Effects of Self-Guided Snorkeling Trails on Corals in a Tropical Marine Park

SAKANAN PLATHONG,* GRAEME J. INGLIS,*†§ AND MICHAEL E. HUBER‡

*Department of Tropical Environment Studies and Geography, James Cook University, Townsville, Queensland 4811, Australia

†Cooperative Research Centre for Ecologically Sustainable Development of the Great Barrier Reef, James Cook University, Townsville, Queensland 4811, Australia

‡Orpheus Island Research Station, James Cook University, Townsville, Queensland 4811, Australia

Abstract: *Underwater trails are intended as interpretative tools in marine parks, but concentrating divers and snorkelers in defined areas may negatively affect the surrounding environment. We examined spatial and temporal patterns in the effects of use of underwater trails on coral reef flats in the Great Barrier Reef Marine Park, Australia. Changes in benthic assemblages were assessed on two new trails used by snorkelers, two unused (control) trails, and two undisturbed areas. Total percent coral cover, numbers of broken colonies, and living coral fragments were counted 6 months before and 6 months after the new trails began to be used. Spatial patterns of effects around concentrated nodes of use were determined by stratified sampling around and away from the interpretative signs within each trail. Despite comparatively low levels of use (approximately 15 snorkelers per trail per week), snorkelers caused significant damage to corals along the trails. Branching corals (non-*Acropora *branching corals and* Millepora *spp.) were most affected. More damage occurred near the interpretative signs than elsewhere on the trails. The numbers of broken branches and damaged coral colonies in the snorkeling trails increased rapidly but stabilized within 2 months of the commencement of use. There was no significant change in overall benthic assemblages within the trails after 6 months of use by snorkelers. Although concentrating snorkelers within confined trails caused increased damage to corals, the effects can be mitigated by appropriate design and placement of the trails and by managing the behavior of snorkelers. Interpretative information should warn users about the damage they may cause when swimming along the trails. Managing the behavior of snorkelers in the water is likely to be more effective in reducing damage than simply applying fixed limits to the amount of use the trails receive.*

Efectos de Senderos para el Buceo Libre con Esnorquel en los Corales Dentro de un Parque Marino

Resumen: *Los senderos submarinos tienen la intención de servir como herramientas interpretativas en los parques marinos, pero la concentración de buzos y buceadores libres en áreas definidas puede tener un efecto negativo en el ambiente de los alrededores. Examinamos los patrones temporales y espaciales de los efectos del uso de senderos submarinos en relieves de arrecifes de coral en el arrecife del Parque Marino de la Gran Barrera de Arrecifes en Australia. Los cambios en los ensamblajes bénticos fueron evaluados en dos senderos nuevos usados por buceadores libres, dos senderos sin usar (controles) y dos áreas sin perturbar. Evaluamos el porcentaje de cobertura de coral, el número de colonias rotas, y fragmentos de coral vivo 6 meses antes y seis meses después de que se iniciara el uso de los senderos nuevos. Los patrones espaciales de los efectos alrededor de nódulos concentrados de uso fueron determinados por un muestreo estratificado alrededor y en sitios lejanos de las señales interpretativas de cada sendero. A pesar de los niveles significativamente bajos de uso (~15 buceadores libres/sendero/semana), los buceadores libres causaron un daño significativo a los corales a lo largo de los senderos. Los corales ramificados (spp. de corales que no pertenecen a* Acropora *o* Millepora*) fueron los más afectados. Se observó más daño cerca de las señales interpretativas que en cualquier otra parte del sendero. Los números de ramas rotas y de colonias de coral dañadas en los senderos se incrementa-*

§Address correspondence to G. Inglis, email g.inglis@niwa.cri.nz

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ron rápidamente, pero se estabilizaron a los dos meses de haber iniciado el uso de los senderos. No hubo un cambio significativo dentro de los senderos después de seis meses de uso. A pesar de que la concentración de buceadores libres dentro de senderos confinados incrementó el daño a los corales, los efectos pueden ser mitigados mediante el diseño y la ubicación apropiada de los senderos y mediante el manejo de la conducta de los buceadores libres. La información interpretativa debería prevenir a los usuarios sobre el daño que ellos mismos pueden ocasionar cuando nadan en estos senderos. El manejo de la conducta de los buceadores libres en el agua probablemente sea más efectivo en la reducción del daño que la simple aplicación de límites fijos a la cantidad de uso que un sendero puede recibir.

Introduction

Visitors to terrestrial parks and wildlife refuges typically confine themselves to the use of well-defined trails and access points. For example, Hendee et al. (1978) estimated that visitors access <10 % of the Mission Mountain Primitive Area in Montana, with most people preferring to use established trails and campgrounds. Trails provide easy access to scenic vantage points, campgrounds, and interpretative information, and they reduce the exposure of visitors to difficult terrain and potential hazards (Hammitt & Cole 1987; Cubit & McArthur 1995). Not surprisingly, the effects of visitation, such as trampled vegetation, litter, and campfires, tend to be distributed in distinctive "nodes" where use is concentrated and along the trails that link these areas (Manning 1979; Garcia & de Lucio Fernandez 1994; Marion & Cole 1996). Appropriate design and placement of walking trails, therefore, can be used to direct visitors away from sensitive environments and into areas that are more resilient to human use (Marion & Cole 1996).

The success of trail management in containing the effects of terrestrial recreation has prompted calls for greater use of underwater trails in managing the effects of visitors to marine parks (Hawkins & Roberts 1993; Marion & Rogers 1994). Large increases in marine tourism around the world have raised questions about the environmental effects of activities such as snorkeling (Robinson 1976; Allison 1996; Inglis et al. 1999) and scuba diving (Davis & Tisdell 1995; Davis et al. 1995; Rouphael & Inglis 1997) within marine protected areas. Divers and snorkelers break corals and other organisms by touching them with their hands, body, and equipment (Talge 1992; Rouphael & Inglis 1995; Allison 1996). Recent research suggests that the direct environmental consequences of these actions are relatively minor (Hawkins & Roberts 1992; Davis & Tisdell 1995; Rouphael & Inglis 1995) in comparison to natural perturbations or other human activities on coral reefs, such as reef walking (Woodland & Hooper 1977; Liddle & Kay 1987; Kay & Liddle 1989; Hawkins & Roberts 1993) and boat grounding and anchoring (Tilmant & Schmahl 1981; Brown & Howard 1985). Nevertheless, as the number of divers and snorkelers increases and activity becomes more concentrated in popular areas, concern about localized deterioration of sites has increased.

Unlike terrestrial recreationists, divers and snorkelers are relatively free to disperse throughout an entire reef site because their movement is not constrained by the physical and biological topography of the surrounding environment (Salm 1986). Underwater trails may be useful in concentrating use within defined areas of reefs to reduce effects on more vulnerable habitats (Hawkins & Roberts 1993). They also offer some important benefits where visitor numbers are large and few interpretive staff are available (Robinson 1976). When information is provided along the trail, snorkelers can be given a better appreciation of an area and be made more aware of rules, safety concerns, and appropriate behavior (Tabata 1991). Snorkeling trails have a long history of use in marine parks. The U.S. Virgin Islands National Park established its first snorkeling trail in 1958. Since then, underwater trails have become popular attractions in a variety of other locations (Robinson 1976; Mitchell & Barborak 1991; Snow 1991; Tabata 1991; Thorsell & Wells 1991). An underwater snorkeling trail is the main attraction at Buck Island National Monument in the United States, where around 90% of the 50,000 annual visitors use it (Thorsell & Wells 1991).

There are, however, some important differences in how recreationists use trails in terrestrial and marine environments which may affect their utility as management tools. On walking trails, environmental degradation is caused by the cumulative effects of repeated use of the same area (Kuss & Graefe 1985). Trampling significantly reduces the height, survival, and growth of plants, with the severity of the effects varying according to the sensitivity of the plant community and the number of users who pass over the area (Kuss & Graefe 1985). In particularly fragile floras, damage accrues after relatively few passes. Trampling in intertidal marine environments has similar effects. Studies have shown significant reductions in the cover and height of corals on tropical reefs (Woodland & Hooper 1977; Kay & Liddle 1989; Neil 1990; Hawkins & Roberts 1993) and of macroalgae and sessile invertebrates on temperate reef platforms (Povey & Keough 1991) caused by walkers using the areas at low tide. Although walkers may actively choose their route to avoid passing through dense vegetation on land or sharp corals on a reef flat, some impact from trampling is usually unavoidable. In contrast, visitors swimming along an underwater path need not come in direct contact with the substratum. The distribution and severity of effects, therefore, may be associated more with the behavior of snorkelers and divers than with the number of passes over a given area (Medio et al. 1997; Rouphael & Inglis 1997).

We examined the environmental effects associated with use of two snorkeling trails established in the Great Barrier Reef Marine Park. Our aim was to determine whether repeated passes by snorkelers caused significant deterioration in coral assemblages along the trails and whether the effects were distributed in characteristic "nodes" of concentrated use and along the paths between them (Manning 1979; Hammitt & Cole 1987). Information on the type, magnitude, and distribution of the damage caused by snorkelers is an important component of any strategy to manage tourism on coral reefs. We discuss our results in relation to the utility of underwater trails for reducing the effects of recreation in these environments.

Methods

Design of the Snorkeling Trails

We conducted our study on a fringing reef at Orpheus Island (lat 18°35′S, long 146°30′E) in the Central Section of the Great Barrier Reef Marine Park. Waters surrounding the island are zoned marine national park B, a "look but don't touch" zone where extractive activities such as collecting and fishing are prohibited. Two sites approximately 100 m apart were selected along the reef edge in Pioneer Bay on the leeward side of the island. The fringing reef in Pioneer Bay is relatively protected from strong waves and winds except for occasional cyclonic disturbances (Hopley et al. 1983; Barnes 1984). In July 1995 we established two snorkeling trails and a control area without a trail at each site. The snorkeling trails were approximately 60 m long × 6 m wide and were oriented parallel to the reef edge. The trails were intended to be self-guiding so that each visitor could follow the path independently of research or local tourism staff, whose presence may have affected their behavior. Each trail consisted of nine 21 × 15 cm stainless steel signs placed at points of interest on a directional trail along the reef edge. The signs were installed at an angle of about 45 degrees to the surface and faced the beginning of the trail so that they could be found easily and read by snorkelers. Information on the signs consisted only of a clearly marked number that corresponded to a map reference and information issued to snorkelers on waterproof laminated sheets. The interpretative information described biological features of interest in the immediate vicinity of each numbered sign and was carried by the snorkelers as they swam along the trail. This eliminated the need for snorkelers to dive below the water surface to read the interpretative information, where they might come into physical contact with corals. It also meant that novice snorkelers could benefit from the information provided at each point of interest.

The trails were used predominately by guests at a resort located on Orpheus Island. Groups of four to eight snorkelers were introduced to the start of the trails by resort staff and allowed to swim along them in their own time. The staff regularly alternated between the two sites so that, on average, each trail was used by around 15 snorkelers per week between January and July 1996. Tourists were used in the experiment to provide a more realistic representation of snorkeling behavior than could be achieved by simply simulating passes along the trails, as is often done in trampling studies (e.g., Kay & Liddle 1989; Povey & Keough 1991).

To distinguish between damage caused by the installation of the trails and that associated with their use by snorkelers, one trail at each site was not used by visitors. Signs were placed along the trail, but tourists taken to Pioneer Bay by the local resort operator were not told of its location or taken to swim along it. Undisturbed control areas at each site did not have trails installed and were not used by snorkelers.

Assessment of Effects

We used line-intercept transects to monitor changes in benthic life forms associated with use of the trails. Six 30-m line transects were placed randomly along each of the two used snorkeling trails, the two unused trails, and the two undisturbed areas. We sampled three times: before setting the trails, 6 months after the trails were installed but before they were used by snorkelers, and 6 months after use by snorkelers.

The percent cover of benthic life forms was estimated for each of 13 life-form categories: branching, tabulate (plate-like), submassive (knob- or wedge-like), and digitate (finger-like) growth forms of *Acropora* and non-acroporiid hard corals; massive (boulder-like), encrusting, and foliose corals; fire corals (*Millepora* spp.); soft corals; other fauna; dead corals; and sand. Sampling followed the standardized line-transect procedures described by English et al. (1994). A diver swam slowly over the transect and recorded transition points between adjacent life forms to the nearest centimeter. The percent cover of each life form was estimated as the proportion of the length of each transect that overlay the life form.

We analyzed changes in percent cover using an unreplicated randomized block design in which trail type (visited trails, unused trails, and undisturbed controls) was a fixed factor. The two sites were treated as random blocks, and time of sampling was a repeated measure.

We assessed changes in the abundance of damaged corals along the marked trails using 1-m^2 quadrats. Within each quadrat we recorded the numbers of hard coral colonies, damaged colonies, recently broken branches, previously broken branches, and number of loose fragments of live coral. Recently broken branches were those that had white tips in which the broken surface had not yet been colonized by algae. Older breakages had brown tips that were characteristic of algal colonization. Branches that had been broken but that were covered by regenerated coral tissue were not counted. Data were collected on six of the life-form types susceptible to mechanical damage: acroporiid corals with branching, tabulate, submassive, and digitate growth forms and nonacroporiid branching corals, submassive corals, foliose corals, and fire corals (*Millepora* spp.). In addition, all living fragments of these life forms found within the sampling quadrats were measured and counted into five length categories: 0–5, 5–10, 10–15, 15–20, and >20 cm. The size-frequency distributions of fragments recorded from the trails before and after their use by snorkelers were compared graphically.

Sampling within each trail type was stratified to describe patterns in the distribution of effects around the interpretative signs and along the trail path. Five 1-m^2 quadrats were distributed haphazardly within a 2-m radius of each of five interpretative signs on each trail. Five additional 12.5-m^2 areas were sampled along the trails at distances at least 4 m away from the signs.

The analytical design followed the logical structure of the BACI (before-after, control-impact) designs recommended by Green (1979) and Underwood (1994) for detecting the effects of human activities. We conducted monthly surveys of the trails for 6 months prior to their use by snorkelers and for an additional 6 months after snorkelers began visiting them. Changes in the abundance of damaged life forms were compared by means of a five-factor analysis of variance in which trail-type (used vs. unused trails), proximity to signs (areas around signs vs. areas away from signs), and the before-versus-after use comparison were fixed factors, sites were random, and monthly variation in damage was nested within the before-versus-after use comparison. Data from the five quadrats sampled at each position along the trail were pooled into one data unit because (1) there were large proportions of zero values at the level of quadrats and (2) variation at the quadrat level was not of primary interest. Variation among the five positions sampled along each trail for each of the sign and no-sign treatments was used as an error term. Month was a repeated measure on each position. With this design, the effects of snorkeling can be inferred if a change occurs in the mean abundance or variability in damaged corals only within the used trails once snorkelers begin to visit them (Underwood 1994).

Results

Cover of Benthic Life Forms

Benthic assemblages on the outer reef flat at Orpheus Island were dominated by massive corals (mean ± SE = 37 ± 0.5%), dead coral platform (31 ± 0.4%), sand (8 ± 0.2%), and soft corals (9 ± 0.3%). Branching growth forms (i.e., branching *Acropora* spp., *Millepora* spp., and other nonacroporiid branching corals), tabulate *Acropora*, foliose corals, nonbranching *Acropora* spp., submassive colonies, and other benthic life forms each comprised an average of <3% of the substratum in the study area. Collectively, the average percentage cover of this group—which represented those corals most susceptible to physical injury—was around 11 ± 0.2%. The relative cover of submassive *Acropora* colonies and non-*Acropora* branching corals varied between the two sites used for the study (Table 1), but the difference was extremely small (<1% cover).

There was no significant change in the percent cover of most life-form categories over the duration of the study in any of the trail types. The installation of snorkeling trails and their use by tourists for 6 months had no effect on the abundance of any of the benthic life forms (Table 1).

Changes in Coral Damage

In contrast, use of the snorkeling trails caused large, significant changes in the numbers of broken and damaged coral colonies along the trails (significant interaction between trail type and before-versus-after use comparison; Table 2). In the 6 months prior to the start of visitation, numbers of broken coral branches in the trails were relatively stable at <10 broken branches/12.5 m^2 (approximately 0.8 branches/m^2). One month after use commenced, however, densities of broken branches and coral fragments increased significantly in trails visited by snorkelers (Fig. 1). There was no corresponding change in the numbers of damaged colonies or coral fragments in the unused trails. Densities of recently broken corals on the snorkeled trails stabilized rapidly and remained around six times greater than in the unused trails for the remainder of the study. The abundance of algal-covered breaks took slightly longer to reach a constant level (significant interaction between trail type and month [before vs. after use]; Table 2), but there was no evidence of further accumulation of injury. Densities of algal-cov-

Table 1. Analysis of variance of changes in percent cover of each life-form category in snorkeling trails, unused trails, and control areas on a reef flat at three times: before installation of the trails, after installation but before use by snorkelers, and six months after snorkeling began.*

		Acroporiid corals						*Non-Acroporiid hard corals*									
		branching		*submassive*		*tabulate*		*branching*		*foliose*		*submassive*		*encrusting*		*massive*	
Source	*df*	F	p	F	p	F	p	F	p	F	p	F	p	F	p	F	p
Trail type	2	0.09	0.913	1.14	0.324	0.44	0.647	1.48	0.232	1.84	0.165	0.97	0.100	1.23	0.297	0.21	0.815
Site	1	1.97	0.163	6.60	0.012	1.21	0.275	4.03	0.048	0.03	0.863	0.27	0.604	0.55	0.459	0.74	0.391
Time	2	0.69	0.593	3.90	0.204	0.77	0.564	4.75	0.174	12.16	0.076	0.87	0.534	0.11	0.904	17.37	0.054
Trail × time	4	0.14	0.967	0.12	0.976	0.06	0.993	0.23	0.921	0.16	0.959	0.11	0.979	0.03	0.998	0.12	0.975
Site × time	2	0.10	0.905	0.15	0.862	0.13	0.877	0.06	0.944	0.07	0.931	0.76	0.471	0.30	0.745	0.03	0.970
Residual	96	MS = 0.19		MS = 0.17		MS = 0.12		MS = 0.09		MS = 0.07		MS = 0.06		MS = 0.15		MS = 9.50	

		Millepora *sp.*		*Soft corals*		*Other fauna*		*Dead coral*		*Sand*	
Source	*df*	F	p	F	p	F	p	F	p	F	p
Trail type	2	0.60	0.553	0.76	0.471	1.87	0.160	0.51	0.600	0.09	0.912
Site	1	0.39	0.534	0.21	0.647	0.07	0.790	3.18	0.078	1.48	0.227
Time	2	13.61	0.068	0.72	0.580	0.82	0.549	2.07	0.325	8.37	0.107
Trail × time	4	0.08	0.987	0.13	0.971	0.15	0.961	0.35	0.845	0.15	0.964
Site × time	2	0.05	0.953	0.14	0.867	0.35	0.709	0.03	0.970	0.07	0.930
Residual	96	MS = 0.90		MS = 2.82		MS = 0.18		MS = 10.00		MS = 2.03	

**Effects of trail installation or of their subsequent use by visitors would be detected as a significant ($\alpha = 0.05$) interaction between trail and time. All analyses were done on square-root-transformed data. MS, mean square estimate of the residual.*

ered breaks stabilized at nearly three branches/m^2 after the trails had been used for 2 months (Fig. 1a).

Coral damage was not distributed evenly throughout the trails but was most evident around the interpretative signs (Fig. 2). During use of the trails, all three indicators of damage occurred in greater abundance near the signs than elsewhere on the trails (significant interaction between trail type, signs, and before-versus-after use comparison; Table 2). On the snorkeled trails, the number of recently broken branches near interpretative signs was 13 ± 1 branches/12.5 m^2, whereas mean density away from signs was 9 ± 1 branches/12.5 m^2. There was,

Table 2. Analysis of variance of changes in the mean abundance of broken coral branches and broken fragments in snorkeled trails and unused trails after 6 months of use.[a]

		Recently broken branches		*Algal-covered broken branches*		*Total fragments*		
Source	*df*	F	p	F	p	F	p	*Denominator no.[b]*
1. Trail type	1	396.68		478.04		289.9		18
2. Site	1	0.90		0.87		6.77		18
3. Sign vs. no sign	1	1.88		4.48		3196.6		5
4. Trail × sign	1	38.96		54.56		16.26		18
5. Site × sign	1	2.17		219.93		0.02		11
6. Before vs. after use: B vs. A	1	656.96		573.49		59.72		8
7. Trail × B vs. A	1	328.33	<0.001[c]	354.68	<0.001[c]	305.59	<0.001[c]	18
8. Site × B vs. A	1	0.61		0.56		5.03		18
9. Sign × B vs. A	1	2.96		277.33		163.65		11
10. Trail × sign × B vs. A	1	8.14	0.005[c]	6.10	0.014[c]	7.12	0.008[c]	18
11. Sign × B vs. A × site	1	2.41		0.19		0.10		17
12. Month (B vs. A)	10	0.46		13.88		0.54		14
13. Trail × month (B vs. A)	10	1.32	0.216	5.55	<0.001[c]	0.86	0.567	18
14. Site × month (B vs. A)	10	2.16		2.51		4.80		17
15. Sign × month (B vs. A)	10	2.05		2.34		5.23		17
16. Trail × sign × month (B vs. A)	10	1.33	0.213	0.57	0.841	1.97	0.035[c]	18
17. Site × sign × month (B vs. A)	10	0.71		0.28		0.41		18
18. Residual	408	MS = 0.34		MS = 0.69		MS = 0.16		

[a]*Sampling in each trail was stratified near to and away from interpretation signs. All analyses were done on square-root-transformed data. MS, mean square estimate of the residual.*
[b]*Numbers indicate source terms and denominators used in the* F *ratio to test each effect.*
[c]*Significant effects of snorkeling (at $\alpha = 0.05$).*

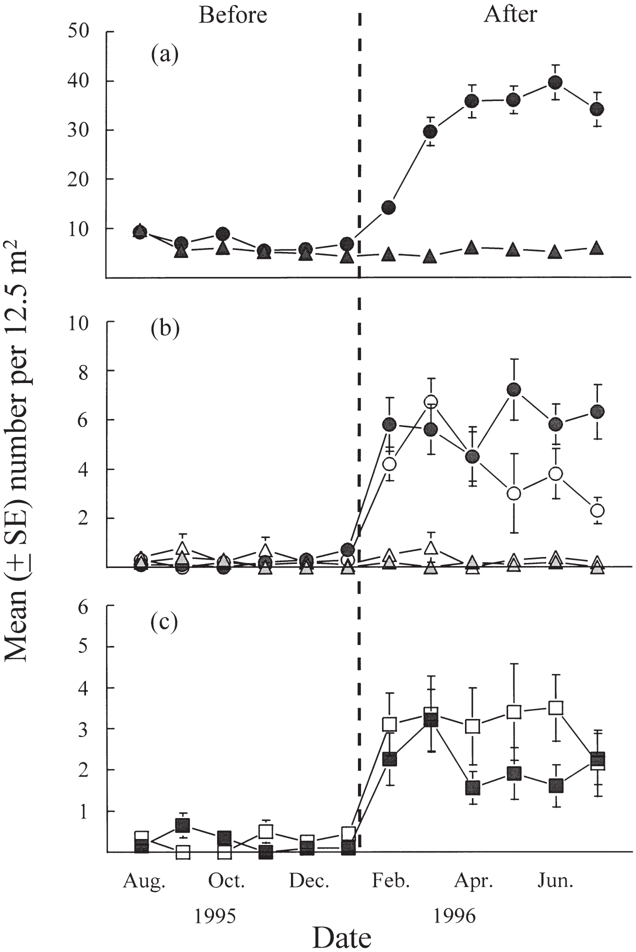

Figure 1. Changes in the abundance of coral injury in the snorkeling trails after visitors began to use them: (a) broken algal-covered branches in the snorkeling trails (circles) and unused trails (triangles), (b) broken coral fragments in areas close to (filled symbols) and between (open symbols) interpretation signs on snorkeling trails (circles) and unused trails (triangles), and (c) broken coral fragments in snorkeling trails at the two reef flat sites.

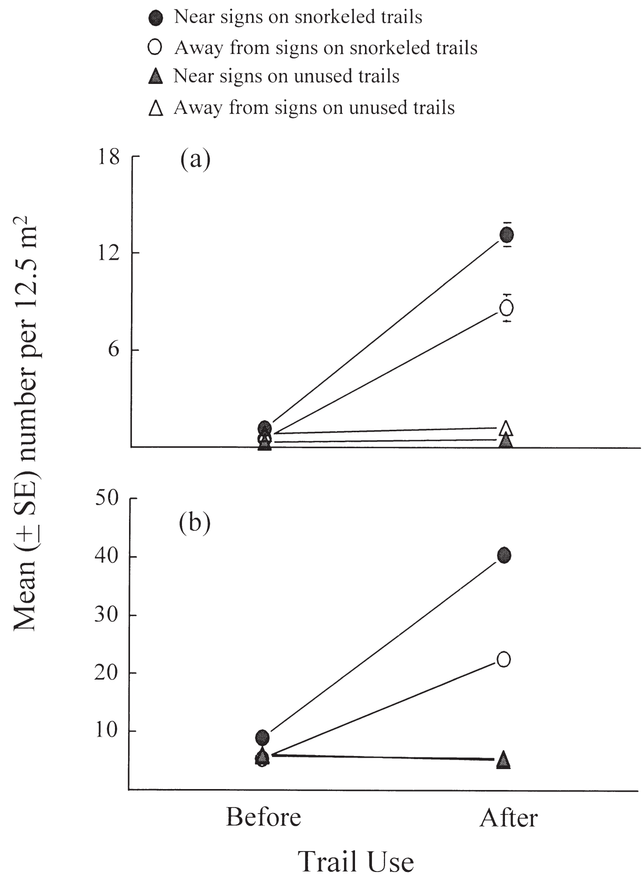

Figure 2. Changes in the overall mean abundance of (a) recent and (b) algal-covered broken coral branches in areas close to (filled symbols) and between (open symbols) interpretation signs along the snorkeling trails (circles) and unused trails (triangles).

however, clear evidence of snorkeling damage along the paths between the signs. Once snorkeling began, densities of broken branches and coral fragments in sections of the trails between the signs were up to four times greater in the used trails than in the control paths (Fig. 2).

The total number of coral fragments also varied significantly among positions near to and away from the interpretative signs. During the first few months of use, there was no difference in the number of coral fragments near signs and away from signs. Both areas contained densities of fragments that were more than six times those found in unused trails (Fig. 1b). After 4 months of use, however, the number of fragments along the pathways declined slightly to an average of approximately 0.6 branches/m^2, whereas densities around the signs remained unchanged (approximately 1.2 branches/m^2).

Fragments of coral broken by the snorkelers were generally <5 cm long (86% of all recorded fragments; Fig. 3). Larger fragments of branching *Acropora* (44%) and *Millepora* spp., up to 15 cm long, were occasionally recorded in the used trails, but they generally comprised <3% of the fragments recorded. The number of fragments <5 cm in length increased dramatically in the used trails after the commencement of snorkeling.

There was also a significant interaction between site and month (within before vs. after) in the mean density of coral fragments (Table 2) which reflected greater variability at one of the sites in the post-use period. Soon after snorkeling started on the trails, the density of fragments at the two sites showed similar patterns of increase (Fig. 1c). In April, 3 months after snorkeling began, densities of fragments at the two sites diverged slightly, with accumulated densities at one site remaining approximately twice as large as at the other site for 3 months.

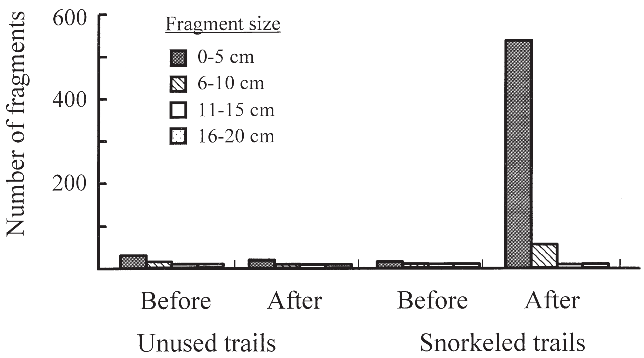

Figure 3. Size distribution of broken coral fragments recovered from the snorkeling trails and unused trails before and after snorkeling began.

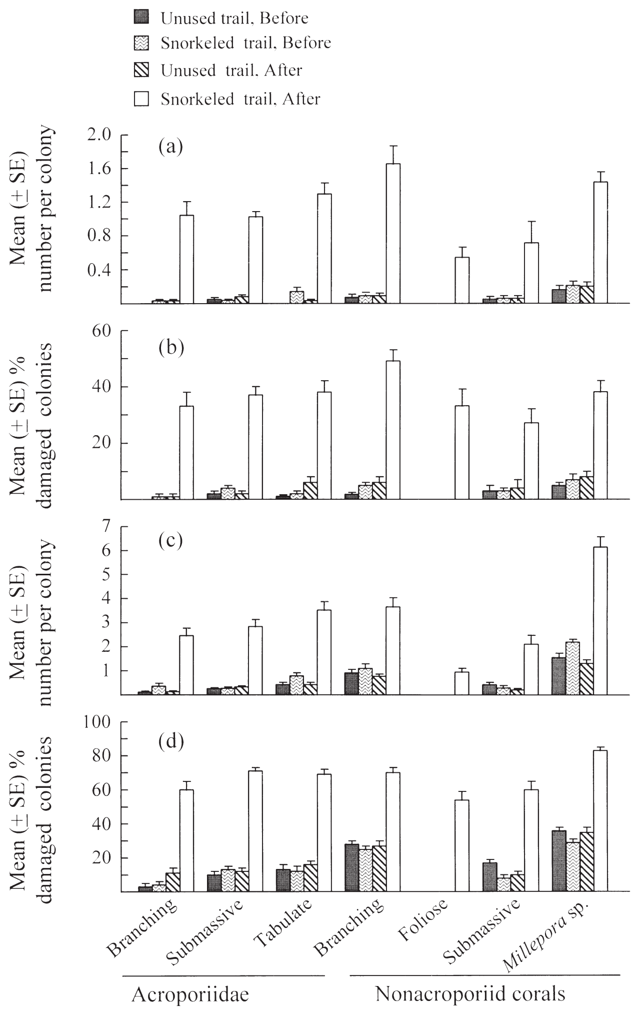

Figure 4. Mean (±SE) number of broken branches per colony and percentage of damaged colonies of each coral type: (a, b) recently broken branches and (c, d) algal-covered broken branches.

Susceptibility of Benthic Life Forms to Snorkeling Damage

Qualitative observations revealed some minor tissue damage to massive and encrusting corals during the study, but these could not be directly related to snorkelers and were not recorded quantitatively. Corals most susceptible to physical damage included species of *Acropora*, nonacroporiids with branching, submassive, and tabulate growth forms, foliose colonies, and fire corals (*Millepora* spp.). Fire corals were the most abundant of the fragile forms at the study sites (approximately 5% cover), followed by submassive *Acropora* spp. (2%). The percentage of these colonies that showed signs of physical damage increased significantly in the used trails once snorkeling commenced. Between 27 ± 5% (submassive non-*Acropora*) and 49 ± 4% (branching non-*Acropora*) of colonies in the snorkeling trails showed signs of recent mechanical injury once snorkeling began on them (Fig. 4). In comparison, <5% of most colonies in areas not visited by snorkelers had recent injuries. The natural densities of older injuries, which had been colonized by algae, were slightly higher. Around 35 ± 3% of *Millepora* colonies in the unsnorkeled trails showed some evidence of prior injury. These levels more than doubled once snorkelers started to visit the trails, with an average of 85 ± 2% of colonies showing signs of injury. Similar magnitudes of change were recorded for most other benthic life forms, where between 55% (foliose corals) and 70% (branching non-*Acropora*) of colonies were affected (Fig. 4).

Discussion

Our data show that relatively small numbers of snorkelers can cause significant deterioration in the condition of coral assemblages along underwater trails. Densities of broken coral branches increased eightfold along the trails once snorkelers began to use them and thirteenfold in areas around interpretative signs. By simultaneously monitoring trails that differed only in the presence of snorkelers, we were able to show that >95% of this damage was caused by the snorkelers themselves, rather than by trail installation or our survey techniques. As in other studies, our observations suggest that most of this damage was caused by the fins of snorkelers when they stood on or inadvertently kicked coral colonies (Talge 1992; Rouphael & Inglis 1995; Allison 1996).

Damage accumulated rapidly, within 1 month of initial visitation, and there were relatively few additional effects with continued use of the trails. Research on the environmental effects of walking trails in terrestrial parks and coral reef flats typically shows a similar pattern, with the most substantial effects on vegetation and corals caused by initial traverses that damage the most vulnerable species (Woodland & Hooper 1977; Hammitt & Cole 1987; Liddle & Kay 1987; Kay & Liddle 1989; Liddle 1991). For example, Woodland and Hooper (1977) found that live coral cover on a reef flat was reduced by as much as 33% following just 18 passes by reef walkers. Similarly, Kay and Liddle (1989) reported that five people trampling on outer reef flats detached as many coral fragments as 20 people. Most of these small fragments are likely to die due to failure to reattach themselves (Highsmith 1982). In areas of strong wave action, they are rapidly removed from the reef edge and are unlikely to settle in habitat suitable for recruitment (Kay & Liddle 1989; Riegl & Cook 1995).

The vulnerability of a colony to damage is a function of its response to mechanical stress and its likely exposure to the stressor. The former is largely related to the morphology of the colony (Liddle & Kay 1987), whereas, in the case of snorkeling trails, the latter is determined by the location of the colony. Thus, branching fire corals (*Millepora* spp.) and non-*Acropora* branching forms were most vulnerable to damage from snorkeling in our study because of their abundance on the reef flat and their erect morphology. Foliose colonies, which Liddle (1991) identified as being least resistant to damage from trampling, and branching *Acropora* spp. (mainly *Acropora formosa*) were not as susceptible to damage by snorkelers because they occurred mostly at depths of 1.5–2 m at Orpheus Island and were less likely to be broken by the fins of snorkelers than the branching, digitate, submassive, and tabulate corals which were more common on the reef flat. Massive and encrusting corals were the most resistant to contact by snorkelers because of their sturdy growth form (Liddle 1991; Riegl & Velimirov 1991; Hawkins & Roberts 1992; Rouphael & Inglis 1995; Riegl & Riegl 1996).

Coral reefs are subject to a variety of recurrent natural disturbances (e.g., hurricanes, floods, predators, diseases) that cause extensive destruction over broad spatial scales (Connell 1997; Hughes & Connell 1999). Consequently, the life histories of many species are well adapted to cope with the type of physical injury we describe here. Reef flat colonies of *Acropora palifera, A. millepora*, and *Pocillopora damicornis*, for example, can survive removal of up to two-thirds of their branches and are able to regenerate >60% of the damaged area within 2 months (Liddle & Kay 1987). Snorkelers generally broke off small fragments (<5 cm) from the distal ends of coral branches, which exposed relatively little surface area. The rate of tissue regrowth over wounds of this size is usually rapid, and recovery of individual branches is likely to occur within 1–2 months of injury (Connell 1973; Brown & Howard 1985; Liddle & Kay 1987).

Although the levels of damage that we recorded in the snorkeling trails were not severe enough to cause changes in the overall abundance or diversity of corals over the 6 months of our study, they did cause a substantial decline in the visual quality of the trails and may be associated with more insidious, long-term changes in the assemblages. Hawkins et al. (1999) recently described a disproportionate decline in old, massive colonies at popular dive sites in Bonaire, which they attribute to the greater frequencies of tissue injury at the sites. Unlike natural disturbances, which have acute, broad-scale effects at infrequent intervals, the continued use of snorkeling trails results in sustained damage to a localized area of reef. Environmental stresses such as this, which increase the frequency of tissue lesions or prevent their closure over prolonged periods, also increase the possibility of successful settlement of pathogens and potential competitors of corals such as macroalgae (Meesters & Bak 1993; Peters 1997). There is, therefore, the possibility that damage associated with snorkeling trails and other recreational activities may interact in complex ways with other natural and anthropogenic stressors to cause long-term change in reef assemblages (Connell 1997; Hughes & Connell 1999).

Managing Recreational Access

Our results raise the question of whether it is preferable to concentrate snorkelers along trails or to spread use over a larger area of the reef. The levels of damage we observed are among the highest recorded in studies of marine recreation. Surveys of coral damage at popular scuba diving sites, for example, have typically recorded between 5% and 20% of hard corals with signs of recent physical injury (Hawkins & Roberts 1992, 1997; Rouphael & Inglis 1997). On reef flats in the Maldives, where snorkeling is the main activity, Allison (1996) found that around 17% of susceptible colonies were broken. Similarly, researchers monitoring offshore snorkeling platforms in the Great Barrier Reef, which may receive up to 80,000 visitors per year, have detected damage in up to 15% of susceptible colonies (Inglis 1997; Nelson & Mapstone 1998). Between 35% and 70% of susceptible coral colonies were broken by snorkelers in the trails that we established. A comparison with our control trails at Orpheus Island suggests that natural causes of breakage affected <5% of colonies.

Where trails are not present, snorkelers and snorkeling effects are distributed patchily over a broad area of the reef flat (Hawkins & Roberts 1993; Allison 1996; Inglis 1997). In these circumstances, the snorkelers are free to choose their own route through the reef matrix and may actively avoid shallow areas or corals that look sharp or fragile, thereby reducing the incidence of coral breakage. When negotiating a snorkeling trail, however, the choice of route is constrained by the need to maintain contact with the path, which may lead swimmers into direct physical contact with the more fragile colony types. These behavioral and situational influences on environmental damage are not often considered in studies of recreation, but we suggest that in marine environments they are at least as important to the distribution and intensity of effects as is the density of visitors.

To some extent, the effects of snorkeling trails are mitigated by the interpretative role they play at reef sites where rangers or other staff are not available. Information provided on the trails can be used to enhance the experience of the snorkelers and encourage appropriate behavior (Tabata 1991; Marion & Rogers 1994). As we have shown, however, careful consideration is needed in the design and placement of trail information to minimize the incidence of damage. Coral damage was more abundant around interpretative signs than elsewhere on the trails. Novice snorkelers are frequently ill at ease floating horizontally and, when near features of interest, may tread water to talk, rest, or adjust poorly fitting equipment (Robinson 1976; Allison 1996). Judicious selection of trail routes and placement of interpretative material may go a long way in reducing the effects we describe. Underwater trails should be located where water is deep enough for snorkelers to avoid fin damage to corals (usually >2 m). Floating rest stations may be set near the beginning, middle, and end of the trail for snorkelers to rest or solve equipment problems. These should be located outside the trail and over sand or where water is deep enough to prevent damage from fins. Periodic closure and rotation of trails may also be an option, but their implementation requires more detailed information on the rate of recovery of damaged colonies. Most important, users of the trails must be made aware of the damage they can inadvertently cause. Short briefings and/or interpretative material that explain how to use the equipment and snorkel safely could considerably reduce the incidence of damage. These measures have already proved effective in reducing damaging behavior by scuba divers (Medio et al. 1997).

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