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Recreational diving impacts and the use of pre-dive briefings as a management strategy on Florida coral reefs

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Abstract Ecotourism often is promoted as an ecologically sustainable activity, but some ecotourism activities negatively impact coastal ecosystems. Impacts of intensive diving tourism on coral reefs remain poorly understood, especially in the Florida Keys. We determined patterns of recreational dive frequency, diver behaviour, and coral damage on reefs near Key Largo, and assessed how pre-dive briefings and other factors affect these damage rates. Recreational divers contacted live stony corals ~ 18 times per scuba dive; most contacts deposited sediment onto corals, but also caused abrasion to coral tissues and fracture of coral skeletons. Divers who received pre-dive ecological briefings caused significantly less coral damage than those who did not, and divers with cameras and/or gloves caused the most damage. The proportion of damaged corals increased significantly with the estimated rate of recreational diving on each reef, and the percent cover of live corals decreased. We conclude that current rates of recreational diving in Key Largo are unsustainable, resulting in damage to >80 % of coral colonies and reduction of live coral cover to <11 % at heavily-dived sites. We recommend that dive tour operators administer pre-dive ecological briefings to all recreational divers, provide extra briefings to camera and glove users, and employ underwater dive guides who intervene when divers inadvertently damage live stony corals. This study provides a scientific basis to support management of intensive ecotourism on Florida coral reefs.

Keywords Ecotourism · SCUBA · Diver behaviour · Dive guide

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Introduction

Ecotourism has been promoted as an ecologically-benign activity that causes little harm to natural ecosystems, and can support the sustainable use of natural resources, especially in developing countries (Wight 1993; Honey 1999; Tuohino and Hynonen 2001). Ecotourism, when properly managed, can enhance public awareness of the importance of biological conservation, provide steady income to local people, and allow non-consumptive use of natural resources (Honey 1999). However, some ecotourism activities potentially cause negative impacts to the natural systems on which they depend, including hiking activities that lead to trampling of vegetation and soil erosion along nature trails (Tuohino and Hynonen 2001), and breakage of delicate corals by diving tourists on tropical reefs (Rouphael and Inglis 1997; Hawkins et al. 1999; Barker and Roberts 2004).

Coral reefs are an important habitat along tropical coastlines, and a vital economic resource that is over utilized and under managed in many countries (Arin and Kramer 2002). They have become more accessible, as ways to reach them have improved, so the number of recreational divers on reefs is rapidly increasing (Hawkins and Roberts 1993). In 1981, an estimated 10 000 scuba divers visited coral reefs in Biscayne National Park near Miami, Florida, USA (Tilmant and Schmahl 1981). At that time, this number was deemed an accurate representation of diver frequency on similar reefs throughout the world. Twenty years later, 250 000–300 000 divers per year visited reefs near Eilat, Israel, accounting for an estimated 400 000 instances of coral damage annually by divers (Zakai and Chadwick-Furman 2002). Large increases in recreational diving have led to more frequent physical contacts between diving tourists and corals, resulting in reef damage largely due to diver inexperience and ignorance (Davis and Tisdell 1995; Barker and Roberts 2004).

Recreational scuba diving often is promoted as a form of ecotourism, and is the most intimate way for tourists to interact with coral reefs. However, due to the delicate structure of reef-building corals, diving can cause both direct (via physical contact) and indirect (via sediment deposition) damage to these unique organisms. Physical pressure on the thin layer of living tissue that covers coral surfaces leads to abrasion (wound formation and crushing of skeletal elements) and tissue removal, and may even fracture large sections of the underlying skeleton (Hawkins et al. 1999). Abraded corals are more susceptible to predation and disease leading to coral death (Rosenberg et al. 2007; Guzner et al. 2010), and fragmented corals settle on the sea floor where they often are covered by sediment and starved of light and nutrients (Hawkins and Roberts 1994). Reef sedimentation also occurs when divers swimming nearby kick up sand from the surrounding soft substrate, covering the reef surface and inhibiting coral recruitment, feeding, and photosynthesis (Hawkins and Roberts 1993; Hasler and Ott 2008).

Efforts by coral reef managers to reduce diver-coral contacts have produced mixed results. Prior to divers entering the water, short briefings are sometimes given by dive shop personnel in an effort to raise reef awareness and discourage diver-coral contacts. These briefings have varying effects on diver behaviour, depending on their length and content (Barker and Roberts 2004). The most successful deterrent to diver damage appears to be direct intervention by underwater dive guides, which can reduce diver-coral contact rates by as much as 80 % (Barker and Roberts 2004).

Frequencies of recreational diving on coral reefs in Florida are some of the highest in the world. In response to a prohibition on boat anchoring in 1998, the Florida Park systems increased the number of mooring buoys around popular reefs, thus increasing the number of boats that can be moored on each reef at any given time (Causey 2002). While buoy use has reduced anchor damage to reefs, it also has led to elevated numbers of divers in the water around popular reefs (pers. comm. John Pennekamp State Park officials), and also likely an increase in diver-coral contacts. Due to minimal governmental involvement in regulating recreational diver behaviour in the Florida Keys, local dive shops are heavily responsible for promoting diver awareness of behaviours that potentially damage reef corals (pers. comm., National Oceanographic and Atmospheric Administration [NOAA]).

Despite interest in coral reef conservation worldwide, few studies have focused on diver impacts to reefs in the Florida Keys. The earliest publication on this subject in Florida concluded that recreational diving was a good source of income for the area, and that parks should encourage more divers because there was no apparent harm to the reefs (Tilmant and Schmahl 1981). This conclusion was made during a period when diving rates were low enough to potentially cause little damage. A decade later, Talge (1992) found that 4–6 % of total live coral cover in Florida was touched by divers on a weekly basis, and concluded that this did not cause permanent harm to the corals, in contrast to more recent findings of severe impacts of diver contacts on corals in other reef regions (Plathong et al. 2000; Zakai and Chadwick-Furman 2002). A recent study by Camp and Fraser (2012) showed that divers in Key Largo exhibit behaviours that negatively impact coral reefs, and that various environmental education tools and strategies could mitigate these diver-coral contacts. However, no published studies in nearly two decades have quantified the proportions of damaged corals on Florida reefs in relation to estimated frequencies of recreational diving. With recent global increases in a wide array of anthropogenic factors affecting coral reefs, including recreational tourism, a reanalysis of recreational diver impacts on Florida reef corals is needed.

We document here variation in the educational practices of dive shops and their effectiveness in reducing reef coral damage at Key Largo, Florida. We quantified coral contact behaviours of recreational divers and their effects on stony corals, and determined how coral condition varies with estimated rates of recreational diving tourism.

Methods

Study sites and dive shops

This study was conducted during May–August 2011 on coral reefs at Key Largo, in the Florida Keys National Marine Sanctuary (FKNMS, Fig. 1), Florida, USA. Study sites were selected that each consisted of a patch reef with a reef flat at 4–13 m depth, to control for effects of varying topography on diver behaviour and reef damage (Hawkins and Roberts 1993; Rouphael and Inglis 1997). Due to the geography of the Florida Keys, all sites were located 8–11 km offshore and were accessible only by boat.

The behaviours of recreational divers were observed during regularly-scheduled dive trips run by commercial dive shops in Key Largo. Four dive shops were selected for examination of their client divers, out of 32 operating dive shops in the Key Largo area, based on four criteria (educational policy, dive guide, location, and cost). In terms of educational policy, dive shops were selected as either members of the Blue Star Program run by NOAA (2/8 shops), or non-members (2/24 shops). The Blue Star program was established in 2009 to reduce impacts of divers and snorkelers on coral reefs in the Florida Keys through increased public awareness. Blue Star dive shops agreed to promote reef conservation awareness through NOAA-mandated dive briefings and informative materials (pamphlets and coral identification cards) available on the dive boat and at the dive shop (http://sanctuaries.noaa.gov/bluestar/welcome.html). In terms of dive guide service

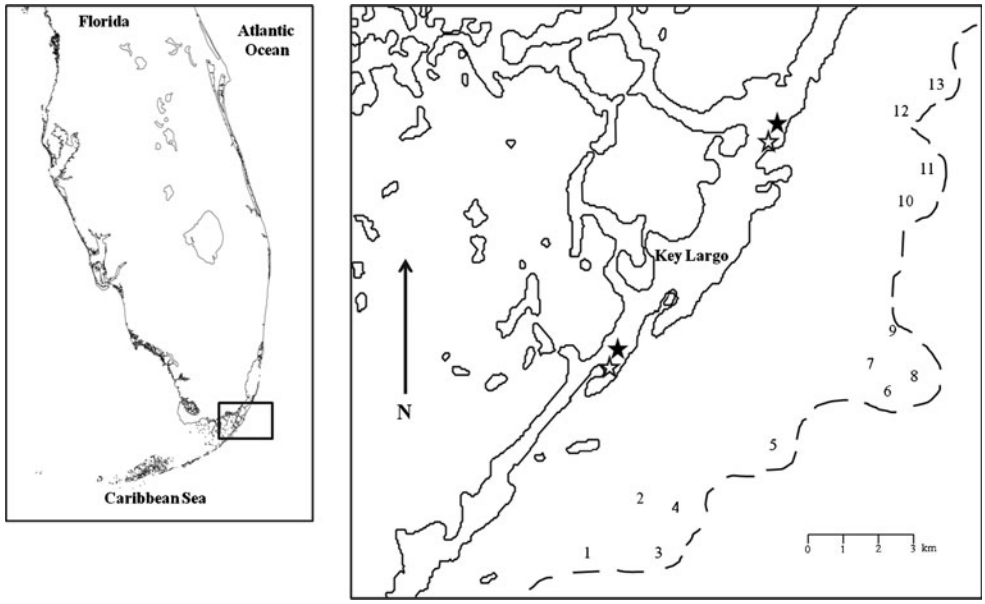

Fig. 1 Map of 4 dive shops and 13 coral reef sites examined at Key Largo, FL. *Stars* represent locations of dive shops (*black* Blue Star certified, *white* Non-Blue Star certified), and *numbers* show locations of reef sites: 1 (Pickles), 2 (White Bank Dry Rocks), 3 (Molasses), 4 (Sand Island), 5 (French), 6 (Grecian Rocks), 7 (Dry Rocks), 8 (Little Grecian), 9 (North Dry Rocks), 10 (South Carysfort), 11 (Carysfort North), 12 (Turtle Rocks), 13 (Northeast Patch). Sites 1–7, 9, 10, 12, and 13 were visited for diver observations, and sites 1, 3, 7, 8, 10, and 11 were visited for benthic surveys of reef condition. *Dotted line* represents the approximate 25 m depth isobath along the edge of the Florida reef tract

(provision of complementary dive guides during every dive), only one dive shop in each of the two Blue Star categories offered complementary dive guides, so these two shops were selected. The other dive shop in each of the 2 educational policy categories was selected based on location: one shop in north Key Largo and one in south, because some of our reef sites were visited by only northern shops (3/11 sites for diver observations, Fig. 1) and some only by southern shops (2/11 sites). In terms of cost per dive, the two least expensive shops were selected from each of the latter two groups because they likely attracted divers with diverse levels of experience. Thus, we selected two dive shops with a dive guide (one Blue Star and one not, both in the south), and 2 shops without a dive guide (one Blue Star and one not, both in the north).

Diver behaviours and impacts on reef corals

During each scuba dive on boat trips with the above four dive shops, the behaviours of 3–5 divers were observed from a distance of 3–4 m underwater (after Barker and Roberts 2004). Each diver was followed by trained observers, and data collection methods were monitored by the authors to ensure consistency. We began to record diver behaviours only after the first 5 min of each dive, because during this period divers focused on descending and initially adjusted their buoyancies. By excluding this initial period from analysis, we focused on diver behaviour during the main roving period of the dive, when divers were likely to alter their behaviours based on any pre-dive briefings. Also because divers often contact corals during their initial descent (Barker and Roberts 2004), by excluding this period we report here conservative estimates of diver damage during the main part of each dive. Divers were selected haphazardly after they entered the water from the dive boat, and their behaviour was observed for 7 min each (after Medio et al. 1997). Divers were not randomly selected while still on the boat (Medio et al. 1997; Barker and Roberts 2004), because they rapidly dispersed upon water entry and were difficult to relocate during the boat to water transition. Observers ranged over the entire patch reef site during the dive, and so located and observed divers haphazardly, without bias as to which divers entered the water more rapidly than others.

We quantified four types of diver contact, based on which part of the diver body contacted live corals: hand, fin, scuba gear (e.g., air tank, spare regulator) and other (e.g., torso, camera, flashlight, after Medio et al. 1997; Zakai and Chadwick-Furman 2002; Barker and Roberts 2004). We also quantified the resulting damage to live stony corals in four categories: sediment deposition, tissue abrasion, skeletal breakage, and no obvious damage. Finally, we recorded the period during each dive when observations began (first vs. second half of the dive), whether an underwater dive guide was present, and whether or not an ecological briefing was administered before the dive.

During each 7-min observation, selected divers were discretely followed as they moved along the reef. Divers were not informed that they were being observed, and if they inquired about our research equipment (dive slates), we informed them that we were conducting surveys on the corals (after Barker and Roberts 2004). Divers were confirmed as belonging to each dive shop by observing the logos on their air tanks. If a diver appeared to become aware of our observations, we discarded the data and moved on to another diver (3 of 243 divers observed). Dive shops also were not made aware of our study beforehand, to prevent them from altering their educational briefings due to our presence (in contrast with Camp and Fraser 2012).

Variation in coral condition among sites

Within the FKNMS, six patch reefs (including four visited for diver observations above, see Fig. 1) were selected that ranged from low to high diver visitation rates, as estimated from the number of mooring buoys at each reef. Mooring buoys were the primary method to secure dive boats to Key Largo patch reefs, so the number of buoys per reef indicated the relative frequency of recreational scuba divers at each reef (pers. comm., NOAA). Little Grecian, Pickles, and Carysfort North were selected as low diver visitation sites (0, 3, and 4 mooring buoys respectively), and South Carysfort, Dry Rocks, and Molasses as high diver visitation sites (15, 23, and 27 mooring buoys respectively). We selected these sites because they were interspersed in terms of level of visitation (Fig. 1), similar in reef size, and all were visited regularly by the dive shops selected above (except for the reef with no mooring buoys, Little Grecian).

The condition of live stony corals at each of these six sites was quantified using 10 band transects, each 10–12 m long, deployed at randomly-selected locations at~10 m depth. We randomly generated numbers that corresponded to degrees on a compass for the orientation of transect placement on each reef, with each transect starting at 50 m from the mooring buoy. We then randomly sampled 4–6 1-m^2 quadrats per band transect, from 20 to 24 possible quadrats (1 m^2 along each side of the 10–12 m transect tape), totaling~50 quadrats per site (~5 quadrats per transect x 10 transects per site x 6 sites=309 quadrats total). This level of sampling provided many replicate quadrats per site, while fitting into the time constraints of each sampling dive. Within each quadrat, stony coral colonies were identified in 12 major coral genera belonging to three growth forms: branching (*Acropora*, *Porites*), massive (*Colpophyllia*, *Dichocoenia*, *Dipoloria*, *Favia*, *Montastraea*, *Siderastrea*) or other (*Agaricia*, *Madracis*, *Stephanocoenia*, *Meandrina*, or other genera, identified using Vernon 2000), which included the most common stony corals in the northern Florida Keys (Goldberg 1973; Vernon 2000). In each quadrat, we recorded the number and condition of all live stony corals, and visually estimated total % live coral cover (after Hawkins et al. 1999; Zakai and Chadwick-Furman 2002). Coral colonies that were on the quadrat edge were counted if at least 50 % of the colony was within the quadrat. Preliminary trials using this visual estimation method in 1-m^2 quadrats provided consistent estimates of coral percent cover.

Each coral colony was recorded as exhibiting 1 of 6 damage conditions: tissue abraded (tissue damage with crushed skeletal elements), broken (fractured skeleton, after Zakai and Chadwick-Furman 2002), sedimented (sediment covering at least part of the colony), tissue mortality (tissue damage but no skeletal damage), diseased (black band along the border between live and dead tissue, or white, moss-like tufts speckling the tissue surface, identified using Humann and Deloach 2002), or undamaged. Feeding scars by corallivorous fishes appeared as circular scoops of removed tissue and skeleton, and were not considered when assessing colony condition (Hawkins and Roberts 1992). Colonies exhibiting multiple damage conditions were categorized according to the dominant damage condition on the colony.

Statistical analyses

Statistical analyses were performed using Systat, v 13. Variation among dive shop categories in rates of diver-coral contact and coral damage, and variation among reefs in coral condition, were assessed using non-parametric Kruskal-Wallis tests (Barker and Roberts 2004). Diver behaviours were observed for 7 min each (see above), then their rates were multiplied by 8.57 to obtain the rate of each behaviour per 60 min, which was the duration of a typical scuba dive at the depths observed here (4–13 m depth below sea surface, see above). Data on the percent cover of live corals was arcsin transformed and analyzed using one-way analysis of variance (Zakai and Chadwick-Furman 2002). All data were normally distributed after transformations and are reported as means± one standard deviation unless otherwise noted. For percentage data, 95 % confidence intervals are shown.

Results

Diver behaviours and impacts on corals

Most recreational scuba divers (70.8 %, N=240) contacted live stony corals at least once per each 7 min observation period, so during a typical 60-min scuba dive, we estimate that each diver contacted live corals about 18 times. Divers most frequently contacted live corals with their fins (12.43± 1.85 contacts per 60-min dive), but also occasionally with their hands (3.04±0.74) and scuba gear (dangling pressure gauges, regulators, etc., 2.32±0.63). Most hand contacts (68 %, N=85) occurred as divers attempted to steady themselves due to poor buoyancy control, while most scuba gear contacts (84 %, N=55) were caused by dangling reserve regulators or dive computers that were not closely tethered to their buoyancy compensator devices. Divers also contacted corals with other parts of their bodies (knee, elbow) or with cameras or other accessories such as dive knives or compasses (0.54±0.27 contacts per dive).

The most frequent type of impact to corals from these behaviours was sediment deposition (9.50±1.59 times per 60-min dive). Divers also abraded coral tissues (3.18±0.73) and fractured coral skeletons (0.79±0.30). About one quarter of diver contacts with corals (25.6 % of 510 contacts, including sediment deposition) resulted in no obvious coral damage (4.68±0.90 instances per 60-min dive).

Rates of coral contact varied significantly among divers from the 4 dive shops examined (Kruskal-Wallis Test, $P<0.001$). Divers from both Blue Star shops contacted corals at similar rates that were significantly lower than those of divers from non-Blue Star shops, whose rates were similar to each other (14.14±2.32 vs. 22.38±2.08 contacts per 60-min dive, respectively, Conover-Inman Test for Pairwise Comparisons, $P<0.001$ for all Blue Star vs. non-Blue Star comparisons). Rates of coral tissue abrasion and sediment deposition by Blue Star divers also were significantly lower than by non-Blue Star divers (Kruskal-Wallis Test, $P<0.01$ and $P<0.001$, respectively; Fig. 2). Blue Star divers deposited sediment onto live corals 6.73±1.52 times per 60-min dive and abraded corals 2.27±0.64 times, while the rates for non-Blue Star divers were almost twice as high, 12.38±1.57 and 4.13±0.81, respectively. Rates of diver-caused coral breakage, and of contact resulting in no obvious damage, did not differ significantly between the 2 two diver groups (Kruskal-Wallis Test, $P=0.05$ and $P=0.09$, respectively).

Overall coral contact rates of divers with guides ($N=94$) did not differ significantly from those of divers without guides ($N=146$, 14.68±1.94 vs. 18.14±2.23 contacts per 60-min dive, respectively, Kruskal-Wallis Test, $P=0.06$). Also, none of the rates of various types of contacts or their impacts on corals differed significantly between divers with dive guides versus those without (Kruskal-Wallis Tests, $P>0.42$ for all comparisons). Coral contact rates did not differ significantly between divers in the northern ($N=142$) and southern region of Key Largo ($N=98$, 16.23±2.01 contacts vs. 17.47±1.66 contacts per 60-min dive, respectively, Kruskal-Wallis Test, $P=0.058$), nor did they between divers observed during the first ($N=123$) versus second half of each dive ($N=117$, 16.58±17.31 vs. 20.15±21.78 contacts per 60-min dive, respectively, Kruskal-Wallis Test, $P>0.20$ for all comparisons; slightly more divers were observed during the first than during the second half of each dive period).

Of the 240 total divers observed, 20.4 % carried an underwater camera, 20.8 % wore diving gloves, and 7.1 % had both a camera and gloves. Divers with a camera and/or gloves (48.3 % of all divers) accounted for 57.7 % of all observed diver-coral contacts, a significantly higher rate of coral contact than for divers without these accessories (21.6±2.1 vs. 15.0±1.2 contacts per 60-min dive, respectively, Kruskal-Wallis Tests, $P<0.05$ for all comparisons). Divers with cameras contacted corals at 20.4±2.4 contacts per 60-min dive, those with gloves at 22.2±1.7, and those with both gloves and cameras at 24.0±2.6 contacts per 60 min (Fig. 3).

Variation in coral condition among sites

The percent cover of live stony corals (both damaged and undamaged) varied significantly among the six reefs examined (Figs. 1 and 4, $N=49$–53 quadrats per reef, ANOVA, $F=86.44$, $P<0.001$). Percent live coral cover did not vary significantly between Pickles (3 buoys, 22.25±2.84 %) and

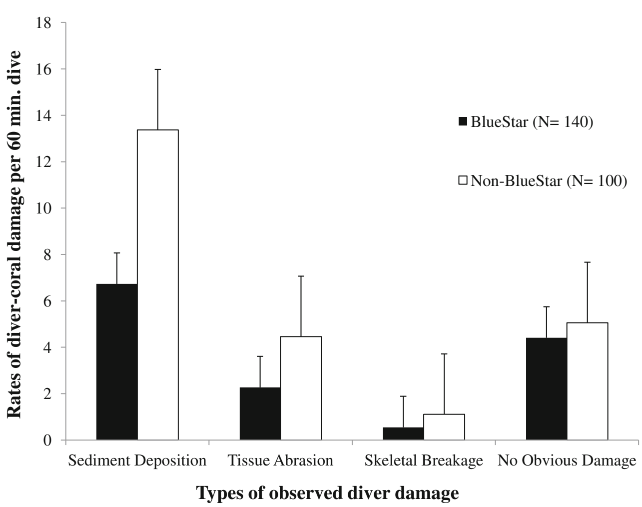

Fig. 2 Variation in rates of damage to stony corals by recreational SCUBA divers from Blue Star versus Non-Blue Star dive shops. Shown are means ± standard deviations of damage rates Sample sizes of numbers of divers observed are given in parentheses

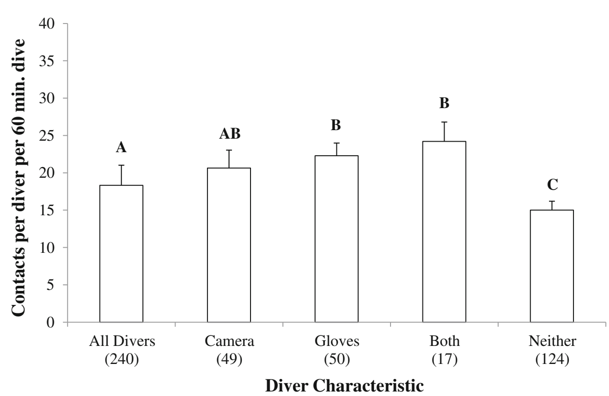

Fig. 3 Variation in coral contact rates among recreational divers with various types of underwater accessories. Shown are means ± standard deviations. *Numbers in parentheses* indicate the number of divers observed in each category

South Carysfort (23 buoys, 24.69±6.48 %), nor between Carysfort North (4 buoys, 32.17±4.02 %) and Dry Rocks (15 buoys, 25.98±4.26 %, Tukey multiple comparisons test, $P=0.46$ and $P>0.10$, respectively, $P<0.05$ for all other comparisons, Fig. 4).

The percent of coral colonies that exhibited some type of damage also varied significantly among reefs (ANOVA, $F=37.46$, $P<0.001$, Fig. 4), with the six reefs sorting into two main groups. The first group contained Little Grecian (0 buoys) and Pickles (3 buoys), which had relatively low percentages of damaged corals that did not differ significantly from each other, but had significantly lower damage rates than did the other 4 reefs examined (Tukey multiple comparisons test, $P<0.05$ for all comparisons), with the exception of Carysfort North (4 buoys), which differed from Little Grecian but not from Pickles or any other site ($P<0.05$ for all comparisons). The second group (Dry Rocks, South Carysfort, and Molasses) also did not differ significantly from each other in their high damage rates (15, 23, and 27 buoys respectively, $P>0.05$ for all comparisons, Fig. 4). The lowest damage occurred on the reef with the fewest mooring buoys (0, Little Grecian) and the highest on the reef with the most mooring buoys (27, Molasses). About half of all corals on the reef with no mooring buoys (Little Grecian) exhibited some form of damage, indicating possibly high background levels of coral damage in this region due to factors other than diver contact (storms, pollution, bleaching, etc.). Almost all live stony corals exhibited some type of damage at the high-buoy reef (Molasses, 82.11±9.11 %) revealing major reef degradation at this site.

Of the five categories of coral damage surveyed, tissue mortality and sedimentation were the most common (35.65±11.64 % and 29.10±10.92 % of all corals, respectively), and occurred at significantly lower rates on reefs with few vs. many buoys (Kruskal-Wallis Test, $P<0.001$, Fig. 5). Coral damage in the form of abrasion and broken skeleton were less common (13.62±2.42 % combined on all corals), but also occurred on a significantly higher percentage of corals at reefs with many versus few buoys (Kruskal-Wallis Test, $P<0.05$, Fig. 4). Coral disease rates were low (4.24±2.95 %) and did not vary significantly between reefs with few versus many mooring buoys (Kruskal-Wallis Test, $P=0.438$, Fig. 4).

Overall, the proportion of damaged colonies varied little among the three major types of coral growth forms (Table 1). Damage rates to branching and other (mostly encrusting and foliaceous) corals were similar, and most had overlapping 95 % confidence intervals, except for branching colonies at Pickles (0.50±0.12) and Molasses (0.81±0.15), and other colonies at Little Grecian (0.43±0.08) and Molasses (0.62±0.1). Rates of damage to massive corals varied more widely, with Little Grecian and Carysfort North grouping separately from the 3 sites with many mooring buoys (Molasses, South Carysfort, and Dry Rocks), and Carysfort North also exhibiting similar damage rates as Pickles (Table 1). The 3 most

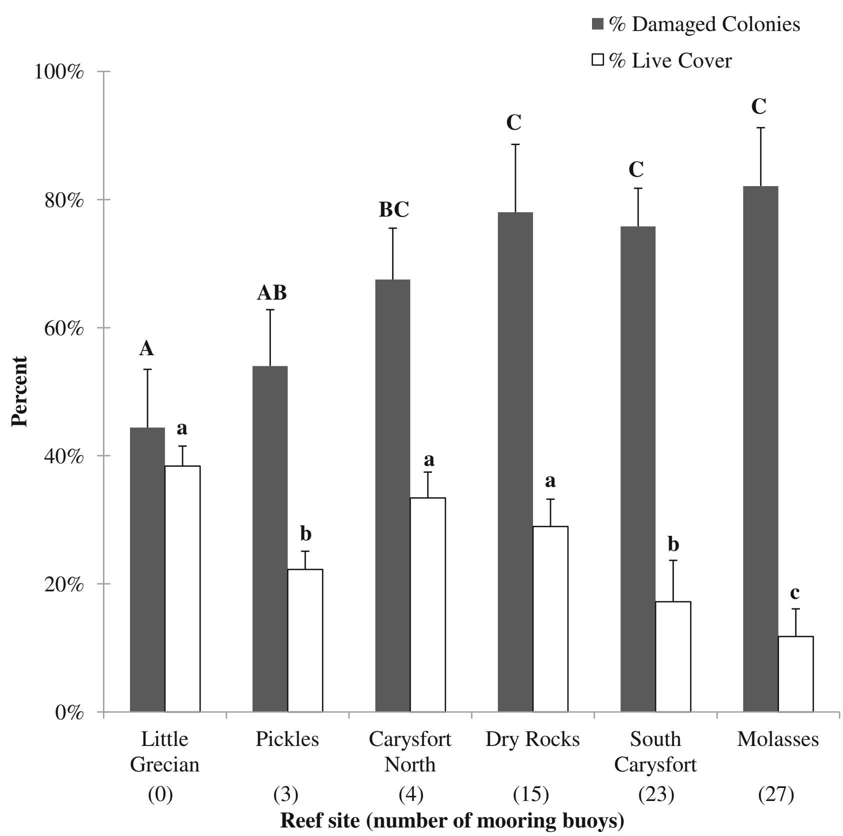

Fig. 4 Variation in the percent cover of live stony corals and the percent of coral colonies damaged (sediment deposition, tissue abrasion, tissue mortality, skeletal breakage, and disease) among 6 patch reefs at Key Largo, Florida. The patch reefs are ordered from low to high the number of mooring buoys per reef, as a proxy for the number of recreational dives per year per reef (see also map, Fig. 1). *Letters above the columns* represent groupings based on Tukey multiple comparisons test (for % Damaged Corals, upper case) and Conover-Inman Test for Pairwise Comparison (for % Live Coral Cover, lower case). See text for details

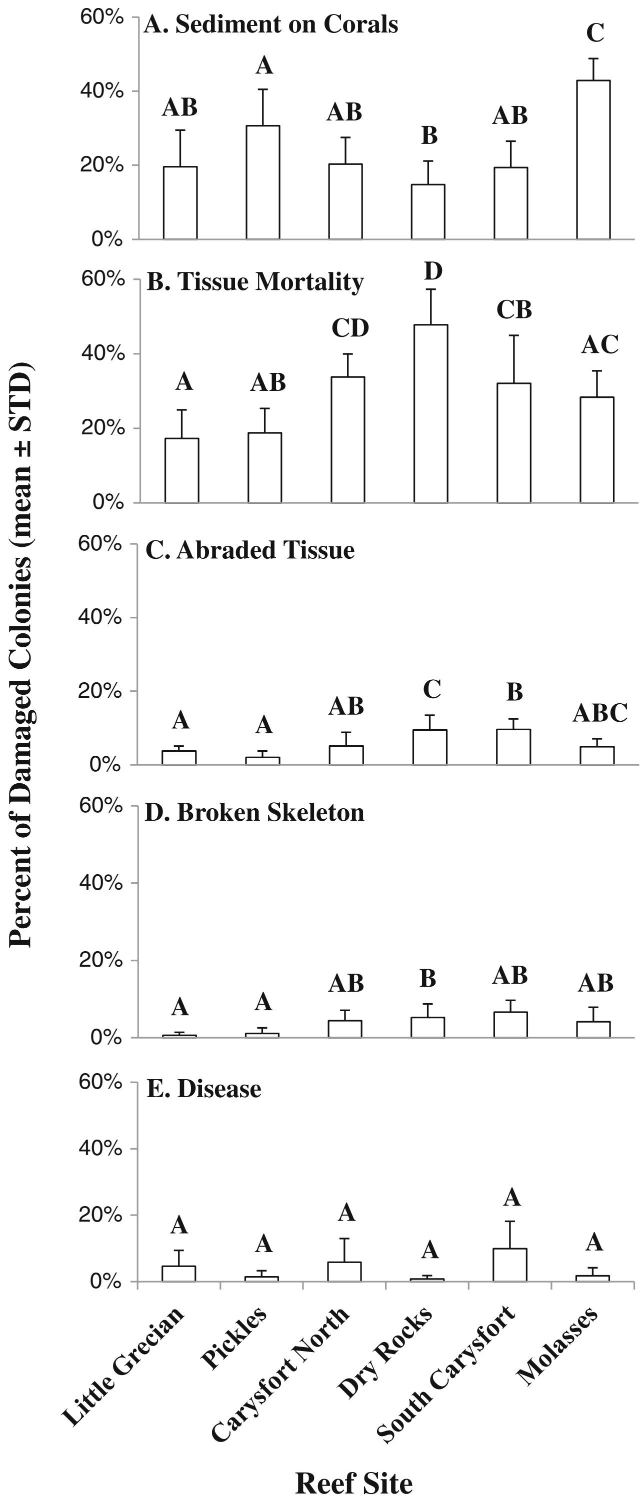

Fig. 5 Variation in rates of 5 types of damage to stony corals among 6 patch reef sites at Key Largo, Florida, ordered from low to high number of mooring buoys per reef (see Figs. 1 and 4 for site details). Letters above columns represent groupings based on Conover-Inman Tests for Pairwise Comparisons

abundant coral genera surveyed were *Agaricia*, *Porites*, and *Siderastrea* (88 % of colonies examined, N=1,666), while the three least common were *Dichocoenia*, *Diploria*, and *Madracis* (1.2 %). Colonies of *Montastraea* and *Dipoloria* (N=92) also occurred infrequently, but often were large (1–4 m diameter) compared to those of the other corals examined (<0.5 m diameter).

Discussion

Overview

Recreational diving is considered to be a form of ecotourism, but intensive diving tourism can cause severe negative impacts to marine ecosystems, especially to coral reefs with delicate coral growth forms. We show here that recreational divers cause substantial direct (skeletal fracture, tissue abrasion) and indirect (deposition of sediment) damage to live stony corals in the Florida Keys. Divers from shops that participate in the NOAA Blue Star program cause significantly less coral damage than do divers from other types of dive shops. Our study also reveals that the percent cover of live stony corals and the proportion of undamaged corals both decrease significantly with estimated rates of recreational diving on reefs in Key Largo.

The Florida Keys attract 3 million visitors per year (Leeworthy and Morris 2010), of which many participate in recreational diving. In the FKNMS, which contains most coral reefs near Key Largo, recreational diving occurs at 100 000–150 000 dives per year, making this one of the most intensively-dived coral reef areas in the world (Leeworthy and Morris 2010). The rates of coral-damaging behaviours observed here are similar to those known for divers in Australia (Rouphael and Inglis 1997), the Red Sea (Zakai and Chadwick-Furman 2002), other parts of the Caribbean (Barker and Roberts 2004), and at other sites in Key Largo (Camp and Fraser 2012). Our observation that fin kicking and deposition of sediment are the most frequent types of diver contacts with corals is also similar to patterns observed for divers in Australia (Harriott et al. 1997) and the Red Sea (Zakai and Chadwick-Furman 2002).

Our results differ from those of early studies in the Florida Keys, which concluded that recreational divers cause little damage to corals (Tilmant and Schmahl 1981; Talge 1992). In contrast, we document that reefs with high estimated levels of diver visitation exhibit low coral cover and high proportions of damaged corals, and that most scuba divers cause some type of damage.

Diver behaviours and impacts on corals

In addition to kicking corals with their fins, we observed divers to contact live corals with their hands, scuba gear, and occasionally their bodies (e.g. knees, elbows). Most contacts

Table 1 Variation in rates of 5 types of damage to 3 types of coral growth forms (Branching, Massive, and Other) among 6 patch reef sites at Key Largo, Florida, ordered from low to high number of mooring buoys per reef. Shown are means ± standard deviations of the proportion of colonies damaged in N=49–53 1-m^2 quadrats examined at each site

Damage	Growth form	Site					
		Little Grecian	Pickles	Carysfort North	Dry rocks	South Carysfort	Molasses
Sediment on corals	Branching	23.3±7.1 %	50.0±9.1 %	14.7±5.1 %	31.4±10.6 %	56.4±12.3 %	53.4±11.7 %
	Massive	14.1±5.4 %	30.7±11.0 %	23.4±8.4 %	21.5±8.4 %	27.5±9.6 %	51.9±18.5 %
	Other	16.8±5.1 %	25.6±12.9 %	18.7±4.2 %	5.4±2.1 %	38.4±12.0 %	16.7±4.6 %
Tissue mortality	Branching	19.7±5.1 %	4.2±2.1 %	29.1±9.2 %	70.4±21.2 %	52.7±14.3 %	55.6±13.7 %
	Massive	14.3±4.2 %	24.2±9.4 %	36.3±11.2 %	46.0±13.2 %	32.5±11.1 %	27.0±9.8 %
	Other	18.1±6.1 %	17.9±6.1 %	35.5±10.1 %	26.5±11.1 %	31.4±8.3 %	47.7±14.1 %
Tissue abrasion	Branching	4.0±2.8 %	4.4±1.0 %	14.4±4.2 %	21.1±8.3 %	21.0±8.2 %	5.7±2.8 %
	Massive	2.4±1.1 %	2.7±1.3 %	11.9±2.3 %	11.5±2.3 %	6.7±2.2 %	6.4±2.7 %
	Other	2.6±1.0 %	1.7±1.0 %	3.4±0.9 %	7.5±2.3 %	0 %	7.6±2.2 %
Skeletal breakage	Branching	2.8±1.3 %	4.7±2.2 %	11.8±3.2 %	8.9±2.1 %	15.6±4.3 %	10.8±3.2 %
	Massive	0 %	1.2±0.9 %	5.0±1.6 %	6.7±1.2 %	8.7±2.2 %	3.6±1.2 %
	Other	0 %	0 %	2.4±1.2 %	8.6±3.1 %	6.0±2.3 %	0 %
Disease	Branching	5.4±2.9 %	0 %	0 %	0 %	7.4±2.3 %	5.4±1.2 %
	Massive	6.4±2.1 %	1.1±0.7 %	5.0±2.3 %	0 %	17.7±5.2 %	1.7±1.2 %
	Other	0 %	3.4±1.2 %	6..5±2.4 %	8.8±2.1 %	0 %	0 %
Total damage	Branching	57.4±12.1 %	50.8±12.3 %	64.5±13.0 %	62.0±14.2 %	60.8±13.4 %	81.6±15.2 %
	Massive	41.2±11.1 %	74.8±15.9 %	59.4±10.5 %	83.7±7.1 %	89.4±7.0 %	87.8±16.5 %
	Other	43.4±8.3 %	59.6±15.4 %	36.7±22.5 %	53.6±18.8 %	53.1±9.0 %	62.7±10.3 %
Total colonies observed	Branching	60	52	45	118	141	83
	Massive	117	95	90	118	121	79
	Other	115	69	50	125	106	102

appeared to be inadvertent, likely due to poor diving skills and/or inexperience. Although some contacts resulted in no obvious coral damage, simply touching live corals can adversely affect their physiological condition (Goreau et al. 1998; Barker and Roberts 2004). Disturbances to the thin mucous layer covering corals also can increase their susceptibility to disease and algal overgrowth (Morrow et al. 2011). Such disturbances are caused by even minimal contacts by divers. As such, documentation of all coral contacts by divers is important, and should be included in future studies of recreational diver impacts on coral reef condition.

We observed that many diver-coral contacts appear to be unintentional, similar to the conclusions of other studies on recreational diver damage (Harriott et al. 1997; Uyarra and Cote 2007). In most cases, the divers observed here appeared to be unaware that they were harming live organisms, so education of divers about the major damage they cause to corals by even minor physical contact could reduce substantially these types of unintended contacts. Our findings also are similar to those of Medio et al. (1997), who demonstrated that after Australian divers were made aware that they were causing harm to living organisms, rates of unintentional contact (i.e., fin kicking, dangling gear) were reduced significantly through the administration of briefings by dive shops. In contrast, Barker and Roberts (2004) concluded that dive briefings did not reduce diver-coral contact rates at St. Lucia (Caribbean), but this may have been due to inconsistencies in the types of briefings delivered. The Blue Star dive shops observed here administered short (1–2 sentences) dive briefings prior to divers entering the water, which explained that divers were in a protected area and should refrain from touching or taking any corals because they are living organisms, important to the health of the reef. While short and simple, this type of briefing reminds divers that corals are living animals and that contact can harm them. Unlike Medio et al. (1997), in the present study we did not conduct a manipulative experiment to test whether dive briefings per se influenced contact rates. Blue Star operators promote reef conservation awareness through a variety of strategies, including online information, coral identification cards, and informative pamphlets. They also display the NOAA Blue Star logo on their websites, shops, and boats. Blue Star certification thus may encourage conservation-orientated divers to use their services more than they do those of non-Blue Star shops. These divers also may be more experienced and better able to control their buoyancy and navigation around reef structures, than are divers who are not conservation-minded. Zakai and Chadwick-Furman (2002) concluded that most diver-coral contacts in the Red Sea are caused by new or inexperienced divers. If Blue Star operators typically attract more experienced and/or conservation-oriented divers than do non-Blue Star operators, this could explain in part the reduced rates of reef contact observed here by these divers. However, it is also likely that dive briefings contributed to mitigation of coral contacts, as concluded by another recent study on the effects of the Blue Star program on diver behaviour (Camp and Fraser 2012).

Although we focussed our analysis on diver damage during the main roving portion of each dive (see Methods), we also observed unintentional coral contacts during the first 5 min of dives. Previous studies have noted that behaviours specific to the beginning of each dive, such as descending too rapidly and initially orientating to surroundings and adjusting gear, can cause substantial damage to reef corals (Barker and Roberts 2004). As such, reef managers could mitigate these types of damage by locating mooring buoys and water entry points over sandy bottom areas away from live reef corals.

Our study shows that after the initial adjustment period at the start of each dive, coral contact rates are uniform throughout the duration of each dive, indicating that these behaviours do not vary as divers are in the water longer or as they travel further from the boat. Factors influencing diver behaviour at the start of the mobile portion of the dive thus appear to resonate throughout the dive, suggesting that conservation awareness or skills acquired prior to the dive likely have a beneficial impact on diver behaviour for the entire duration of each dive.

Diver-coral contact rates did not vary with spatial factors that varied among the dive shops examined, such as dive shop and reef site location along the 5 km coastal area near Key Largo, so diver behaviours did not appear to be affected by reef or dive shop characteristics that varied from north to south along this reef tract. Our observation that the presence of underwater dive guides does not impact rates or types of diver-coral contacts contrasts with a recent study in which dive guide presence reduced diver-coral contacts (Barker and Roberts 2004). This difference appears due to the dive guides actively intervening when they witnessed divers contacting the reef in the previous study, whereas in our study they did not. The dive guides observed here served mainly as tour guides and swam in front of the divers, leading them to locations around the reef. Dive guides in the Florida Keys could improve their services by observing client divers more closely, and intervening when they see them damage corals.

The high rates observed here of coral contact by divers with cameras were similar to those known for Australia and other Caribbean locations (Medio et al. 1997; Rouphael and Inglis 2001; Barker and Roberts 2004). Camp and Fraser (2012) recently reported no effect of camera use on coral contact rates by divers, but their low sample size (only 12 divers observed with cameras) may have hindered detection of a pattern. Divers using underwater cameras potentially have greater diving experience (Rouphael and Inglis 2001; Barker and Roberts 2004), and thus better buoyancy and maneuvering skills than other divers, but we observed that both camera and glove users behaved more carelessly underwater than did divers lacking these accessories. Camera users appeared distracted from paying attention to reef contacts, and often kicked the reefs as they swam along taking pictures, leading to severe coral abrasion in the form of long fin tread marks on the reef. Divers with cameras crashed into and fragmented entire colonies while attempting to adjust their cameras. Divers with gloves appeared to be more willing to touch live corals with their hands than did those not wearing gloves. Glove users held onto live corals while they peered into crevices in search of fish and other reef inhabitants, and grabbed corals to steady themselves while they adjusted their buoyancy. These types of behaviours cause users of underwater cameras and gloves in inflict substantial damage on corals at Key Largo. At least some of this enhanced damage could potentially be mitigated by pre-dive briefings aimed at alerting divers to take extra care when using these types of accessories.

Variation in coral condition among sites

We observed that both the proportion of undamaged corals and the percent cover of live corals decreased as estimated diving rates increased on reefs, suggesting a possible cause-effect relationship. While this was a correlative pattern, and thus not proven to be cause-effect, the low and high visitation reefs were interspersed along the coast, and the only obvious factor that differed among them was the number of buoys for dive boat attachment. We conclude that high diving rates appear to negatively impact the condition of some reefs, similar to the conclusions of Hodgson (1999) on a global scale. The reef observed here with the most damage (Molasses: 27 buoys, 82 % of corals damaged, 12 % coral cover) is one of the most heavily dived sites in the world (pers. comm., NOAA official). In stark contrast, the least-visited reef Little Grecian had no mooring buoys, half the coral damage and >3x the live coral cover. We visited Little Grecian using a private charter boat that used GPS to locate the reef, then dropped us off, and motored nearby until we surfaced and signalled for a pick up. Due to these multiple logistical barriers, recreational diving at this site likely is rare, leading to the much better coral condition that we observed. However, coral condition did not vary precisely with mooring buoy number among our sites, indicating that other factors contribute to the observed variation. Overlap among sites in the proportion of damaged corals may be due in part to variation in % live coral cover, because a site with low % cover also contains few colonies to damage and vice versa. If levels of coral cover were higher at sites with many mooring buoys, their coral damage levels might be even greater. Also, even the sites with few mooring buoys had relatively high proportions of damaged corals (>40 %), indicating high background levels of coral damage in this region. Reefs in the Florida Keys are disturbed by hurricanes, bleaching, overfishing, and many other pressures (Ball et al. 1967; Fitt et al. 2001), which likely caused the high background levels of damage observed here on reefs visited rarely by recreational divers. Current long-term monitoring programs in the Florida Keys include a Water Quality Protection Program and an Ecological Research and Monitoring Program, which record changes in abiotic parameters (ie. water temperature, dissolved nutrients) and various ecological conditions on the reefs (ie. algal blooms, fish kills, NOAA 2007), but do not yet include specific monitoring of recreational diving impacts

Our observation that corals had similar damage rates regardless of growth form differs from previous results in which branching colonies were more impacted by divers than were massive colonies (Hawkins and Roberts 1993; Zakai and Chadwick-Furman 2002). This discrepancy may be due to variation in branching coral types among regions. Many branching corals in past studies belonged to the genus *Acropora*, in which colonies often form long thin branches that project far above the reef substratum. At our sites the major branching corals were *Porites* that form compact colonies and may not fracture as easily as the more delicate branching corals in other studies. At our sites occurred many dead fragments of *Acropora* that were covered by encrusting organisms and appeared to have died prior to our study, leaving only the sturdier branching corals (*Porites*) and reducing the potential for variation in breakage among coral types. *Acropora* coral abundance has declined drastically during the past few decades in Florida (Williams 2008), leading to limited diversity of branching corals in this area.

Conclusions and recommendations

Dive-based recreational tourism is a major economic activity in the Florida Keys, and healthy reefs are a valuable natural resource because divers use the quality and quantity of marine life as criteria for dive site selection (Dixon and Sherman 1991; Kenchington 1993; Pendleton 1994; Wielgus et al. 2002). While some studies have proposed that divers mainly seek destinations with warm clear waters (Hawkins and Roberts 1994), others have found that divers care about the quality of the reefs they visit (Medio et al. 1997), and are willing to pay more to visit visibly healthier reefs (Wielgus et al. 2002; Schuhmann et al. 2008).

Improved management of recreational diving tourism on Florida reefs is needed to maintain their aesthetic natural appeal and biological characteristics, and to ensure that they remain a valuable economic resource for ecotourism in this region. Based on our findings, we recommend the following steps to reduce the widespread damage currently being caused by recreational divers on these reefs: (1) Provision of pre-dive ecological briefings to all recreational divers, (2) Inclusion of extra briefings for divers with cameras and gloves about potential coral-damaging behaviours, (3) Increased use of underwater dive guides who intervene when they observe divers damaging corals, (4) Establishment of diver entry points over sandy areas away from stony corals, and (5) Promotion of dive shop involvement in environmental educational frameworks such as NOAA's Blue Star program.

The public is becoming increasingly aware of issues in biological conservation, and public pressure is likely to grow concerning activities that clearly harm the environment. Environmental groups in the Florida Keys such as REEF (Reef Environmental Education Foundation, www.reef.org) are pushing for more sustainable diving practices. The NOAA Blue Star program offers a framework for conservation-minded individuals to locate dive shops committed to reef preservation, and also educates non-conservation minded divers. Increased diver demand for conservation-orientated diving operations can encourage more dive shops to incorporate conservation principles into their existing operations, creating a positive feedback loop that enhances both the knowledge and implementation of sustainable coral reef management. This study provides a scientific basis to support the management of diving tourism on economically important coral reefs in the Florida Keys.

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