3	3	6	8	5	2	3		
Porites astreoides			1															
Porites furcata							1											
Porites porites		1		1		1									1			4
Siderastrea siderea						1				1		1						
Unknown		1					2											

ASP (or "sea fan disease"), a fungal disease affecting octocorals (Nagelkerken et al. 1997a, 1997b; Santavy et al. 2001), occurred in quadrats of five of the 18 study sites (C-C-E1, C-MNT-E1, C-MT-E1, C-MT-W2, and V-C-S1). Site C-MNT-E1 had four separate incidences of sea fan disease on *Gorgonia* *ventalina* (0.36 incidences/m^2). The other four sites each had a single incidence of Aspergillosis on *G. ventalina* (0.09 incidences/m^2) (**Table 15**).

BBD is caused by the cyanobacterium *Phormidium corallyticum* and progresses across live coral live tissue (in faviids, agaricids, and gorgonians) in a band, leaving behind bare coral skeleton (Antonius 1981; Rützler et al. 1983a, 1983b). Black-band disease was seen on *Diploria strigosa*, *Montastraea annularis*, and *Siderastrea siderea* in quadrats at four of the sites: C-MNT-E1, V-MNT-S1, V-MT-S1, and V-MT-S3 (**Table 15**).

DSD manifests itself as small, dark, and round areas that grow over time on corals (e.g., *M. annularis*, *S. siderea*, *S. radians*, and *S. intercepta*) (Gil-Agudelo and Garzón-Ferreira 2001). This disease was found on *S. siderea* in quadrats at two sites on the east side of Culebra (C-C-E1 and C-MNT-E1) (**Table 15**). Additionally, there were three opportunistic observations of dark spots disease outside of the quadrats in three different military non-target sites of Vieques.

RBD affects sea fans (e.g., *Gorgonia* spp.) and hard corals (e.g., *Agaricia*, *Colpophyllia*, *Mycetophyllia*, and *Stephanocoenia*) (Santavy and Peters 1997). In this study it was witnessed on *G. ventalina* in a quadrat at one Vieques site (V-MNT-N1) (**Table 15**).

WP is caused by the bacterium, *Aurantimonas coralicida* (Dustan 1977). It creates a sharp line between healthy and diseased tissue. White plague was found on one *Montastraea annularis* colony in a quadrat at site C-MT-W3 (**Table 15**).

WBD affects acroporids in the Caribbean and other parts of the world (Gladfelter 1982). This disease caused the mortality of *Acropora* throughout the Caribbean, reducing coral cover substantially on most reefs (Aronson and Precht 2001). A distinction between the two types of white band disease (Type I and II) was not possible here; that distinction requires observing changes over time. The disease usually begins at the base of the coral and spreads out in a white band. It has also been known to begin at mid-branch. White band disease was recorded on *Acropora cervicornis* during quadrat surveys at three sites on the east side of Culebra (C-C-E1, C-MNT-E1, and C-MT-E2), one site on the west side of Culebra (C-MT-W2) and two sites off Vieques (V-MNT-S2, V-MT-N2) (**Table 15**).

Bleaching has been documented world-wide and is associated with a number of causes including reduced salinity, increased or decreased light levels, temperature, exposure to chemicals (including copper ions, cyanide, herbicides, and pesticides), and biological factors (e.g., bacteria) (Hoegh-Guldberg 1999). Corals have bleached in mass and died as a result of anomalous and prolonged increases in seawater temperature (Hoegh-Guldberg 1999). All sites at Culebra and Vieques contained bleached coral colonies (**Tables 15** and **17**). In June 2003 we observed bleaching in 19 taxa of scleractinians. Over 59% of the cases involved *Montastraea* spp.; this taxon was affected in 14 of the 18 sites. Two species that were moderately affected by bleaching (eight cases each) were *Acropora cervicornis* and *Porites porites* (**Table 17**).

Predation on live corals by reef fishes (in particular parrotfishes) causes the scraping and excavating of live tissue and sometimes the coral skeleton (Bruckner et al. 2000). Such tissue and skeleton destruction results in bare white spots known as "fish bites." Fish bites were observed at six of the 18 study sites (**Table 15**). Four coral species were affected: *Diploria strigosa*, *Montastraea annularis, M. cavernosa,* and *Porites porites.* Fish bites were observed mostly on *M. annularis* (8 out of 11 observations).

3.2 REEF FISH CENSUSES

3.2.1 Abundance

Fish abundance was characterized as the average number of individual fishes observed among the three sampling stations per study site (**Figure 17**).

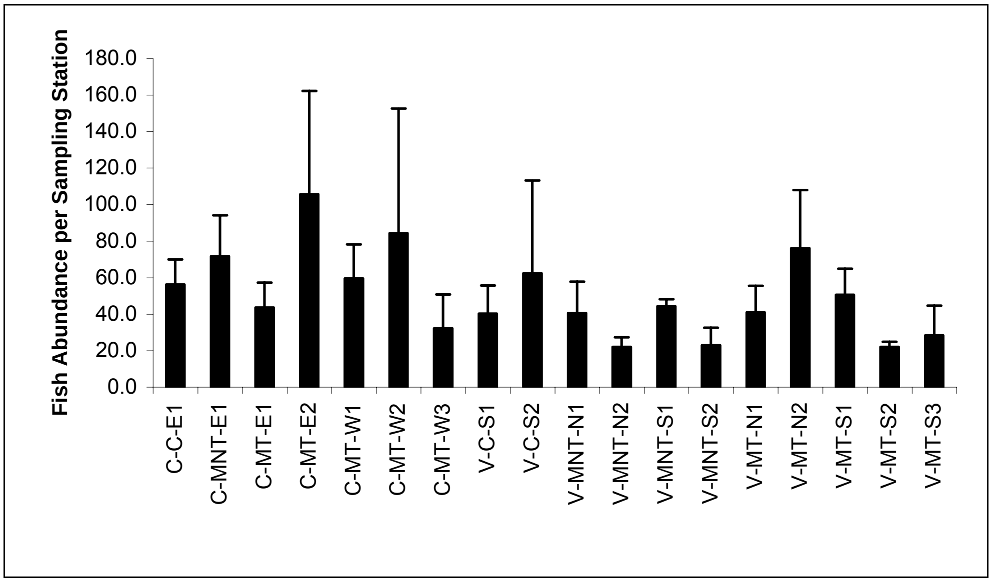

Figure 17. Fish abundance (mean number of individuals per sampling station ± standard deviation) at 18 study sites around Culebra (C) and Vieques (V).

The log-transformed mean abundance of fishes was significantly different between some study sites ($F_{0.05(2),\ 17,\ 35}$ = 2.64, P<0.01). The highest mean abundance was found at the Culebra site C-MT-E2, with an average abundance of 106 fishes per sampling station. The difference in mean abundances was significantly different between C-MT-E2 and the Vieques sites V-MNT-N2 (the site with the least abundance, with an average abundance of 22 fishes per sampling station) (Tukey test, q = 5.578, $q_{0.05,\ 35,18}$ = 5.379) and V-MNT-S2 (Tukey test, q = 5.535, $q_{0.05,\ 35,18}$ = 5.379). Other comparisons of mean abundances between study sites were not significantly different. It is interesting to note that the site with the greatest abundance is a former military target site, and that the two sites with the least abundance were non-target sites.

3.2.2 Species Richness, Diversity, and Evenness

Fish species richness was characterized as the average number of fish species observed among the three sampling stations per study site (**Figure 18**).

The non-log-transformed mean fish species richness was significantly different between some study sites ($F_{0.05(2),\ 17,\ 35}$ = 3.18, P<0.001). Significant differences in mean species richness existed between the Culebra site C-MT-W2 (the site with highest mean species richness with an average of 17 species per sampling station) and seven other sites: C-MT-E1, V-MT-S3, V-MT-S2, V-MT-S1, V-MNT-N2, V-MT-N2, and V-MNT-S2 (**Table 18**).

Table 18. Significant differences of mean fish species richness between study sites as found using the Tukey test.

Comparison	q calculated	$q_{0.05,\ 35,\ 18}$
C-MT-W2 vs C-MT-E1	6.489	5.379
C-MT-W2 vs V-MT-S3	6.229	5.379
C-MT-W2 vs V-MT-S2	5.456	5.379
C-MT-W2 vs V-MT-S1	5.970	5.379
C-MT-W2 vs V-MNT-N2	5.710	5.379
C-MT-W2 vs V-MT-N2	5.710	5.379
C-MT-W2 vs V-MNT-S2	5.451	5.379

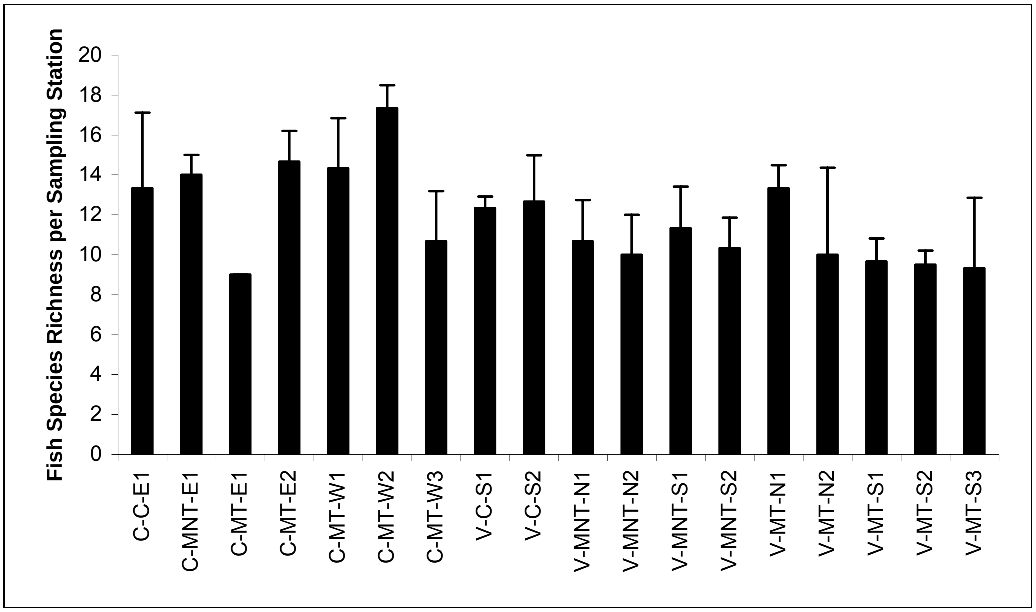

Figure 18. Fish species richness (mean number of species per sampling station ± standard deviation) at 18 study sites around Culebra (C) and Vieques (V).

The Shannon-Wiener diversity index (*H'*) was calculated for each sampling station. The *H'* values were then used in turn to determine evenness. Hence, the diversity values are not presented here.

No clear pattern emerged between the evenness (relative diversity) scores and the study sites (**Figure 19**). However, it was interesting to note that, when evenness scores were averaged for each of the three study site categories, the mean for military target sites was 0.772, the mean for military non-target sites was 0.763, and the mean for civilian sites was 0.727.

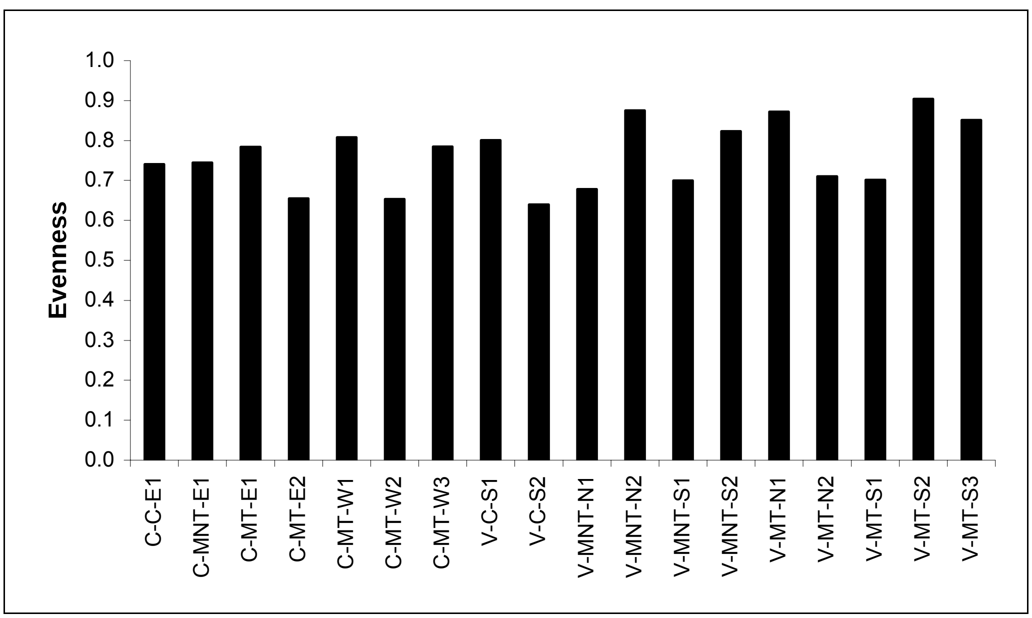

Figure 19. Fish species evenness (relative diversity) at 18 study sites around Culebra (C) and Vieques (V).

3.2.3 Mean Length

The mean length of fishes was estimated as the weighted mean of the average length of each species factored by the number of individuals of each species at each sampling station (**Figure 20**).

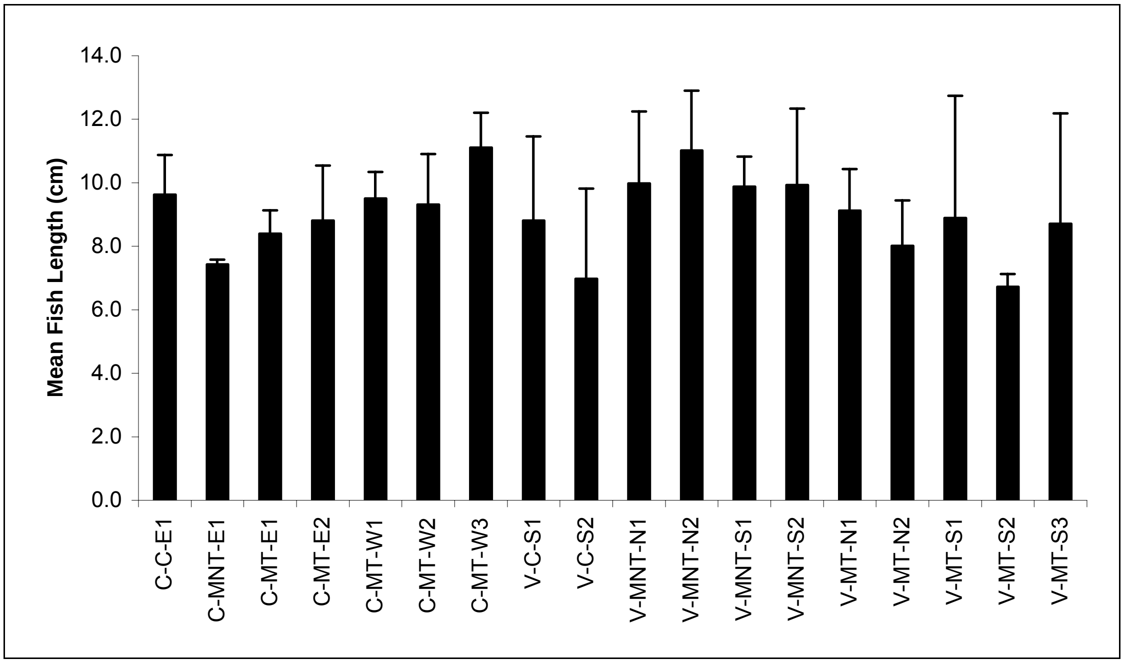

Figure 20. Mean fish length (cm) at 18 study sites around Culebra (C) and Vieques (V).

3.3 HERBIVORE ABUNDANCE

To determine the abundance of herbivores within each site, we censused echinoids during LPI and juvenile coral surveys, and herbivorous fishes during fish stationary counts.

3.3.1 Herbivores in Linear Point Intercept Surveys

Four taxa of echinoids were observed during the LPI surveys: *Diadema antillarum* (long-spined urchin), *Echinometra* spp. (including *E. lucunter* [rock-boring urchin] and *E. viridis* [reef urchin]), *Eucidaris tribuloides* (slate-pencil urchin), and *Tripneustes ventricosus* (West Indian sea egg) (**Table 19**). *Diadema antillarum* and *Echinometra* spp. were the most abundant and common echinoids in the LPI surveys. *Eucidaris tribuloides* and *T. ventricosus* were scarce. There were no echinoids in LPIs of four of the sites (V-C-S1, V-C-S2, V-MNT-S1, and V-MNT-S2). In the remaining sites, total observations ranged from 2 to 93 echinoids per site, corresponding to 0.014 to 0.670 echinoids per square meter, respectively (**Table 19**). Sites with the greatest abundances of echinoids were V-MT-S3 (93 individuals, 0.67 echinoids/m^2), V-MT-S2 (69 individuals, 0.745 echinoids/m^2 [based on four transects, not six]), and V-MT-N2 (29 individuals, 0.21 echinoids/m^2) (**Table 19**).

There were on average 2.56 echinoids (± 2.84 *SE*) per LPI transect survey (or 0.122 echinoids/m^2). Even though there was a significant difference in the abundance of echinoids between sites in LPI surveys (arcsine transformed data, $F = 2.31$, $P<0.005$), a Tukey test comparing mean abundance by site did not reveal significant differences between sites. This may stem from the fact that high mean numbers of echinoids were associated with high within-site variability (**Figure 21**). Notwithstanding this variability, two Vieques sites, V-MT-S2 and V-MT-S3, stood out from all other sites with relatively high mean numbers of echinoids: 17 and 16 echinoids per transect, respectively. At all other sites, we found less than five echinoids on average per LPI transect (**Figure 21**).

Table 19. Total number of echinoids per taxon found within a 1-m distance on either side of the LPI transects at Culebra (C) and Vieques (V) study sites (*n* = 6 transects per site, except *n* = 4 for site V-MT-S2).

Taxa	C-C-E1	C-MNT-E1	C-MT-E1	C-MT-E2	C-MT-W1	C-MT-W2	C-MT-W3
Diadema antillarum	1	0	0	1	0	7	0
Echinometra spp.	1	3	4	7	2	11	2
Eucidaris tribuloides	0	0	0	0	0	1	0
Tripneustes ventricosus	1	1	0	0	0	0	1
Total observations	3	4	4	8	2	19	3
Echinoid Density (ind/m^2)	0.022	0.029	0.029	0.058	0.014	0.137	0.022

Taxa	V-MNT-N1	V-MNT-N2	V-MT-N1	V-MT-N2	V-MT-S1	V-MT-S2	V-MT-S3
Diadema antillarum	6	1	16	25	1	26	87
Echinometra spp.	8	3	1	4	0	43	2
Eucidaris tribuloides	0	0	0	0	0	0	4
Tripneustes ventricosus	0	0	1	0	0	0	0
Total observations	14	4	18	29	1	69	93
Echinoid Density (ind/m^2)	0.101	0.029	0.130	0.208	0.007	0.745	0.670

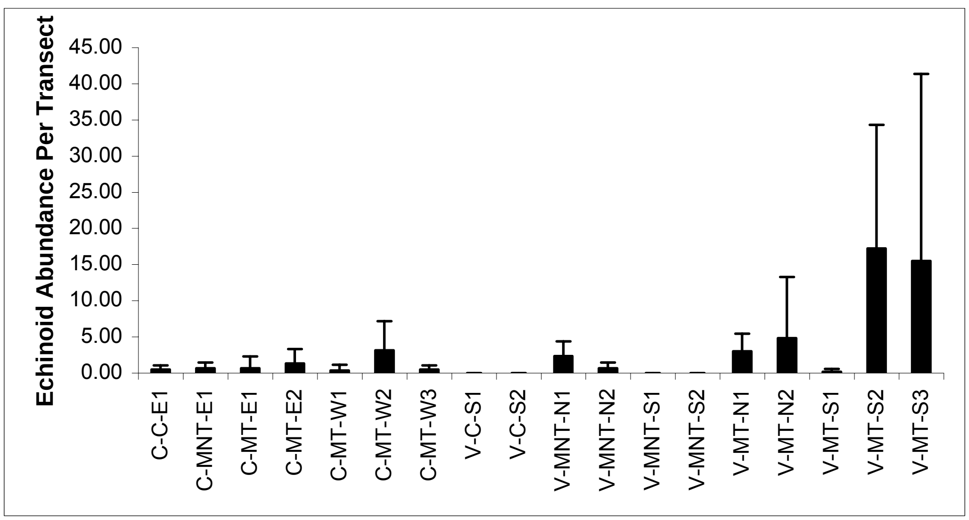

Figure 21. Mean echinoid abundance per LPI transect at Culebra (C) and Vieques (V) study sites (mean ± standard deviation, *n* = 6 transects per site, except *n* = 4 for site V-MT-S2).

Because observations of echinoids were evenly distributed between echinoid taxa at the C-C-E1 site, C-C-E1 had the greatest echinoid diversity (Shannon-Wiener index, *H'*) despite the fact that only three individual echinoids were found for all six LPIs (**Tables 20** and **21**). As a result, the diversity at C-C-E1 was significantly greater than five of the seven Vieques sites (*t* test, α = 0.05; **Table 21**). Significant differences in diversity that are probably more realistic because of greater within-site echinoid abundance include the greater diversity found at C-MT-W2 and V-MNT-N1 compared to V-MT-N2, V-MT-S1, and V-MT-S3.

Table 20. Diversity (Shannon-Wiener index, *H'*) of echinoid species on and 1 m around LPI transects at Culebra (C) and Vieques (V) study sites.

C-C-E1	0.477	V-MT-N1	0.185
C-MT-W2	0.364	V-MT-N2	0.174
V-MNT-N1	0.297	C-MT-E2	0.164
V-MT-S2	0.288	V-MT-S3	0.122
C-MT-W3	0.276	C-MT-E1	0
C-MNT-E1	0.244	C-MT-W1	0
V-MNT-N2	0.244	V-MT-S1	0

Table 21. Results of *t* tests (following Hutcheson 1970) comparing echinoid species diversity (Shannon-Wiener index, *H'*) from LPI transects between study sites at Culebra (C) and Vieques (V).

Site	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3	V MNT-N1	V MNT-N2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
C-C-E1														
C-MNT-E1	ns													
C-MT-E1	ns	ns												
C-MT-E2	P<0.01	ns	ns											
C-MT-W1	ns	ns	ns	ns										
C-MT-W2	ns	ns	ns	ns	ns									
C-MT-W3	ns	ns	ns	ns	ns	ns								
V-MNT-N1	P<0.001	ns	ns	ns	ns	ns	ns							
V-MNT-N2	ns	ns	ns	ns	ns	ns	ns	ns						
V-MT-N1	P<0.002	ns	ns	ns	ns	ns	ns	ns	ns					
V-MT-N2	P<0.001	ns	ns	ns	ns	P<0.01	ns	P<0.02	ns	ns				
V-MT-S1	ns	ns	ns	ns	ns	P<0.001	P<0.02	P<0.001	P<0.001	ns	ns			
V-MT-S2	P<0.001	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns		
V-MT-S3	P<0.001	ns	ns	ns	ns	P<0.001	ns	P<0.001	ns	ns	ns	ns	P<0.001	

3.3.2 Herbivores in Juvenile Coral Quadrat Surveys

Four echinoid taxa were observed in juvenile coral quadrats: *Diadema antillarum*, *Echinometra* spp., *Eucidaris tribuloides*, and *Tripneustes ventricosus* (**Table 22**). As with the LPI surveys, *D. antillarum* and *Echinometra* spp. were the most abundant and common echinoids found in the juvenile coral quadrats. Compared to the LPI surveys, there were more sightings of *Eucidaris tribuloides* in juvenile coral quadrats. There were few observations of *Tripneustes ventricosus* (i.e., four observations among 795 quadrats). As with the LPI surveys, no echinoids were found at sites V-C-S1, V-C-S2, V-MNT-S1, and V-MNT-S2. At the remaining sites, total observations ranged from 2 to 45 echinoids per site, corresponding to 0.18 and 4.00 echinoids per square meter, respectively (**Table 22**). Unlike the LPI surveys (where the greatest abundances were at sites V-MT-S3, V-MT-S2, and V-MT-N2), the sites with the greatest abundance of echinoids were C-MNT-E1 (40 individuals, 3.56 echinoids/m^2), V-MNT-N1 (43 individuals, 3.82 echinoids/m^2), and V-MT-N1 (45 individuals, 4.00 echinoids/m^2) (**Table 22**).

Table 22. Total number of observations of echinoid taxa found within juvenile coral quadrats at Culebra (C) and Vieques (V) study sites (*n* = 45 quadrats per site, except *n* = 30 for site V-MT-S2).

Taxa	C-C-E1	C-MNT-E1	C-MT-E1	C-MT-E2	C-MT-W1	C-MT-W2	C-MT-W3
Diadema antillarum	4	6	4	3	9	5	5
Echinometra spp.	3	31	1	7	5	2	6
Eucidaris tribuloides	1	3	0	2	0	2	0
Tripneustes ventricosus	0	0	0	1	0	1	0
Total observations	8	40	5	13	14	10	11
Echinoid Density (ind/m^2)	0.711	3.556	0.444	1.156	1.244	0.889	0.978

Taxa	V-MNT-N1	V-MNT-N2	V-MT-N1	V-MT-N2	V-MT-S1	V-MT-S2	V-MT-S3
Diadema antillarum	26	3	32	1	8	16	14
Echinometra spp.	11	1	13	0	4	8	1
Eucidaris tribuloides	4	2	0	1	1	0	0
Tripneustes ventricosus	2	0	0	0	0	0	0
Total observations	43	6	45	2	13	24	15
Echinoid Density (ind/m^2)	3.822	0.533	4.000	0.178	1.156	3.200	1.333

There was on average 0.31 echinoids (± 0.72 *SE*) per juvenile coral quadrat (or 1.29 echinoids/m^2). The ANOVA of mean abundance of echinoids per juvenile coral quadrat revealed significant differences of mean abundance between sites (arcsine transformed data, F = 8.55, P<0.0005). A Tukey test showed that sites V-MT-N1, V-MNT-N1, C-MNT-E1, and V-MT-S2 (in decreasing order of abundance) contained significantly greater abundances of echinoids than all other sites (α = 0.05) (**Figure 22**; **Table 23**).

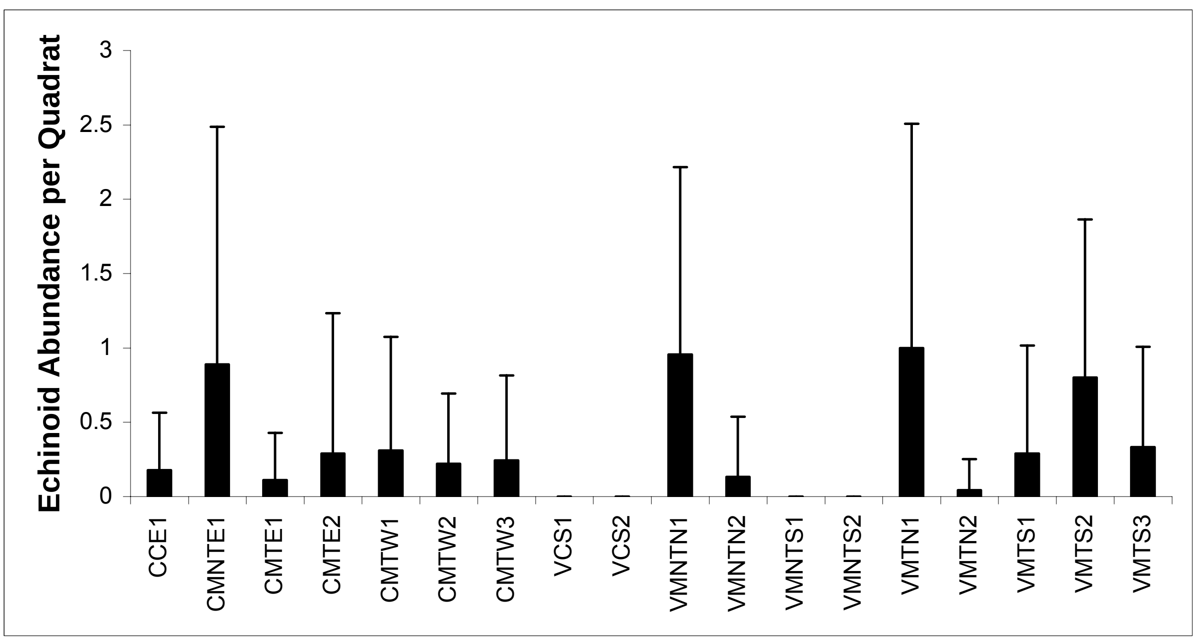

Figure 22. Mean abundance of echinoids per juvenile coral quadrat at Culebra (C) and Vieques (V) study sites (mean ± standard deviation, *n* = 45 quadrats per site, except *n* = 30 for site V-MT-S2).

Table 23. Tukey test comparisons for mean echinoid abundance as observed in juvenile coral quadrats at Culebra (C) and Vieques (V) study sites.

Site	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3	V MNT-N1	V MNT-N2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
C-C-E1														
C-MNT-E1	ns													
C-MT-E1	ns	ns												
C-MT-E2	ns	ns	ns											
C-MT-W1	ns	ns	ns	ns										
C-MT-W2	ns	ns	ns	ns	ns									
C-MT-W3	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05								
V-MNT-N1	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	ns							
V-MNT-N2	ns	ns	ns	ns	ns	ns	P<0.05	P<0.05						
V-MT-N1	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	ns	ns	P<0.05					
V-MT-N2	ns	ns	ns	ns	ns	ns	P<0.05	P<0.05	ns	P<0.05				
V-MT-S1	ns	ns	ns	ns	ns	ns	P<0.05	P<0.05	ns	P<0.05	ns			
V-MT-S2	ns	P<0.05	ns	ns	ns	ns	ns	ns	P<0.05	ns	P<0.05	ns		
V-MT-S3	ns	ns	ns	ns	ns	ns	ns	P<0.05	ns	P<0.05	ns	ns	ns	

Echinoid species diversity (Shannon-Wiener index, *H'*) in juvenile coral quadrats ranged from 0.53 and 0.11 (**Table 24**). For six of the study sites (in decreasing order of diversity: C-WT-W2, C-MT-E2, V-MNT-N1, V-MNT-N2, C-C-E1, V-MT-S1) the echinoid diversity ranged from 0.53 to 0.37 and was significantly greater than at the remaining eight sites where echinoids were observed (*t* test, **Table 25**).

Table 24. Diversity (Shannon-Wiener index, *H'*) of echinoid species in juvenile coral quadrats at Culebra (C) and Vieques (V) study sites.

Site	H'	Site	H'
C-MT-W2	0.5301	C-MT-W3	0.2992
C-MT-E2	0.5025	C-MNT-E1	0.2937
V-MNT-N1	0.4415	C-MT-W1	0.2831
V-MNT-N2	0.4392	V-MT-S2	0.2764
C-C-E1	0.4231	V-MT-N1	0.2611
V-MT-S1	0.3729	C-MT-E1	0.2173
V-MT-N2	0.3010	V-MT-S3	0.1064

3.3.3 Herbivores in Reef Fish Surveys

Herbivorous fish abundance and species composition – All sites contained herbivorous fishes. We observed a total of 11 herbivorous fish species (**Table 26**). Those species belonging to the families Acanthuridae and Scaridae, as well as the yellowtail damselfish (*Microspathodon chrysurus*), were categorized as herbivores (the inclusion of the yellowtail damselfish, but not other pomacentrids, follows Pattengill-Semmens and Gittings [2003]). There were 38.9 herbivorous fishes (± 28.6; mean ± *SD*) per site as observed during stationary counts (**Figure 23**). The log-transformed mean number of herbivorous fish species was not significantly different between study sites ($F_{0.05(2), 17, 35}$ = 1.70, $P > 0.10$).

Table 25. Results of *t* tests (following Hutcheson 1970) comparing echinoid species diversity (Shannon-Wiener index, *H'*) in juvenile coral quadrats between study sites at Culebra (C) and Vieques (V).

Site	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3	V MNT-N1	V MNT-N2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
C-C-E1														
C-MNT-E1	ns													
C-MT-E1	ns	ns												
C-MT-E2	ns	ns	ns											
C-MT-W1	ns	ns	ns	P<0.01										
C-MT-W2	ns	ns	ns	ns	ns									
C-MT-W3	ns	ns	ns	ns	ns	P<0.01								
V-C-S1	ns	ns	ns	ns	ns	ns	ns							
V-C-S2	ns	ns	ns	ns	ns	ns	ns							
V-MNT-N1	ns	ns	ns	ns	ns	ns	ns							
V-MNT-N2	ns	ns	ns	ns	ns	ns	ns	ns						
V-MT-N1	P<0.02	ns	ns	P<0.005	ns	P<0.005	ns	P<0.002	P<0.02					
V-MT-N2	ns	ns	ns	P<0.02	ns	P<0.01	ns	P<0.005	ns	ns				
V-MT-S1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns			
V-MT-S2	ns	ns	ns	P<0.01	ns	P<0.005	ns	P<0.005	ns	ns	ns	ns		
V-MT-S3	P<0.002	P<0.02	ns	P<0.001	P<0.02	P<0.001	P<0.02	P<0.001	P<0.002	ns	P<0.01	P<0.01	P<0.02	

Table 26. List of herbivorous fish species observed at Culebra and Vieques during stationary counts.

Family	Scientific Name	Common Name
Acanthuridae	*Acanthurus bahianus*	Ocean surgeonfish
Acanthuridae	*Acanthurus chirurgus*	Doctorfish
Acanthuridae	*Acanthurus coeruleus*	Blue tang
Pomacentridae	*Microspathodon chrysurus*	Yellowtail damselfish
Scaridae	*Scarus iseri*	Striped parrotfish
Scaridae	*Scarus taeniopterus*	Princess parrotfish
Scaridae	*Scarus vetula*	Queen parrotfish
Scaridae	*Sparisoma aurofrenatum*	Redband parrotfish
Scaridae	*Sparisoma chrysopterum*	Redtail parrotfish
Scaridae	*Sparisoma rubripinne*	Yellowtail parrotfish
Scaridae	*Sparisoma viride*	Stoplight parrotfish

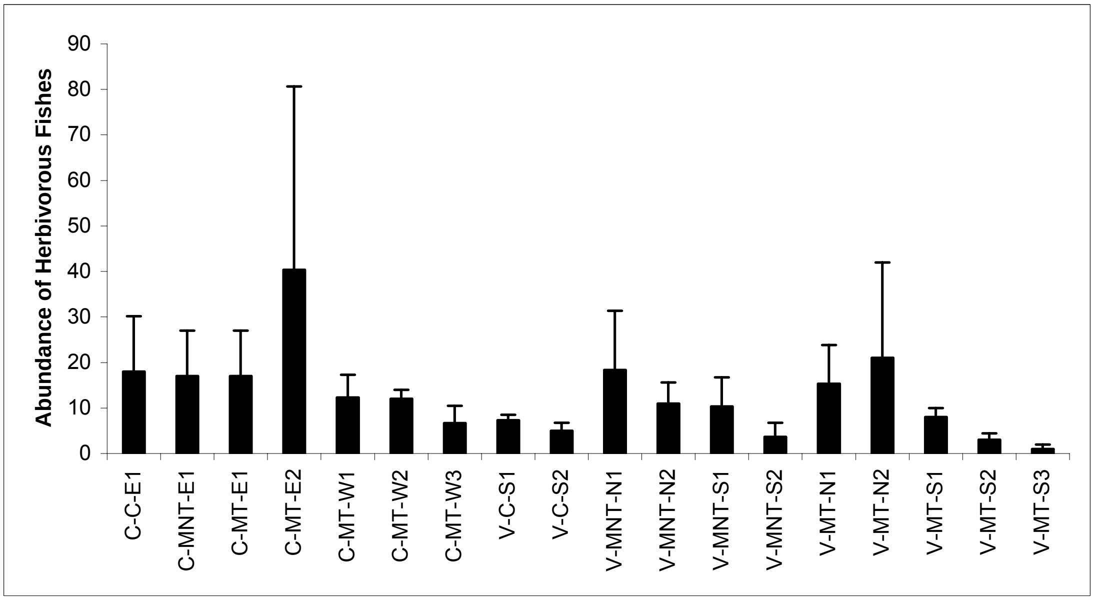

Figure 23. Mean abundance (± *SD*) of herbivorous fishes per site at Culebra (C) and Vieques (V) (three stationary counts per site, except two counts at site V-MT-S2).

Herbivorous fish species were also characterized by the average number of species observed among the three sampling stations per study site (**Figure 24**). On average, there were less than four herbivorous fish species per site (3.8 ± 0.2 *SE*, *n* = 18). The redband parrotfish (*Sparisoma aurofrenatum*) and the stoplight parrotfish (*Sparisoma viride*) were each observed in 17 of the 18 study sites. In contrast, the redtail parrotfish (*Sparisoma chrysopterum*) and the yellowtail parrotfish (*Sparisoma rubripinne*) were each observed in only one of the study sites. The most abundant herbivorous fishes were the stripped parrotfish (*Scarus iseri*; 181 observations over 14 sites) and the blue tang (*Acanthurus coeruleus*; 147 observations over 15 sites) (**Table 27**).

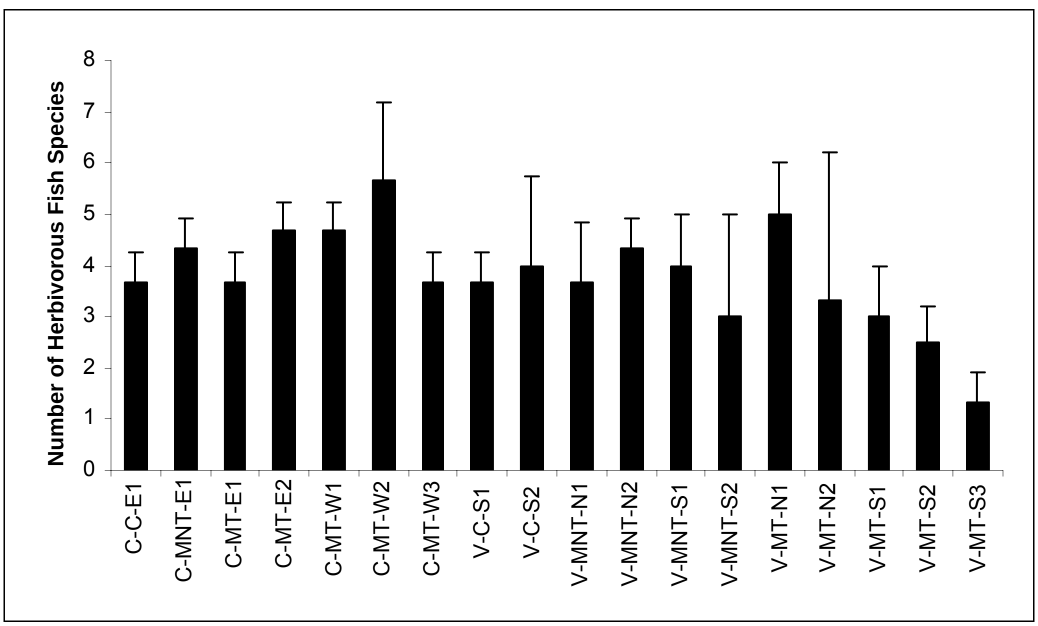

Figure 24. Herbivorous fish species (mean number of species per sampling station) at 18 study sites around Culebra (C) and Vieques (V).

Table 27. Abundance of herbivorous fishes per site at Culebra (C) and Vieques (V) (three stationary counts per site except two at site V-MT-S2).

SPECIES	C-C-E1	C-MNT-E1	C-MT-E1	C-MT-E2	C-MT-W1	C-MT-W2	C-MT-W3
Blue tang	1	7	0	81	5	7	4
Doctorfish	0	0	0	0	0	0	0
Ocean surgeonfish	1	14	0	3	11	8	5
Princess parrotfish	0	0	1	0	0	2	0
Queen parrotfish	0	1	0	0	0	0	0
Redband parrotfish	13	10	9	16	13	9	8
Redtail parrotfish	0	0	2	0	0	0	0
Stoplight parrotfish	5	1	1	8	1	2	2
Striped parrotfish	34	14	2	12	8	11	1
Yellowtail damselfish	0	4	0	1	0	2	0
Yellowtail parrotfish	0	0	0	0	1	0	0
Total	54	51	15	121	39	41	20

SPECIES	V-C-S1	V-C-S2	V-MNT-N1	V-MNT-N2	V-MNT-S1	V-MNT-S2	V-MT-N1	V-MT-N2	V-MT-S1	V-MT-S2	V-MT-S3
Blue tang	2	1	7	4	2	0	7	13	5	0	1
Doctorfish	0	0	0	2	0	0	0	0	0	3	2
Ocean surgeonfish	7	4	31	5	10	3	10	3	13	0	0
Princess parrotfish	0	2	0	0	3	0	0	0	0	0	0
Queen parrotfish	0	0	0	0	0	1	0	0	0	0	0
Redband parrotfish	9	3	6	10	11	6	4	0	0	1	4
Redtail parrotfish	0	0	0	0	0	0	0	0	0	0	0
Stoplight parrotfish	1	3	1	1	1	2	9	21	3	2	0
Striped parrotfish	4	3	0	8	8	0	23	45	0	8	0
Yellowtail damselfish	0	4	1	2	0	1	8	3	2	0	0
Yellowtail parrotfish	0	0	0	0	0	0	0	0	0	0	0
Total	23	20	46	32	35	13	61	85	23	14	7

Diversity and evenness of herbivorous fishes – The diversity of herbivorous fish species ranged from 0.82 and 0.42 (**Table 28**). There were no obvious trends in terms of the amount of diversity by site category (civilian, military target, and military non-target). The diversity at sites V-MT-N2, V-MT-S1, V-MT-S2, and V-MT-S3 was consistently significantly less than at V-C-S2, C-MT-W2, V-MNT-N2, V-MT-N1, and C-MNT-E1 (*t* test, following Hutcheson [1970]; **Table 29**).

Table 28. Species diversity (Shannon-Wiener index, *H'*) of herbivorous fishes found at 18 study sites around Culebra (C) and Vieques (V) (three stationary counts per site except two at site V-MT-S2).

Site	H'	Site	H'
V-C-S2	0.815398	V-MNT-S2	0.598379
C-MT-W2	0.7594	V-MT-N2	0.523476
V-MNT-N2	0.744777	C-MT-E1	0.5233
C-MNT-E1	0.7190	V-MT-S1	0.491748
V-MT-N1	0.712271	V-MT-S2	0.484832
V-MNT-S1	0.666541	C-MT-E2	0.4674
C-MT-W1	0.6512	C-C-E1	0.4352
C-MT-W3	0.6145	V-MNT-N1	0.42761
V-C-S1	0.600242	V-MT-S3	0.415055

Table 29. Results of t test comparisons of herbivorous fish diversity at 18 study sites around Culebra (C) and Vieques (V).

Site	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S1	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
C-C-E1																		
C-MNT-E1	ns																	
C-MT-E1	ns	ns																
C-MT-E2	ns	P<0.001	ns															
C-MT-W1	ns	ns	ns	ns														
C-MT-W2	ns	ns	ns	ns	ns													
C-MT-W3	ns	ns	ns	ns	ns	P<0.02												
V-C-S1	ns	ns	ns	ns	ns	P<0.01	ns											
V-C-S2	ns	ns	ns	ns	ns	ns	ns	ns										
V-MNT-N1	ns	P<0.001	ns	ns	P<0.002	P<0.001	P<0.02	P<0.02	P<0.001									
V-MNT-N2	ns	ns	ns	ns	P<0.02	ns	ns	ns	ns	ns								
V-MNT-S1	ns	ns	ns	ns	P<0.02	ns	ns	ns	P<0.005	ns	ns							
V-MNT-S2	ns	ns	ns	ns	ns	ns	ns	ns	P<0.01	ns	ns	ns						
V-MT-N1	ns	ns	ns	ns	ns	ns	ns	ns	P<0.02	ns	ns	ns	ns					
V-MT-N2	ns	P<0.001	ns	ns	ns	P<0.001	ns	ns	P<0.001	ns	P<0.001	P<0.01	ns	P<0.001				
V-MT-S1	ns	P<0.002	ns	ns	ns	P<0.001	ns	ns	P<0.001	ns	P<0.002	P<0.02	P<0.001	P<0.002	ns			
V-MT-S2	ns	P<0.01	ns	ns	ns	P<0.005	ns	ns	P<0.005	ns	P<0.01	ns	ns	P<0.01	ns	ns		
V-MT-S3	ns	P<0.05	ns	ns	P<0.02	P<0.002	ns	ns	P<0.001	ns	P<0.05	P<0.02	P<0.001	P<0.005	ns	ns	ns	

Legend:

“ns” = “not significant” (i.e., no significant difference between the two sites).

There was a lower evenness of herbivorous fishes at sites C-C-E1 and V-MNT-N1 compared with other sites (**Figure 25**). These sites also figured among those with the lowest diversity in herbivorous fishes (**Table 28**). Yet, there were no apparent differences between mean evenness values by site category. Mean evenness was 0.82 for all civilian sites, 0.83 for all military target sites, and 0.81 for all military non-target sites.

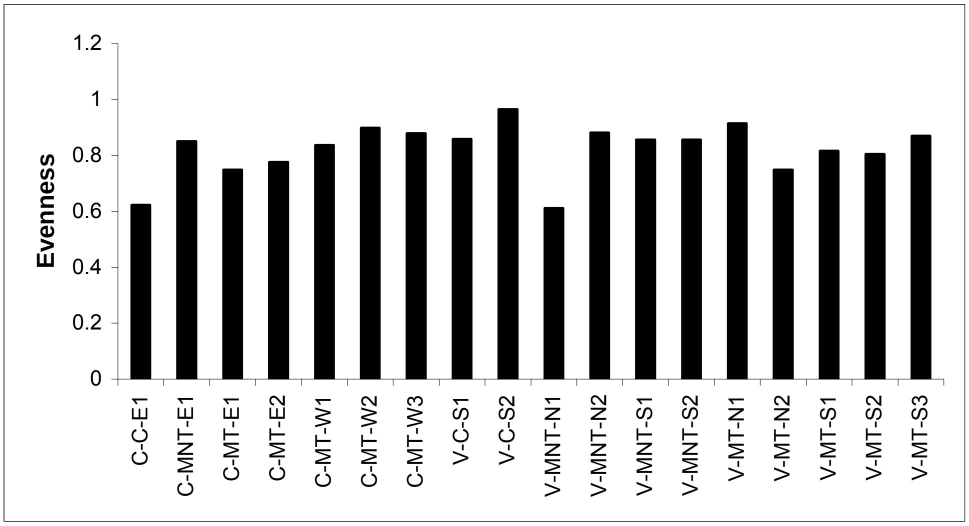

Figure 25. Herbivorous fish species evenness (relative diversity) at 18 study sites around Culebra (C) and Vieques (V).

Mean length – The mean length of herbivorous fishes by site was determined using the weighted average length (**Figure 26**). Small herbivorous fishes characterized all study sites.

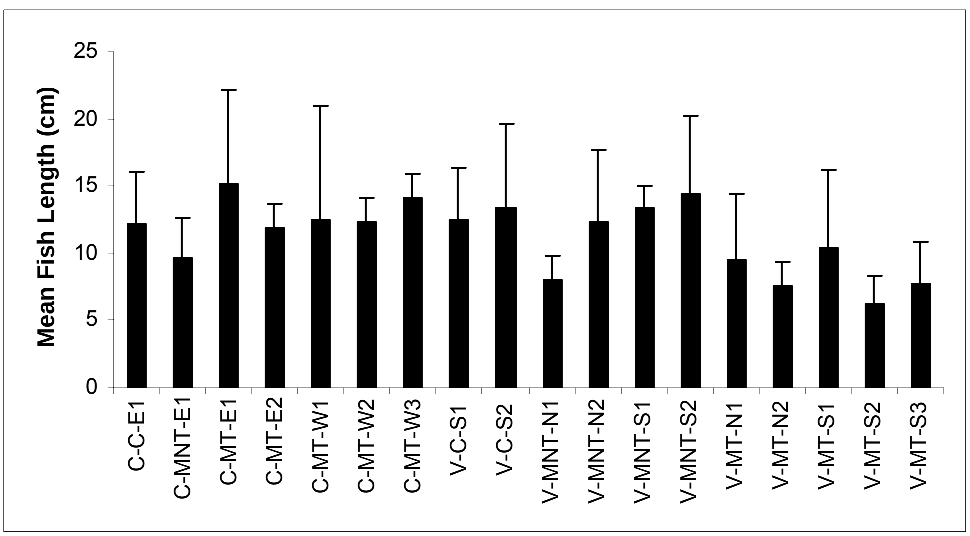

Figure 26. Herbivorous fish mean length at 18 study sites around Culebra (C) and Vieques (V).

3.4 WATER QUALITY

Temperature, salinity, dissolved oxygen, pH, and turbidity were measured at all sites except site V-MNT-S1 (**Table 30**). No data were collected at site V-MNT-S1 because of equipment failure. Readings were recorded every 20 minutes during the visit to each study site. On average, six data points per parameter

Table 30. **Water quality parameters collected at 17 study sites around Culebra (C) and Vieques (V) (no data available at V-MNT-S1).**

Variable	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3
Depth (m)	3.8	2.8	3.9	3.0	2.7	5.4	2.8
Duration (min)	120	120	120	120	120	120	120
Temperature (ºC)	28.2 (28.1-28.4)	28.5 (28.4-28.5)	28.2 (28.1-28.2)	28.5 (28.5-28.6)	28.3 (28.2-28.3)	28.2 (28.2-28.3)	28.3 (28.3-28.4)
Salinity (ppt)	36.10 (36.06-36.14)	36.06 (35.99-36.11)	36.10 (36.03-36.17)	35.97 (35.96-35.98)	35.99 (35.98-36.00)	36.16 (36.15-36.17)	36.15 (36.12-36.16)
Turbidity (NTU)	1.6 (0.0-2.1)	2.9 (1.6-6.4)	2.0 (0.4-3.6)	0.3 (0.0-0.6)	1.0 (0.7-1.1)	0.6 (0.4-1.1)	1.2 (0.7-1.5)
Dissolved Oxygen (mg/l)	6.21 (6.12-6.29)	6.20 (5.99-6.46)	6.20 (6.08-6.31)	6.59 (6.35-6.83)	6.31 (6.23-6.41)	6.18 (6.15-6.22)	6.26 (6.13-6.36)
pH	8.00 (7.97-8.01)	8.02 (8.01-8.02)	7.99 (7.98-8.00)	8.04 (8.03-8.04)	8.00 (7.98-8.02)	8.00 (8.00-8.01)	8.02 (8.01-8.02)

Variable	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
Depth (m)	6.0	5.3	16.9	6.6	2.1	2.6	2.6	2.3	1.5	5.4
Duration (min)	120	100	20	100	120	100	120	120	80	120
Temperature (ºC) (range)	28.2 (28.1-28.2)	28.4 (28.4-28.4)	28.2 (N/A)	28.4 (28.4-28.4)	28.7 (28.7-28.8)	28.5 (28.5-28.5)	28.3 (28.1-28.4)	28.1 (28.1-28.2)	29.6 (29.5-29.6)	28.0 (27.9-28.2)
Salinity (ppt)	36.11 (36.10-36.13)	36.12 (36.11-36.13)	36.17 (N/A)	36.19 (36.18-36.20)	36.14 (36.13-36.16)	36.09 (36.06-36.10)	36.12 (36.11-36.14)	36.11 (36.09-36.13)	36.13 (36.12-36.14)	36.04 (35.87-36.09)
Turbidity (NTU)	5.0 (4.5-6.3)	4.7 (4.3-5.0)	3.1 (N/A)	2.8 (2.5-3.6)	0.4 (0.0-2.5)	4.8 (4.2-5.8)	3.3 (0.0-5.6)	5.7 (4.3-6.8)	11.9 (7.1-22.0)	8.5 (4.0-13.7)
Dissolved Oxygen (mg/l)	6.32 (6.24-6.36)	6.56 (6.51-6.59)	6.17 (N/A)	6.27 (6.23-6.30)	6.67 (6.61-6.72)	6.66 (6.56-6.75)	6.38 (6.17-6.55)	6.08 (5.98-6.18)	6.83 (6.35-7.25)	6.23 (5.92-6.45)
pH	8.00 (7.98-8.01)	8.04 (8.03-8.04)	8.00 (N/A)	8.02 (8.01-8.02)	8.01 (8.00-8.02)	8.05 (8.05-8.06)	8.03 (8.02-8.05)	8.01 (8.00-8.02)	8.07 (8.04-8.12)	8.01 (7.97-8.03)

were collected per site. At site V-MNT-N1, only one set of readings was collected. Except for turbidity, the mean value of a given parameter was almost identical between sites: seawater temperature = 28.39°C (± 0.08 *SE*), salinity = 36.10 parts per thousand (ppt) (± 0.01 *SE*), dissolved oxygen = 6.36 mg/l (± 0.05 *SE*), and pH = 8.02 (± 0.01 *SE*). Mean seawater turbidity was 3.50 NTU (± 0.73 *SE*) and the range of turbidity was 0-22 NTU for all sites (**Figure 27**). Sites that had a relatively broad range of turbidity included C-C-E1, C-MNT-E1, C-MT-E1, V-MNT-S2, V-MT-N2, V-MT-S2, and V-MT-S3 (**Table 30**). Sites that had a consistently above average turbidity (i.e., turbid sites) were all located at Vieques: V-C-S1, V-C-S2, V-MT-N1, V-MT-S1, V-MT-S2, and V-MT-S3. Sites with a consistently less than average turbidity (i.e., clear sites) were C-MT-E2, C-MT-W1, C-MT-W2, and C-MT-W3.

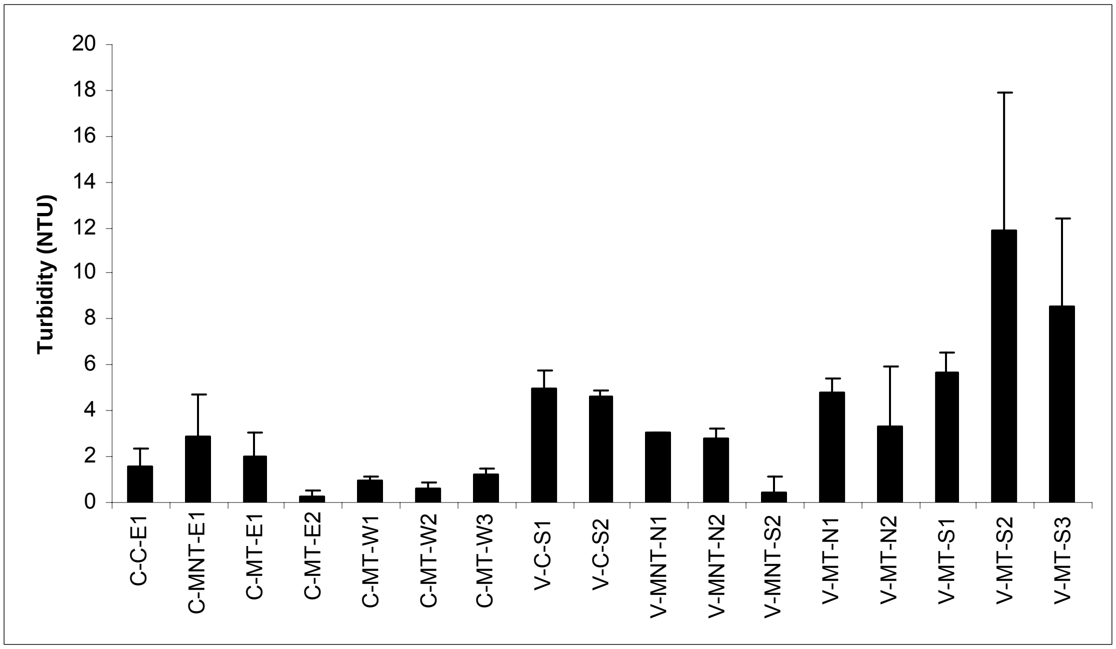

Figure 27. Seawater turbidity (NTU) (mean ± standard deviation) at 17 study sites around Culebra (C) and Vieques (V) (no data available at V-MNT-S1).

4.0 DISCUSSION

4.1 CONDITION OF FRINGING REEFS AT CULEBRA AND VIEQUES

The relative condition of the fringing reefs surveyed at Culebra and Vieques was determined using a composite of survey data on corals, fishes, algae, juvenile corals, echinoids, and herbivorous fishes. Specific survey data used here as proxy indicators of reef condition included percent coral cover, coral species richness, juvenile coral abundance, topographic complexity, fish species richness, fish abundance, herbivorous fish abundance, echinoid abundance, macroalgae cover, turf algae cover, incidence of coral diseases, and incidence of coral bleaching. To examine the relative condition of fringing reefs at Culebra and Vieques, we combined a Bray-Curtis distance measure with an Unweighted Pair Group Method with Arithmetic Averages (UPGMA) linkage method to perform a cluster analysis of the proxy indicators and to generate associated dendrograms (Sneath and Sokal 1973; McCune and Mefford 1999). Survey data that were particularly useful for the cluster analysis were those where significant differences between sites had been detected by ANOVA and then detailed by the respective Tukey test.

Two types of data were used for the cluster analyses: actual values (non-transformed) (Kramer 2003) and ranked/transformed values from significant Tukey groupings of study sites. Actual values were used in the first of three cluster analyses. Ranked/transformed data were used in the other two cluster analyses. The following example illustrates the use of ranked/transformed data. A Tukey test of parameter A at 18 sites revealed four significant groupings such that site 1 was significantly different from sites 2 through 18; sites 2, 3, and 4 were significantly different from 5 through 18; sites 5, 6, and 7 significantly different from 8 through 18; and sites 8 through 18 were not significantly different from each other. Parameter A was evaluated for its contribution to reef condition, such that the highest score (in this case "4") was attributed to the site associated with the best representation of that parameter. For example, parameters that correlated positively with reef condition included percent coral cover, coral species richness, juvenile coral abundance, topographic complexity, fish diversity, fish abundance, herbivorous fish abundance, and echinoid abundance. For each of these parameters, the highest score was assigned to the study site(s) with the highest mean value of the parameter. Parameters that correlated negatively with reef condition included macroalgae cover, turf algae cover, incidence of coral diseases, and incidence of coral bleaching. For each of these parameters, the lowest score was assigned to the study site(s) with the highest mean value of the parameter. The rank value for a given reef condition indicator for a given site was then numerically weighted by multiplying the grouping rank by the number of groupings divided by the number of sites. A cluster analysis was performed on these ranked and weighted values. The final data transformation involved assigning a biological weighting factor to the already ranked and weighted values. Those parameters that were deemed most diagnostic of reef condition – coral percent cover, fish abundance, and macroalgae cover – were multiplied by two to account for their ecological importance. The third cluster analysis was performed on these biologically weighted data.

Since the ranked values by site are unitless, the numerically weighted and numerically/biologically weighted values can be totaled to obtain relative indices of reef condition by site (**Tables 31**, **32**, and **33**). The reef condition index for the numerically weighted values ranged from 5.2 to 1.2 (mean = 3.2), and from 7.6 to 1.3 (mean = 4.2) for the numerically/biologically weighted values (**Table 33**). The highest reef condition index (best reef condition) was found at sites C-C-E1, C-MT-W2, and C-MT-W1, and the lowest reef condition index was associated with sites V-C-S1, V-MT-S1, and V-MT-S3 (**Table 33**). Sites with an "average condition" were V-MNT-N2, V-MNT-S1, V-MNT-S2, and V-C-S2. "Above average" sites were C-MT-E2, C-MT-W3, C-MNT-E1, and V-MT-S2. "Below average" sites were V-MNT-N1, V-MT-N1, C-MT-E1, and V-MT-N2. Overall, the Culebra study sites were in better condition than the Vieques sites, based on percent coral cover, coral species richness, juvenile coral abundance, topographic complexity, fish species richness, fish abundance, herbivorous fish abundance, echinoid abundance, macroalgae cover, turf algae cover, incidence of coral diseases, and incidence of coral bleaching as indicators of reef condition.

Table 31. **Numerically weighted values of reef condition indicators at 18 study sites around Culebra(C) and Vieques (V).**

Reef Condition Indicator	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3
Percent coral cover (%)	1.111	1.111	0.278	0.556	0.556	1.111	1.111
Coral species richness (n)	1.111	1.111	1.111	1.111	1.111	1.111	1.111
Juvenile hard corals (m^{-2})	0.167	0.000	0.167	0.167	0.167	0.333	0.167
Topographic complexity index	1.389	1.389	0.278	1.389	1.389	1.389	1.389
Fish species richness (n)	0.111	0.111	0.000	0.111	0.111	0.111	0.111
Fish abundance (n)	0.111	0.111	0.111	0.111	0.111	0.111	0.111
Macroalgae cove (%)	1.111	0.000	0.000	0.556	1.389	0.833	0.000
Turf algae cover (%)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Coral diseases (m^{-2})	0.000	0.000	0.000	0.000	0.111	0.000	0.000
Coral bleaching (m^{-2})	0.111	0.111	0.111	0.000	0.000	0.000	0.000

Reef Condition Indicator	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S1	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
Percent coral cover (%)	0.278	0.833	0.556	1.111	0.556	1.111	0.278	0.278	0.278	1.111	0.000
Coral species richness (n)	1.111	1.111	1.111	1.111	1.111	0.833	0.000	0.000	0.278	0.556	0.000
Juvenile hard corals (m^{-2})	0.167	0.167	0.000	0.000	0.167	0.000	0.000	0.000	0.000	0.167	0.167
Topographic complexity index	0.000	0.556	0.556	1.111	0.833	1.389	1.389	1.389	0.556	1.389	0.833
Fish species richness (n)	0.111	0.111	0.111	0.000	0.111	0.000	0.111	0.000	0.000	0.000	0.000
Fish abundance (n)	0.111	0.111	0.111	0.000	0.111	0.000	0.111	0.111	0.111	0.111	0.111
Macroalgae cove (%)	0.000	0.278	0.000	0.000	0.556	0.000	0.000	0.000	0.000	0.000	0.000
Turf algae cover (%)	0.000	0.000	0.000	0.000	0.000	0.000	0.167	0.000	0.000	0.333	0.000
Coral diseases (m^{-2})	0.000	0.000	0.000	0.000	0.000	0.000	0.111	0.111	0.111	0.111	0.000
Coral bleaching (m^{-2})	0.111	0.000	0.000	0.111	0.000	0.000	0.000	0.111	0.111	0.111	0.111

Table 32. Numerically/biologically weighted values of reef condition indicators at 18 study sites around Culebra(C) and Vieques (V).

Reef Condition Indicator	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3
Percent coral cover (%)	2.222	2.222	0.556	1.111	1.111	2.222	2.222
Coral species richness (n)	1.111	1.111	1.111	1.111	1.111	1.111	1.111
Juvenile hard corals (m^{-2})	0.167	0.000	0.167	0.167	0.167	0.333	0.167
Topographic complexity index	1.389	1.389	0.278	1.389	1.389	1.389	1.389
Fish species richness (n)	0.111	0.111	0.000	0.111	0.111	0.111	0.111
Fish abundance (n)	0.222	0.222	0.222	0.222	0.222	0.222	0.222
Macroalgae cove (%)	2.222	0.000	0.000	1.111	2.778	1.667	0.000
Turf algae cover (%)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Coral diseases (m^{-2})	0.000	0.000	0.000	0.000	0.111	0.000	0.000
Coral bleaching (m^{-2})	0.111	0.111	0.111	0.000	0.000	0.000	0.000

Reef Condition Indicator	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S1	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
Percent coral cover (%)	0.556	1.667	1.111	2.222	1.111	2.222	0.556	0.556	0.556	2.222	0.000
Coral species richness (n)	1.111	1.111	1.111	1.111	1.111	0.833	0.000	0.000	0.278	0.556	0.000
Juvenile hard corals (m^{-2})	0.167	0.167	0.000	0.000	0.167	0.000	0.000	0.000	0.000	0.167	0.167
Topographic complexity index	0.000	0.556	0.556	1.111	0.833	1.389	1.389	1.389	0.556	1.389	0.833
Fish species richness (n)	0.111	0.111	0.111	0.000	0.111	0.000	0.111	0.000	0.000	0.000	0.000
Fish abundance (n)	0.222	0.222	0.222	0.000	0.222	0.000	0.222	0.222	0.222	0.222	0.222
Macroalgae cove (%)	0.000	0.556	0.000	0.000	1.111	0.000	0.000	0.000	0.000	0.000	0.000
Turf algae cover (%)	0.000	0.000	0.000	0.000	0.000	0.000	0.167	0.000	0.000	0.333	0.000
Coral diseases (m^{-2})	0.000	0.000	0.000	0.000	0.000	0.000	0.111	0.111	0.111	0.111	0.000
Coral bleaching (m^{-2})	0.111	0.000	0.000	0.111	0.000	0.000	0.000	0.111	0.111	0.111	0.111

Table 33. Sum of numerically weighted and numerically/biologically weighted values of reef condition (RC) indicators at 18 study sites around Culebra (C) and Vieques (V).

Numerically Weighted		
Order	Site	RC Index
1	C-C-E1	5.222
2	C-MT-W2	5.000
3	C-MT-W1	4.944
4	C-MT-E2	4.000
5	C-MT-W3	4.000
6	C-MNT-E1	3.944
7	V-MT-S2	3.889
8	V-MNT-N2	3.444
9	V-MNT-S1	3.444
10	V-MNT-S2	3.333
11	V-C-S2	3.167
12	V-MNT-N1	2.444
13	V-MT-N1	2.167
14	C-MT-E1	2.056
15	V-MT-N2	2.000
16	V-C-S1	1.889
17	V-MT-S1	1.444
18	V-MT-S3	1.222

Numerically/Biologically Weighted		
Order	Site	RC Index
1	C-C-E1	7.556
2	C-MT-W2	7.056
3	C-MT-W1	7.000
4	C-MT-W3	5.222
5	C-MT-E2	5.222
6	C-MNT-E1	5.167
7	V-MT-S2	5.111
8	V-MNT-S1	4.667
9	V-MNT-N2	4.556
10	V-MNT-S2	4.444
11	V-C-S2	4.389
12	V-MNT-N1	3.111
13	V-MT-N1	2.556
14	C-MT-E1	2.444
15	V-MT-N2	2.389
16	V-C-S1	2.278
17	V-MT-S1	1.833
18	V-MT-S3	1.333

Of the seven study sites at Culebra, three ranked as having the best reef conditions, three ranked as above average sites, and one ranked as a below average site. For the 11 Vieques study sites, one site was above average, four were average, three were below average, and three had the worst reef conditions.

Vieques civilian sites had average and below average reef conditions indicating either that the civilian sites were as impacted as the military non-target and target sites or that the Vieques sites were different from the Culebra sites for some reason. If all the Culebra and Vieques sites had been identical before any human impacts, then the above comparisons between sites based on reef condition indices would suggest that Culebra target sites recovered from military impacts to a condition equivalent to sites outside the military bombing impact area (i.e., sites C-C-E1 and C-MNT-E1). Since the study sites did have different environmental settings (e.g., northern versus a southern exposure), varying degrees of isolation from human impacts, and different histories of bombing impacts, it is reasonable to identify the fringing reefs of Vieques (civilian and military sites) as being different from the Culebra sites mainly because of different environmental settings. Yet, Vieques military target sites V-MT-S1 and V-MT-S3 (**Figure 4**) had the lowest reef condition index values because they had been impacted by bombing practice (as inferred by the presence of ordnance and the proximity to bombing targets [**Figure 6**]) and exposed to multiple recent hurricane impacts. In contrast with these two sites, site V-MT-S2, although located well within the LIA, had an above average reef condition index. One possible explanation for this is that site V-MT-S2 was spared from bombing impacts as it lay close and immediately east of the Vieques Observation Post 1, a non-target military structure (**Figure 4**).

Three out of the four Vieques military non-target sites exhibited average reef conditions comparable or superior to the Vieques civilian sites. This may imply that the isolation of the military non-target sites benefited from their isolation from public use and physical impacts caused by bombing. The Vieques military target sites located on the north side of the LIA (V-MT-N1 and V-MT-N2) had below average reef conditions but better conditions than those located on the south side of the LIA. One possible explanation for this is the difference in target arrays and types of bombing: targets placed along the southern boundary of the Vieques LIA were concentrated and used for Naval gunfire support practice, whereas targets along the north shore were scattered (i.e., relatively isolated from one another) and used for ATG bombing practice.

The isolated bull's-eye ATG bombing target at site C-MT-E1 (Cayo Botella) (**Figure 3D**) had a below average reef condition that was comparable to the military target sites on the north side of the Vieques LIA (sites V-MT-N1 and V-MT-N2). The cumulative impacts of repeated bombing practice at Cayo Botella during the Vietnam conflict and of storm surge (Hurricanes David and Frederic in 1979; Hurricane Hugo in 1989), may have caused it to resemble the worst of the Vieques sites (sites V-MT-S1 and V-MT-S3). The remaining Culebra study sites, and in particular the former military sites, had above average to best reef conditions. The condition of site C-MT-W2 (west side of the Flamenco Peninsula) was as good as C-C-E1, the top-ranking site in terms of reef condition. A study site located along the east side of the Flamenco Peninsula would have probably yielded a lower reef condition index because the bull's eye ATG target and all Naval gunfire support targets were located closer to the eastern shoreline of the peninsula. Unfortunately, because of strong easterly winds, we could not operate at such a site during our survey. We did, however, observe ordnance at C-MT-W2 as proof of military training. Further, site C-MT-W3, located at Cayo Luis Peña and outside the former firing range, also contained several pieces of ordnance. Boaters, divers, and beachgoers currently utilize this site; on the day that we studied this reef, people were visiting the Cayo Luis Peña beach, and anchor scars and overturned coral heads were observed underwater.

The civilian site C-C-E1, located off the southeastern side of Culebra and usually exposed to storm surge, has apparently been spared from much of the human and natural disturbances that have affected the other 17 sites at Culebra and Vieques. Garrison et al. (2000) surveyed another civilian site at Culebra, Dewey Reef ("Site D"). It is located west of the town of Dewey, is removed from former military training operations, but is impacted by the effluent of raw and treated sewage. This site is characterized by low hard coral cover (8.9%), low spatial complexity, and a reef substrate dominated by macroalgae (Garrison et al. 2000). The Vieques civilian sites (sites V-C-S1 and V-C-S2), although relatively close to land and the town of Esperanza, had better reef conditions than Dewey Reef. We did not notice any evidence of anchoring damage at V-C-S1 and V-C-S2, despite these reefs being local dive sites (Dennis Johnson, personal communication). We did, however, notice an uncharacteristically high density of fish bites at the Vieques civilian sites, particularly concentrated on the dead stands of *A. palmata*.

The overall condition of each of the fringing reefs at the Culebra and Vieques study sites can be further examined using dendrograms of cluster analyses performed on reef condition values corresponding to the reef condition categories where significant differences were found between sites by category. Actual values of reef condition (**Table 34**), as well as values derived from ANOVA and Tukey test groupings (**Table 31**), can be used as the input for the cluster analyses. Actual values used here had different units, were non-additive, and could, therefore, not be used to produce a reef condition index. Yet the cluster analysis, based on actual values of reef condition, provided a useful means to visualize the relative similarity of the sites as a function of reef condition. The same was done using the ranked and weighted values.

The dendrograms of the two UPMGA analyses performed on the similarity matrices consisting of ranked and weighted values were identical (**Figure 28**; **Table 35**). The UPMGA analysis performed on the similarity matrix containing actual values yielded dendrogram clusters that were similar but not entirely congruent with those based on ranked and weighted values (**Figure 29**; **Table 35**). Therefore, the three UPMGA analyses produced two types of dendrograms. The dendrograms based on ranked and weighted values produced clusters that were more spread out than the clusters based on actual values. Further, seven of the sites (V-C-S2, V-MT-N2, C-MT-W3, V-MNT-S1, V-MNT-N2, V-MNT-S2 and V-MT-S2) did not cluster the same way in the two types of dendrograms. In all three dendrograms, the clusters formed by sites C-C-E1, C-MT-W2, C-MT-W1, and C-MT-E2 represented the most favorable reef conditions. The clusters formed by sites V-C-S1 and V-MT-S3 represented the least favorable reef conditions. Although the cluster analysis of actual values positioned sites V-C-S2 and V-MT-N2 among sites representing the best reef conditions, the cluster analysis of ranked and weighted values placed V-C-S2 and V-MT-N2 among sites with the least favorable reef conditions. Further, the cluster analysis of actual values clustered sites C-MT-W3, V-MNT-S2, V-MNT-N2, and V-MT-S2 at the lower end of reef conditions, while the cluster analysis of ranked and weighted values placed them in the “average” range.

Table 34. Actual values of reef condition indicators at 18 study sites around Culebra (C) and Vieques (V).

Reef Condition Indicator	C C-E1	C MNT-E1	C MT-E1	C MT-E2	C MT-W1	C MT-W2	C MT-W3
Percent coral cover (%)	27.67	14.33	5.67	9.00	10.33	27.00	12.00
Coral species richness (n)	9.67	8.67	11.67	10.17	13.83	12.67	11.17
Juvenile hard corals (m^{-2})	1.24	0.89	1.24	1.16	2.76	4.89	1.87
Topographic complexity index	0.51	0.44	0.22	0.41	0.38	0.40	0.34
Fish species richness (n)	3.67	4.33	3.67	4.67	4.67	5.67	3.67
Fish abundance (n)	56.33	71.67	43.67	105.67	59.67	84.33	32.33
Herbivorous fish abundance (n)	3.67	4.33	3.67	4.67	4.67	5.67	3.67
Macroalgae cove (%)	5.67	30.67	50.00	15.67	2.67	8.00	39.00
Turf algae cover (%)	51.67	35.67	34.33	57.33	45.33	51.00	33.33
Coral diseases (m^{-2})	0.44	0.89	0.27	0.53	0.00	0.18	0.71
Coral bleaching (m^{-2})	0.18	0.36	0.36	0.89	0.98	0.80	1.60

Reef Condition Indicator	V C-S1	V C-S2	V MNT-N1	V MNT-N2	V MNT-S1	V MNT-S2	V MT-N1	V MT-N2	V MT-S1	V MT-S2	V MT-S3
Percent coral cover (%)	4.00	11.67	10.33	12.67	6.33	18.33	2.67	5.00	4.33	23.50	2.33
Coral species richness (n)	11.33	10.67	10.17	12.83	13.50	6.67	4.67	3.50	7.50	4.75	4.00
Juvenile hard corals (m^{-2})	0.98	1.07	0.53	0.36	1.33	0.27	0.27	0.53	0.62	1.33	1.51
Topographic complexity index	0.19	0.24	0.24	0.29	0.26	0.47	0.41	0.42	0.23	0.30	0.28
Fish species richness (n)	3.67	4.00	3.67	4.33	4.00	3.00	5.00	3.33	3.00	2.50	1.33
Fish abundance (n)	40.33	62.33	40.67	22.00	44.33	23.00	41.00	76.00	50.67	22.00	28.33
Herbivorous fish abundance (n)	3.67	4.00	3.67	4.33	4.00	3.00	5.00	3.33	3.00	2.50	1.33

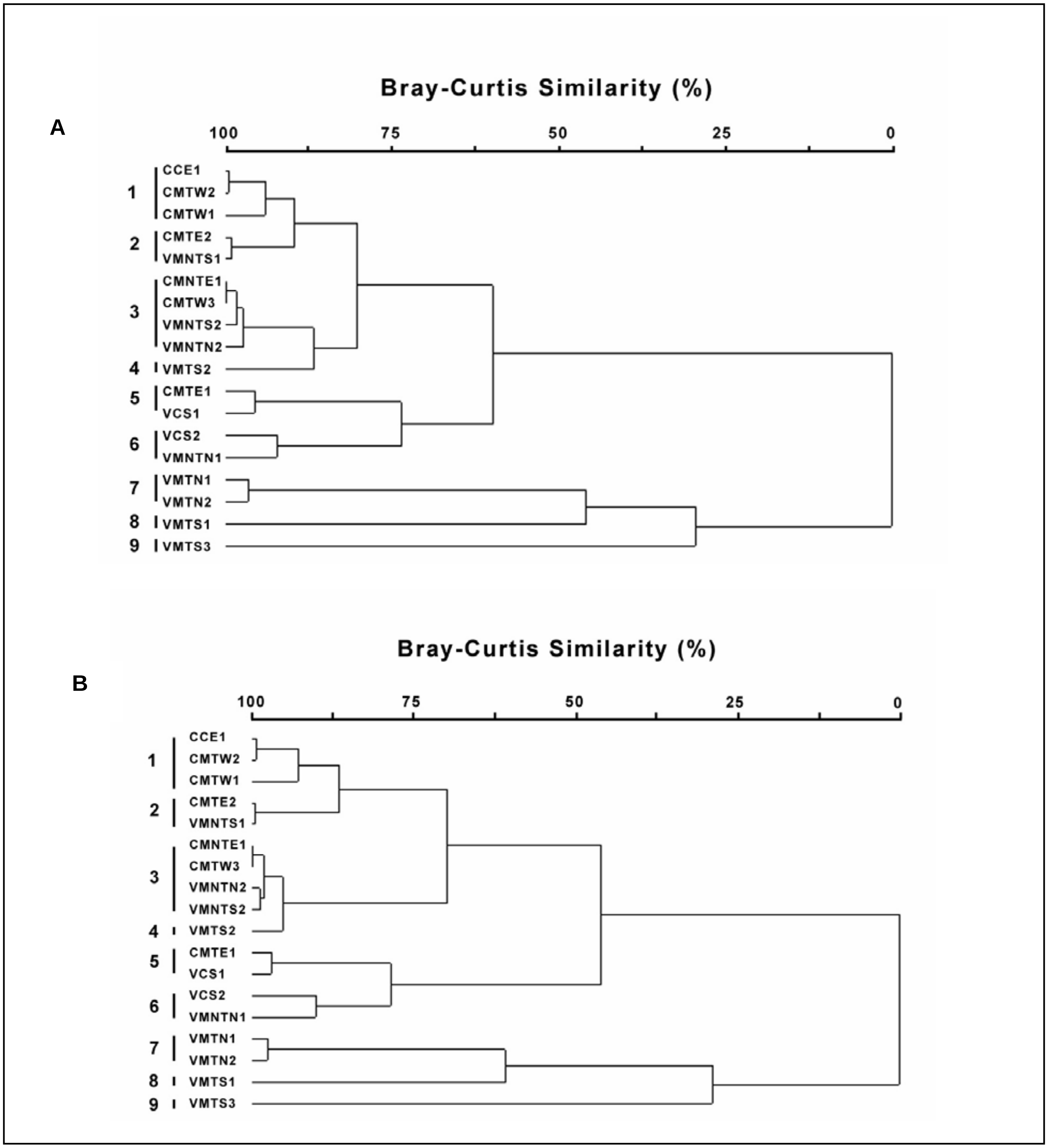

Figure 28. (A) Dendrogram of site similarity based on numerically weighted values of reef condition indicators at 18 study sites around Culebra (C) and Vieques (V). (B) Dendrogram of site similarity based on numerically and biologically weighted values of reef condition indicators at 18 study sites around Culebra (C) and Vieques (V).

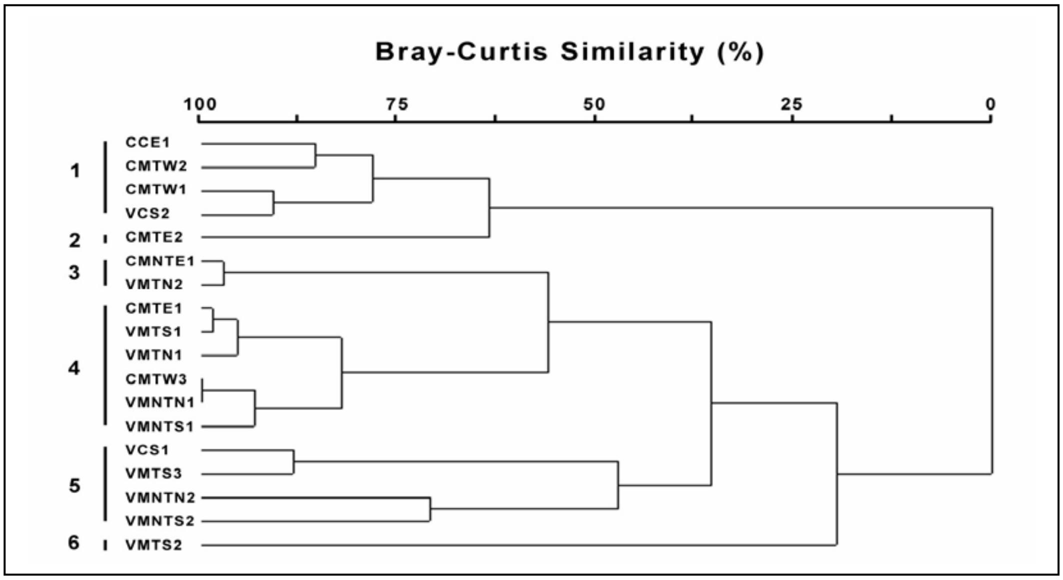

Figure 29. Dendrogram of site similarity based on actual values of reef condition indicators at 18 study sites around Culebra (C) and Vieques (V).

Table 35. Comparison of reef condition indicators clustering by UPGMA analysis of three Bray-Curtis similarity matrices at 18 study sites around Culebra (C) and Vieques (V): similarity matrix with actual values of reef condition indicators, similarity matrix with ranked and numerically weighted data, and similarity matrix with ranked and numerically and biologically weighted values.

Cluster	Actual Values	Ranked and Numerically Weighted Values	Ranked and Numerically and Biologically Weighted Values
1	C-C-E1 C-MT-W2 C-MT-W1 V-C-S2	C-C-E1 C-MT-W2 C-MT-W1	C-C-E1 C-MT-W2 C-MT-W1
2	C-MT-E2	C-MT-E2 V-MNT-S1	C-MT-E2 V-MNT-S1
3	C-MNT-E1 V-MT-N2	C-MNT-E1 C-MT-W3 V-MNT-S2 V-MNT-N2	C-MNT-E1 C-MT-W3 V-MNT-S2 V-MNT-N2
4	C-MT-E1 V-MT-S1 V-MT-N1 C-MT-W3 V-MNT-N1 V-MNT-S1	V-MT-S2	V-MT-S2
5	V-C-S1 V-MT-S3 V-MNT-N2 V-MNT-S2	V-C-S1 C-MT-E1	V-C-S1 C-MT-E1
6	V-MT-S2	V-C-S2 V-MNT-N1	V-C-S2 V-MNT-N1
7		V-MT-N1 V-MT-N2	V-MT-N1 V-MT-N2
8		V-MT-S1	V-MT-S1
9		V-MT-S3	V-MT-S3

In comparing Culebra and Vieques sites in the dendrograms, the Culebra sites (civilian, military target, and military non-target) generally clustered as sites with the most favorable reef conditions. Relative to the clusters of most favorable conditions, the Vieques sites generally clustered as sites with reef conditions ranging from average to worst. This corroborates the analysis based on the reef condition index.

4.2 COMPARING CIVILIAN, MILITARY NON-TARGET, AND MILITARY TARGET SITES

The UPMGA analyses of similarity matrices consisting of actual values and ranked values of reef condition by site produced dendrograms showing that the 18 study sites did not cluster cleanly into the three pre-designated categories (i.e., civilian, military target, military non-target) (**Figures 28** and **29**). With few exceptions, the UPMGA analyses done on similarity matrices consisting of averaged actual values and averaged ranked values by site type and island (civilian, military target, military non-target, Culebra, Vieques) produced dendrogram clusters suggesting island specific effects (**Figure 30**).

The dendrogram of the cluster analysis of the averaged actual values formed three clusters: (1) averaged Culebra and Vieques civilian sites, (2) averaged Culebra military target and military non-target sites, and (3) averaged Vieques military target and military non-target sites. This contrasted with the cluster analyses of the averaged ranked and weighted data: the Vieques and Culebra averaged ranked and weighted civilian sites did not belong to the same cluster. Also, the averaged ranked and weighted Vieques military target sites (V-MT) formed a separate cluster both for the numerically weighted and the numerically and biologically weighted values. Further, the averaged ranked and weighted values of the Culebra civilian and military target sites clustered together. The Culebra military non-target sites clustered with the Culebra civilian and military target sites for the cluster analysis of numerically weighted data but not for the numerically and biologically weighted data. For the latter analysis, the Culebra military non-target sites clustered with the Vieques military non-target sites (**Figure 30**).

Instead of producing clusters of site types, the two sets of UPMGA analyses based on site-specific and site type-specific reef condition indicators produced clusters without regard to *a priori* expectations. There are several potential explanations for this. Perhaps our analysis of the data reflects reality, in that at a scale larger than point impacts there is little to no correlation between reef condition and the history of military use of a particular location. The complexity of coral reef ecosystems makes assessments of reef health especially problematic. The parameters that were chosen for this study (e.g., reef fishes, corals) are logistically practical and intuitively obvious, and thus are fairly standard among coral reef biologists. However, "logistically practical" does not necessarily correlate, but could, with the "most appropriate measure of reef condition." There may be other reef organisms that may be more appropriate keystone or yardstick species from a biological standpoint. A different set of organisms may yield different conclusions. Also, a different methodology in data collection, or data analysis, may have different results. Given all these theoretical conundrums, the path we chose is the most defensible in that our methods parallel those of multitudes of coral reef researchers before us (and the theoretical issues with which they had to wrestle) and our data can be compared to other studies more readily than if we had charted an entirely independent course.

Perhaps the questions we are asking depend on different scales of observation, as so many questions in ecology do. If the fringing reefs off Vieques and Culebra were more similar to each other than to fringing reefs elsewhere in the Caribbean, maybe we could better appreciate the military impact on these two islands by comparing their overall datasets with similar data from other islands in the Caribbean. Fringing reefs throughout the Caribbean have been subjected to many natural and anthropogenic impacts, and many interesting comparisons could be made. Also, how do the fringing reefs of Vieques and Culebra compare to those of other islands that have been used for Navy target practice? For example, what is the health status of fringing reefs around Farallon de Medinilla (an island in the Northern Marianas still used for Navy target practice) (DON 2004)? What is the condition of fringing reefs around Kahoolawe and Kaula Rock, two islands in Hawaii used for Navy target practice (Steve Smith, personal communication)?

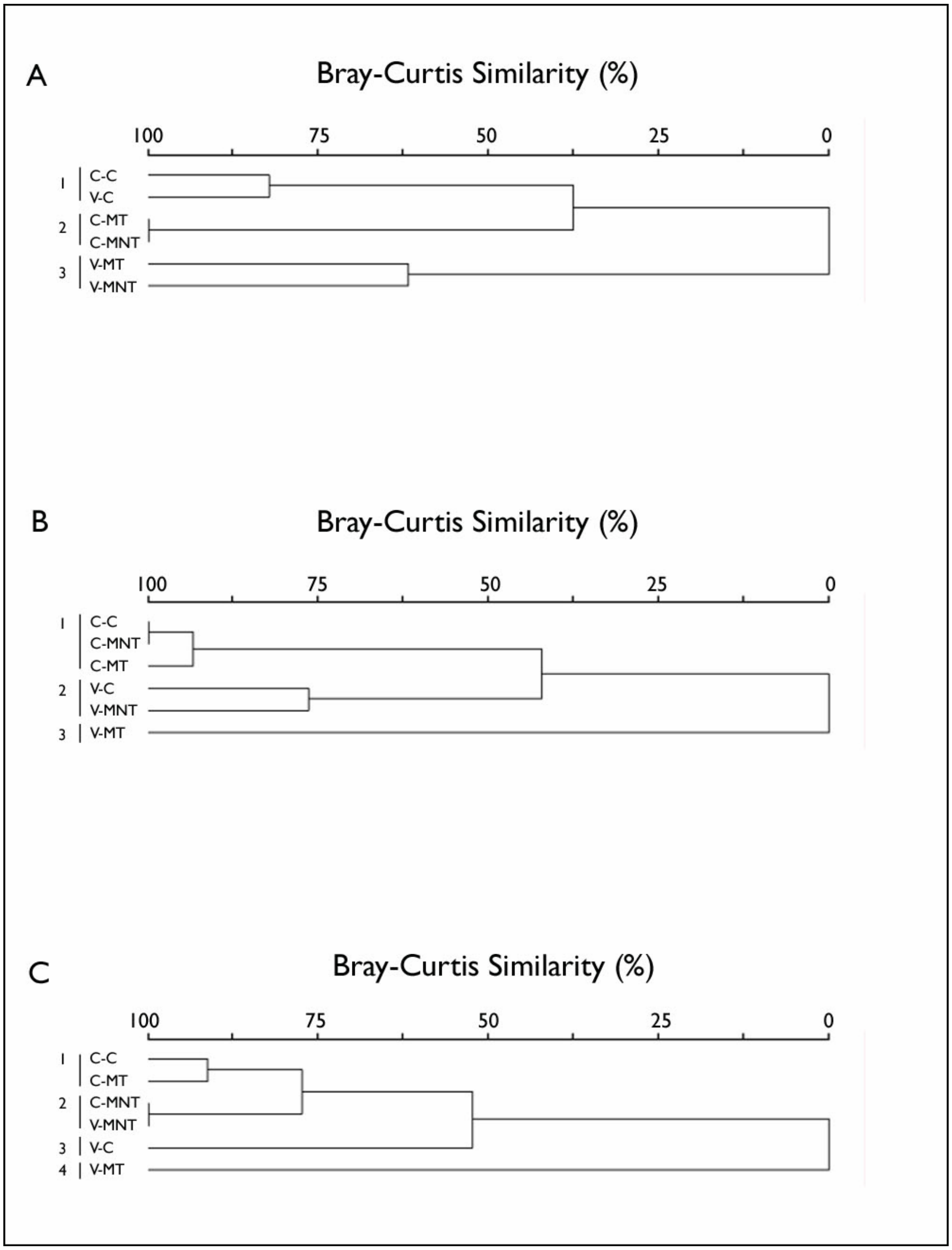

Figure 30. (A) Dendrogram of site type similarity based on averaged actual values of reef condition indicators by site type (civilian [C], military non-target [MNT], and military target [MT]) at 18 study sites) around Culebra (C) and Vieques (V). (B) Dendrogram of site type similarity based on averaged numerically and biologically weighted values of reef condition indicators by site type (civilian [C], military non-target [MNT], and military target [MT]) at 18 study sites around Culebra (C) and Vieques (V).

Ultimately, most of the questions addressed in this report involve a temporal scale. When questions of "impacts" are raised, what we really want to know is the before and after conditions surrounding a particular event (e.g., hurricane, bombing, etc.). Unfortunately, pre-impact assessments rarely exist and creative methodologies must attempt to account for past conditions. Looking to the future, it is crucial to compile as much data now to provide a baseline. As coastal development potentially looms on the horizon for Vieques, it is important to document the resources that stand to be lost.

4.3 MILITARY IMPACTS ON FRINGING REEFS AT CULEBRA AND VIEQUES

Over the years, some of the objective scientific discussion regarding the military's (Navy's) impact on the environmental health of Vieques and Culebra has been overshadowed by subjective political and sociological debate. Despite studies to the contrary (e.g., Raymond and Dodge 1980; Dodge 1981; Antonius and Weiner 1982), the general public maintained that the Navy's activities had caused permanent and irreparable damage to all the coral reefs and marine ecosystems within the Navy's potential sphere of impact. For example, the residents of Vieques expressed concern about the health effects of eating fish caught around Vieques, to the point where a study was commissioned by the Agency for Toxic Substances and Disease Registry (ATSDR 2003). The general public believed that Navy activities had somehow caused increased and unsafe levels of metal contaminants in food fishes (DuBow 2004). The perceptions of the public proved to be unfounded; food fishes (including those caught around the LIA and near the wreck of the ex-USS Killen) were found safe to eat, even on a daily basis (ATSDR 2003). Another public fear was that the ex-USS Killen was emitting unsafe levels of radiation. In truth, the radiation levels from the wreck were indistinguishable from background levels and posed no public health hazard (ATSDR 2003). Despite the scientific results, suspicion and distrust of the military remains high on Vieques and Culebra.

Supposedly objective scientists are not immune from the socio-political climate. For example, Garcia et al. (2000) wrote, "In the particular case of Culebra and Vieques islands, historical bombing during military training activities have caused severe destruction of coral reef fisheries and reef frameworks…. Most coral reefs located in the eastern half of the 35 km long Vieques Island are still suffering from the impacts of military training activities." These statements (and others) by Garcia et al. (2000) are diametrically opposite the findings of Antonius and Weiner (1982) and other studies. Also, it is misleading to imply that all former military lands (i.e., "… the eastern half of … Vieques ….") have been affected. There are over 116 km (72 mi) of shoreline on 35 km (22 mi) long Vieques Island, 72 of which wrap around the former Navy lands of eastern Vieques; of those 72 km (45 mi), only 8.7 km (5.4 mi) are adjacent to the former LIA. Thus, the former LIA shoreline (i.e., the shoreline potentially affected by Navy bombing) comprises only 12% of the shoreline around eastern (i.e., formerly Navy-owned) Vieques.

Coral reefs around the world are continuing to decline due to steadily increasing threats from direct human pressures and indirect pressures of global climate change (Wilkinson 2002; Hughes et al. 2003). The coral reefs around Puerto Rico are typical in this respect, as most reefs are highly degraded due to a variety of anthropogenic causes (Garcia et al. 2000; Causey et al. 2002). The present status of Puerto Rican coral reefs is among the most critical in the Caribbean (Causey et al. 2002).

4.4 PROTECTING THE REEFS OF CULEBRA AND VIEQUES

The designation of former Navy lands as a USFWS national wildlife refuge is probably not enough to protect them. Enforcement will most likely have to go hand-in-hand with protection. Also, public education is crucial in creating a stakeholder mentality in the local populace. Local organizations that are currently providing community education on coral reef conservation are CORALations, based on Culebra (CORALations 2004) and the Vieques Conservation and Historical Trust (VCHT 2004). In addition to education, CORALations has been a proponent of fisheries management (including marine reserves) and the establishment of mooring buoys.

One mitigating factor in the worldwide destruction of coral reefs is the establishment of marine protected areas (MPAs) (Wilkinson 2002). The benefit of MPAs, especially as a haven for reproductive fishes, has been well documented (Johnson et al. 1999; Roberts et al. 2001). The conservation value of MPAs is not limited to within the boundaries of the reserve, but rather extends into adjacent areas as well (Roberts et al. 2001). Biological responses inside marine reserves appear to develop quickly and last through time (Halpern and Warner 2002).

Coastal marine areas, whether protected or not, have traditionally been perceived by user groups (particularly fishermen) as areas of open access. This has created problems of enforcement, even within MPAs. The beneficial effects of MPAs have been shown to fall short in the absence of appropriate enforcement. Despite educational efforts targeting fishermen, lauding the fisheries benefits of MPAs, individual fishermen selfishly break the rules to profit in the short term. Little regard is given to the nature of the reproductive biology of commercially important fishes, and to how critical it is to have reserve areas where fishes of an appropriate age and size can contribute to the recruitment of both the reserve and outlying areas. Dramatic evidence of the fishermen's myopia is the extinction of many spawning aggregations of groupers throughout the Caribbean (Domeier et al. 2002).

The success of MPAs lies in the enforcement of the rules that govern the reserve. Various user-groups cannot be expected to act in a conservation-minded fashion in the absence of enforcement (Hardin's [1968] "The tragedy of the commons" examines human behavior and natural resources). Enforcement in civilian areas is particularly problematic, as resources (e.g., personnel, equipment, money) are usually quite limited. In contrast, military areas, by virtue of their greater security, already have an enforcement infrastructure in place. Although marine areas immediately adjacent to military lands may or may not be designated as MPAs, many such marine areas are de facto MPAs due to their proximity to military lands and the associated security enforcement. Such "conservation zones," existing as secondary effects from primary military activities, are common at many military bases. For example, the largest remaining old-growth stand of longleaf pine (*Pinus palustris*) is at Eglin Air Force Base (Eglin Air Force Base 2001), and the Marine Corps Base – Hawaii provides safe haven for over 50 species of waterbirds, including all four of Hawaii's endangered waterbirds (Drigot 2000). Much of the quality of terrestrial and marine ecosystems at Vieques is directly due to the sequestering of large tracts of land by the Navy for many decades. The transfer of land from the Navy to the USFWS should help protect the terrestrial environment of Culebra and Vieques. The establishment of MPAs should do the same for the marine environment. In December 1999, the government of Puerto Rico declared a marine reserve around Cayo Luis Peña and northwestern Culebra (Garrison et al. 2000).

4.5 Overall Assessment of the Fringing Reefs at Culebra and Vieques

Despite decades of training exercises by the U.S. military on Vieques and Culebra, the fringing reefs around the military portions of these islands appear to be just as healthy as the marine areas off non-military (i.e., civilian) sectors. Negative impacts from such exercises, especially live-fire exercises, have probably been very localized in areas adjacent to bombing targets of the LIA (e.g., Bahia Salina del Sur, Vieques). Because the areal extent of the former military lands greatly exceeded the area of the LIAs, much more shoreline and adjacent reefs and seagrass meadows were probably protected than were impacted. Although not expressly forbidden in waters adjacent to military lands, deleterious human activities (e.g., fishing, diving, and anchoring) may have been diluted or excluded by the presence of the military and the schedule of military exercises. Also, the existence of the military base necessarily precluded civilian coastal development on military lands. On other islands in the Caribbean (mainland Puerto Rico is an excellent example), uncontrolled coastal development (e.g., commercial, residential, and recreational) has triggered a cascade of environmental degradation and ecological disasters. Our observation of a sanctuary-like effect from military presence is in concordance with the results of other studies (e.g., Dodge 1981; Antonius and Weiner 1982).

Damage to reefs adjacent to LIAs has certainly been documented. For example, Rogers et al. (1978) found increased cratering in bays and reefs associated with increased range activities from 1972 through 1978. Macintyre et al. (1983) documented destruction from naval bombardment of a *Porites*/*Acropora* community at the eastern end of the north shore of Bahia Salinas del Sur. However, other impacts to reefs have also been documented and in many cases these impacts are much more devastating than military activities. For example, storm waves from Hurricane David (1979) almost completely destroyed the entire north shore *Porites* community in Bahia Salinas del Sur, along with most of the *Acropora palmata* on the south coast of Vieques (Raymond and Dodge 1980; Macintyre et al. 1983). For Culebra, Garrison et al. (2000) noted impacts such as coral diseases (e.g., white-band disease in the late 1970s and early 1980s), the *Diadema* die-off of 1983, hurricanes (e.g., David and Frederic in 1979, Hugo in 1989, and Marilyn in 1995), ship anchors, ship groundings, sediment runoff (exacerbated by poor civilian land management practices), sewage input, and overfishing. In the litany of coral reef impacts, military impacts are relatively minor compared with other factors, both natural and anthropogenic.

The population structure of reef organisms is often expressed as "percent cover" of a given taxon. Two of the major taxonomic groups examined by many coral reef researchers are corals and macroalgae. One of the most dramatic trends over the past 30 years has been the apparent shift in dominance from hard corals (scleractinians) to macroalgae on Caribbean reefs in the early 1980s (Hughes 1994; Aronson and Precht 2001). Coral cover was observed as high as almost 60% at Discovery Bay, Jamaica in 1977, but by 1982 had dropped to less than 10%; coral cover has not been above 10% since then (Aronson and Precht 2001). In 1978 off Vieques, Rogers et al. (1978) observed coral covers ranging from 0 to 63% ($\bar{x}$ =19% over 16 transects). Off Culebra and Vieques, about half of our study sites had coral covers less than 10%, while no site had more than 27% coral cover (**Figure 9**). Also, more than half our sites had macroalgae covers of over 30% (**Figure 10**). These observations support Aronson and Precht's (2001) contention of a phase shift from coral dominance to macroalgae dominance in the Caribbean in recent years. Even remote offshore reefs of Belize, presumably removed from the effects of overfishing and anthropogenic nutrient loading, have experienced such a phase shift (McClanahan et al. 1999). Interestingly, coral reefs at the Flower Garden Banks National Marine Sanctuary in the Gulf of Mexico still support relatively high coral covers (~50%) and low levels of macroalgae (<10%) (Pattengill-Semmens and Gittings 2003).

Reef fishes were characterized in this study by abundance, species richness, and mean length. The value of each parameter was considered positively correlated to reef "health" or "condition." The species composition of reef fishes in our study was similar to other surveys conducted at Culebra and Vieques (REEF 2004), with the bluehead wrasse (*Thalassoma bifasciatum*) the most abundant species in our case. Few large fish were seen, and the mean fish length per site was always low (<12 cm, <4.7 in). This is increasingly typical of other sites around the Caribbean (and worldwide) and is symptomatic of overfishing. The paucity of large individuals is particularly alarming for recruitment; large females have a tremendously disproportionate contribution to a population's reproductive output. Without large individuals, stock recovery is more difficult and population viability is more tenuous.

Overall, the Culebra sites we surveyed appeared to be in better condition when considering the sum of the proxy indicators of reef condition (corals, fishes, algae, juvenile corals, echinoids, and herbivorous fishes) (**Table 33**). Yet, the Culebra sites contained more incidences of coral maladies than the Vieques sites. The UPMGA analyses on similarity matrices consisting of proxy indicators of reef condition suggest that the reefs of Culebra and Vieques are different types of reefs or reef environments (**Figures 28**, **29**, and **30**). Turbidity was the only environmental parameter that was consistently higher at Vieques during the course of our survey (**Figure 27**; **Table 30**). More turbidity data from Vieques and Culebra would be needed to verify that Vieques fringing reefs are consistently bathed by water that is naturally more turbid than at Culebra. Although reefs can function under turbid conditions, turbidity negatively affects their level of development (e.g., Kleypas 1996). Sedimentation rates on Vieques nearshore reefs (fringing and crest) are significantly greater than in deeper reefs (18 m water depth) (DON 2003b). Further, sedimentation rates on nearshore reefs at Vieques do not differ between the LIA and the EMA, and do not differ between the north and south sides of the island (DON 2003b). One possible explanation for the differences in turbidity levels we observed between Culebra and Vieques maybe different nearshore circulation (tidal currents) as it affects sediment resuspension.

Within the Culebra reef complex and in terms of overall reef condition, sites located in areas of former military targets, including Cayo Botella (C-MT-W2) and Cayo Lobito (C-MT-W1), were comparable to the civilian site (C-C-E1) located outside of the former military training area (**Table 33**): relatively high coral cover, low macroalgal cover, high coral species richness, high topographic complexity, high abundance of juvenile corals and number of juvenile coral genera, low incidences of coral maladies, and high abundances of fishes and fish species. Within the Vieques reef complex, and again in terms of overall reef condition, military non-target sites V-MNT-N2 (Punta Campanilla), V-MNT-S1 (Bahia La Chiva), V-MNT-S2 (Bahia La Chiva) compared favorably with site V-MT-S2 (Bahia Salina del Sur), the Vieques reef site with the highest overall reef condition score (**Table 33**). The sites with the overall lowest reef condition score were V-MT-S1 and V-MT-S3 located at the southeastern edge of Bahia Salina del Sur and closest to military targets.

5.0 RECOMMENDATIONS

The waters around Culebra and Vieques are important economic, ecological, recreational, and esthetic resources. To maintain the value of these resources in all aspects, the resources must be **assessed**, **protected by law**, and **protected by enforcement**. To address these concerns, we recommend the following:

5.1 ASSESSMENT

Permanent monitoring stations—Permanent monitoring stations should be established on coral reefs around Culebra and Vieques. Permanent markers can be relatively inexpensive, low-tech, and easy to install (e.g., metal rods epoxied into drilled holes in dead coral). Permanent markers are crucial for temporal studies, in which changes to the reef are documented over time. Surveying and photographing the exact same spot over time changes can be detected. Stations should be established in areas of different levels of protection (e.g., no protection, partial protection, no-take zones). Vieques reefs contain such permanent monitoring sites in 18 locations: six in the EMA and 12 in the LIA (DON 2003b). Study designs should be rigorous enough to detect chronic impacts (Osenberg et al. 1992).

Number of study sites—The number of study sites should be maximized. Coral reefs are not distributed evenly along the coast, but rather are patchy. Even on a given reef, there are significant differences in structural complexity and biodiversity from one portion of the reef to the next. By increasing the number of study sites, a better reflection of reality will be generated from the collected data.

Spatial scale—The analysis of study sites should be made in such a manner as to answer questions of spatial scale. Some features of reef ecosystems are observable only at small scales, while others are detected at large scales (Aronson et al. 1994). Multi-scale approaches to study design and data analysis should be made to account for these differences.

Temporal scale—Study sites and monitoring stations should be evaluated over a long time frame. Natural and anthropogenic factors can function in both short and long time frames. Changes to the reef ecosystem can occur at rates not detectable by short-term studies. Monitoring studies should be long enough to detect long-term changes, but also frequent enough to detect short-term variations. For example, Connell et al. (1997) studied a reef in Australia for 30 years.

Catastrophic events—Surveys should be conducted, when possible, before and after catastrophic events (e.g., hurricanes). Given the importance of stochastic events to shaping the physical structure and biodiversity of coral reefs (e.g., Woodley et al. 1981), it is crucial to opportunistically collect data whenever significant disturbances occur. By having “baseline” information prior to a catastrophic event, the full impact of such an event can be measured.

Photographic transects—Photographic transects, using both video and still techniques, should be made of as many reefs as possible, especially of study sites and monitoring stations. Photographic surveys can be very cost effective, covering large areas in a relatively short period of time at a relatively low cost. Still photo transects should be converted into photo-mosaics. These products (i.e., videotapes and photomosaics) are valuable tools for research, public education, conservation, and marketing. As visual animals, humans are especially receptive to visual information. The photographic products should reflect several time scales. If changes occur, the evidence should be compelling (due to its visual nature) even to non-professionals.

Species identification—Species identification photographs should be taken on an opportunistic basis. Often, during underwater biotic surveys, biologists are forced to make a quick judgment as to the species identification of a given organism. By photographing problematic individuals, field identifications can be “ground-truthed” when back on land. Identification photographs can later be used for field guide materials in subsequent surveys, as well as in any educational materials that may be generated for public use.

Commercial/artisanal fishing—Surveys should be conducted of commercial/artisanal fishermen working off of Culebra and Vieques. Such surveys are crucial for determining the impact of fisheries activities on reef health. Ideally, the collected data would include weight landed by species, length/weight measurements of individual fish, location of catches, and gear employed. The number of fishermen, as well as their home ports and/or offloading ports, would first need to be determined. Surveys could be voluntary, or a mandatory component of the permit process. Some survey techniques include mail-in questionnaires, weighing and measuring catches at offloading sites, and observing fishermen while at sea. A long-term study would help determine the impact on fishing of various conservation activities (e.g., the establishment of fisheries regulations, the establishment of no-take zones, the increase of enforcement activities).

Recreational diving—Surveys should be conducted of charter dive operators working off of Culebra and Vieques. Such surveys are crucial for determining the impact of diving activities on reef health. Ideally, the collected data would include the number of dives per diver per dive site per day. Much of this information should already be available in log books kept by dive shops. Based on survey results, inferences about diver impacts at certain sites may be made. Also, recommendations about installing mooring buoys at popular sites may be made.

Sedimentation—Sediment loading of reef areas should be studied. High sediment loads can negatively impact reef corals. High loads are often symptomatic of poor land management practices and pollution controls. Sediment traps can be placed directly on the reef to measure the sediment influx onto the reef. Also, water samples can be collected at the mouth of rivers and streams to measure sediment loads from runoff. Turbidity can be easily and inexpensively measured (using a Secchi disk and/or turbidometer) to document the extent of coastal sediment plumes.

Land use—Land use patterns on Culebra and Vieques should be documented. As awareness increases on how land use affects neighboring coral reefs, data should be available to help develop mitigation strategies to decrease runoff of sediments and pollutants. Forestry and agricultural practices, as well as development (commercial, industrial, and residential), should be closely monitored.

Educational programs—Educational programs on marine conservation should be emphasized in the schools and communities of Culebra and Vieques. The inter-connectivity of all aspects of the environment should be emphasized. Ultimately, it is up to the citizens of Culebra and Vieques to be stewards of their own environment. Once a conservation ethic has been established in the local populace, environmental regulations and outside interference will be less necessary. On Culebra, community education on coral reef conservation is already available (CORALations 2004).

5.2 PROTECTION BY LAW

Fisheries management—Fisheries management regulations that prevent the severe ecological destruction of overfishing should be promulgated. Such regulations should include a combination of the following strategies:

- **Limited entry**: the number of fishermen should be regulated. Permits should be required for existing fishermen. New fishermen should only be permitted if the resource can be exploited at sustainable levels. If resource utilization is already beyond sustainable limits, permit fees should be set high enough to drive some fishermen out of the industry.
- **Seasonal closures**: The effects of overfishing are exacerbated by the harvest of reproductive individuals and by the targeting of breeding assemblages. Seasonal breeding cycles are typical of many reef fishes and other marine organisms. However, many of these species are particularly vulnerable to fishermen at these crucial times. Also, the harvesting of mature reproductive individuals has a much more destructive effect on recruitment than does the take of younger and non-reproductive individuals. Fishing should be prohibited during those times when reef fishes are breeding.
- **Area closures**: There are some regions of the coastal environment that are more crucial to the life history of fishes and other organisms than others. Specific locations are repetitively

used by organisms for feeding, breeding, and/or resting. In order to maintain healthy populations, these areas must be protected from the depredations of fishing and other human activities. If the areas are used by fishes on a seasonal basis perhaps fishing could be allowed during off-peak times.

- **Length/weight limits**: One sign of overfishing is the decrease in the average length and weight of harvested species. By setting higher length/weight limits, more individuals are allowed to reach maturity, recruitment is increased, and average sizes increase back towards natural levels.
- **Equipment restrictions**: Some fishing gear is too efficient at removing all individuals. Other gear is too non-selective and results in high levels of bycatch (i.e., species that are not targeted). Yet other gear is deadly to all organisms and does not allow for the release of unwanted individuals. Some gear and techniques are very destructive to the environment. Fishing gear and techniques should be developed (and required) such that there is minimal bycatch, non-targeted individuals can be released alive, and minimal collateral damage occurs to the environment.
- **No-take zones**: Certain marine areas should be established such that no deleterious human activities are allowed at any time of the year. These no-take zones should be large enough to support breeding assemblages of reef organisms, particularly commercially important species of fishes. Some analyses suggest that a minimum of 20 to 30% of the reef area should be designated as a no-take reserve (Bohnsack et al. 2000). The recovery of populations within no-take zones has a spill-over effect into adjacent areas, increasing the number and size of fishes available to fishermen.

Mooring buoys—Mooring buoys should be established along ecologically sensitive portions of the coast. Dive boats and fishing boats should be required to tie to a mooring buoy, rather than anchor (drifting would be allowed). The cost of placing and maintaining mooring buoys could be covered by a surcharge assessed to recreational divers (collected by dive shops and charter boats), as well as by a portion of the permit fee charged to dive charter boats and fishermen. Visitation rates per mooring buoy should be tracked such that visitation quotas can be established; over-visitation to certain sites can be mitigated through visitation quotas.

Recreational diving reef etiquette—Charter dive boat operators should be required, as part of their pre-dive briefings, to remind divers about proper reef etiquette (e.g., maintain neutral buoyancy; do not touch corals and other organisms; do not collect organisms, dead or alive; do not harass sea turtles, sleeping fishes, and other organisms). The collection of souvenir specimens should be made illegal.

Coastal development—Coastal development should be legally restricted in areas adjacent to sensitive coastal ecosystems. Resort, commercial, and residential development are each destructive to marine resources. Development often increases sediment and pollutant loads in runoff, and destroys coastal mangroves (with their filtering and buffering capacity). Such coastal development should be prohibited near MPAs. A regional coastal development plan should be adopted.

Point-source pollution—Point-source polluters should be required to treat effluents to environmentally safe levels. Sewage treatment plants and coastal industries can be relatively easily monitored (e.g., by testing samples from the outfall pipe) to ensure that steps have been taken to decrease pollutant loads.

Watershed management—Island-wide land management regulations should be instituted to decrease non-point-source pollution. In particular, forestry and agricultural practices should be regulated to decrease erosion and to decrease the use of pesticides and fertilizers. All watersheds should be mapped, and areas of potential impact should be modeled.

5.3 PROTECTION BY ENFORCEMENT

Fishing—Marine patrols should be greatly increased, especially in no-take zones. Fishermen should be monitored for adherence to permits, area/time closures, size limits, and gear. Without highly visible deterrents (and substantial penalties), the temptation to cheat is too great. Violators of fisheries regulations should be prosecuted and punished to the fullest extent of the law. The repercussions for violating the law should greatly exceed any economic benefit derived from ignoring the law. Violators should be fined, imprisoned, and/or have their boat confiscated.

Pollution—Point-source polluters can be monitored at outfall pipes. Violators can be fined if effluents are not in compliance with regulations. Non-point-source polluters are more difficult to track. Streams can be monitored for turbidity (due to increased erosion) and chemicals (e.g., pesticides, fertilizers). Sources can be identified by back tracking through the watershed. Violators should be fined.

Recreational diving—If dive operators are sympathetic to regulations on diver behavior, they can serve as a sort of "dive police" and help keep bad diver behavior minimized. It is incumbent on dive masters on charter dive boats to set the tone about proper underwater behavior and reef etiquette. Divers who blatantly ignore reef guidelines should have their diving privileges revoked.

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