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Biological Conservation 112 (2003) 383–389
BIOLOGICAL CONSERVATION
www.elsevier.com/locate/biocon

The effects of trampling on Hawaiian corals along a gradient of human use

Ku'ulei S. Rodgers*, Evelyn F. Cox

Hawai'i Institute of Marine Biology, PO Box 1346, Kāne'ohe, HI 96744, USA

Received 25 May 2002; received in revised form 11 October 2002; accepted 13 October 2002

Abstract

Coral transplantation was used to evaluate the response of corals to trampling by determining growth and mortality at sites that ranged along a gradient of human use. Human use was measured with observational sampling. A clear progression of coral survivorship along the gradient was evident. Survivorship dropped from 70% at the low impact site to 55% at the medium impact site. Total loss (0% survivorship) was reported from the high impact site after only 8 months, equivalent to less than 200,000 total visitors or 63 people in the water per hour. Where transplanted corals survived, there was no difference in growth, presumably due to the control of activities of people in the water at those sites.

Keywords: Trampling; Corals; Transplantation; Human use surveys; Anthropogenic stress

1. Introduction

Hawai'i receives over 7 million visitors a year, 85% of whom use the nearshore resources. The tourist population in Hawai'i contributed over $11 billion to the state's economy in 1998, making tourism the number one industry. The multiplier effect of tourist spending is responsible for over one-third of all personal income in the state (Hawai'i DBEDT, 2000). To accommodate the 6 million visitors a year using marine resources, over 1000 ocean recreation companies exist. The impact from overuse has generated increasing concerns about sustainability and carrying capacities within the industry.

Many Hawaiian reefs are easily accessible to the human population as they are located within close proximity of major urban centers of resident and tourist concentration. Use by residential and visitor populations has increased on both spatial and temporal scales. Anthropogenic impacts to reefs are thus greatly increased.

Corals can serve as indicators of decline in the environment. They typically occur in pristine areas, and decline and eventually disappear as impacts are sustained. These indicators can be linked to human impacts. This can be extremely useful in monitoring anthropogenic impacts on reefs in attempts to predict the effects of disturbance (Keough and Quinn, 1991).

Studies of breakage of corals have generally concentrated on the impact associated with SCUBA diving. Damage has been documented worldwide, including reports from French Polynesia (Tilmant, 1987), Australia (Rouphael and Inglis, 1995), the Caribbean (Tratalos and Austin, 2001), and Hawai'i (Tabata, 1992).

Fewer studies have focused on the effects of trampling on corals due to activities of skin divers and waders. Information available is limited to areas of the world that are characterized by a high percent of fragile, highly branched corals (Woodland and Hooper, 1977; Liddle and Kay, 1987). Results from one regional study may not be applicable to predicting damage in another area. Regional variations in species composition, climate and habitat diversity prevent large-scale spatial extrapolation. Hawaiian reefs differ from reefs throughout the tropical Pacific in that the most dominant genus, *Acropora*, is not found in the main Hawaiian Islands. In Hawai'i, Harrington (1999) has used qualitative methods to report the effects of damage by skin divers and waders.

* Corresponding author. Tel.: +1-808-236-7440; fax: +808-236-7443.

E-mail address: kuuleir@hawaii.edu (K.S. Rodgers).

0006-3207/03/$ - see front matter
PII: S0006-3207(02)00336-1

With the complexity and spatial and temporal variability of coastal marine ecosystems it is extremely difficult to isolate specific impacts. An ideal study of the impact of humans on coral reefs should have randomization, replication of treatments and multiple non-impacted sites. This is not always possible in large-scale community level experiments. Sites must be selected based on the perceived degree of impact. Under these conditions relationships between ecological distance and gradients of human impacts can be a quantified measure of the extent of damage (Bernstein and Smith, 1986).

This study was designed to quantitatively address the impacts to corals by skin divers and waders. This research used transplantation of corals into sites along a perceived gradient of human use and evaluated the response of corals to trampling by measuring coral growth and mortality.

2. Study sites

Three sites were selected, representing a gradient that ranged from low to high human use by skin divers and waders. To differentiate between induced and natural damage, a control group for each site was established. The non-impacted control stations had similar physical and chemical characteristics as the impacted experimental stations. Corals were transplanted into each station for an 11-month period followed by measurement of growth and survivorship. Human use was quantified at each site.

2.1. Kāne'ohe Bay—Island of O'ahu

Kāne‘ohe Bay is located on the northeast coast on the island of O‘ahu (Fig. 1). It is the largest embayment in the State of Hawai'i and the most extensively studied. It covers an area of 5670 ha (Hunter, 1993).

The medium and low impact sites were located within Kāne'ohe Bay. Patch reef #39 in the North Bay was visited daily, except Sundays and federal holidays, by two small commercial operators. This patch reef encompasses 17,068 m^2 (Hunter, 1993). This site represented an area of low impact with <5000 users per year.

The adjacent patch reef #42 served as the non-impacted station and had no commercial activities and received minimal recreational use by residents. This reef is slightly larger than patch reef #39, covering 24,008 m^2.

The medium use site was located on patch reef #8, more commonly known as Checker Reef, in the Central Bay. This site was used on a daily basis, except Sundays and federal holidays, by a large commercial operator. This is by far the largest patch reef within Kāne'ohe Bay, 320,841 m^2. Approximately 50,000 people visited this site annually. Activity was confined to the leeward, south side of the reef. The windward north side of the reef served as the associated non-impacted control station and received no commercial visitors and minimal local use.

2.2. Kahalu'u Beach Park—Island of Hawai‘i

Kahalu'u Beach Park is located on the west coast of the Island of Hawai'i (Fig. 2). This beach park is one of the most popular skin diving beaches on the Big Island, accommodating approximately 350,000 visitors a year (County of Hawai‘i, 1998). Although the skin diving area is an estimated 2 ha, most activity occurs in a relatively small, shallow area. This easily accessible, high impact station is heavily used by tourists and residents alike with the main activities being skin diving and wading. The associated non-impacted station was located on the south side of the bay in an area where minimal activity occurred. This section of the bay had limited human use due to difficult accessibility.

3. Methods

3.1. Physical and chemical parameters

A mean of three measurements was used from three independent collection periods for most physical and chemical parameters (salinity, water clarity, and water motion) over the 11-month period corals remained in the field. Other water quality parameters such as chlorophyll and nutrients were not measured as these parameters are similar in all sectors of Kāne'ohe Bay (Laws and Allen, 1996; CISNET, 2001). Salinity was measured with a refractometer. Visibility was determined using two widely established methods, total suspended solids (TSS in mg/l) and secchi disk distances. Two-liter sampling bottles were used to collect subsurface water for determination of TSS. Samples were filtered through a millipore manifold and suspended solids were collected onto preweighed glass microfiber Whatman GF/C filters. Filters were dried at 60 °C for 24 h and TSS determined from weight of particulate matter and volume filtered. Horizontal secchi disk distance measurements were made using a standard 30-cm diameter white disk attached to a 50-m transect line. Plaster of paris clod cards (Jokiel and Morissey, 1993) were used to compare water motion between impacted and non-impacted stations.

Temperature was recorded to verify that extreme fluctuations did not occur. Temperature was recorded with an Onset HOBO H8 temperature data logger enclosed in a waterproof case. Temperature was recorded at 1-h sampling intervals over the 11-month data collection period that corals remained in the field. Temperature loggers were deployed at patch reef 42 in the north sector of Kāne'ohe Bay and in Kahalu'u Bay.

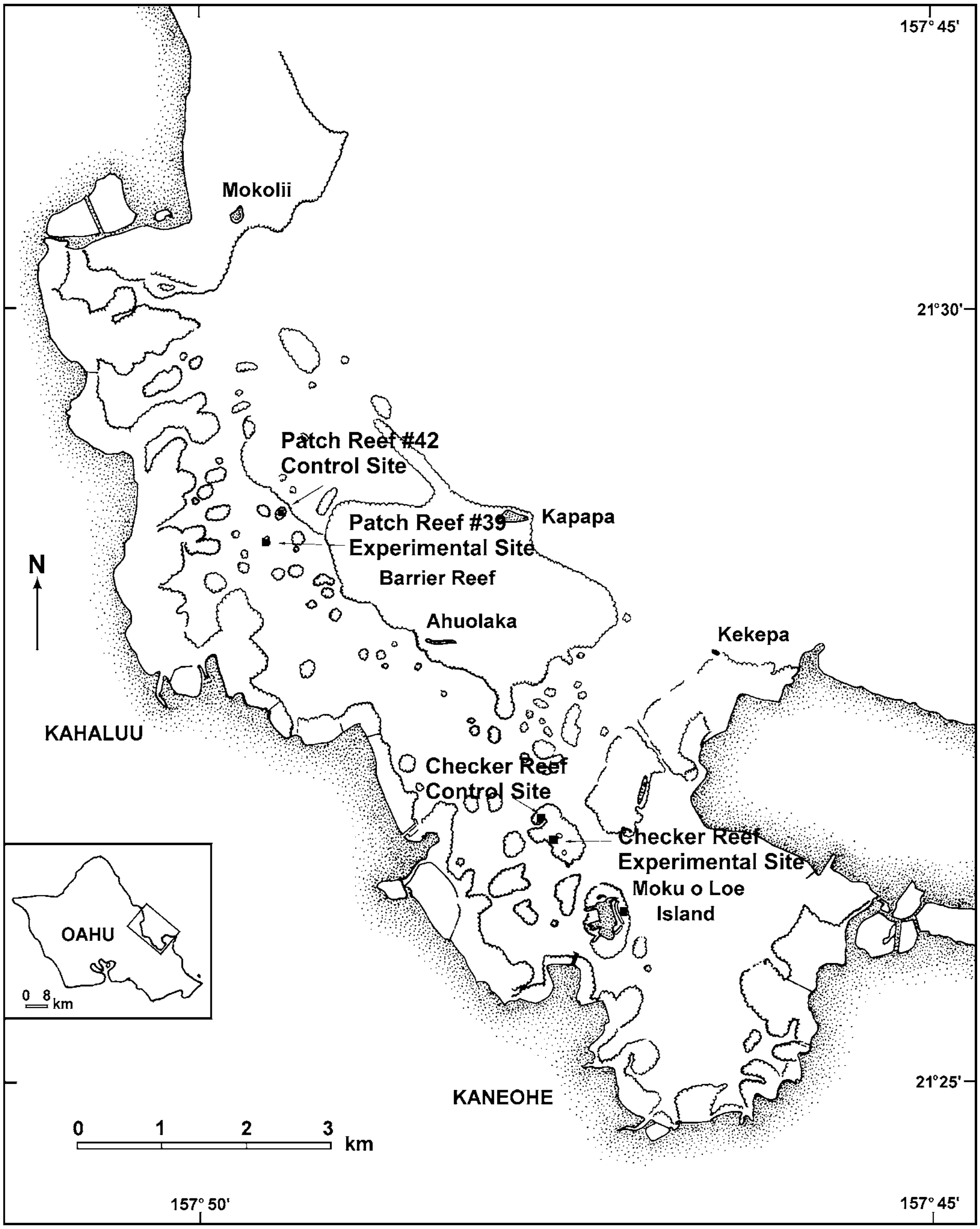

Fig. 1. Coral transplantation sites in Kāne'ohe Bay, O'ahu, Hawai'i.

Data from the Hawai'i Institute of Marine Biology's weather station, located on Moku o Lo'e, were used to approximate temperatures at the adjacent Checker Reef site.

3.2. Biological parameters

Fish abundance at the impacted and non-impacted stations was determined using four fixed width strip transects (4 m wide by 50 m in length). Percent cover of coral and non-biological substrate were measured at each station. A 1 m^2 PVC quadrat was placed at 25 randomly selected points along each of three 50 m replicate transects for these visual estimates.

3.3. Human use surveys

Human use assessment was quantified at each site through non-invasive visual surveys and verified by visitor count data obtained through the Hawai'i State Lifeguard Services where available. At hourly intervals, all persons in the water or on the shore were categorized as to activity. Based on diurnal patterns of use from prior pilot studies, sample days were randomly selected

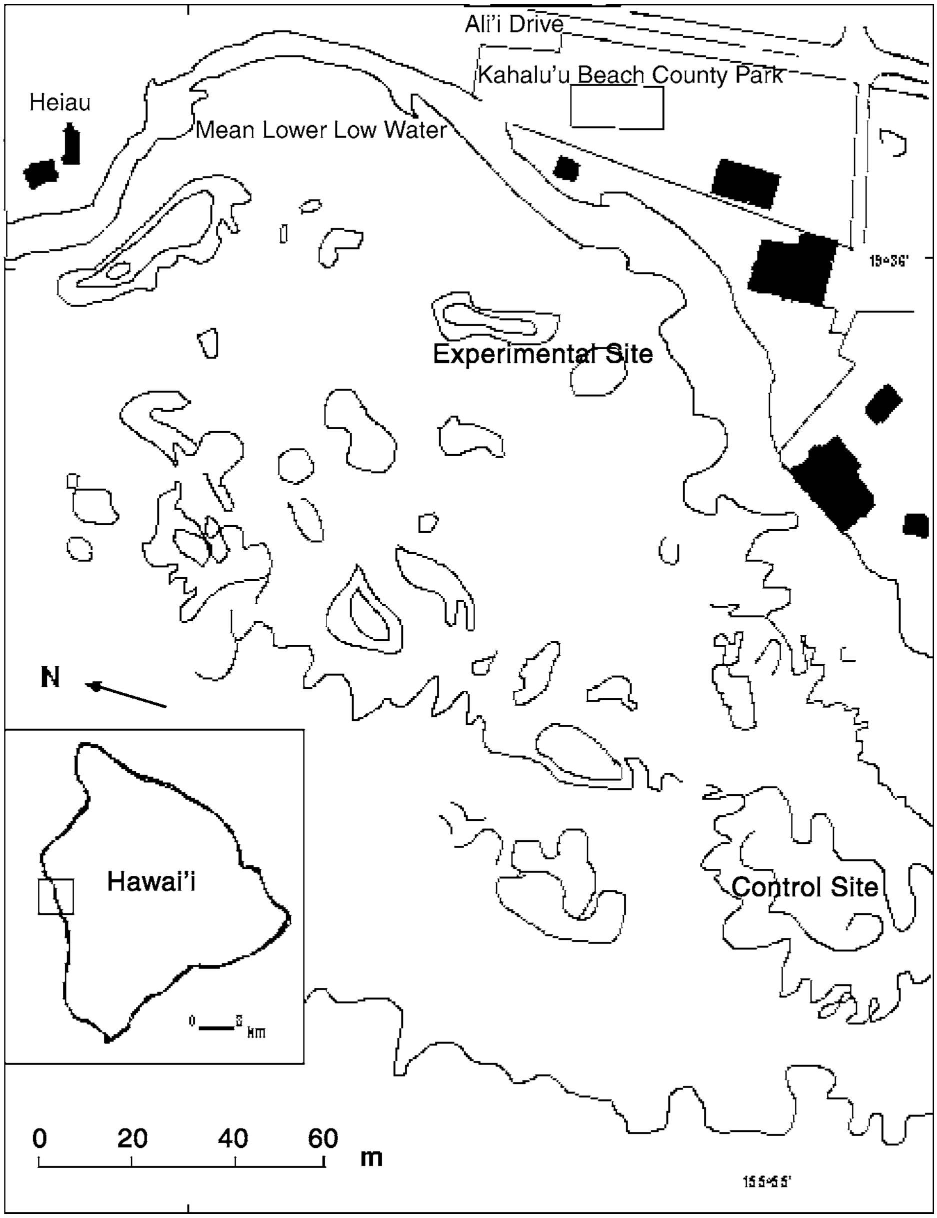

Fig. 2. Coral transplantation sites in Kahalu'u Bay, Island of Hawai'i.

for each of the three sites. The calendar year was divided into four seasons to address seasonal variations in visitor activity. Fifteen weekdays, six weekends and one holiday per quarter were surveyed, providing an equal ratio of actual weekdays to weekend days to holidays. This design was used at the high use site where visitation is not temporally restricted. In Kāne'ohe Bay, commercial use is restricted to weekdays, Saturdays and state holidays. Since state mandated restrictions determine use, two categories for random date selection were chosen. A ratio of days allowing commercial use and days restricting use were used to generate random dates at the medium and low impact sites. Estimates of human activity were based on daily observation periods of 9 h. for the high and medium use sites and 4 h. for the low use site. These observation periods were selected based on pilot studies conducted at each site and encompassed 99% of all activity.

3.4. In situ *coral transplantation*

Ten colonies of *Porites compressa* (finger coral) and 10 colonies of *Pocillopora meandrina* (cauliflower or rose coral) were selected from the general vicinity of each site. Colonies between 20 and 30 cm were cut or chiseled in half to produce clones of similar size. This procedure allowed for paired comparisons of clonemates at impacted and non-impacted sites. Corals were stained with Alizirin red for an 8-h period. This biological stain incorporated by the coral leaves a permanent marker in the skeleton visible to humans. Alizarin powder was dissolved in a small amount of seawater and diffused in 880 l of seawater (final concentration 15-ppm) in two tanks at the laboratory at the Hawai'i Institute of Marine Biology (116.5×116.5×65 cm) for the corals at the nearby Kāne'ohe Bay sites. At Kahalu'u corals were incubated in four tubs (1 m×45 cm×45 cm) under field conditions. Concentrations of alizarin below 20 ppm are not deleterious to corals (Lambert, 1974). Aeration of corals was supplied by airline in the lab and battery operated aquarium pumps in the field.

Half of each colony was transplanted into the impacted station within resident coral colonies; the other half was placed in the non-impacted station. Corals were inconspicuously identified and secured with wire to short unobtrusive markers or attached to natural areas on the reef with plastic cable ties. The corals remained in the field for a period of 11 months. At the end of this period, the area was thoroughly searched for colonies that may have been detached and moved. This is sufficient time to encompass seasonal variations in growth and to allow time for measurable growth. Growth, as linear extension, was evaluated by measuring the distance from the Alizarin band to the outer most portion of the skeleton. Paired comparisons of genetically identical impacted and non-impacted colonies provided an index for impact based on the level of impact at each station.

4. Results

4.1. Physical and chemical parameters

Salinity, visibility, and depth were not significantly different for impacted and non-impacted stations at all three sites (Table 1). Water motion was significantly different at the medium and low use sites. The medium impact site showed 20% lower water motion at the impacted station relative to the non-impacted station (ANOVA $P<0.049$). The low impact site exhibited the opposite with slightly higher water motion (6%) at the impacted station (ANOVA $P<0.003$). Results revealed no significant difference in water motion at the high impact site.

4.2. Biological parameters

At the high impact site there were statistically significant differences in fish abundance and coral cover (Table 1). There was higher coral coverage at the non-impacted station relative to the impacted station (ANOVA $P=0.003$). There were no differences in these parameters at the medium and low impact sites.

4.3. Human activity surveys

4.3.1. High use site

Activity levels remained high throughout the year at the high use site. An average of 152 people in the water per hour during peak daylight hours was estimated from 18 June 1999 to 14 June 2000 at the impacted station. Activity at the non-impacted station was minimal with an average of 0.1/h. The number of people in the water per hour engaging in activities allowing possible contact with corals was 62/h at the impacted station and 0.1/h at the non-impacted station.

Based on the measured counts per hour and days per quarter, total use during activity hours was estimated. There were 290,540 users at the impacted site over the 11-month period the transplanted corals remained in the field.

The largest activity category at the impacted site was sunbathing (58.6%), followed in decreasing frequency by skin diving (20.9%), wading (10.1%), employees (3.8%), surfing (3.6%), swimming (2.9%), SCUBA diving (0.1%), and fishing (0.1%).

4.3.2. Medium use site

Activity levels remained constant from 10:00 to 14:00 h daily, except Sundays and federal holidays, at the impacted station. Activity at all other times was minimal. The number of people per hour at the impacted

Table 1
Summary of mean values for physical, chemical, and biological parameters at all study sites[a]

Site		Diffusion increase factor (DF) (mean±S.D.)	Total suspended solids (TSS) (mg/l^{-1}) mean±S.D.)	Secchi distance (m) mean±S.D.)	Mean coral cover (%) (mean±S.D.)	Fish abundance (mean±S.D.)
High	Impact station	12.5±2.8	6.9±2.3	4.5±2.6	1.6±0.1	14.7±4.2
	Non-impact station	10.4±3.3	7.3±0.2	14.7±3.0	34.1±8.9*	52.0±16.5*
Medium	Impact station	13.4±2.4*	8.6±4.8	6.6±0.1	13.8±0.6	320.0±27.2
	Non-impact station	16.2±2.5*	8.0±4.8	6.8±0.6	25.5±9.6	420.0±103.0
Low	Impact station	15.6±2.1*	5.2±4.1	13.9±3.1	76.5±20.0	194.0±106.0
	Non-impact station	10.8±2.3*	6.1±4.0	10.3±0.5	89.3±6.7	95.3±5.7

[a] All values except those marked with * were not significantly different between impact and non-impact sites. Those marked with * were significantly different ($P<0.05$, ANOVA).

station was significantly higher (23.1/h) relative to the non-impacted station (0.1/h).

Types of activities in decreasing order were boating (38.5%), skin diving (13.2%), SCUBA (11.9%), windsurfing (11.1%), banana boating (10.3%), jetskiing (7.8%), canoeing (6.0%), kayaking (1.1%), and fishing (0.1%). The number of people in the water per hour engaging in activities allowing possible contact with corals was small at both impacted (2.6/h) and non-impacted stations (0.01/h).

4.3.3. Low use site

Peak activity times were between 13:00 and 14:00 h. Extremely low numbers of people visited this reef at other daylight hours, thus, total number of people per hour (2.6) was very low. The total number of people per hour in the water with possible contact with the corals was much lower (1.1). Most people visiting this reef remained on the boat (68.9%), while skin diving was the second most popular activity (30.8%). Fishing accounted for the remainder of the distribution (0.4%). The non-impacted station exhibited minimal use (0.001/h).

4.4. In situ *coral transplantation*

The effects of trampling caused statistically significant reductions in the number of remaining transplanted colonies, and differed significantly between impacted and non-impacted stations at all three sites. The magnitude of decline was astounding and the progression of loss was rapid at the high impact site. None of the 20 colonies at the impacted station remained after an 11-month period. The number of colonies remaining mirrored the differences in human use. While at the high impact site survivorship was 0, the medium site had 55% survivorship and the low impact site 70% (paired t test, $P > 0.05$; Fig. 3).

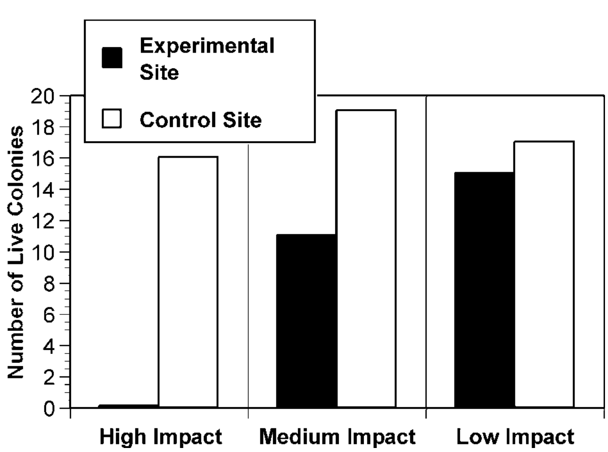

Fig. 3. Survivorship along a gradient of human use.

4.5. Growth

Paired comparisons of clonemates showed no significant difference in mean linear extension rates at either the low or medium impact sites. No growth comparisons were made for the high impact site, as no transplanted colonies remained at the impacted station.

5. Discussion

Coral coverage can reflect the anthropogenic history of a site. Impacted and non-impacted stations were expected to be similar as they were located in close proximity of each other, had similar exposure, and showed only minor differences in physical parameters. Yet, major biological differences in community structure between impacted and non-impacted stations were found at the high human use site. Fish abundance and coral coverage were significantly lower at the impacted station. Detrimental effects of trampling can reduce coral cover and fish populations are dependent upon coral for shelter. Fish as mobile organisms can also be deterred from using areas with human activity.

Extensive damage can occur at sites with high human use. Continuous impact results in total mortality. The effects of trampling caused statistically significant reductions in the number of surviving transplanted colonies. A progression of coral survivorship along a gradient of impact is evident. Survivorship dropped from 70% at the low impact site to 55% at the medium impact site. No corals remained (0% survivorship) at the high impact site after only 8 months, the equivalent of approximately 200,000 total visitors or 63 people in the water per hour. Few transplants were lost at stations with low levels of use (Fig. 3). Further research is needed to expand this range of survivorship by surveying additional sites along the gradient of impact.

Although direct cause and effect can not be established through observational surveys alone, association between impact and mortality is strong. There was 100% coral loss at the high use site. Trampling is a plausible explanation for this loss. Alternative explanations were ruled out. Flood events and damaging storm surf were not recorded at this site during this period.

It is possible for cryptic corals, colonies in deeper water, and the sides of massive colonies to survive in high impact areas. Trampling will not directly affect corals in crevices or deeper water, and in shallow waters the typical impacts to corals occur on top of the colonies.

A clear pattern of decreasing coral cover with increased use emerged along sites. There was an inverse relationship between percent coral cover and use at sites. Community populations at sites with a long history of use are expected to have lower coral cover. This was reflected at the high impact site with <2% coral cover in the impacted area compared to over 34% cover at the station unaffected by trampling. Keough and Quinn (1991) also described this gradient along their sites.

At sites with medium and low levels of stress, no noticeable effects on growth were exhibited between impacted and non-impacted colonies. It is probable that growth differences were not found because little direct impact to the experimental colonies occurred. The total number of people at each site was considerably higher than the number in the water potentially having direct contact with corals. The commercial operator at the medium use site minimizes impact to corals by conducting activities in deeper waters away from the reef flat. Those on the reef flat are all required to wear personal flotation devices, further minimizing contact with the substrate. The commercial operators frequenting the low use site also provide floatation for skin divers. Long foam tubes are used by inexperienced skin divers. More experienced skin divers were not using floatation, but they were also less likely to contact the substrate. In water counts of direct contact with corals would be useful to estimate actual rates of contact.

Although this study failed to demonstrate a difference in growth between impacted and non-impacted regions due to lack of contact, simulated trampling experiments conducted simultaneously with this study determined a strong negative correlation between trampling and coral growth (Rodgers et al., in press).

Transplantation is not recommended as a means of restoration unless the original impact at that site has been removed. Corals transplanted in this study suffered high mortality under continuous trampling pressure at the impacted stations. Clearly transplantation as a mitigation for human trampling would not restore coral cover in these continually trampled areas. At sites with moderate or low levels of impact, transplantation may be a viable method for habitat restoration.

Acknowledgements

We would like to thank Dr. Paul Jokiel and the Hawai'i Coral Reef Initiative for project support. This journal article is Hawai'i Institute of Marine Biology contribution #1140.

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