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Spatial dynamics and substrate impacts of recreational snorkelers and SCUBA divers in Hawaiian Marine Protected Areas

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Abstract We quantified spatial dynamics and substrate impacts of snorkelers and SCUBA divers within four Hawaiian MPAs to determine: (1) whether coral reefs in these areas are being damaged by recreational activities, and (2) how damage might be mitigated. Observers secretly followed snorkelers and SCUBA divers, and used handheld Global Positioning System (GPS) units to record their geographic tracks and substrate contacts. Most activities occurred within relatively small, well-defined areas associated with access points. Despite heavy use, recreation impact was low at Hawaiian MPAs because most fragile corals occurred below the maximum depth of the dominant recreational activity (snorkeling). SCUBA diving was only common at one MPA with physically durable benthic habitats. GPS tracking provided useful insights into how recreational impacts to MPAs could be reduced. General topography could be used to predict where visitors will go, and designated access points could be used to focus substrate contact away from fragile habitats.

Keywords Snorkeling · SCUBA diving · Recreation impact · Ecotourism · Coral damage · GIS

Abbreviations

AM	animal movement
GPS	global positioning system
KUD	kernel utilization distribution
MLCD	Marine Life Conservation District
MPA	marine protected area
SCUBA	self-contained underwater breathing apparatus
SNUBA	a portmanteau of “snorkel” and “scuba”

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Introduction

The field of recreation ecology examines visitor impacts on protected natural areas and provides information for managing those impacts (Leung and Marion 2000). Recreation ecology has historically focused on visitor impacts in terrestrial parks and wilderness areas but has more recently evaluated recreation impacts on coral reefs (Leung and Marion 2000; Plathong et al. 2000; Barker and Roberts 2004). To date, studies of recreation impacts on coral reefs have been limited to three main types: (1) Benthic surveys where coral damage was compared between high and low traffic areas (e.g., Hawkins and Roberts 1992; Jameson et al. 1999; Zakai and Chadwick-Furman 2002); (2) Direct impact (‘real time’) studies where people engaging in specific activities were individually followed to determine the frequency and extent of damage to corals (e.g., Harriot et al. 1997; Walters and Samways 2001; Barker and Roberts 2004); and (3) Experimental manipulations where the resilience of different coral species to physical contact was evaluated using simulated trampling, mechanical strength testing and tissue regeneration and fragment survival experiments (e.g., Liddle and Kay 1987; Riegl and Riegl 1996; Rodgers et al. 2003). Detailed, empirical data quantifying the spatial qualities (extent, distribution and association) of recreation impacts on coral reefs are currently lacking. In terrestrial environments, such knowledge has proved critical for understanding magnitude of recreation impacts, evaluating their significance, and prioritizing management and maintenance needs (Leung and Marion 2000). This type of information may be equally important for successful management of recreation impacts on coral reef habitats.

Hawaiian Marine Protected Areas (MPAs) are utilized by hundreds of visitors every day and concern exists that recreation impacts are damaging fragile coral reef habitats at these sites (Cesar and van Beukering 2004). The most common recreational activities occurring in Hawaiian MPAs (snorkeling and SCUBA diving) are known to damage coral in other geographic regions (e.g., Plathong et al. 2000; Rouphael and Inglis 2001). Trained observers used waterproofed Global Positioning System (GPS) units to track individual divers and obtain high resolution spatial information on recreation impacts within four Hawaiian MPAs. The goal was to use this novel, empirical approach to obtain a better understanding of the overall usage patterns and mechanisms of human impact at MPA sites, and identify simple strategies for reducing recreation impacts on these areas.

Methods

Study sites

The term Marine Life Conservation District (MLCD) is used to describe MPAs in Hawaii. The four MPAs utilized in this study were Honolua-Mokuleia MLCD (Maui), Kealakekua Bay MLCD (Hawaii), Manele-Hulopoe MLCD (Lanai) and Pupukea MLCD (Oahu) (Fig. 1). These MPAs range in size from 0.2 to 1.3 km^2 and were created over the past four decades with the primary goal of providing opportunities for recreational snorkeling and SCUBA diving. Extractive activities such as fishing are banned from all or part of these MPAs, but non-commercial, non-extractive recreational activities are unrestricted at these sites (i.e., visitor numbers are not controlled and no entry fees are charged). Commercial recreational activities (e.g., commercial, boat-based snorkeling tours) are regulated via a limited permit system. Up to 80% of all recreational users observed at these MPAs arrive on boat-based, commercial snorkel tours (C.G.M unpublished data). Each of these sites contain bays that have calm, sheltered conditions for at least part of the year, and a variety of benthic habitats including live coral, coralline algae, uncolonized pavement, volcanic rock, boulders and sand (Fig. 1). Mechanically fragile corals (primarily *Porites compressa* and *Montipora* spp.) are found at all four sites but are rare at Pupukea, which is seasonally exposed to high surf. Recreational activities at these sites are dominated by swimming, snorkeling and SCUBA diving, with most visitors gaining access to MPA waters either from the shore or on commercial charter vessels.

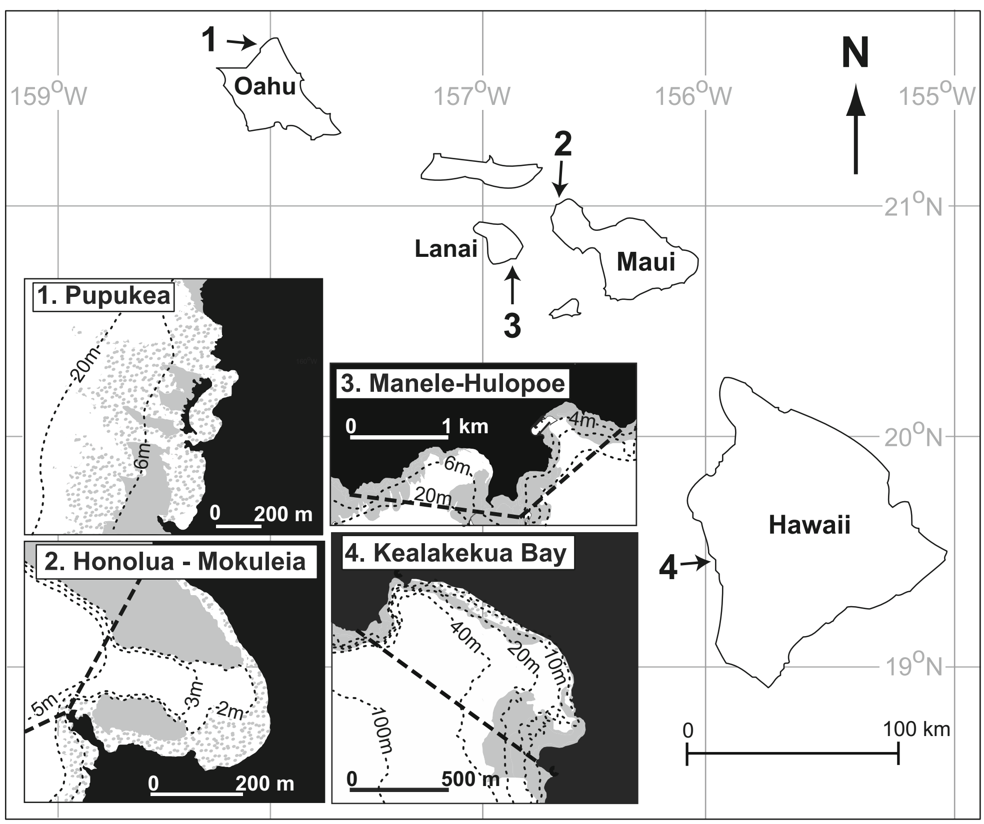

Fig. 1 Locations of the four Marine Protected Area (MPA) study sites. *Insets* illustrate the geography and major habitat types at each MPA; land (*black*), consolidated reef (*light shading*), boulders (*stippled shading*) and sand (*unshaded*). *Dotted lines* show depth contours (m). *Dashed lines* indicate the MPA boundaries

Focal observations

At each MPA site, observers equipped with snorkeling gear and a GPS unit followed individual snorkelers or SCUBA divers for the duration of their dives (i.e., from point of entry to point of exit from the water). The general terms 'dive', 'diver' and 'diving' are used to describe both SCUBA and snorkeling activities unless otherwise specified. The general approach was for observers to blend in with the crowd and remain undetected by their focal observation subjects, which included a broad cross-section of the people utilizing each MPA site. Observers recorded the spatial track of each subject by towing a handheld GPS unit (Garmin 12XL) contained in a waterproof bag and mounted on a small float to prevent loss of satellite contact due to submergence. The GPS units were set to automatically log position at 10 s intervals throughout the track. Observers manually entered GPS waypoints to record locations where subjects made physical contact with the substrate. The maximum GPS estimated positional error (EPE) during tracks was 4 m, and extensive prior testing was carried out to ensure that diver tracks would be accurately recorded. Observers used preformatted waterproof data sheets to record information about the person being followed (gender, approximate height, weight and age), the activity that they were involved in (snorkeling, SCUBA or SNUBA), the origin of the activity (shore or boat) and any substrate contact observed (e.g., type of contact, substrate type and result of contact). These data sheets were concealed on the back of fish identification cards commonly carried by visitors at MPA sites.

Calculation of annual visitor numbers

In order to calculate the annual number of divers using these sites, daily snorkeler and SCUBA diver counts were carried out at each of the four MPAs. Observers selected vantage points from which divers and snorkelers could be seen entering and exiting the water, and kept a running tally of the number of divers using the site between 0800 and 1800 hours. It had been previously determined that this time period included >95% of all recreational activities occurring daily at these sites (C.G.M unpublished data). This previous study also revealed that there were no significant seasonal or weekly (weekday versus weekend) differences in mean number of users at any site except Pupukea MLCD, where user numbers were significantly higher during the summer and on weekends, and near zero throughout the winter high surf season. Therefore, the annual number of snorkeler and SCUBA dives at all sites except Pupukea MLCD was calculated by multiplying average daily visitor numbers by 365. Annual values for Pupukea MLCD were obtained by first calculating separate mean daily values for both weekdays and weekend days, and then multiplying these by the appropriate number of weekdays and weekend days in the 5-month summer dive season.

Data analyses

Tracking data were overlaid on georeferenced high resolution color aerial photographs and benthic habitat maps, and the ArcView® Animal Movement (AM) extension (Hooge and Eichenlaub 1997) was used to carry out quantitative spatial analyses. The AM location statistics function was used to calculate the distance traveled by each individual diver and the AM kernel utilization distribution analysis to quantify the areas used by divers at each of the four MPA sites (see Fig. 2). The kernelling method yields a series of contours indicating areas with different probabilities of finding a diver. Kernel contour estimates are influenced by clustering of position fixes and hence useful for revealing core areas of use within larger activity spaces.

A multifactorial General Linear Model (Sokal and Rohlf 1995) was used to analyze the effects of diver characteristics (gender, age, size), activity type (snorkel or SCUBA) and origin of activity (boat or shore) on mean dive duration and mean number of substrate contacts. Dive duration and substrate contact data were log transformed prior to analysis in order to satisfy normality and equality of variance assumptions required for parametric testing (Sokal and Rohlf 1995). Where the results of the GLM indicated significant effects, ANOVAs with post hoc Bonferroni pairwise comparison of means were used to determine which groups were significantly different from one another. χ^2 analyses were used to test the significance of associations between the frequency of contact with different substrate categories (live or uncolonized) and the activity type (SCUBA or snorkel).

Results

Focal observations

From April to August 2003 a total of 234 divers (205 snorkelers, 25 SCUBA and 4 SNUBA divers) were followed for a total of 129 h at four MPA sites (Table 1). Diver tracking revealed that: (1) recreation impacts on coral reef habitats were generally low, (2) SCUBA divers had a greater impact per dive than snorkelers, (3) boat based activities had less impact per dive than shore based activities, and (4) individual behavior was important in determining recreation impacts.

Divers made 1,340 substrate contacts within MPA boundaries, but the majority (86%) were with inert substrates (sand and uncolonized rock), hence only 14% were with live substrates (coral, coralline algae and sessile invertebrates).

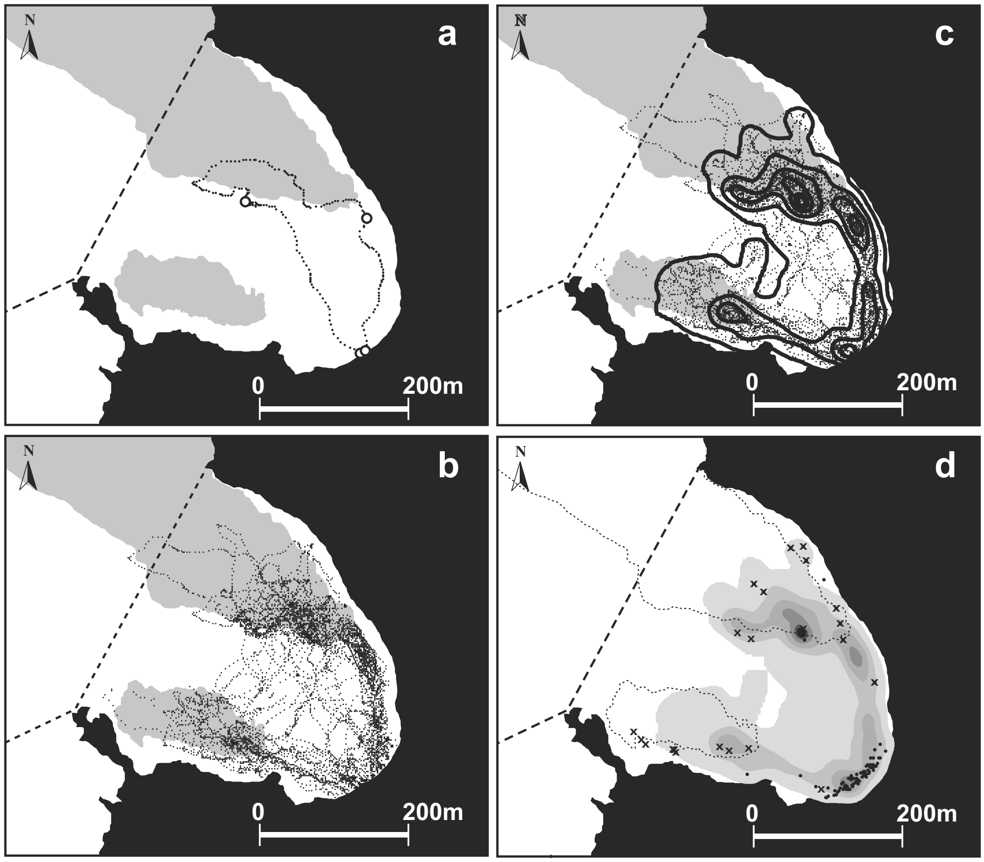

Fig. 2 Illustration of kernel utilization distribution (KUD) calculation for snorkelers at Honolua bay, Maui. Major habitat types are illustrated as follows; land (*black*), consolidated reef (*light shading*), boulders and sand (*unshaded*). *Heavy dashed lines* indicate the Marine Protected Area boundary. **a** Geographic track (*dotted line*) and substrate contact locations (*open circles*) of a single snorkeler. **b** Geographic tracks (*dotted lines*) of 41 snorkelers. **c** Geographic tracks of 41 snorkelers overlaid with KUD contours (*bold lines*). **d** KUD contours (5%, 10%, 25%, 50%, 75% and 95% contours illustrated from darkest to lightest shading respectively) showing core snorkeling areas (*darkest shading* = 5% KUD) within the main snorkeling area (*lightest shading* = 95% KUD) at Honolua, overlaid with substrate contact locations (*X* = live substrate contacts, points = uncolonized substrate contacts). Note that in this panel consolidated reef habitat is illustrated by a *light dashed outline* to differentiate it from the KUD contours

Only nine incidences of obvious substrate damage (0.7% of all substrate contacts) were observed. Only eight (5%) of 153 observed contacts with live coral resulted in visually obvious damage (broken branches or tissue abrasion), of which seven were caused by shore-based snorkelers.

Although their underlying mean substrate contact rates were similar, SCUBA divers had significantly more substrate contact per dive than snorkelers because SCUBA dives lasted twice as long as snorkel dives, and covered larger areas of habitat (Table 2). SCUBA divers also ranged into deeper zones of higher coral cover, and hence contacted live substrates significantly more often than snorkelers (χ^2=58.2, *df* 1, $p<0.001$). Seventy-six (29%) of 266 substrate contacts by SCUBA divers were with live substrates (coral, coralline algae or sessile invertebrates), compared to 112 (10%) of 1,074 snorkeler substrate contacts.

Table 1 Summary of focal observation sampling effort at four Hawaii Marine Protected Area sites

MPA site	Number of divers tracked	Total focal observation time (h)	Total distance covered (km)	Total substrate contacts observed
Honolua-Mokuleia	51	27.1	29.8	160
Kealakekua	80	39.3	29.2	447
Manele-Hulopoe	32	16.1	15.1	144
Pupukea	71	46.6	40.5	589
Total	234	129.1	114.6	1,340

Table 2 Results of ANOVAs comparing mean (±SD) durations and substrate contact rates of dive activities by type (SCUBA versus snorkel) and origin (shore versus boat)

	SCUBA	Snorkel	*F*	*df*	*p*
Mean dive duration (min)	59.8 (4.0)	30.0 (1.1)	35.1	1, 232	<0.0001
Substrate contacts per dive	10.2 (1.6)	5.4 (0.5)	6.3	1, 232	0.013
	Shore	Boat	*F*	*df*	*p*
Mean dive duration (min)	34.1 (2.6)	27.6 (1.3)	4.6	1, 232	0.033
Substrate contacts per hour	13.7 (1.0)	2.3 (0.8)	109.5	1, 232	<0.001
Substrate contacts per dive	6.7 (0.6)	0.7 (0.3)	108.6	1, 232	<0.001

Shore-based divers had significantly more substrate contacts per dive (or per hour) than boat-based divers, primarily because shore-based divers waded on entry to the water (Table 2). Boat-based snorkelers rarely touched the substrate (mean=0.7 contacts per dive), accounting for only 4–9% of all substrate contacts observed. Seventy-one percent of boat based snorkelers had no contact with the substrate, compared to only 3.5% of shore-based snorkelers and SCUBA divers.

General diver characteristics (gender, age, size) had no significant effect on substrate contact rates but the behavior of individual divers was clearly important in determining overall recreational impact on MPA sites. For example, the total number of substrate contacts observed per dive in this study ranged from 0 to 62 (mean=5.8), and half of all substrate contacts observed were made by only 16% of divers followed.

Annual numbers of snorkel and SCUBA dives

The calculated annual number of snorkel dives at the four Hawaii MPA sites ranged from 28,000 at Manele-Hulopoe MLCD to 100,000 at Kealakekua MLCD (mean=66,000) (Table 3). The annual number of SCUBA dives was considerably lower (1,400–2,000) at all sites except Pupukea MLCD (22,500) (Table 3).

Spatial distribution of activities and substrate contacts

Within each MPA, recreational divers utilized 2–55% of the total surface area and less than 15% of the total area of reef habitat. Diving activities were most concentrated within core areas of up to 6,800 m^2, containing reef habitats and/or points of access to the water (Figs. 2, 3, 4 and 5). The general topography of each MPA determined the overall shape of recreation activity spaces (Figs. 2, 3, 4 and 5). Snorkelers remained within the confines of obvious terrestrial features (e.g., rocky promontories, emergent reef), and spent most time over shallow (<3 m) reef substrates, whereas SCUBA divers ranged deeper and oriented to underwater features (reef walls, spur and groove formations) (Figs. 2, 3 and 4). Each MPA had primary water access points that served as ‘anchors’ for snorkel and SCUBA activity spaces. The different access points utilized by boat-based and shore-based snorkelers resulted in different activity space ‘footprints’, but the core use areas of both subgroups overlapped (Fig. 5).

Substrate contacts were clustered (55–75% of all contacts observed) at shoreline access points where people stood and waded as they entered and exited the water, but were relatively rare in intensively-used, shallow reef habitat away from these access points. For example, at Honolua Bay only 7% of substrate contacts occurred in the most intensively used (non-shoreline access) areas of reef habitat (Figs. 2 and 5). The frequency of diver contacts with live substrates increased with depth and distance from shoreline entry points (Figs. 2, 3 and 4).

Discussion

Focal observations revealed patterns of diver impact and behavior consistent with those described in previous studies. For example, other studies have found that snorkelers have less substrate impact than SCUBA divers, and boat-based diving activities have less impact than shore-based diving activities (Talge 1990; Barker and Roberts 2004). Previous studies have also shown that a relatively small proportion of divers are responsible for most of the damage to fragile habitats (Harriot et al. 1997; Medio et al. 1997; Rouphael and Inglis 2001). However, previous studies have not quantified these patterns in a spatially-explicit manner. We used GPS tracking to show that spatial patterns of diving activities in Hawaiian MPAs generally mirror those observed in terrestrial parks, where visitors typically restrict themselves to a small proportion (<10%) of the total park area, associated with well-defined trails and access points (Hendee et al. 1978; Hammitt and Cole 1987; Cubit and MacArthur 1995). MPA shoreline access points are analogous to the distinctive “nodes” observed in terrestrial parks, where recreation impacts (e.g., trampled vegetation, litter and campfires) are concentrated (Garcia and de Lucio Fernandez 1994; Marion and Cole 1996). However, little actual ecological impact was observed at shoreline access points because wading primarily occurred on uncolonized substrates (although we cannot rule out that colonization is being prevented by continued trampling).

Table 3 Annual number of SCUBA and snorkel dives at sites around the world

Geographic location	Dive site name	Dives per year		Source
		SCUBA	Snorkeler	
Australia, Great Barrier Reef	Heron Island	16,000	–	Harriot et al. 1997
Australia, Great Barrier Reef	Lady Elliot Island	10,000	–	Harriot et al. 1997
Australia, Great Barrier Reef	Solitary Island	2,000	–	Harriot et al. 1997
Australia, Great Barrier Reef	Orpheus Island	–	3,120	Plathong et al. 2000
Australia, Great Barrier Reef	Unspecified high use site	2,500	–	Rouphael and Inglis 1997
Australia, Great Barrier Reef	Unspecified low use site	800	–	Rouphael and Inglis 1997
Caribbean, Bonaire	Jerrys Jam	5,101	–	Hawkins et al. 1999
Caribbean, Bonaire	Carls Hill	5,074	–	Hawkins et al. 1999
Caribbean, Bonaire	Forrest	3,850	–	Hawkins et al. 1999
Caribbean, Grand Cayman	Paradise Reef	17,827	–	Tratalos and Austin 2001
Caribbean, Grand Cayman	Aquarium	8,700	–	Tratalos and Austin 2001
Caribbean, Grand Cayman	Royal Palms	6,001	–	Tratalos and Austin 2001
Caribbean, Grand Cayman	Armchair	794	–	Tratalos and Austin 2001
Caribbean, Grand Cayman	Smiths Cove	754	–	Tratalos and Austin 2001
Caribbean, Grand Cayman	Jax Dax	588	–	Tratalos and Austin 2001
Red Sea, Egypt, Ras Mohammed Nat. Pk.	Unspecified high use mooring	20,000	–	Medio et al. 1997
Red Sea, Egypt, Hurghada	Small Giftun	121,200	29,700	Jameson et al. 1999
Red Sea, Egypt, Safaga	Ras Abu Soma	45,600	9,750	Jameson et al. 1999
Red Sea, Egypt, Hurghada	El Fanous	43,200	11,250	Jameson et al. 1999
Red Sea, Egypt, Hurghada	Gotta Abu Ramada	12,900	3,450	Jameson et al. 1999
Red Sea, Egypt, Hurghada	CS Giftun Canal	3,600	0	Jameson et al. 1999
Red Sea, Israel, Eilat	Unspecified high use site	30,000	–	Zakai and Chadwick-Furman 2002
Red Sea, Israel, Eilat	Caves	16,352	–	Zakai and Chadwick-Furman 2002
Red Sea, Israel, Eilat	Central Reserve	8,168	–	Zakai and Chadwick-Furman 2002
Red Sea, Israel, Eilat	Lighthouse	5,980	–	Zakai and Chadwick-Furman 2002
Red Sea, Israel, Eilat	Japanese Gardens	4,396	–	Zakai and Chadwick-Furman 2002
Hawaii, Oahu	Pupukea MLCD	22,493	47,721	This study
Hawaii, Hawaii Island	Kealakekua MLCD	1,440	103,320	This study
Hawaii, Lanai	Manele-Hulopoe MLCD	1,740	28,216	This study
Hawaii, Maui	Honolua MLCD	2,045	83,880	This study
Hawaii, Oahu	Hanauma Bay MLCD	–	818,140	Cesar and van Beukering 2004
South Africa, Sodwana Bay	Two-Mile Reef, High use site	28,000	–	Walters and Samways 2001

The diver tracking method also revealed additional high-use/low impact nodes where divers congregated and floated above the reef without touching it. This physical separation of divers from fragile habitats was a major factor in the low recreation impact observed during this study. Thus although Hawaii MPA sites were heavily used in comparison to those in other geographic locations (Table 3), this did not translate into high recreation impact because most fragile corals (e.g., *P. compressa*; Rodgers et al. 2003) were located below the maximum depth of impact of the dominant recreational activity (snorkeling). This phenomenon distinguishes aquatic from terrestrial recreation activities, such as hiking, where participants cannot traverse fragile habitats without impact. SCUBA diving is the aquatic activity most likely to produce impact patterns resembling those of terrestrial activities because SCUBA divers are intimately associated with the substrate, orient to obvious underwater features, and thus often have overlapping tracks. However, the only site in this study where SCUBA diving was common (Pupukea MLCD) had low recreation impact because of low coral cover, dominated by physically durable species that are resistant to damage from the most common types of diver contacts (fin and hand contacts) (Grigg 1998; Rodgers et al. 2003; Riegl and Riegl 1996).

The diver tracking technique provided useful general insights into recreational diving activities that can be

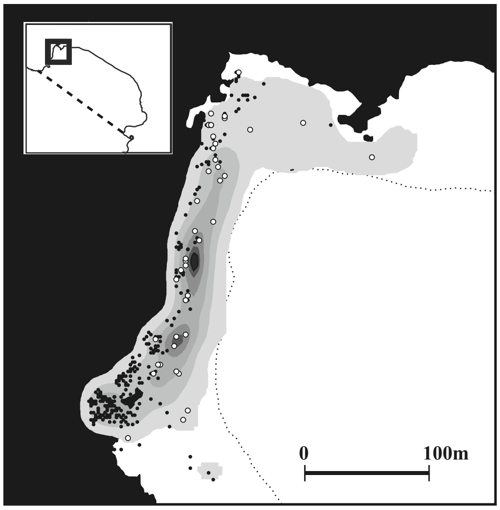

Fig. 3 Kernel utilization distribution (KUD) contours (5%, 10%, 25%, 50%, 75% and 95% contours illustrated from *darkest to lightest shading* respectively) showing distribution of snorkeling activities (N=80 snorkelers) and substrate contacts (*open circles* live substrate, *closed circles* uncolonized substrate) at Kealakekua Bay MLCD, Hawaii. *Shading* illustrates major habitat types; land (*black*), consolidated reef (*dashed outline*), boulders and sand (*unshaded*). *Inset* shows location of the area of detail inside Kealakekua Bay

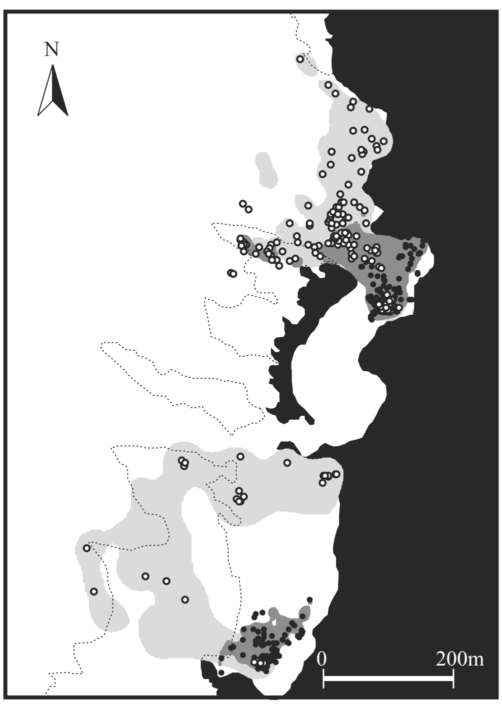

Fig. 4 Distribution of snorkeling and SCUBA diving activities at Pupukea MLCD, Oahu. Major habitat types are illustrated as follows; land (*black*), consolidated reef (*dotted outline*), boulders and sand (*unshaded*). *Dark grey shading* snorkeling activity space (95% kernel utilization distribution [KUD], N=53 snorkelers), *light grey shading* SCUBA activity space (95% KUD, N=18 SCUBA divers), *closed circles* snorkeler substrate contacts, *open circles* SCUBA substrate contact points

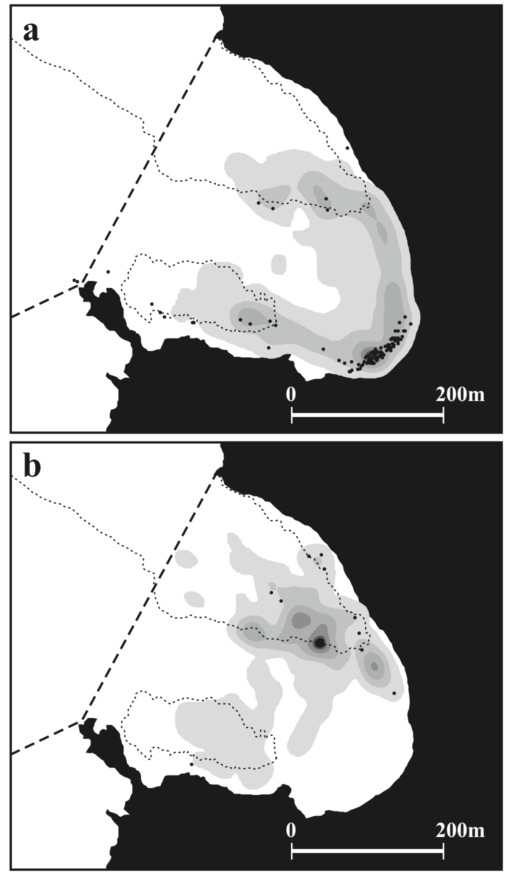

Fig. 5 Habitat utilization distribution and substrate contact points for **a** shore-based and **b** boat-based snorkelers at Honolua Bay (Honolua-Mokuleia MLCD). Major habitat types are illustrated as follows; land (*black*), consolidated reef (*dotted outline*), boulders and sand (*unshaded*). *Heavy dashed lines* indicate the MPA boundary. Kernel utilization distribution (KUD) contours (5%, 10%, 25%, 50%, 75% and 95% contours illustrated from *darkest to lightest shading* respectively) showing core snorkeling areas (*darkest shading* 5% KUD) within the main snorkeling area (*lightest shading* 95% KUD), overlaid with substrate contact locations (*closed circles*)

directly applied to management of MPAs and other sensitive sites without having to track additional users. For example, general topographical features could be used to predict where visitors will go (e.g., snorkelers are unlikely to visit reefs situated beyond obvious terrestrial landmarks) and used to manage their recreation impacts. Access points (shoreline access points or vessel moorings) 'anchor' recreation activity spaces and could be situated to focus recreation impact away from fragile habitats. The abundance and vertical distribution of fragile habitats at management sites could be used to determine the types and amounts of recreational activities permitted. For example, sites where fragile corals are abundant below depths of 2 m may be able to support large numbers of snorkelers but relatively few SCUBA divers (especially beginners who are particularly prone to damaging corals; Allison 1996). In a broader context, quantifying the fine-scale spatial qualities of wilderness recreation activities could provide broad insights into recreation impacts and yield simple management measures for reducing those impacts.

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