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Abstract

Recreational boating is increasingly popular and provides social and economic benefits, but can also have ecological impacts, including damage from anchoring on sensitive seabed habitats like coral reefs. Mooring buoys are commonly used to manage anchoring activity, and I tested whether they moderated anchoring on coral reefs in the British Virgin Islands. A spatial survey revealed that overall boat use (moored plus anchored) was 3.6 times higher at sites with moorings than those without. The density of boats anchored on coral reef was, however, reduced by roughly half at sites with moorings. A survey of two sites before and after moorings were installed confirmed that the addition of moorings increased the total number of boats at a site, but reduced the rate of anchoring on reef. At any given site, the rate of anchoring on reef increased as the total number of boats present increased, but the effect of crowding was diminished at sites with moorings. Moorings can thus be an effective management tool for mitigating anchor damage to sensitive habitats, and because boat densities continue to rise worldwide, these findings focus attention on discovering why moorings reduce the tendency of boats to anchor on reef as sites become more crowded.

Key words

Anchoring; British Virgin Islands; Coral Reefs; Mooring buoys; Recreational boating.

1. Introduction

Recreational boating is an important and rapidly growing component of the tourism industry in many coastal areas (Burgin and Hardiman, 2011), and provides an array of economic and social benefits (Kenchington, 1993). Boating activity can also have a variety of social, cultural, and ecological impacts (Burgin and Hardiman, 2011; Lloret, 2011). Ecological impacts arise from anchor damage, pollution from waste discharge (Grigg, 1994) and anti-fouling paint (Carbery et al., 2006), littering (Abu-Hilal and Al-Najjar, 2004), increased turbidity and erosion (Liddle and Scorgie, 1980), sound (González Correa et al., 2019; Whitfield and Becker, 2014), spread of invasive species(West et al., 2007), and vessels striking animals (Kemper et al., 2005). Successful management of increasing levels of boat activity, therefore, requires understanding the spatial and temporal occurrence of these impacts and how they are influenced by alternate management tools.

Boat anchoring, defined as short-term deployment of an anchor to the seabed to keep a boat in one location, can cause damage to the seabed that creates substantial ecological impacts, particularly when anchoring occurs on sensitive habitats like coral reefs (Flynn and Forrester, 2019; Forrester et al., 2015; Giglio et al., 2017; Kininmonth et al., 2014) and seagrass beds (Creed and Amado Filho, 1999; Francour et al., 1999; Hendriks et al., 2013; Lloret et al., 2008). The extent of damage from anchoring varies according to the type and size of anchor used, and the adjacent length of chain that contacts the seabed (Milazzo et al., 2004), suggesting that regulating the type of anchor used is a potential tool for mitigating anchor damage. More frequently, however, potential anchor damage is managed by establishing no anchoring areas as part of marine protected area (MPA) zoning (Beeden et al., 2014; Horta e Costa et al., 2016), or by installing markers to indicate the location of sensitive habitat (Great Barrier Reef Marine Park Authority, 2002). Mooring buoys, defined as buoys affixed to the seabed to which boats can be secured, allow boats to stay at a site without the need for anchoring. For this reason, they represent another common approach to mitigate anchor damage (Halas, 1985, 1997), and are often a component of MPA zoning plans (Gibson et al., 1998; Great Barrier Reef Marine Park Authority, 2018; McClanahan et al., 2005; Morales-Nin et al., 2010).

Evidence on the effectiveness of mooring buoys in reducing damage to the seabed is mixed. Surveys of ecologically sensitive seagrass beds showed improved seagrass growth and shoot density at sites with moorings (Marbà et al., 2002; Sagerman et al., 2020), but in some areas the structures that secure the moorings themselves to the seabed can cause damage to adjacent seagrass (Hastings et al., 1995; La Manna et al., 2015; Montefalcone et al., 2008; Sagerman et al., 2020; Walker et al., 1989). The level of support for the use of mooring buoys related to a perception that moorings can reduce impacts on seabed communities varies among locations and boater groups (Diedrich et al., 2013; Lloret et al., 2008; Settar and Turner, 2010). Boat moorings can, however, have positive social impacts independent of the potential for anchor damage; they can allow more efficient use of anchoring space and can increase the perceived safety, comfort and well-being of boaters (Balaguer et al., 2011; Diedrich et al., 2011), which suggests that any reduction in the deployment of anchors in sensitive habitats associated with the use of mooring buoys may be partly coincidental. Consistent with these reports of variable boater attitudes and perceptions, some anchoring has been observed in areas where seagrass is present at several Mediterranean locations, despite regulations prohibiting anchoring in seagrass and the presence of moorings (Diedrich et al., 2011; Diedrich et al., 2013; La Manna et al., 2015). There has, however, been little quantitative study of the benthic habitat where anchors are deployed and the extent to which rates of anchoring in sensitive habitat change when mooring buoys are installed (Lloret et al., 2008). Further quantitative analysis of how mooring buoys influence where, and how often, boats deploy anchor are thus of value for management.

Crowding is one factor plausibly influencing why some boats continue to anchor in sensitive habitats, even in areas with mooring buoys. Associated with an increase in the numbers of recreational boats globally, is a growing potential for sites with moorings to be fully occupied and for an increasing density of anchored yachts at sites where no mooring buoys have been installed (Diedrich et al., 2011; Gonson et al., 2016; Smallwood and Beckley, 2008; Venturini et al., 2018). Although boater's perception of crowding is not always directly related to boat density (Tseng et al., 2009), increasing proximity to other boats can reduce boaters perceptions of satisfaction and safety (Diedrich et al., 2011), which may prompt boaters who might otherwise not anchor in sensitive habitats to do so. There have been, however, no quantitative tests of how boat crowding affects the rate of anchoring in sensitive habitat.

In this study, I addressed three questions about the effectiveness of moorings in preventing anchoring on one sensitive habitat - coral reefs. (*Q1) Does boat activity differ between sites with and without moorings?* I predicted that mooring presence would increase the attractiveness of a site to boaters, and so overall boat activity would be greater at sites with mooring buoys than at sites without. I also predicted that boaters would use moorings, rather than setting anchor, when possible and so the rate of anchoring on reef would be lower at sites with moorings. *(Q2) Does establishing moorings at a site alter boat activity?* I predicted that when moorings were established at a site, this would trigger a subsequent increase in overall use, but that anchoring on reef would decline after mooring installation. *(Q3) Does the rate of anchoring on coral reef vary with crowding?* At any given site, I predicted that anchoring on coral reef would occur more frequently as boat density increased so there were fewer moorings available and, or, less space to anchor on sand. I also predicted that the presence of mooring buoys would mitigate the increasing tendency of boats to anchor on reef as a site became more crowded.

2. Methods

2.1 Study Location

The British Virgin Islands (BVI) provide an excellent setting to examine the influence of moorings on boat activity because it hosts a large fleet of recreational boats and has an extensive network of mooring buoys that was established, in part, to reduce anchor damage. Roughly 1100-1500 yachts (12-16 m in length) operate within BVI territorial waters (personal communication with Janet Oliver, BVI Charter Yacht Society, 2014; Trish Baily, BVI Association of Reef Keepers, 2014). Revenue from tourism accounted for 27% of the BVI's GDP in 2013, with boating comprising the largest shared of that revenue (World Travel and Tourism Council, 2014). The BVI also has a substantial network of mooring buoys that dates to the 1970s (Howell et al., 2002). There are currently 66 sites with ~200 moorings managed by the National Parks Trust in the BVI, plus several additional "unofficial" and private mooring sites. The National Parks Trust moorings are designated for daytime use only, but many of the private moorings are for overnight stay and charge a small user fee (personal communications with Nancy Pascoe, National Parks Trust of the Virgin Islands, 2014; Lianna Jarecki, HLS Community College, 2013).

Recent estimates suggest the BVI contains roughly 138 km^2 of coral reef (Sheppard, 2013), of which roughly 24% is in sheltered leeward areas where is possible to anchor under typical weather conditions (Flynn and Forrester, 2019). Anchoring on coral reef is prohibited anywhere in BVI, and anchoring is completely prohibited within 14 Fisheries Protected Areas and 6 Fisheries Priority Areas that all include areas of coral reef (Virgin Islands Fisheries Regulations, 2003). However, despite the network of moorings and regulations designed to protect sensitive habitats, substantial impacts of boat anchoring on coral reefs in the area have been reported (Flynn and Forrester, 2019; Forrester et al., 2015).

2.2 Does boat activity differ between sites with and without moorings?

To quantify the level of anchoring activity at sites with and without moorings, I recorded the number of anchored and moored boats at six sites with moorings and six without (an after-control-impact design (Underwood, 1997). All 12 sites were used regularly as anchorages and were situated on the leeward sides of islands, usually within bays. One of the sites is a Fisheries

Priority Area and 8 of the sites are proposed MPAs (Gardner et al., 2008). All sites contained areas of coral reef and sandy areas suitable for anchoring (Table S1; Figure 1).

At each site, I quantified the observed density of moored and anchored boats using 138 satellite images (Google Earth Pro, map data from Digital Globe, CNES/Airbus & NASA; e.g. Figure 2) plus occasional aerial photographic images (n = 3) and in-situ observations (n = 5). Images and observations were made from 2004-2017 on calm clear days throughout the year (n = 7-18 per site, Table S1). Virtually all boats observed moored or at anchor were yachts 9-18 m in length (Figure 2). Smaller boats, primarily inflatable dinghies used as yacht tenders, were sometimes present but were rarely attached directly to moorings or anchored, so only boats of estimated length > 7 m were included in the survey.

Each boat surveyed was classified as moored or anchored, and any boats rafted together were counted as one. At sites with mooring buoys, moored boats could be distinguished from those at anchor because the location of moorings was determined using a portable GPS unit during ground-truthing visits to each site (n = 2-6 visits per site). The location of each mooring was established on the satellite images using its GPS coordinates. In some cases, mooring buoys and lines were also directly visible in the satellite images (e.g. Figure 2).

Damage to the seabed is caused by the anchor itself, and by the adjoining length of anchor chain that sweeps back and forth across the substratum as the wind and tide swing the boat on its anchor. Areas of coral reef, sand and other seabed habitats (primarily seagrass beds) were visible from the satellite images (e.g. Figure 2). The identity of seabed habitats in the images was verified by the author on SCUBA or snorkel, and their boundaries were recorded using a portable GPS unit, during the previously mentioned ground-truthing visits to each site. The anchor and adjoining section of anchor chain were, however, not visible for most boats in the satellite images, so their position was estimated assuming that the boat followed accepted anchoring conventions (United States Coast Guard, 1971) (Figure S1). Each anchored boat was classified based on whether its anchor and/or the adjoining ≈ 5 m section of anchor chain was estimated to lay primarily on (1) sand or seagrass, (2) coral reef, or (3) substrata of unknown or uncertain composition. Using sites as replicates (Table S1), I compared boat use at sites with and without moorings using Mann-Whitney U tests. The seabed habitat where boats anchored may sometimes have been misclassified due to errors in mapping habitat and estimating anchor chain length, and the following section provides a direct test for misclassification rates.

2.3 Does establishing moorings at a site alter boat activity?

To test whether establishing moorings altered boat activity, I performed an intervention analysis at two sites before and after moorings were installed (Box and Tiao, 1965; Stewart-Oaten and Bence, 2001). The sites were White Bay (10.2 ha) and Muskmelon Bay (31.2 ha), both of which are on the leeward side of Guana Island (Figures S2 and S3). Both sites are used as anchorages and are close to the leeward side of the island. Muskmelon Bay is, however, designated as a Fisheries Priority Area where anchoring is prohibited. The shoreline at both sites is fringed with coral reef with a shallow slope, gradually increasing from 0-10 m in depth. The White Bay site was limited to this area, so all boats anchored at this site could damage coral reef. At Muskmelon Bay, the site also included offshore areas comprising sand and seagrass (15-18 m depth) and a steep reef slope (10-15 m depth) that connects the inshore and offshore areas.

Mooring buoys were installed in White Bay between November 2013 and February 2014 and 8-15 buoys were present from 2014-2018. I quantified the number of anchored and moored boats in White Bay using the methods just described for the BVI-wide survey. For this site, most of the data were compiled from photographs taken from Guana Island (n = 365; Figure S4), supplemented with occasional satellite images (n = 6) and direct observations (n = 15).

Guana Island has been a long-term research site (4-8 weeks per year for 28 years) and so I was able to ground truth estimates of the seabed habitat on which boats were anchored for a subset of photographs (n = 30) and satellite images (n = 3). Of 37 anchored boats in these images, 2 boats (5%) were misclassified (1 boat on sand was classified from the image as anchored on reef, and 1 boat anchored on reef was misclassified as being on sand).

I used a linear mixed model (LMM) to test whether the rate of anchoring changed after the installation of moorings. The observations (y) were annual means of the number of boats anchored on reef (7-38 observations per year) from 2006-2018. Observations were made at the same time of year (June-August) and at times of day when boats were likely to have been present overnight (6-8 AM and 5-7 PM), so they account for potential effects of seasonality and time of day. The LMM included terms for period (m = before and after moorings present) and year within period (t) and allowed for autocorrelated errors (AR1):

$$y = b_0 + b_1{*}m + b_2{*}t + b_3{*}m{*}t + error.$$

The coding of m and t was designed so that b_0 estimated the anchoring rate at the end of the before period, b_1 estimated the anchoring rate at the end of the after period, b_2 estimated change in anchoring over time during the before period (i.e. the slope) and b_3 estimated change in the slope during the after period (Maric et al., 2015).

A second, far smaller set of before-after observations (n = 17) was compiled from Muskmelon Bay, where 16 moorings were installed and present for most of 2014. Fifteen of the moorings were then removed, and one mooring remained from 2015-2018. I made a descriptive analysis of boat activity to assess whether the pattern was consistent with the results from White Bay.

2.4 Does the rate of anchoring on coral reef vary with crowding?

Using data from the spatial survey, I tested whether the number of boats anchored on reef was related to crowding (measured as the number of other boats present at the site) using a generalized linear model (GLM) appropriate for count data (a negative binomial distribution with log-link function, and using site area as an offset to adjust the regression estimates to boat density). Because the effect of crowding might depend on the presence of moorings and differ among sites, I also included terms for mooring presence (yes or no), the interaction between mooring presence and number of other boats present, and sites (nested within mooring presence).

3. Results

3.1 Does boat activity differ between sites with and without moorings?

A total of 376 boats were observed in the spatial survey, of which 50% were moored and 50% were anchored. Of the 189 boats at anchor, 34% were anchored on reef. Total yacht density (boats / ha) was greater by a factor of 3.6 at sites with moorings (mean ± SE = 0.13 ± 0.03) than at sites without moorings (mean ± SE = 0.47 ± 0.08), and this difference was statistically significant (Mann-Whitney U = 34.0, p = 0.009). The density of boats anchored on sand or unknown substrata differed little between sites with and without moorings (Mann-Whitney U = 17.0, p = 0.94; Figure 3). The mean density of boats anchored on reef was, however, reduced by roughly 50% at sites with moorings relative to sites without moorings, but this reduction was not statistically significant (Mann-Whitney U = 6.0, p = 0.065; Figure 3). I can exclude the possibility that, where moorings are present, anchoring on reef only occurs once all moorings are occupied because moorings were fully occupied during just 9% of observations (Table S1).

3.2 Does establishing moorings at a site alter the level of boat use and anchoring behaviour?

In the decades prior to the installation of moorings in White Bay, there was a steady increase in the rate of anchoring on coral reef at the site (Figure 4). This increasing trend was also apparent in the more detailed analysis of the 8 years prior to mooring installation (LMM: b_2 = -0.06, t = --3.71, df = 4.3, p = 0.019; Figure 5a). The number of boats anchored on reef was, however, reduced significantly after moorings were added (LMM: b_1= -0.41, t =-3.99, df = 4.3, p = 0.014; Figure 5a). The rate of increase in anchoring over time was also slightly reduced after moorings are installed, but this change was not significant (LMM: b_3 = 0.40, t = 1.101, df = 4.5, p = 0.326; Figure 5). The installation of moorings in Muskmelon Bay was also associated with an increase of overall boat use and a reduction in anchoring on reef, so this small sample of observations was qualitatively consistent with the pattern observed in White Bay (Figure S5).

3.3 Does the rate of anchoring on coral reef vary with crowding?

There was support for the hypothesis that anchoring on reef occurs more frequently when a site is crowded. There was a generally positive relationship between the density of boats anchored on reef and crowding (Figure 6). Importantly, the rate of increase in anchoring on reef with crowding was more than twice as great at sites without moorings than at sites with moorings (GLM: crowding x mooring presence interaction term, Wald χ^2 = 6.42, df = 1, p = 0.011). In other words, the presence of moorings mitigates the increasing tendency of boats to anchor on reef as a site becomes more crowded (Figure 6).

4. Discussion

Although the spatial survey and before-after study both have weaknesses, in combination they provide the first clear test of the hypothesis that boat moorings can reduce anchoring in sensitive habitats. Spatial surveys alone do not allow unequivocal assignment of cause-and-effect (e.g. Lloret et al., 2008) because sites are not selected at random for mooring installation so factors other than the presence of moorings might differ among the two sets of sites (Underwood, 1997). Nonetheless, as I predicted fewer boats were anchored at sites with moorings even though more boats were present. Before-after studies (e.g. Gonson et al., 2016) share a related limitation because it is hard to exclude the possibility that an unobserved event coinciding with mooring installation actually caused the changes in boat activity (Stewart-Oaten and Bence, 2001). This caveat notwithstanding, the installation of moorings triggered the predicted reduction in anchoring and increase in overall visitation. The advantage of performing both tests is that the likelihood of spurious correlations undermining both the spatial survey and before-after study is small. A further benefit of performing both tests is that, although the results from the spatial survey alone did not support rejection of the null hypothesis of no mooring effect with the conventional type 1 error rate ($p < 0.05$), the consistent result of both tests provides clear support for the conclusion that boat moorings substantially reduced the rate of anchoring on coral reef in the BVI.

Few other studies have quantified the effect of installing moorings on anchoring in sensitive habitats, which precludes generalizations about their impact in other regions. In apparent contradiction of my findings, an approximate doubling of the number of boats present at coastal sites in New Caledonia from 2008-2013 was associated with a comparable increase in the number of boats deploying anchors, but no change in the number using mooring buoys (Gonson et al., 2016). The seabed habitats where boats anchored were not recorded in New Caledonia, but studies of boat activity in the Mediterranean describe boats anchoring in areas containing ecologically sensitive habitat, in this case seagrass beds, despite regulations prohibiting anchoring in seagrass and the presence of moorings (Diedrich et al., 2011; Diedrich et al., 2013; La Manna et al., 2015). One study in this region quantified the seabed habitat in which boats deployed their anchors and found a much higher rate of anchoring in seagrass beds (48%) than the rate of anchoring on reef I observed in the BVI (Lloret et al., 2008). Whether mooring presence influenced the rate of anchoring in seagrass is, however, uncertain because although moorings were present at some sites, they were used by just 7% of boats present and their effect on anchoring locations was not tested (Lloret et al., 2008).

Despite the fact that the network of mooring buoys was widely used by boaters in the BVI and is clearly one of the main reasons why most (84%) boaters were not anchored on reef over the past 15 years, the minority of boaters that anchored on coral reef (16%) have caused substantial and widespread damage to this habitat (Flynn and Forrester, 2019; Forrester et al., 2015). Boat densities in the BVI have increased over time (Everitt, 2007; Olsen, 1978), as they have elsewhere (Burgin and Hardiman, 2011; Gonson et al., 2016), and a likely contributory factor to this damage is that the period when many moorings were installed (1960s-1990s) and began to be managed by the BVI National Parks Trust preceded a major increase in the size of the yacht fleet. The BVI government has plans to expand its current network of MPAs and evaluate the use of mooring buoys (Gardner et al., 2008). The spatial analysis suggests that adding moorings can increase use of a site by more than 3-fold while also roughly halving the rate of anchoring on coral reef. The results of this study suggest that mooring buoys, when coupled with site selection that considers ecological sensitivity to anchor damage, can be an effective component of future plans to manage boating activity and abate damaging minority behaviours (Sagerman et al., 2020).

Key to resolving apparent variability in the response of boaters to mooring buoys is a better understanding of the attitudes and perceptions that influence decisions about anchoring. Consistent with my findings, mooring buoys can increase boaters likelihood of selecting a site (McAuliffe et al., 2014) and enhance the perceived safety, comfort and well-being of boaters (Balaguer et al., 2011; Diedrich et al., 2011). A perception that moorings reduce impacts on seabed communities can increase support for their use (Diedrich et al., 2013), but my finding that some boaters anchor on coral reef regardless of mooring presence is consistent with reports that some boaters are unconcerned or unaware of potential damage to sensitive habitats (Lloret et al., 2008; Settar and Turner, 2010). Of most interest for future analysis is my finding that that the presence of moorings mitigates the increasing tendency of boats to anchor on reef as sites becomes more crowded. Boat moorings in the BVI were rarely fully occupied, a finding consistent with surveys elsewhere (Balaguer et al., 2011; Smallwood and Beckley, 2008; Venturini et al., 2018) so anchoring on reef cannot always be explained as a simple response to the lack of available mooring buoys or space in sandy habitat for anchoring. Crowding can negatively affect boaters perceptions of safety and enjoyment (Ashton and Chubb), but perceived crowding is not always directly related to boat density (Tseng et al., 2009). My results suggest the hypothesis that negative aspects of perceived crowding are reduced at sites with mooring buoys. As the size of yacht fleets steadily increases worldwide, it will thus be informative to test this hypothesis directly and clarify any links to the likelihood of anchoring or leaving to find an alternate site.

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Reference List

Abu-Hilal, A H, Al-Najjar, T, 2004. Litter pollution on the Jordanian shores of the Gulf of Aqaba (Red Sea). Marine Environmental Research 58:39-63. 10.1016/j.marenvres.2003.12.003

Ashton, P G, Chubb, M, 1972. A preliminary study for evaluating the capacity of waters for recreational boating. Journal of the American Water Resources Association 8:571-577. 10.1111/j.1752-1688.1972.tb05179.x

Balaguer, P, Diedrich, A, Sardá, R, Fuster, M, Cañellas, B, Tintoré, J, 2011. Spatial analysis of recreational boating as a first key step for marine spatial planning in Mallorca (Balearic Islands, Spain). Ocean & Coastal Management 54:241-249. https://doi.org/10.1016/j.ocecoaman.2010.12.002

Beeden, R, Maynard, J, Johnson, J, Dryden, J, Kininmonth, S, Marshall, P, 2014. No-anchoring areas reduce coral damage in an effort to build resilience in Keppel Bay, southern Great Barrier Reef. Australasian Journal of Environmental Management 21:311-319. 10.1080/14486563.2014.881307

Box, G E, Tiao, G C, 1965. A change in level of a non-stationary time series. Biometrika 52:181-192.

Burgin, S, Hardiman, N, 2011. The direct physical, chemical and biotic impacts on Australian coastal waters due to recreational boating. Biodiversity and Conservation 20:683-701. 10.1007/s10531-011-0003-6

Carbery, K, Owen, R, Frickers, T, Otero, E, Readman, J, 2006. Contamination of Caribbean coastal waters by the antifouling herbicide Irgarol 1051. Marine Pollution Bulletin 52:635-644. 10.1016/j.marpolbul.2005.10.013

Creed, J C, Amado Filho, G M, 1999. Disturbance and recovery of the macroflora of a seagrass (*Halodule wrightii* Ascherson) meadow in the Abrolhos Marine National Park, Brazil: an experimental evaluation of anchor damage. Journal of Experimental Marine Biology and Ecology 235:285-306. 10.1016/s0022-0981(98)00188-9

Diedrich, A, Balaguer Huguet, P, Tintoré Subirana, J, 2011. Methodology for applying the Limits of Acceptable Change process to the management of recreational boating in the Balearic Islands, Spain (Western Mediterranean). Ocean & Coastal Management 54:341-351. https://doi.org/10.1016/j.ocecoaman.2010.12.009

Diedrich, A, Terrados, J, Arroyo, N L, Balaguer, P, 2013. Modeling the influence of attitudes and beliefs on recreational boaters' use of buoys in the Balearic Islands. Ocean & Coastal Management 78:112-120. 10.1016/j.ocecoaman.2013.02.027

Everitt, J, 2007. Chasing Twenty-first Century smokestacks: tourism research in the British Virgin Islands. Prairie Perspectives: Geographical Essays 10:89-112.

Flynn, R L, Forrester, G E, 2019. Boat anchoring contributes substantially to coral reef degradation in the British Virgin Islands. PeerJ 7:e7010. 10.7717/peerj.7010

Forrester, G E, Flynn, R L, Forrester, L M, Jarecki, L L, 2015. Episodic Disturbance from Boat Anchoring Is a Major Contributor to, but Does Not Alter the Trajectory of, Long-Term Coral Reef Decline. PLoS ONE 10:e0144498. 10.1371/journal.pone.0144498

Francour, P, Ganteaume, A, Poulain, M, 1999. Effects of boat anchoring in *Posidonia oceanica* seagrass beds in the Port-Cros National Park (north-western Mediterranean Sea). Aquatic Conservation: Marine and Freshwater Ecosystems 9:391-400. 10.1002/(sici)1099-0755(199907/08)9:4<391::aid-aqc356>3.3.co;2-#

Gardner, L, Smith Abbott, J, Woodfield-Pascoe, N, 2008. British Virgin Islands Protected Areas System Plan 2007-2017. Trust B N P: Tortola, British Virgin Islands.

Gibson, J, McField, M, Wells, S, 1998. Coral reef management in Belize: an approach through Integrated Coastal Zone Management. Ocean & Coastal Management 39:229-244.

Giglio, V J, Ternes, M L F, Mendes, T C, Cordeiro, C A M M, Ferreira, C E L, 2017. Anchoring damages to benthic organisms in a subtropical scuba dive hotspot. Journal of Coastal Conservation 21:311-316. 10.1007/s11852-017-0507-7

Gonson, C, Pelletier, D, Gamp, E, Preuss, B, Jollit, I, Ferraris, J, 2016. Decadal increase in the number of recreational users is concentrated in no-take marine reserves. Marine Pollution Bulletin 107:144-154. 10.1016/j.marpolbul.2016.04.007

González Correa, J M, Bayle Sempere, J-T, Juanes, F, Rountree, R, Ruíz, J F, Ramis, J, 2019. Recreational boat traffic effects on fish assemblages: First evidence of detrimental consequences at regulated mooring zones in sensitive marine areas detected by passive acoustics. Ocean & Coastal Management 168:22-34. https://doi.org/10.1016/j.ocecoaman.2018.10.027

Great Barrier Reef Marine Park Authority, 2002. Cairns Area Plan of Management: a Guide to the Amended Cairns Area Plan of Management. Authority G B R M P: Townsville, Queensland, Australia.

Great Barrier Reef Marine Park Authority, 2018. Whitsundays Plan of Management 1998: includes the 2017 amendment as in force 1 January 2018. Authority G B R M P: Townsville, Australia.

Grigg, R W, 1994. Effects of sewage discharge, fishing pressure and habitat complexity on coral ecosystems and reef fishes in Hawaii. Marine Ecology Progress Series 103:25-34. 10.3354/meps103025

Halas, J, 1985. An unique mooring system for reef management in the Key Largo National Marine Sanctuary, Proceedings of the fifth international coral reef congress, Tahiti 27 May- 1 June 1985, pp. 237-242.

Halas, J, 1997. Advances in environmental mooring technology, in: Richmond R H (Ed.), Proceedings of the 7th International Coral Reef Symposium. University of Guam Press, Guam, pp. 1995-2000.

Hastings, K, Hesp, P, Kendrick, G A, 1995. Seagrass loss associated with boat moorings at Rottnest Island, Western Australia. Ocean & Coastal Management 26:225-246. https://doi.org/10.1016/0964-5691(95)00012-Q

Hendriks, I E, Tenan, S, Tavecchia, G, Marbà, N, Jordà, G, Deudero, S, Álvarez, E, Duarte, C M, 2013. Boat anchoring impacts coastal populations of the pen shell, the largest bivalve in the Mediterranean. Biological Conservation 160:105-113. https://doi.org/10.1016/j.biocon.2013.01.012

Horta e Costa, B, Claudet, J, Franco, G, Erzini, K, Caro, A, Gonçalves, E J, 2016. A regulation-based classification system for Marine Protected Areas (MPAs). Marine Policy 72:192-198. https://doi.org/10.1016/j.marpol.2016.06.021

Howell, C, Petrovic, C, Baily, T, Hastings, M, 2002. International Coral Reef Initiative Country Report: British Virgin Islands. Foundation I R: Tortola, British Virgin Islands.

Kemper, C M, Flaherty, A, Gibbs, S E, Hill, M, Long, M, Byard, R W, 2005. Cetacean captures, strandings & mortalities in South Australia 1881-2000, with special reference to human interactions. Australian Mammalogy 27:37-47.

Kenchington, R, 1993. Tourism in coastal and marine environments—a recreational perspective. Ocean & coastal management 19:1-16.

Kininmonth, S, Lemm, S, Malone, C, Hatley, T, 2014. Spatial vulnerability assessment of anchor damage within the Great Barrier Reef World Heritage Area, Australia. Ocean & Coastal Management 100:20-31. 10.1016/j.ocecoaman.2014.07.003

La Manna, G, Donno, Y, Sarà, G, Ceccherelli, G, 2015. The detrimental consequences for seagrass of ineffective marine park management related to boat anchoring. Marine Pollution Bulletin 90:160-166. https://doi.org/10.1016/j.marpolbul.2014.11.001

Liddle, M J, Scorgie, H R A, 1980. The effects of recreation on freshwater plants and animals: A review. Biological Conservation 17:183-206. 10.1016/0006-3207(80)90055-5

Lloret, J, 2011. Environmental impacts of recreational activities on the mediterranean coastal environment: The urgent need to implement marine sustainable practices and ecotourism, Ecotourism: Management, Development and Impact. Nova Science Publishers, Inc.: Hauppauge, NY, pp. 135-157.

Lloret, J, Zaragoza, N, Caballero, D, Riera, V, 2008. Impacts of recreational boating on the marine environment of Cap de Creus (Mediterranean Sea). Ocean & Coastal Management 51:749-754. https://doi.org/10.1016/j.ocecoaman.2008.07.001

Marbà, N, Duarte, C M, Holmer, M, Martínez, R, Basterretxea, G, Orfila, A, Jordi, A, Tintoré, J, 2002. Effectiveness of protection of seagrass (*Posidonia oceanica*) populations in Cabrera National Park (Spain). Environmental Conservation 29:509-518.

Maric, M, de Haan, E, Hogendoorn, S M, Wolters, L H, Huizenga, H M, 2015. Evaluating Statistical and Clinical Significance of Intervention Effects in Single-Case Experimental Designs: An SPSS Method to Analyze Univariate Data. Behavior Therapy 46:230-241. https://doi.org/10.1016/j.beth.2014.09.005

McAuliffe, S, Potts, J, Canessa, R, Baily, B, 2014. Establishing attitudes and perceptions of recreational boat users based in the River Hamble Estuary, UK, towards Marine Conservation Zones. Marine Policy 45:98-107. 10.1016/j.marpol.2013.11.009

McClanahan, T, Mwaguni, S, Muthiga, N, 2005. Management of the Kenyan coast. Ocean & Coastal Management 48:901-931.

Milazzo, M, Badalamenti, F, Ceccherelli, G, Chemello, R, 2004. Boat anchoring on *Posidonia oceanica* beds in a marine protected area (Italy, western Mediterranean): effect of anchor types in different anchoring stages. Journal of Experimental Marine Biology and Ecology 299:51-62. 10.1016/j.jembe.2003.09.003

Montefalcone, M, Chiantore, M, Lanzone, A, Morri, C, Albertelli, G, Bianchi, C N, 2008. BACI design reveals the decline of the seagrass Posidonia oceanica induced by anchoring. Marine Pollution Bulletin 56:1637-1645.

Morales-Nin, B, Grau, A M, Palmer, M, 2010. Managing coastal zone fisheries: a Mediterranean case study. Ocean & Coastal Management 53:99-106.

Olsen, D A, 1978. British Virgin ISlands Coastal waters - use and conservation. Foundation I R: Tortola, British Virgin Islands.

Sagerman, J, Hansen, J P, Wikström, S A, 2020. Effects of boat traffic and mooring infrastructure on aquatic vegetation: A systematic review and meta-analysis. Ambio 49:517-530. 10.1007/s13280-019-01215-9

Settar, C, Turner, T, 2010. Coral reefs and residents of the U S Virgin Islands A relationship of knowledge, outdoor activities and stewardship. Revista De Biologia Tropical 58:197-212.

Sheppard, C R, 2013. Coral reefs of the United Kingdom overseas territories. Springer.

Smallwood, C B, Beckley, L E, 2008. Benchmarking recreational boating pressure in the Rottnest Island reserve, Western Australia. Tourism in Marine Environments 5:301-317.

Stewart-Oaten, A, Bence, J R, 2001. Temporal and spatial variation in environmental impact assessment. Ecological Monographs 71:305-339. 10.1890/0012-9615(2001)071[0305:tasvie]2.0.co;2

Tseng, Y-P, Kyle, G T, Shafer, C S, Graefe, A R, Bradle, T A, Schuett, M A, 2009. Exploring the Crowding–Satisfaction Relationship in Recreational Boating. Environmental Management 43:496. 10.1007/s00267-008-9249-5

Underwood, A J, 1997. Experiments in ecology: their logical design and interpretation using analysis of variance. Cambridge University Press: Cambridge, United Kingdom.

United States Coast Guard, 1971. Official recreational boating guide. US Department of Transportation, Coast Guard: Washington DC.

Venturini, S, Massa, F, Castellano, M, Fanciulli, G, Povero, P, 2018. Recreational boating in the Portofino Marine Protected Area (MPA), Italy: Characterization and analysis in the last decade (2006–2016) and some considerations on management. Marine Policy. https://doi.org/10.1016/j.marpol.2018.06.006

Virgin Islands Fisheries Regulations, 2003. Statutory Instrument No. 20. Ministry of Natural Resources and Labour G o t B V I: Tortiola, British Virgin Islands.

Walker, D, Lukatelich, R, Bastyan, G, McComb, A, 1989. Effect of boat moorings on seagrass beds near Perth, Western Australia. Aquatic botany 36:69-77.

West, E J, Barnes, P B, Wright, J T, Davis, A R, 2007. Anchors aweigh: fragment generation of invasive *Caulerpa taxifolia* by boat anchors and its resistance to desiccation. Aquatic botany 87:196-202.

Whitfield, A K, Becker, A, 2014. Impacts of recreational motorboats on fishes: A review. Marine Pollution Bulletin 83:24-31. 10.1016/j.marpolbul.2014.03.055

World Travel and Tourism Council, 2014. Travel and Tourism Economic Impact 2014: British Virgin Islands. Council T W T a T: London, United Kingdom.

Figures

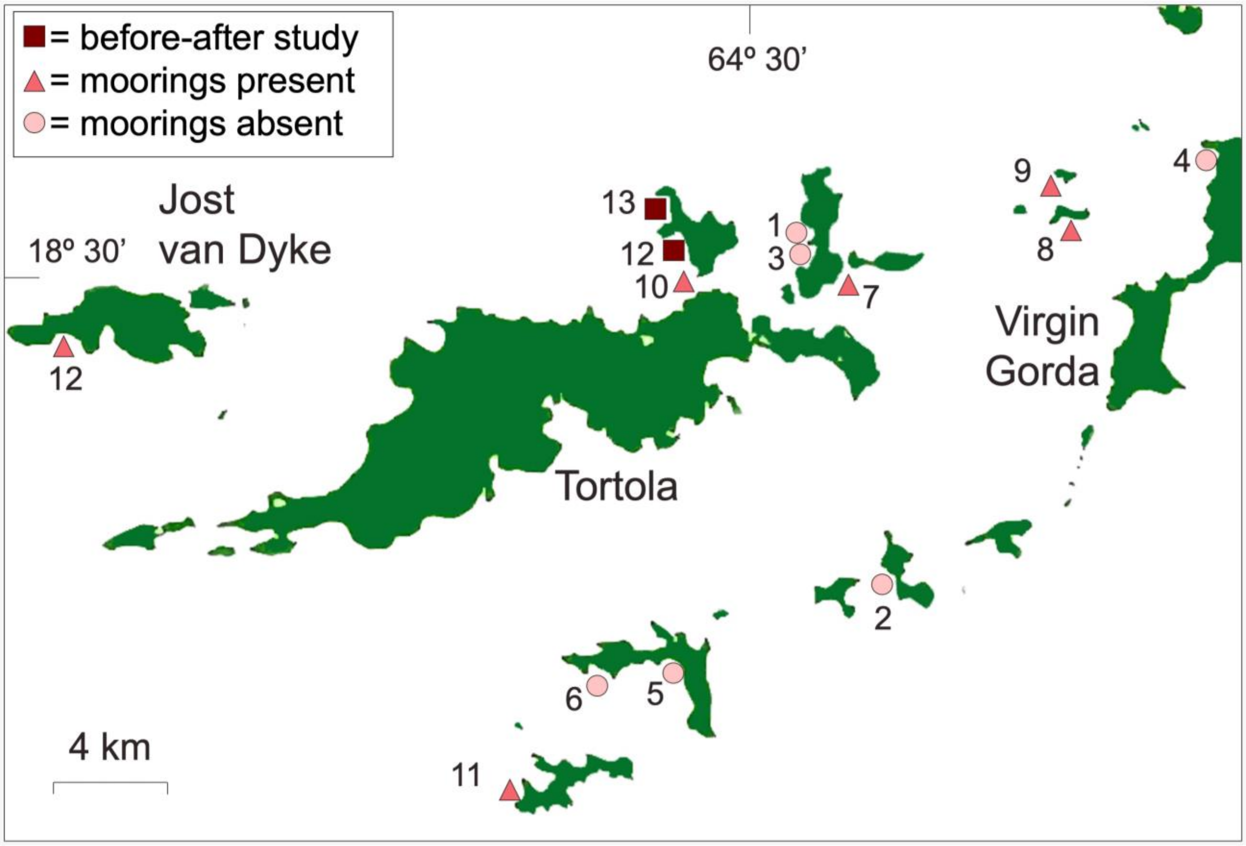

Figure 1. A map of the study sites. Numbers for sites with and without moorings correspond to site numbers in Table S1. Sites for the before-after study are White Bay (12) and Muskmelon Bay (13).

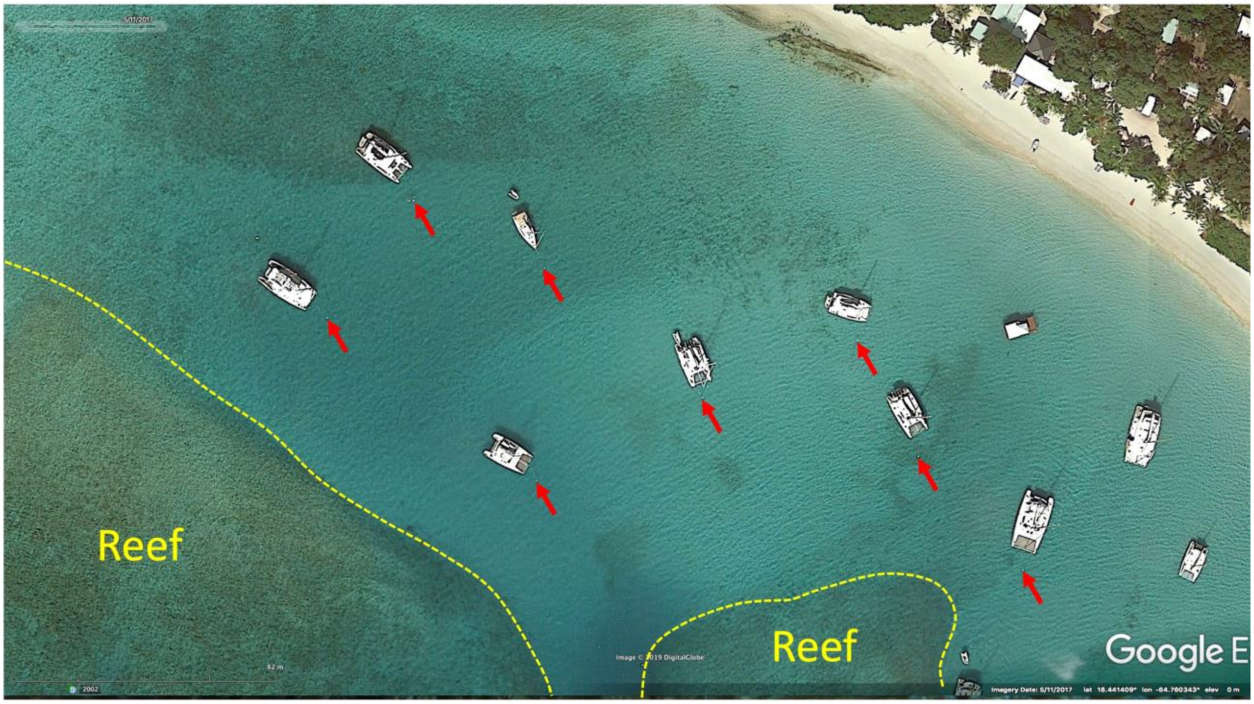

Figure 2. An example of the satellite images used to quantify boats anchored and moored at sites in the British Virgin Islands, with locations of mooring buoys indicated using red arrows. The approximate locations of two areas of shallow reef are also indicated using yellow dotted lines. The image shows part of White Bay, Jost van Dyke. Image copyright Google: Digital Globe.

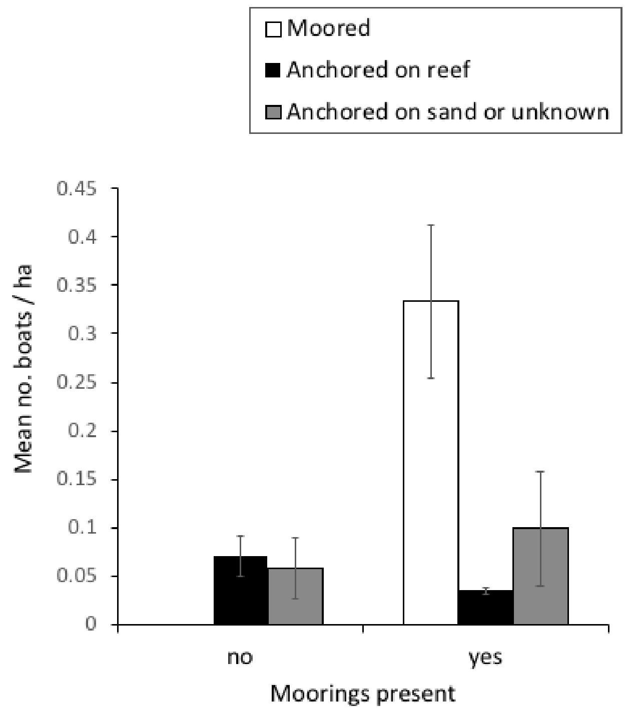

Figure 3. Boat activity at sites with and without moorings. Plotted are means (± SE) of the density of boats moored and anchored.

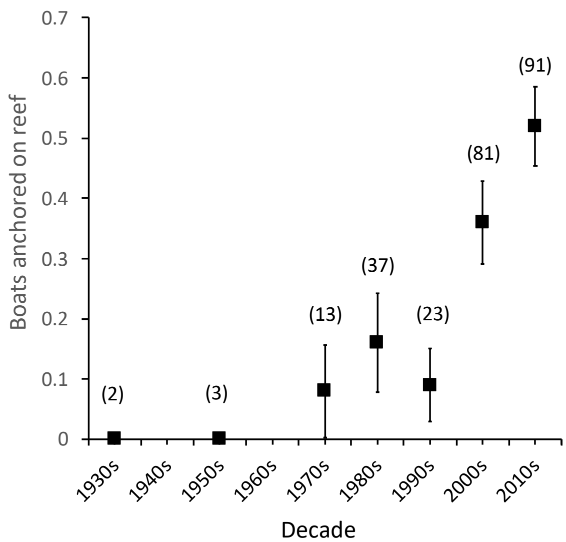

Figure 4. Long-term change in the number of boats anchored on coral reef in White Bay, Guana Island. Plotted are means (± SE) for each decade, with sample sizes above each data point. Data for 2010s include only years before moorings were installed (2010-2013).

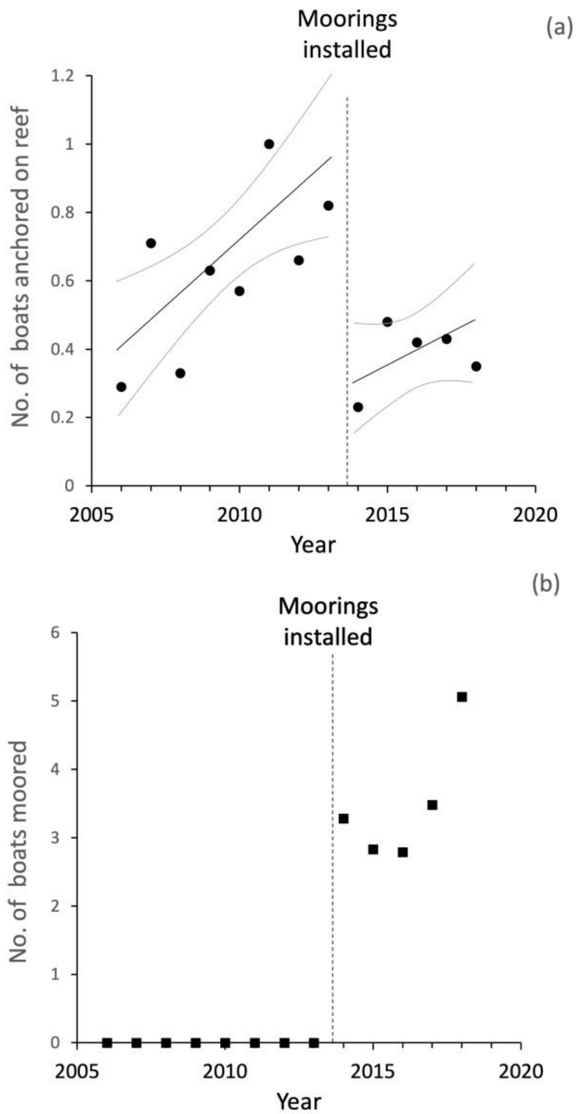

Figure 5. The effect of installing moorings on boat activity in White Bay, Guana Island. Plotted are annual means for (a) the number of boats moored at the site and (b) the number of boats anchored on coral reef. For boats anchored (a), regression lines (with 95% CI) from the linear mixed model used to test for an effect of mooring installation are also plotted.

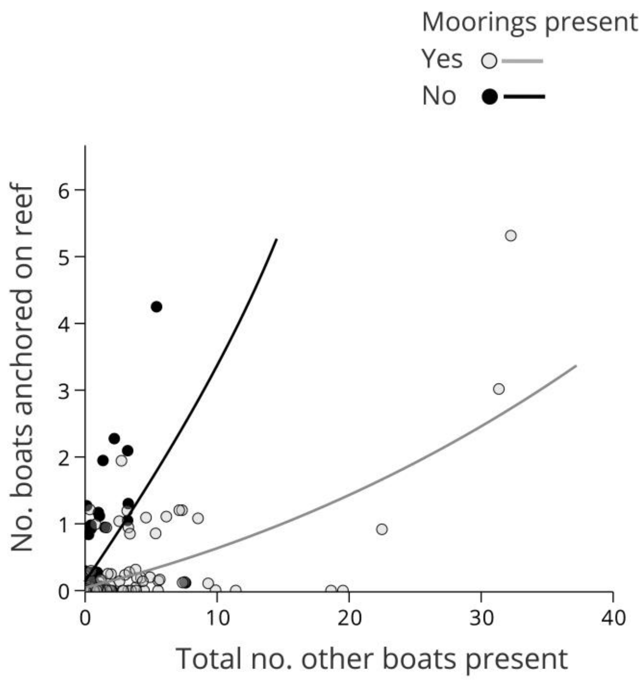

Figure 6. The effect of the number of other boats present at a site on the rate of anchoring on coral reef. Data are plotted separately for observations at sites with and without moorings and show best fit lines from a generalized linear model fit to the data. Many points overlap, so point symbols are jittered slightly and semi-transparent to better visualize the data.