University of Miami

An assessment of unreported boat grounding damage to shallow-water corals in the Florida Keys

Steven J. Lutz

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Abstract

The serious physical damage to corals from the occasional large ship grounding is a highly visible and major impact to coral reefs in the Florida Keys. However, smaller vessels continuously damage corals. Unreported damage caused by small vessels that are able to leave a grounding incident under their own power is underestimated.

In this study 315 shallow-water massive coral colonies from 49 reef sites within the northern Florida reef tract were examined for signs of boat grounding damage (propeller scars and boat hull scrapes). Boat grounding damage was found throughout the range but it appears that the extent of damage is not currently a threat to the overall health of corals in the northern Florida reef tract. However, shallow-water massive corals in two much-visited reef areas did show high signs of impact. If visits by small vessels continue to expand, the associated damage to localized reef areas could become serious.

Acknowledgments

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1.0 Introduction

1.1 Rationale

For thousands of years coral reefs have survived natural impacts, such as storms, diseases and predation. What they cannot withstand is the combination of these natural impacts with severe or repeated anthropogenic damage, such as overfishing, sedimentation, and excess nutrients. Reefs around Jamaica and San Andres have been devastated by this combination (Hughes, 1994; Hallock, 1993) and Florida reefs are being widely reported to decline (Porter and Meier, 1992; LaPointe, 1993). Indeed, according to Wilkinson (1992) South Florida's reefs are so 'threatened' that they may disappear in 20 to 40 years.

Anthropogenic impacts to corals can be divided into direct and indirect (Grigg and Dollar, 1990). Indirect anthropogenic impacts include poor water quality and high sedimentation rates (Glynn, 1989; Shinn, 1989; Ward, 1990; Cole, 1990; LaPointe, 1993; Dustan, 1997). These and other indirect impacts are currently under research throughout the Florida Keys. This study focuses on the incidence of direct physical damage to corals produced by small boat groundings in northern Florida Keys reefs. The focus is on the effects of boat collision due to carelessness and accidents, that result in physical abrasion and coral fragmentation. High profile shallow-water massive corals are susceptible to damage from careless boating around reefs due to their shallow surface depth. This damage is typified by narrow scars or nicks in coral surfaces due to contact with propeller skegs and boat hulls. Understanding the aggregate effects of physical damage by boaters, commercial and sport fisher persons, divers and snorkelers is important to revealing the carrying capacity of the Florida Key's coral resources.

This report is the first attempt to estimate the geographic distribution and severity of unreported boat groundings on shallow-water massive corals throughout the Florida reef tract.

1.2 Background

1.2.a Previous Research

1.2.a.1 Larger Vessel Groundings

For centuries, since the times of the first European explorers, large vessels have been crashing into Florida's reefs. Indeed, overgrown shipwrecks are major tourist attractions and some reefs, such as Alligator, Carysfort, and Looe Key Reef, are named for vessels that wrecked on them. Extensive research has been done on the damage and rehabilitation of larger vessel groundings (Dennis and Bright, 1988; Gittings et al, 1988; Causey, 1990; Wheaton et al, 1992; Miller et al, 1993). The initial impact crushes individual corals but this damage is inconsequential compared to the subsequent extensive destruction that can be caused by as large vessel stranded on a coral reef. For example, perhaps the most famous large vessel incident, the *Wellwood*, a 122m freighter, ran aground on Molasses Reef off Key Largo, in August 3, 1984, severely damaging 1500m^2 of reef by mechanical abrasion from the stranded ships hull. Table 1.2.a.1.1 lists some recent large vessel groundings in the Florida Keys:

Table 1.2.a.1.1

Some Recent Large Vessel Groundings in the Florida Reef Tract

Vessel	Size (ft)	Date	Location	Reef Impact
Ice Fog & barge	70	1973	Molasses Reef	Barge grounded on reef.*
Capt. Allen	60	1973	Middle Sambo	Aground on reef flat.*
Lola	110	1976	Looe Key	Aground on spur.*
Robby Dale	70	1977	Looe Key	Reported Aground.*
2 shrimp boats	-	1982	Looe Key Reef	Aground on spur.*
Wellwood	400	1984	Molasses Reef	4,865m^2 impacted.
Mini-Laurel	215	1984	Molasses Reef	513m^2 impacted.
Alec Owen Maitland	155	1989	Carysfort Reef	1610m^2 impacted.
Elpis	470	1989	Elbow Reef	3,073m^2 impacted.
Mavro Vetranic	475	1989	Dry Tortugas	3,465m^2 impacted.

* Impacted area not available.

(Jaap, 1984; Miller et al, 1993; Wheaton et al, 1992)

1.2.a. 2 Small Vessel Groundings

Previous studies of coral health have indicated that widespread damage may be caused by unreported small boat groundings (Dustan, 1977; Jaap, 1984; Voss, 1988; Causey, 1990; Tilmant, 1987; Tilmant and Schmale, 1982). However, no specific surveys have been done on this type of damage. For example, in the most comprehensive study to date, Tilmant and Schmale (1982), used 30 minute observation surveys of reefs with buoys and reefs without buoys to estimate coral damage in Biscayne National Park. They measured the incidence of cuts, scars and abrasions without encrusting overgrowth or apparent new growth along with other types of coral damage. Their general conclusion was that boat operation seriously affected large individual colonies and that the main cause was boat groundings. However, they found that a significant amount of "natural" physical damage also occurs during winter storms.

According to the Florida Department of Environmental Protection (Skinner, 1993; Deaton, 1995) there were 58 reported boat groundings on patch reefs in John Pennekamp Coral Reef State Park from 1983 through 1995. In total 17,335 ft^2 of patch reef was damaged, with an assessed value of $884,129.83. Frequency of boat groundings occurred seasonally, peaking in early summer (April through July), and coinciding with increased boat visitation. A general increase in boat groundings per year was noted. The main species of coral damaged was *Montastraea annularis* (*sensu lato*), due to its abundance and high profile. Mosquito Banks was found to be the most impacted area in the Park. The total number of groundings reported was considered conservative and represented only vessel grounding incidents actually witnessed by park officials, smaller vessels being assumed to have left the scene. For example, Deaton (1995) found 9 incidents of unreported damage while conducting other marine research.

1.2.b Policy and management

Corals are protected in all marine parks in the Florida Keys. The "removal or damaging" of corals is prohibited and all vessels are required to be operated in a manner that does not strike or damage natural features (Causey, 1990). Currently, the main deterrent to this type of damage is by fines and litigation. For example, assessed values of damage have ranged from $106.54 (an 8.8 ft^2 area of reef damaged containing *M. annularis*, by a 20' open fisherman boat on Mosquito Bank, in 1992) to $166,976.10 (a 1,261.0 ft^2 area of reef damaged containing *M. annularis*, *Porites astreoides*, soft corals, sponges, algae, and fire coral on Mosquito Bank, by a 42' cabin cruiser boat, in 1987). The rate of assessed value for damaged *M. annularis* in John Pennekamp Coral Reef State park, in 1994, was $263.17 per. square foot (Deaton and Duquesnel, 1996). Fines assessed per incident vary depending upon the extent of damage and the circumstances surrounding the incident.

The National Park Service has expressed concern over the amount of damage to shallow coral reefs caused by boat propellers, hulls, and keels (Biscayne National Park, 1996). They noted that while vessels rarely become stranded as a result of grounding on a reef the frequent sightings of broken coral indicates that coral reef groundings are seriously under-reported. The National Park Service identifies three categories of reef damage, see Table 1.2.b.1:

TABLE 1.2.b.1

National Park Service Coral Damage Classifications

Level I:	Damage has occurred to reef framework: This is evidenced by the obliteration of spurs and similar formations; cracks in reef framework; excavations caused by propeller; production of rubble, either directly by the ship or secondarily from reef matrix exposed to wave action. The likelihood of secondary damage is high if mediation measures are not implemented.
Level II:	One or more coral colonies have been destroyed. In this category individual colonies or "heads" are overturned, fractured ore obliterated; branches are broken. Although there is substantial damage to individual colonies there is little chance of secondary damage.
Level III:	Damage is limited to superficial scrapes of living tissue and/or broken small branches. In this category little chance is perceived of secondary damage.

(Biscayne National Park, 1996)

According to the Florida Keys National Marine Sanctuary (NOAA, 1996b) the placement of additional channel/reef markers is a high priority. 'Resource damage' is noted to be occurring in areas lacking these navigational aids. These markers are to be placed in well-defined and prioritized locations after preliminary assessments and recommendations are made. Additionally, the placement of additional mooring buoys is a high priority. Mooring buoys have been used as an effective management tool to minimize damage from boating activity, specifically anchoring, around reefs (NOAA, 1996b).

Small boat damage is also recognized by UNESCO in their Coral Reef Management Handbook (Kenchington and Salvat, 1988) as an impact from commercial and recreational vessels. It lists the threats of small boat groundings in the following table:

TABLE 1.2.b.2

UNESCO; threat of small boat damage to coral reefs

1. Small boats can cause considerable physical damage to shallow reef areas, particularly at low tide.
2. Inexperienced boat drivers can cause considerable physical damage to both reefs and their own boats.
3. On intensively used reefs a system to keep boats away from shallow, fragile areas may be necessary.

(Kenchington and Salvat, 1988)

1.2.c Vessel information

The reefs of the Florida Keys are a major attraction for the continuously growing number of permanent residents, seasonal residents, and tourists. This is evidenced in the intensity of boating activity supported by 163 marinas with 5,127 boat slips throughout the Florida Keys. In 1993 there were 19,441 boats registered in Monroe County, by 1994 this figure had risen by almost 1000 to 20,405 registered boats (Boating Research Center, 1994_1 and 1994_2). Many boats are trailered or motored down to reefs off the Florida

Keys. In 1974, in Dade, Broward, and Palm Beach counties combined, there were only 65,500 registered boats. In 1994 there were over 115,700 registered boats in these counties (FL. D.M.V., 1995; Boating Research Center, 1994b).

The purpose of this study was to examine the coral damage caused by recreational and commercial vessels classified by the US Coast Guard as class A (less than 16 ft.) and class 1 (16 ft to less than 26 ft.) (Boating Research Center, 1994b). The majority of registered vessels fall into these size classes. In Monroe and Dade counties class A and class 1 boats are mainly used for pleasure and commercial purposes and are typically driven by gasoline engines (Boating Research Center, 1994b). According to Tables 1.2.c.1 and 1.2.c.2, pleasure craft from 16 to 26 ft in length are the most likely vessel found in the Florida reef tract. These figures do not take into consideration the use from unregistered vessels, boats that are trailered down from other counties, and unregistered sailboats that have no motor.

TABLE 1.2.c.1

Length of Registered Boats in Dade and Monroe Counties, 1994

	Length in feet					
County	Less than 16	16 to 26	26 to 40	40 to 65	65 and over	Total
Dade	13,355	25,140	4,595	780	53	43,923
Monroe	5,818	11,172	27,62	618	35	20,405

(Boating Research Center, 1994a)

TABLE 1.2.c.2

Registered Boats in Dade and Monroe County, Propulsion and Use 1994

DADE COUNTY

(Length in feet)

	Less than 16	16 to 26	Total
PROPULSION			
Power	5,605	10,850	16,455
Other	213	332	545
Total	58,18	11,172	16,990
USE (Excluding Dealer + Canoes)			
Pleasure	4,951	9,249	14,200
Commercial	748	1,893	2,641
Total	5,699	11,142	16,841

MONROE COUNTY

(Length in feet)

	Less than 16	16 to 26	Total
PROPULSION			
Power	12,214	24,535	36,749
Other	1,141	605	1,746
Total	13,355	25,140	38,495
USE (Excluding Dealer + Canoes)			
Pleasure	12,774	24,035	36,809
Commercial	217	1,035	1,252
Total	13,355	25,140	38,495

(Boating Research Center, 1994a)

2.0 Setting

2.1 Marine milieu of the Florida Keys

The Florida coral reef tract is a discontinuous bank barrier reef. It curves northeastward, extending from the Dry Tortugas in the southeastern Gulf of Mexico to Fowey Rocks, close to Miami. The development of coral reefs and their distribution throughout the Florida Keys is strongly influenced by the amount of water exchange between the Straits of Florida and the continental shelf. In this regard the most important factor is landmass which acts as a barrier to water transport from Florida Bay and Biscayne Bay. Extensive reef development is found off areas of large land mass, such as Key Largo and Elliot Key (in the north) and from Big Pine Key to Key West (in the south), which protect them from the detrimental influence of Florida Bay waters. There is little reef development off the middle Keys, which have smaller landmass (Ginsburg and Shinn, 1964 and 1993; Shinn et al, 1989; Jaap and Hallock, 1990).

Two major types of reef are present in the Florida reef tract; (1) patch reefs; and (2) bank or outer reefs (Shinn, 1963; Voss 1988), see Figure 1. Patch reefs occur throughout the Florida reef tract. They are particularly abundant in the waters off northern Elliot Key and south Key Largo which holds over 5000 patch reefs. The greatest densities of patch reefs are found seaward of Hawk Channel and inshore of the outer reef tract (Marszalek et al., 1977). Patch reefs typically occur in water 2-9 meters deep and characteristically range from 30 to 700 meters in diameter (Jaap and Hallock, 1990). The coral species that act as the framework builders of patch reefs include *Siderastrea siderea*, *Diploria strigosa*, *D. labyrinthiformis*, *Colpophyllia natans*, *Montastraea annularis*, and *M. faveolata*. These corals have been termed boulder or massive corals (Humann, 1993). *M. annularis* (*senso lato*) is particularly important as it has been described as a 'keystone' species (Hudson, 1981) and can exhibit lateral growth as it approaches sea level. This massive coral can be found growing in individual colonies, or heads, and in groups of amalgamated colonies, or clusters, growing together, see Figure 1. They can grow, in area, up to 100m^2 and have up to 5 m of relief (Ginsburg and Shinn, 1993). For the purposes of this study, an individual head and a cluster of heads will be refered to together as a 'head/cluster'.

There are two basic types of patch reef: the near-shore reef and the offshore reef. Both are found landward of bank reefs. Near-shore patch reefs are typified by large clusters of *M. annularis*. Offshore patch reefs are typified by clusters of *M. annularis* and a 'campus' area of smaller corals and sea fans built up on a shallow hard-ground adjacent to coral clusters , see Figure 1.

As noted, bank or outer reefs are found off areas where large landmass protects them fromwater flux from Florida Bay. There are 96km of bank or outer reefs along the shallow shelf edge (Marszaleck et al., 1977). These reefs can be divided into three zones: the reef crest, the fore reef, and the back reef. The reef crest is typified by the shallower branching coral *Acropora palmata* and coral rubble. The fore reef is typified by deep massive corals such as *M. annularis* and M. *faveolata* followed by the shallow branching coral *A. palmata.* The back reef is typified by coral rubble and shallow boulder corals growing in waters protected from ocean swells by the reef crest, see Figure 1.

Although *Acropora palmata* is commonly found growing close to the surface this coral was not included in the survey. The reason is that, while *A. palmata* may be frequently damaged by careless boaters, this coral species also particularly vulnerable to natural fragmentation during storms. This renders it difficult to distinguish between the two sources of damage (Fong and Lirman 1995; Highsmith 1982).

2.2 Economic factors

Coral reefs are vital to South Florida's economy (NOAA, 1996). Living coral on reefs is highly valued by visitors to the Florida Keys (English, 1996). Between twenty to

FIGURE 1
Florida reef types

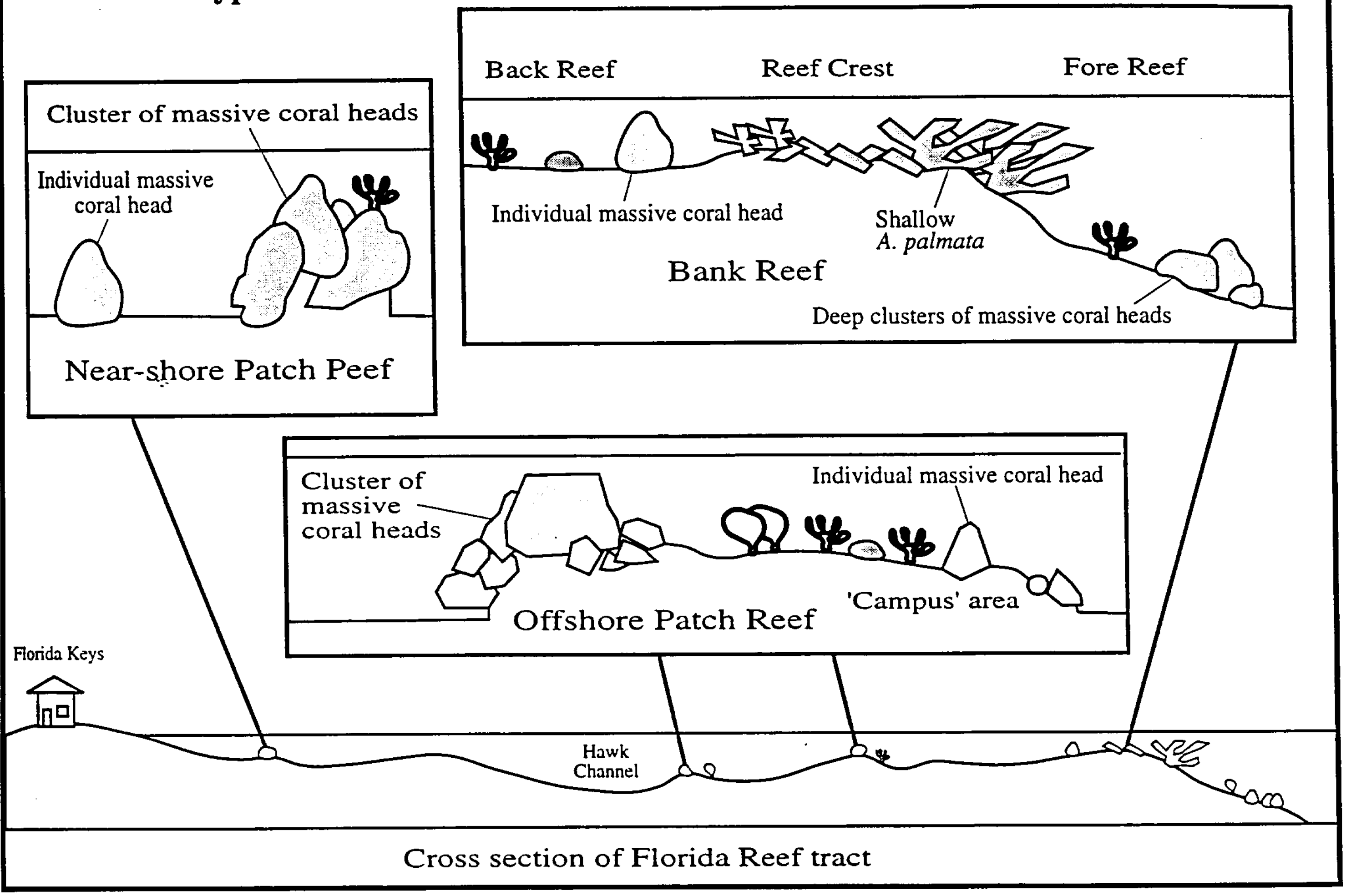
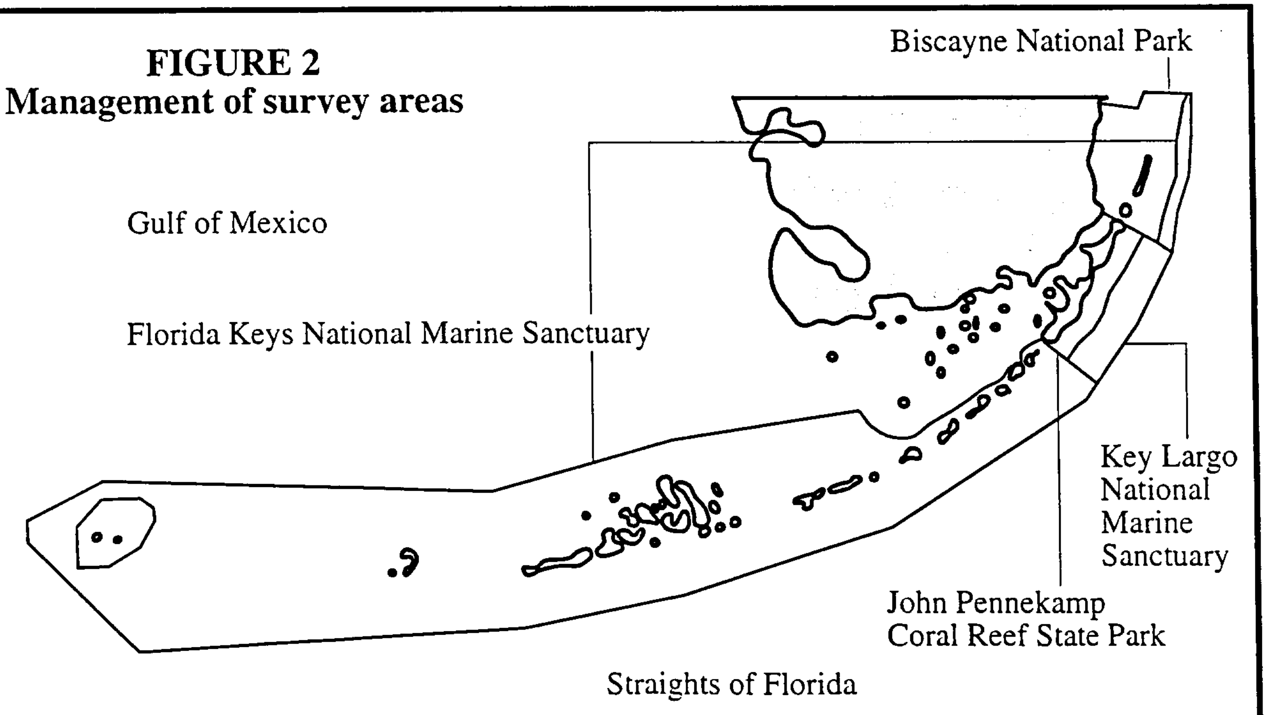


FIGURE 2
Management of survey areas



thirty percent of all tourists visiting the Florida Keys participate in diving and snorkeling activities (Kearny and Centaur, 1990). From June 1995 to July 1996, visitors to Monroe County spent an estimated $1.3 billion, resulting in an estimated tourist contribution to employment in Monroe County of 21,848 jobs (English, 1996).

Coral reefs provide food and shelter for a wide range of invertebrates and fishes, making them valuable producers of natural resources. Commercial fishing represents nine percent of Monroe County's private sector employment (White, 1991).

2.3 Resource Management in Survey Areas

Reefs surveyed were located within the jurisdiction of Biscayne National Park, John Pennekamp Coral Reef State Park, the Key Largo National Marine Sanctuary, and the Florida Keys National Marine Sanctuary, see Figure 2. As stated, corals are protected in all marine parks in the Florida Keys. The "removal or damaging" of corals is prohibited. Navigational aids currently in use throughout the Florida Keys include channel markers, triangular reef towers, and 'danger reef' signs.

Biscayne National Park (BNP) is located in the southern part of Dade County Florida. The park includes waters of Southern Biscayne Bay to Northern Card Sound and offshore to the 10 fathom depth contour. The park is located 24km south of Miami, Florida and is readily accessible to a large portion of the over 44,000 recreational boaters of Dade County (Boating Research Center, 1994_2). The coral reefs of BNP represent the northern limit of the Florida reef tract.

John Pennekamp Coral Reef State Park State Park was the first underwater state park in the United States. It covers approximately 702 square nautical miles. The park has 53,661 acres of submerged land and 2,350 acres of uplands (DEP.).

The Key Largo National Marine Sanctuary was designated in 1975 to protect and preserve 191km^2 of Florida reef tract. Protected reefs include Carysfort and Molasses reef. It is estimated that the Key Largo National Marine Sanctuary has well over one million visitors annually (NOAA, 1996_1).

The Florida Keys National Marine Sanctuary (FKNMS) was designated, by Congress, in 1990. It covers 2,774 square nautical miles of submerged lands and comprises 130km of bank reefs that stretch from Fowey Rocks to the Marquesas (NOAA, 1996_1). Boaters from Monroe and Dade county have ready access to FKNMS waters.

3.0 Materials and Methods

3.1 Survey methodology

From August 1996 to January 1997 49 reef areas with high profile coral head/clusters were surveyed throughout the Northern Florida Keys reef tract (see Figures 3 and 4). Carysfort Reef was the only bank or outer reef surveyed for shallow-water massive coral head/clusters. Munson Heads were the only inshore patch reefs surveyed. All other reef sites surveyed were offshore patch reefs. For each reef site, the exact depth and diameter of each coral head or cluster found within 2m of the surface was recorded. Geographic location was recorded with a hand-held GPS. The survey depth of 2m was chosen to accommodate the tidal range (~1.5m) in the northern Florida Keys, determined by inspection of tide tables (NOAA 1997). To account for tidal variation, all *in situ* depth measurements were standardized to depth below spring mean low water tide level. The standardized depths ranged from 0.1 to 1.0 meters (see Appendix). Since the maximum depth of typical hulls and/or propellers for the vessels in question is approximately 1m (Kanitz, 1997; Kern, 1997), all corals were potentially susceptible to this form of damage.

Underwater observations of direct physical damage were estimated using a meter rule marked in 10 and 2cm increments and recorded as the extent of surface area destroyed. Damage was classified into one of three categories (see table 3.0.1 below, & Figure 5 (a,b,c,d,e)). Damage found on each cluster-head was scored as the number of incidents in each damage class. This damage was later summed to estimate the mean damage in cm^2, see Appendix. Of the 315 shallow-water massive coral colonies surveyed, 312 were *Montastraea* spp. and 3 were *Siderastea siderea*. *Montastraea* spp. were identified according to the classifications of Weil and Knowlton (1994). *M. annularis* and *M. Faveolata* were the only *Montastraea* spp. recorded in the survey.

These two coral species (Knowlton et al., 1992; Knowlton et al., 1997) commonly co-occur. Shallow massive corals are termed head-clusters for the purposes of this study.

TABLE 3.0.1

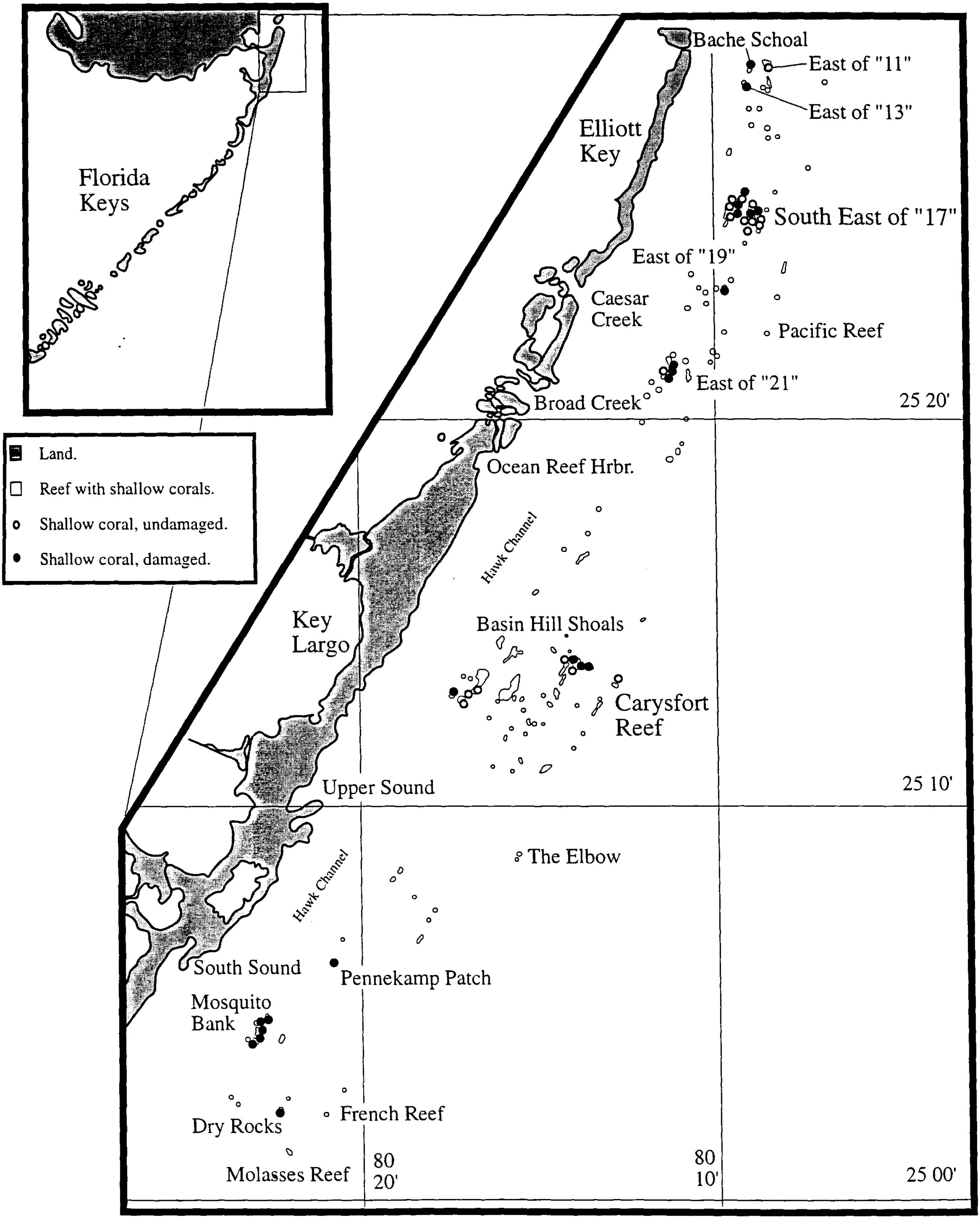
Coral Damage Classification

Class A	<100cm^2 destroyed (mean 25cm^2).
Class B	100-900cm^2 destroyed (mean 400cm^2).
Class C	>900cm^2 destroyed (mean 1000cm^2).

Recent direct physical damage was easily identifiable and came in two forms, collision and scarring. When collision occurs a coral can be crushed and split, by a vessel's hull into multiple fragments and hull paint is often driven into the coral (see Figure 5 (a,b,f)). Propeller scaring incidents remove live coral, exposing the skeleton. Propeller scarring occurs in typical scar like striations (see Figure 5 (d)), and can chip large fragments of coral (see Figure 5 (c,d,e)). Any damage whose source was not readily identifiable, for example, surfaces completely overgrown by turf algae (corallites not exposed or identifiable), was not included.

The coral damage classifications used in this survey subdivide the Park Service's classifications levels II and III (Table 1.2.b.1). The few incidents of class C damage found in this survey destroyed large areas of the top portions of coral colonies. No secondary damage was noticed.

FIGURE 3: Shallow-water reefs in Northern Floroda reef tract.



FIRURE 4: Shallow-water reefs surveyed, north and south Florida reef tract.

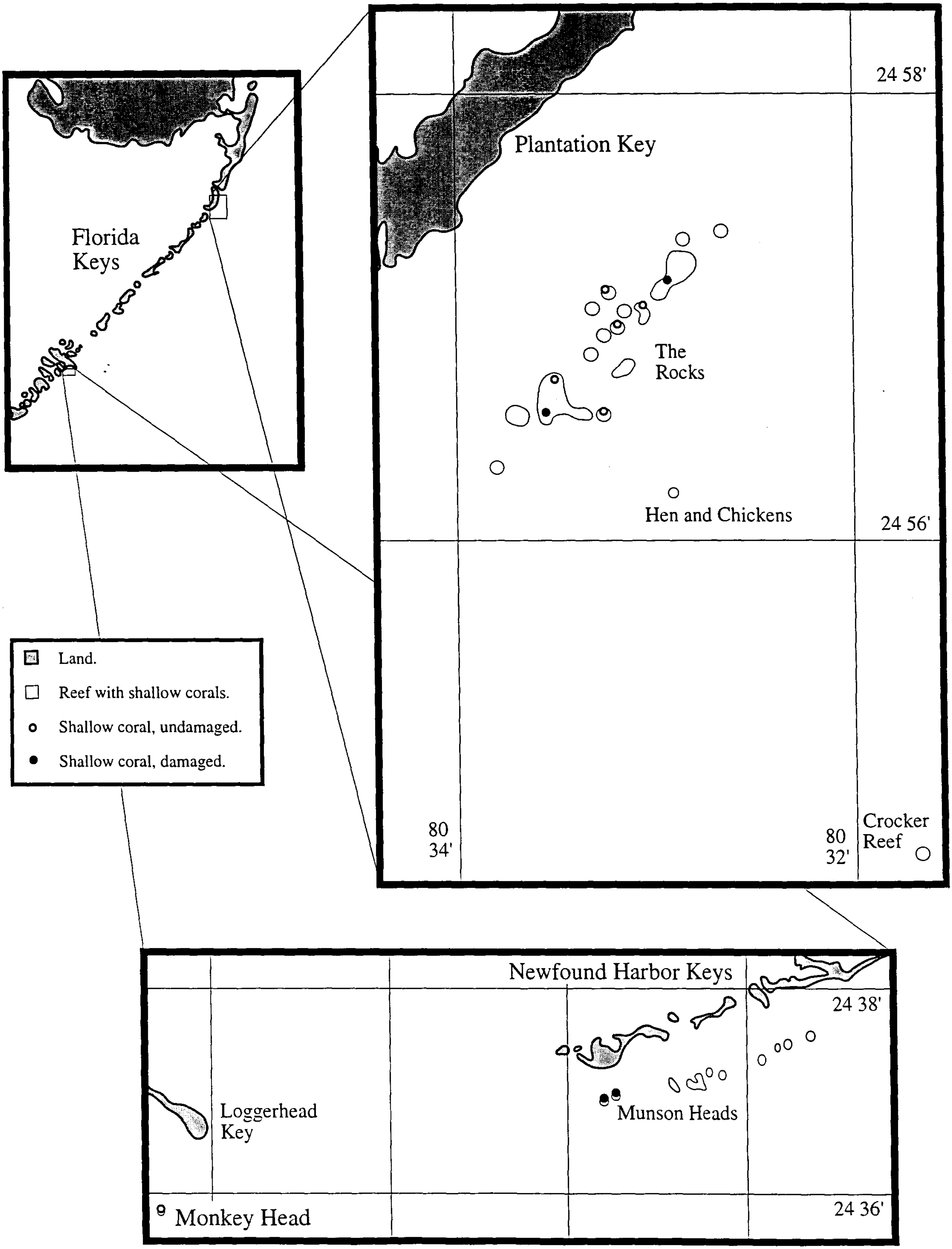
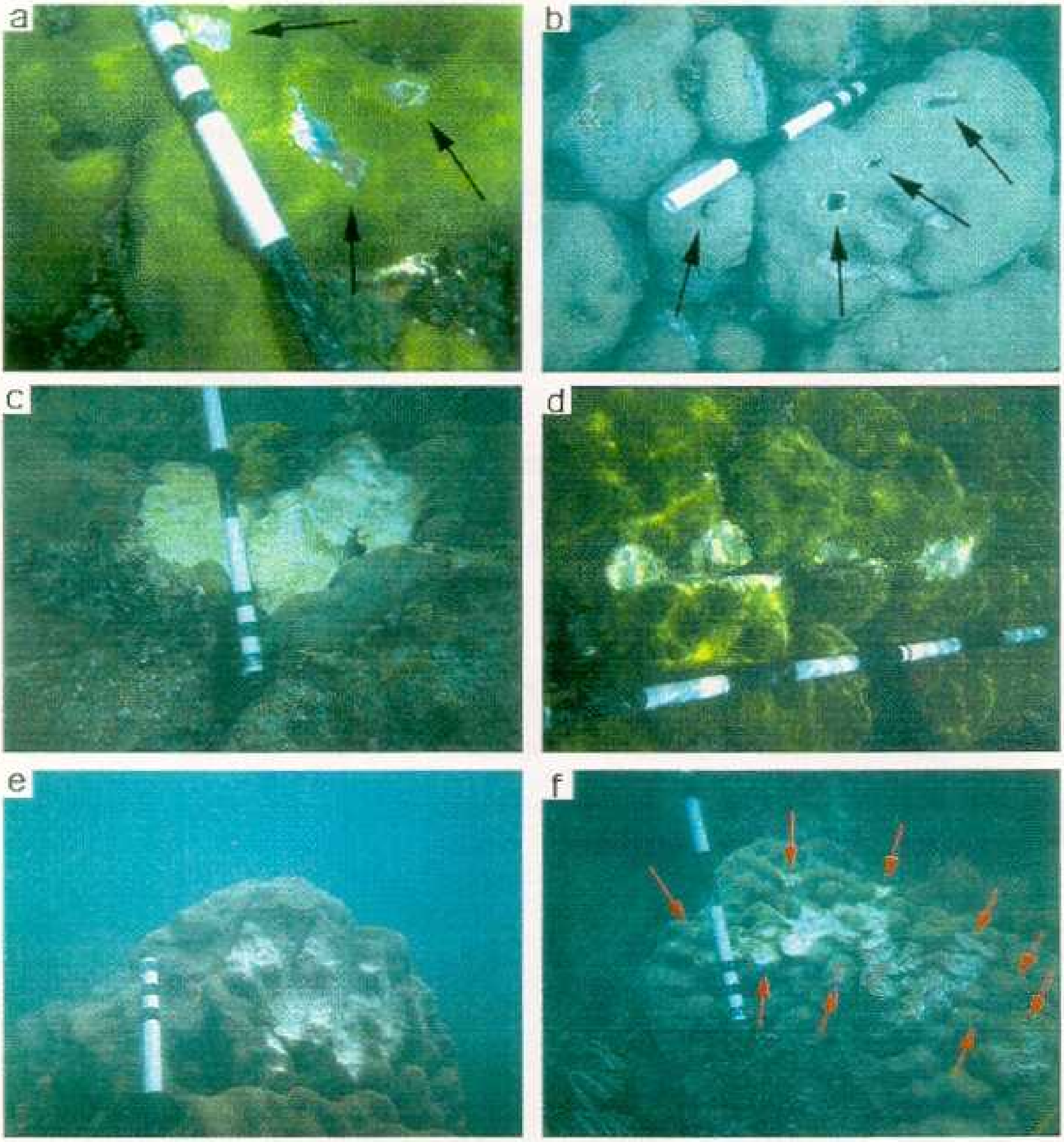


FIGURE 5

Damage to various head/clusters



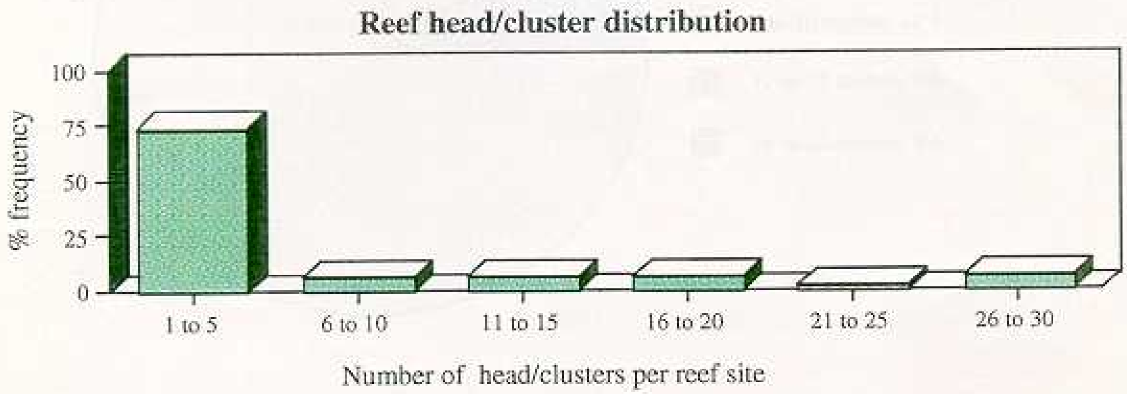
(**a**) 100cm^2 destroyed, head/cluster # 287, Munson Head #1. (**b**) 125cm^2 destroyed, head/cluster # 54, reef area southeast of marker 17. (**c**) 100cm^2 destroyed, head/cluster # 199, Mosquito bank. (**d**) 450cm^2 destroyed, head/cluster # 39, reef area southeast of marker 17. (**e**) 1000cm^2 destroyed, head/cluster # 97, Basin Hill Shoals. (**f**) 1000cm^2 destroyed, head/cluster # 4, Bache Shoal. Underwater observations of cm^2 damage were estimated using a meter rule (shown above) marked in 10 and 2cm increments.

3.2 General shallow coral patch reef characteristics

3.2.a Head/cluster distribution of reef sites

In total, 49 individual reef sites were surveyed. Reefs surveyed contained from 1 to 28 shallow-water head/clusters. In Table 3.2.1 it can be seen that the majority of reefs contained from 1 to 5 head/clusters:

TABLE 3.2.1

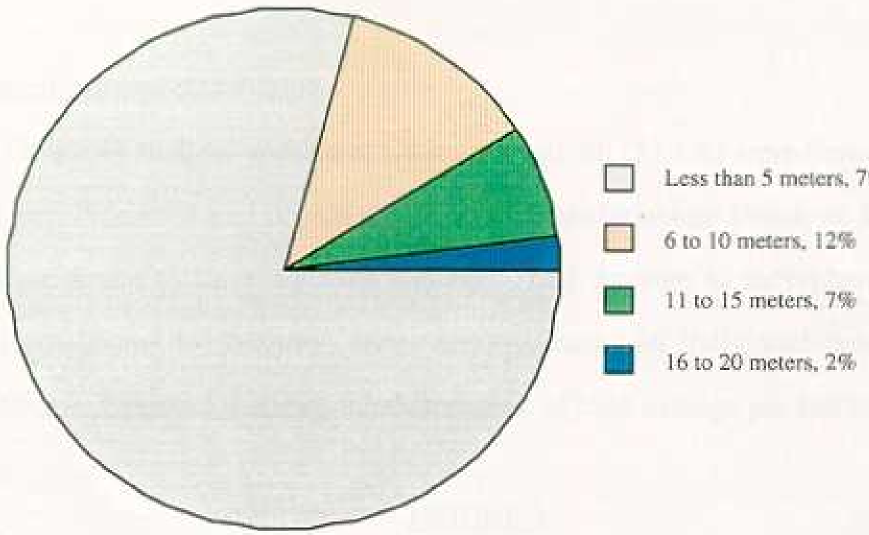


3.2.b Size distribution of head/clusters

In total, 315 coral head/clusters were surveyed. Individual head/clusters ranged in size from less than one meter (a singular head) to 18 meters in diameter (a large cluster of amalgamated heads). The majority of head/clusters were less than 5 meters in diameter, (see Table 3.2.2).

FIGURE 6

Diameter of head/clusters in meters

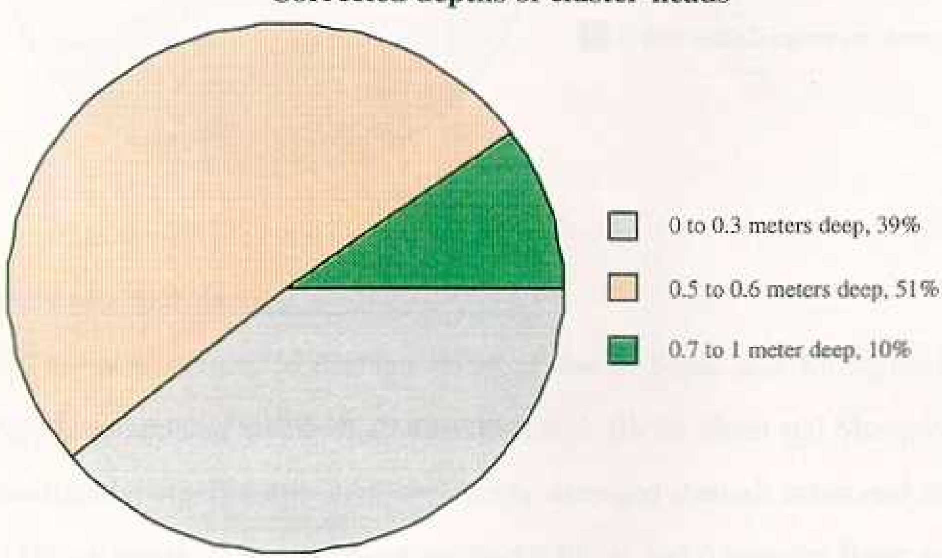


3.2.c Depth of the top surfaces of head/clusters

As previously mentioned, depth at time of observation was corrected to mean low water level. This corrected depth of the top surfaces of head/clusters ranged from 25 cm to 1 meter, with the majority 0.25 to 0.75 meters deep, see Table 3.2.3:

FIGURE 7

Corrected depths of cluster-heads



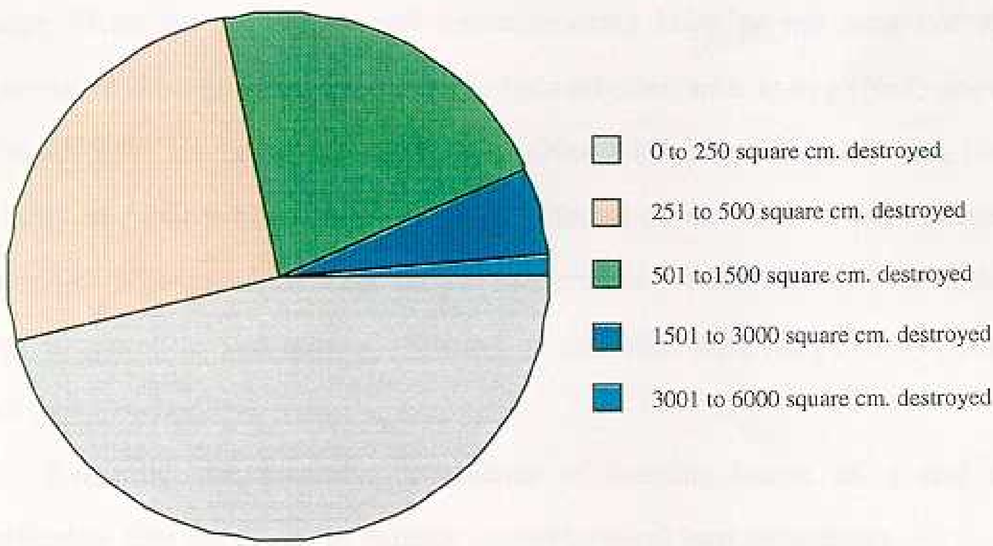
4.0 Results

4.1 General damage distribution

Of the 49 shallow-water reef sites surveyed, 28 (57.1%) were found with signs of damage, see Figures 3 and 4. Of the 315 coral head/clusters found on those reefs, 79 (25%) were found to have signs of damage. Total damage to individual head/clusters ranged from $25cm^2$ to $5800cm^2$. Most damage found on individual head/clusters was under $250cm^2$. Table 4.1.1 shows the distribution of total damage per head/cluster:

FIGURE 8

Damage distribution on head/clusters



4.2 Reefs with high damage levels

The total amount of damage found at Bache Shoal and Mosquito Banks was $20{,}200cm^2$, comprising 60.2% of all damage found. Bache Shoal and Mosquito Bank are not, statistically, significantly more frequently damaged than all other reef sites: 48.5% +/- 12.3% of head/clusters damaged on Bache Shoal and Mosquito Bank compared to 28.9% +/- 5.98% damaged on all other reef sites (Unpaired one-tailed t-test, P=0.1238).

However, when damage occurs, the extent of damage (cm^2 per head/cluster) for Bache Shoal and Mosquito Bank is much more severe than all other reef sites: $3366cm^2$ +/- $1570cm^2$ (n=6) on Bache Shoal and Mosquito Bank compared to $775cm^2$ +/- $109cm^2$ (n=22) on all other reef sites (unpaired one-tailed t-test, P=0.0017).

In conclusion, therefore, small boat grounding damage to shallow water massive coral head/clusters found on Bache Shoal and Mosquito Bank is significantly higher than average damage on all other reefs.

4.3 Effect of mooring buoys on damage incidence

Of the 7 reef sites with mooring buoys surveyed, all but one (85%) had signs of damage. Of the 42 reefs without mooring buoys surveyed, 22 (52.3%) had signs of damage. However, whether a reef has a mooring buoy or not does not affect the frequency of damage: 37.3% +/- 16.5% for reef sites with buoys (N=7) compared to 30.3% +/- 5.9% for reef sites without buoys (N=42) (Unpaired 2-tailed t-test, P=0.6629). Similarly, the extent of damage (mean cm^2) found on reef sites is not affected by the presence or absence of mooring buoys: $1415cm^2$ +/- $485cm^2$ (N=22) on reefs without buoys compared to $1021cm^2$ +/- 485cm2 on reef sites with buoys (n=6) (Unpaired 2-tailed t-test, P=0.6815).

Evidently, the presence or absence of mooring buoys on a reef does not significantly alter the degree of damage caused by small boat groundings.

4.4 Effect of number of shallow head/clusters on incidence of damage

Reef sites surveyed contained from one to 28 shallow-water massive coral head/clusters. Total amount of damage found on head/clusters per reef site ranged from 25 to $10,925cm^2$ coral destroyed. The 49 reefs surveyed in this study were divided into three, head/clusters per site, size categories: small reefs (0 to 5 head/clusters per reef); medium reefs (6-15 head/clusters per reef); and large reefs (>15 head/clusters per reef).

Damage amongst these reef size classes was distributed in the following proportions: 17 of the 36 (42.2%) small reefs had signs of damage, 6 of the 4 (66.6%) medium reefs had signs of damage, and 7 of the 7 (100%) large reefs had signs of damage.

A significant correlation exists between the number of shallow-water head/clusters per reef site and the amount of damage (mean total cm^2 per reef site): large reefs = 2557cm^2 +/- 1414cm^2 (N=36); medium reefs = 700cm^2 +/- 375cm^2 (N=6); small reefs = 421cm^2 +/- 117cm^2 (N=7) (One-way ANOVA; P=0.0055). Additionally, a significant correlation exists between the number of shallow-water head/clusters per reef site and the mean number of damaged head/clusters per reef site: large reefs = 5.0 +/- 0.976 (N=36); medium reefs = 2.5 +/- 1.147 (N=6); small reefs = 0.806 +/- 0.19 (N=7) (One-way ANOVA; P=0.0001).

The number of shallow-water head/clusters per reef site does not correlate with mean damage incident, or wound, size: large reefs = 431cm^2 +/- 158cm^2 (N=17); medium reefs = 218cm^2 +/- 68cm^2 (N=4); small reefs = 528cm^2 +/- 125cm^2 (N=7) (One-way ANOVA; P=0.3548).

4.5 Effect of head/cluster diameter on damage incidence and extent

The 315 shallow-water massive coral head/clusters surveyed in this study were divided up into three size categories: small (<5m diameter); medium (5-10m in diameter); and large (>10m in diameter), see Table 3.0.1. Damage amongst these size classes was distributed in the following proportions: 54 of the 240 (22.5%) small head/clusters were damaged, 17 of the 47 (36.1%) medium head/clusters were damaged, 8 of the 28 (28.5%) large head/clusters were damaged. Diameter of head/clusters does not affect how often it is damaged (X^2=3.075; df=2; P=>0.10).

However, head/cluster diameter is related to the extent of damage (mean cm^2 per head/cluster size class): small head/clusters = 77cm^2 +/- 15cm^2 (N=240); medium head clusters = 282cm^2 +/- 131cm^2 (N=47); large head/clusters = 194cm^2 +/- 109cm^2 (N=28)

(One-way ANOVA; P=0.0087). Head/clusters of medium and large size appear to have damaged disproportionately more damage than those in the small size class.

4.6 Effect of depth of coral on damage incidence and extent

The depth below mean low water level, of the top surfaces of the 315 shallow-water head/clusters surveyed in this study, ranged from 0 to 1.0m. These depths were divided up into three depth categories: 0 to 0.3m depth; 0.4 to 0.6m depth; and 0.7 to 1.0m depth. Damage incidence amongst the depth classes was distributed in the following proportions: 37 of the 123 (30%) 0 to 0.3m deep head/clusters had signs of damage, 37 of the 161 (22.9%) 0.4 to 0.6m deep head/clusters had signs of damage, 5 of the 31 (16.1%) 0.7 to 1.0m deep head/clusters had signs of damage. Damage extent (total cm^2 of coral damaged per head/cluster) amongst the depth classes was distributed in the following proportions: 15,200cm^2 of the 0 to 0.3m deep head/clusters coral was destroyed, 21,775cm^2 of the 0.4 to 0.7m deep head/clusters coral was destroyed, 700cm^2 of the 0.7 to 1.0m deep head/clusters coral was destroyed. The three depth categories do not significantly differ from each other in both damage incidence (One-Way ANOVA; P=0.245) and extent (One-Way ANOVA; p=0.1367).

Neither, when damage occurs, does the depth of the top surfaces of shallow-water head/clusters affect the extent of damage (mean cm^2 per damaged head/clusters) caused: 0 to 0.3m depth = 578cm^2 +/- 171cm^2 (N=37); 0.4 to 0.6m depth = 410cm^2 +/- 76cm^2 (N=37); 0.7 to 1m depth = 140cm^2 +/- 67cm^2 (N=5) (One-way ANOVA; P=0.411).

5.0 Discussion of Results

5.1 Damage and regeneration

Most of the damage found on individual head/clusters was under $250cm^2$, see Figure 5. Although this form of damage is widespread, a total of $33{,}525cm^2$ of coral damaged, does not appear to contribute to any specific decline in the health of corals in the Florida Keys reef tract. However, it is very possible that it may be important to the health of localized head/clusters.

Meesters (1995) conducted a series of experiments investigating regeneration in scleractinian corals. He induced small artificial lesions on the tops of bleached and unbleached colonies of *Montastraea annularis* and found that many top lesions on bleached colonies enlarged to many times their initial size, occasionally resulting in the death of the entire colony. Because *M. annularis* may be very sensitive to bleaching (Meesters, 1995; Goreau and Macfarlane, 1990; Szmant and Gassman, 1990) related boat grounding damaged areas could be lethal.

Within a week of a scarring event, filamentous algae colonize exposed skeleton and inhibit coral regeneration. This form of injury differs from natural storm damage because it occurs predominantly on the tops of colonies rather than the sides. In contrast, damage caused by storm rubble tends to occur more often on the sides of large colonies, rather than the tops. Coral scarring may affect the total health of the colony by forcing the coral to reallocate resources to regeneration, and away from growth, reproduction, and combating disease.

Because coral scars from boating tend to occur on the top side, their detrimental effects may be more substantial than other types of lesions. Additionally, larger lesions may not completely heal (Bak, 1977, Meesters, 1995): partial regeneration may occur at the edges, but turf algae or other reef organisms establish themselves within the scar area and become well established by the time the healing margin of the coral wound reaches them. The encrustation of some organisms, in a scar area, (e.g. boring sponges, encrusting zoanthids etc.) can lead to further bioerosion of the colony. In addition, herbivorous fish pecking at the edge of a scar can consume turf algae and coral at the same time (Glynn, 1990).

5.2 Bache Shoal and Mosquito Bank

As stated, the total amount of damage found at Bache Shoal and Mosqutio Banks comprised 60.2% of all damage found. These reefs show impact levels significantly higher than all other reefs. Bache Shoal is the closest shallow reef with mooring buoys to metropolitan Miami, see Figure 3. It also has a triangular reef tower and channel marker at its north tip. All shallow head/clusters surveyed at Bache Shoal were damaged, indicating that current reef protection methods in this area are not enough. Mosquito Bank, which is located directly in the line of boat traffic coming from slips on Key Largo and the South Sound, also has a high percentage (42.6%) of head/clusters damaged, indicating a high level of use and the need for additional protection, see Figure 3. The high percentage of damage found on Mosquito Bank adds support for the Florida Department of Environmental Protection's findings (Deaton and Duquesnel, 1996. Skinner et al, 1993).

5.3 Damage and mooring buoys

Reefs with mooring buoys attract more recreational boaters than reefs without mooring buoys. One would expect to find higher levels of damage to shallow-water massive corals at reef sites with mooring buoys, such as at Bache Shoal. When considering damage on Bache Shoal and similar reefs, careful thought should be placed on increased user pressure. However, when considering damage throughout all reef sites, the presence or absence of mooring buoys on a reef does not significantly alter the frequency or extent of damage caused by small boat groundings. In conclusion, more recreational boaters may be drawn to reefs with mooring buoys but they appear to avoid any significant additional damage to shallow-water massive corals.

5.4 Damage in relation to the number of head/clusters per reef site

Reefs with 5 or more shallow-water head/clusters are more susceptible to small boating damage than reefs with less than 5 shallow-water head/clusters. The more shallow-water head/clusters that a reef has, the more damage incidents or wounds found, but the mean wound size remains the same, regardless of reef size. I believe that these 'larger' reefs attract more small vessels. Although reefs with less than 5 shallow-water head/clusters are more numerous, they may not be as attractive to small boat operators, as reefs with 5 or more shallow-water head/clusters, because they have less relief, associated fish populations, and amount of live coral.

5.5 Damage in relation to head/cluster diameter

The larger in diameter, a shallow-water head/cluster, the more damage found, but the frequency of damage remains the same, regardless of diameter size. One interpretation of this relationship is that damage, with regard to head/cluster diameter, is overall infrequent and occurs at random. However, when damage occurs, the larger in diameter a head/cluster is, the greater chance a single boat damage incident will result in more damage.

5.6 Damage in relation to depth

The depth of the top surfaces of shallow-water head/clusters, within 1 meter depth range from spring low tide, does not significantly alter either the degree or extent of damage caused by small boat groundings. Therefore, all corals, within a 1 meter depth range from spring low tide, are susceptible to small boat damage. I believe that if the sample depth range of this survey had been extended to 2 or 3 meters there would be a significant correlation of frequency and extent of damage with depth, this, however, would have greatly lengthened survey time.

6.0 Recommendations and Conclusion

The most important question raised by this study is whether unreported boating damage is a significant threat to the health of high profile corals in the Florida Keys reef tract. The Florida Keys reef tract is a vast natural structure most of which remains submerged out of vessel contact range during tidal fluctuations. While damage from small boat contact does not currently pose a serious threat to its survival, its accumulative damage can degrade and destroy the structure of localized areas of shallow-water corals and coral clusters.

A trend in high user pressure is evidenced by the yearly increase of over 4000 registered vessels in Dade, Broward, Monroe, and Palm Beach Counties (Boating Research Center 1994_1 and 1994_2). Indeed, it appears likely that continued high user pressure on the most frequented reefs will, in time, degrade the aesthetic and recreational qualities of the reefs. Additionally, a high and relentless incidence of damage to these colonies will result in loss of the larger and older massive coral colonies. For these reasons this study proposes a number of recommendations for management.

It is necessary to identify all shallow reefs with high levels of user impact. Criteria for identifying these reefs could include a high percentage, such as over 40%, of shallow-water coral heads having damage. This study has identified two such reefs, Bache Shoal and Mosquito Bank. Additional shallow reef markers should be placed on these reefs. The placement of additional mooring buoys should be considered, as they appear to counteract high user pressure. Consideration should be given to their proximity to shallow-water corals, as to not danger them from boats 'racing' to the moorings. Special attention should also be placed on reefs with over 15 shallow-water head/clusters and head/clusters over 5m in diameter. This study has identified these head/clusters as being more prone to the occurrence of shallow boat groundings. Education is also vital for avoiding further damage. Local and tourist boaters should be targeted for additional instruction on how to navigate in tropical waters. The general public should be made aware of the value of coral reefs as a natural resource and national treasure.

In conclusion, the reefs of the Florida Keys, located near the northern limit of their biogeographic range, are already under considerable natural stress (Causey, 1990). Additionally, hurricane damage, winter cold snaps, disease, bleaching episodes, and El-Nino related temperature patterns can cause coral mortality (Davis, 1982; Porter et al, 1982; Roberts et al, 1982; Jaap, 1988; Glynn, 1990; Szmant and Gassman, 1990; Meier and Porter, 1994; Dustan and Halas, 1997). For these reasons, alone, further detrimental anthropogenic impacts must be minimized.

7.0 References

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Appendix

Reef site	Location Latitude/Longitude	Head/cluster #
Bache Shoal	25° 29.156/80° 08.942	1 - 6
East of "11"	25° 28.699/80° 08.913	7
East of "13"	25° 29.222/80° 08.471	8
SE. of "17" #1	25° 25.420/80° 08.862	9 - 11
SE. of "17" #2	25° 25.522/80° 09.200	12 - 14
SE. of "17" #3	25° 25.327/80° 08.782	15 - 17
SE. of "17" #4	25° 25.474/80° 08.928	18
SE. of "17" #5	25° 25.585/80° 08.978	19 - 22
SE. of "17" #6	25° 25.590/80° 09.010	23 - 24
SE. of "17" #7	25° 25.219/80° 08.849	25
SE. of "17" #8	25° 25.241/80° 08.917	26
SE. of "17" #9	25° 25.198/80° 08.929	27
SE. of "17" #10	25° 25.209/80° 09.086	28 - 30
SE. of "17" #11	25° 25.180/80° 08.905	31 - 34
SE. of "17" #12	25° 25.380/80° 08.950	35 - 36
SE. of "17" #13	25° 25.470/80° 08.960	37 - 38
SE. of "17" #14	25° 25.330/80° 08.890	39 - 41
East of "19"	25° 23.320/80° 09.722	42
East of "21" #1	25° 21.460/80° 11.000	43 - 48
East of "21" #2	25° 21.320/80° 11.200	49
East of "21" #3	25° 21.250/80° 11.230	50 - 54
East of "21" #4	25° 21.220/80° 11.180	55 - 56
Basin Hill Shoals #1	25° 12.795/80° 17.256	57 - 74
Basin Hill Shoals #2	25° 12.900/80° 17.160	75 - 76
Basin Hill Shoals #3	25° 13.010/80° 17.140	77 - 79
Basin Hill Shoals #4	25° 12.750/80° 17.200	80 - 81
Basin Hill Shoals #5	25° 14.452/80° 14.098	82 - 92
Basin Hill Shoals #6	25° 13.724/80° 13.804	93 - 97
Basin Hill Shoals #7	25° 13.774/80° 14.028	98 - 102
Basin Hill Shoals #8	25° 13.800/80° 13.725	103 - 107
Basin Hill Shoals #9	25° 14.160/80° 13.560	108 - 110
Basin Hill Shoals #10	25° 13.850/80° 13.550	111 - 115
Carysfort Reef	25° 12.620/80° 13.320	116 - 127
Pennekamp Patch	25° 06.677/80° 20.495	128 - 153
Mosquito Bank #1	25° 04.530/80° 22.970	154 - 171
Mosquito Bank #2	25° 04.366/80° 22.780	172 - 179
Mosquito Bank #3	25° 04.198/80° 23.080	180 - 192
Mosquito Bank #4	25° 04.142/80° 22.990	193 - 197
Mosquito Bank #5	25° 04.009/80° 22.965	198 - 225
Dry Rocks	25° 02.685/80° 22.166	226 - 244
The Rocks #1	24° 56.714/80° 33.520	245 - 246

The Rocks #2	24° 56.550/80° 33.550	247 - 250
The Rocks #3	24° 57.180/80° 33.320	251 - 252
The Rocks #4	24° 56.900/80° 33.200	253 - 257
The Rocks #5	25° 56.880/80° 33.300	258 - 259
The Rocks #6	24° 57.100/80° 33.300	260 - 262
Munson Head #1	24° 36.882/81° 23.660	263 - 289
Munson Head #2	24° 36.860/81° 23.698	290 - 313
Monkey Head	24° 35.785/81° 28.693	314 - 315

Head/cluster #	Head/cluster diameter (in meters)	Depth (in meters)	Damage (in cm^2)
1	8	0.3	725
2	4	0.5	25
3	1.2	0.5	50
4	4	0.6	1000
5	10	0.3	125
6	4	0.1	25
7	4	0.5	125
8	4	0.5	0
9	8	0.4	650
10	4	0.5	75
11	3.5	0.4	400
12	6	0.5	0
13	2	0.5	0
14	2.2	0.4	0
15	8	0.3	1800
16	6	0.3	0
17	4	0.3	0
18	3.5	0.2	500
19	3.5	0.4	0
20	2	0.6	0
21	1.4	0.5	0
22	1.6	0.4	0
23	12	0.3	0
24	2	0.4	0
25	6	0.5	0
26	2.3	0.6	1025
27	2	0.7	50
28	8	0.4	0
29	2	0.8	0
30	2	0.8	0
31	1	0.5	0
32	1.2	0.6	0
33	8	0.6	0
34	2	0.4	0
35	2.2	0.99	0
36	4	0.5	0
37	5	0.5	0
38	3	0.6	0
39	13	0.2	450
40	3	0.7	0
41	4	0.7	0
42	2	0.4	800
43	11	0.4	0
44	2	0.6	0
45	2	0.4	0
46	0.6	0.6	400
47	2	0.3	50

Head/cluster #	Head/cluster diameter (in meters)	Depth (in meters)	Damage (in cm^2)
48	1	0.4	0
49	18	0.3	1600
50	9	0.4	0
51	2.3	0.2	25
52	1.5	0.2	550
53	1	0.3	25
54	6	0.2	125
55	1	0.2	0
56	1.2	0.2	0
57	1	0.9	0
58	1	0.9	0
59	1	0.6	0
60	6	0.1	25
61	2	0.1	0
62	2	0.1	0
63	3	0.1	50
64	5	0.2	0
65	10	0.3	400
66	8	0.4	0
67	5	0.1	0
68	6	0.9	125
69	1	0.4	0
70	1	0.3	0
71	3	0.4	0
72	4.5	0.4	0
73	2	0.3	0
74	2.1	0.6	0
75	1	0.2	0
76	1.2	0.3	0
77	3	0.2	0
78	5	0.5	0
79	2	0.4	0
80	2	0.5	0
81	7	0.3	0
82	1	0.7	0
83	1.5	0.7	0
84	1	0.5	0
85	1.5	0.3	0
86	2	0.3	0
87	2	0.1	0
88	1.8	0.2	0
89	1.5	0.3	0
90	2	0.3	0
91	2	0.3	0
92	5	0.2	0
93	0.8	0.6	0
94	2	0.1	50
95	4	0.1	75
96	1.5	0.2	400
97	1.2	0.3	1000
98	1.2	0.2	0
99	2	0.2	0
100	6	0.3	0
101	1.2	0.2	0
102	8	0.3	400
103	5	0.5	0
104	2	0.1	0
105	5	0.5	0
106	3	0.5	0

Head/cluster #	Head/cluster diameter (in meters)	Depth (in meters)	Damage (in cm^2)
107	1.5	0.5	0
108	2	0.2	0
109	2	0.3	0
110	1.4	0.5	0
111	6	0.3	800
112	2	0.4	0
113	6	0.2	0
114	1.4	0.4	0
115	1.1	0.5	25
116	0.5	0.2	0
117	1.6	0.4	0
118	2	0.4	0
119	2.4	0.2	0
120	2.1	0.2	0
121	2	0.2	0
122	2	0.4	0
123	1.8	0.2	0
124	1.4	0.2	0
125	1.3	0.3	0
126	1.4	0.3	0
127	2	0.2	0
128	2	0.2	0
129	1	0.3	0
130	1.4	0.4	0
131	3	0.4	25
132	0.8	0.3	400
133	2	0.4	0
134	1.5	0.4	0
135	1.6	0.4	25
136	1	0.4	0
137	1	0.6	0
138	2	0.8	0
139	2	0.9	0
140	6	0.4	0
141	1.4	0.4	0
142	1.6	0.6	0
143	1.8	0.5	0
144	1.4	0.6	0
145	1.4	0.4	825
146	1.8	0.7	0
147	1.6	0.4	0
148	1.8	0.6	0
149	2.1	0.4	0
150	2	0.4	0
151	2	0.7	0
152	1	0.4	0
153	1	0.4	25
154	15	0.3	0
155	0.6	0.3	0
156	1.2	0.8	100
157	2	0.5	25
158	1.2	0.6	800
159	1.2	0.3	0
160	1.1	0.3	0
161	1.2	0.5	0
162	1.3	0.6	0
163	1.4	0.5	25
164	1.1	0.6	0
165	3	0.5	50

Head/cluster #	Head/cluster diameter (in meters)	Depth (in meters)	Damage (in cm^2)
166	1.2	0.3	400
167	1.1	0.5	800
168	1	0.4	100
169	1.8	0.7	0
170	6	0.8	0
171	1.4	0.6	0
172	2.1	0.4	0
173	1.1	0.5	0
174	1.8	0.1	0
175	0.6	0.6	0
176	1.6	0.3	25
177	1.4	0.3	0
178	1.2	0.5	0
179	1	0.3	0
180	3	0.4	0
181	3.6	0.3	0
182	0.8	0.3	0
183	2	0.3	500
184	1.3	0.3	0
185	0.6	0.2	25
186	0.8	0.3	25
187	0.8	0.4	400
188	1.2	0.3	0
189	1.4	0.5	800
190	4	0.3	0
191	1.2	0.4	0
192	0.6	0.4	25
193	13	0.3	100
194	15	0.3	2625
195	3	0.3	0
196	2	0.3	0
197	9	0.3	500
198	1.5	0.4	75
199	1	0.1	400
200	2	0.4	900
201	1.2	0.3	0
202	1.2	0.4	0
203	1	0.3	0
204	1.2	0.4	0
205	2	0.4	0
206	1.2	0.7	0
207	3	0.4	800
208	1	0.8	400
209	1.2	0.4	0
210	3	0.4	0
211	12	0.4	550
212	3	0.4	0
213	12	0.3	0
214	3	0.4	0
215	8	0.1	5800
216	1.4	0.4	0
217	1	0.3	0
218	1.2	0.3	0
219	1.2	0.4	0
220	1	0.3	0
221	1	0.3	0
222	1.3	0.3	0
223	1.8	0.4	0
224	1.5	0.7	0