**Habitat, fishing and biodiversity control grazing potential on coral reefs**

**Authors**

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**Abstract**

**Introduction**

Herbivory is crucial to ecosystem function and community structure across terrestrial and aquatic ecosystems, playing a key role in cycling nutrients (Metcalfe et al. 2014), regulating species diversity and productivity (Royo et al. 2010, Prieditis et al. 2017), and controlling habitat regime shifts (Zimov et al. 1995; Hughes et al. 2007; Keesing and Young 2014, Verges et al. 2014). Herbivory processes are generally measured at local scales relevant to individual behaviours and population sizes, which restricts our understanding of how ecosystem functions operate across larger spatial scales. Furthermore, anthropogenic pressures typically impact ecosystem processes, including herbivory, across much larger areas (ref, Wather et al. 2010?). Therefore, developing our understanding of both natural and anthropogenic drivers on herbivory at large scales requires the integration of fine-scale herbivory observations with macroecological datasets. Such analyses are particularly relevant for coral reef ecosystems, which are facing multiple damaging human pressures and where herbivory is a key ecosystem function (Hughes et al. 2007; Cheal et al. 2010, Hughes et al. 2017).

On tropical coral reefs, the removal of algae by herbivorous fishes is a critical process which clears space for coral settlement and growth (Bellwood et al. 2004). Herbivorous fishes can be categorized into browsers, which remove established macroalgae, and a diverse guild of grazers (Green & Bellwood 2009). Within the grazers, observations of feeding morphology and behaviour have been used to categorise species into two distinct grazing functions: cropping and scraping (Bellwood and Choat 1990; Polunin et al. 1995; Green and Bellwood 2009). Cropping species in the *Acanthuridae* and *Siganidae* families target filamentous turf algae and detritus, which maintains algae in cropped states, promoting coral settlement and preventing transitions to fleshy macroalgae (Arnold et al. 2010). Scraping species graze dead coral substrate to consume microscopic epiphytes and epilithic and endolithic phototrophs (Choat and Clements 2018). By removing detritus and epilithic algal matrix (EAM), scrapers promote coral recruitment by clearing settlement space (Bonaldo & Hoey 2014). Combined, cropping and scraping are considered essential functions which help sustain coral-dominated states (Bellwood et al. 2004, Hughes et al. 2007, REF).

Mature algae can proliferate in the absence of sufficient grazing pressure (Mumby et al. 2006; Burkepile and Hay 2008), and correlative analyses of fished reef ecosystems have provided evidence of grazing biomass thresholds below which reefs become algae dominated (Graham et al. 2015; Jouffray et al. 2015; Robinson et al. 2018). Herbivorous fish populations are overexploited across much of the tropics (Edwards et al. 2014), which has compromised grazing functions on reefs which fail to maintain herbivore biomass thresholds (Bellwood et al. 2012, Graham et al. 2015, Robinson et al. 2018). However, fishing effects can be confounded by bottom-up influences of the environment/habitat on herbivore assemblages (Russ et al. 2015), whereby species-specific habitat associations structure herbivore assemblages across a range of spatial scales (Hoey & Belwood 2008; Doropoulos et al. 2013) and benthic compositions (Hoey & Bellwood 2011; Heenan et al. 2016). Bottom-up influences of fish populations may be particularly strong when fish rely on habitat for both structure and food, such as algal cropping fishes which are generally small and particularly dependent on the reef matrix for shelter (Wilson et al. 2008). Thus, herbivore assemblage structure are often mediated by both habitat composition and fishing intensity but links between these drivers and grazing functions are not well resolved, particularly at macroecological scales.   
 Patterns in herbivore biomass are widely used to imply changes in herbivore functioning on coral reefs (e.g., Nash et al. 2016; Robinson et al. 2018). However, biomass data overlooks size- and species-specific differences in feeding rates and functional roles and so measures of grazing impacts have been developed by integrating information on XTZ of croppers and feeding behaviours of scrapers (Bellwood and Choat 1990; Bellwood et al. 2003) to estimate grazing rates. Furthermore, though allometric grazing ~ body size relationships (Lokrantz et al. 2008; Nash et al. 2013) indicate that the functional role provided by larger species is disproportionately greater (Bonaldo and Bellwood 2008), grazing potential may also depend on community size structure (Bellwood et al. 2012). Abundance decreases logarithmically with increasing body size, meaning that an assemblage of many small-bodied fish may be functionally equivalent to an assemblage of several large-bodied individuals (Munday and Jones 1998; Lokrantz et al. 2008). Indeed, size-selective fishing which removes larger individuals (Robinson et al. 2017) and species (Taylor et al. 2014) has produced fish communities dominated by small-bodied fishes, but links between size distribution and grazing rate are unexplored.

Irrespective of body size, assemblage-level grazing rates may also depend on species composition, whereby functional impact varies according to species’ relative abundances and to interspecific variation in bite rates (Hoey and Bellwood 2008). Thus, grazing function is influenced by the species composition of the herbivore assemblage, which implies that habitat- or fishing-induced shifts in biodiversity can result in a disproportionate loss of function. Indeed, composition changes appear to underpin diversity ~ ecosystem functioning relationships on coral reefs, whereby grazing intensity is greatest in speciose grazer assemblages (Burkepile & Hay 2008, Lefcheck et al. 2019). Yet in these studies, biodiversity effects are realised at the scale of individual quadrats, for grazing pressure exerted by individual fishes. As a result, analysis of biodiversity ~ function effects at the scale of entire reefs and relevant to the characteristics of resident fish populations are lacking.

Here, we assess the drivers of herbivore functioning on coral reefs across four regions in the Indo-Pacific (Fig. S1). Our macroecological-scale analysis includes 131 reef sites, spanning a benthic gradient from coral to macroalgal dominance and a fishing gradient from open-access fisheries to no-take fishing zones and near-pristine wilderness areas. By integrating feeding observations with underwater visual census (UVC) data on grazing fish abundance, we measured potential grazing levels at the scale of reef sites, which is highly relevant for understanding how benthic and fishing influences may alter ecosystem functioning (Nash et al. 2016). Using estimates of potential grazing, we examine 1) how fishing pressure and benthic composition influences the functioning of two major feeding groups (croppers and scrapers), and 2) consider the dependence of potential grazing on the biomass and size structure of grazer assemblages.

**Methods**

*Survey methods*

Grazing fish assemblages were surveyed using point counts of 7 m radius (Seychelles) or belt transects of 50 m length (Maldives, Chagos, GBR) conducted on hard-bottom reef slope habitat at 3-8 m depth. Surveys were designed to minimise diver avoidance or attracting fish, and conducted by a single observer (NAJG). In point counts, large mobile species were censused before smaller territorial species. In belt transects, large mobile fish (> xxcm total length, TL) were surveyed in a 5-m wide belt while simultaneously deploying the transect tape, and small site-attached species (< xxcm TL) within a 2-m wide belt were recorded in the opposite direction. For both survey types, all diurnal, non-cryptic (>8 cm TL) reef-associated fish were counted and their TL estimated to the nearest centimetre. Length measurements were calibrated by estimating the length of sections of PVC pipe and comparing it to their known length prior to data collection each day. Fish lengths were then converted to body mass (grams) using published length-weight relationships (Froese and Pauly 2018), and standardised by survey area to give species-level biomass estimates that were comparable across datasets (kg ha-1). The UVC dataset included 101 herbivore species, with 11 species common to all four regions (Table S1). Although we combined two UVC methods to estimate fish biomass, point counts and belt transects give comparable biomass estimates (Samoilys and Carlos 2000).

Following fish surveys, benthic habitat composition was surveyed with eight 10-m line intercept transects (Seychelles), or eight 50-m point intercept (benthos recorded every 50 cm) transects (Maldives, Chagos Archipelago, and Great Barrier Reef). We recorded the cover of hard corals, macroalgae and turf algae, as well as non-living substrate (rock, bare substrate, rubble and sand). The structural complexity of the reef was visually estimated on a six-point scale, ranging from 0 (no vertical relief) to 5 (complex habitat with caves and overhangs) (Polunin and Roberts 1993), which correlates strongly with a range of other methods for capturing the structural complexity of coral reefs (Wilson et al. 2007). Survey methods and site descriptions for each region are described in the Supplementary Material.

*Herbivore feeding observations*

Feeding observations of Indo-Pacific grazing fishes provided species-level estimates on bite rates of croppers and scrapers. Surveys were conducted in the Red Sea (AH), Indonesia (AH), and GBR (AH and AGL). We analysed feeding observations for species observed in the UVC dataset (n = 39). Briefly, an individual fish of a target species was haphazardly selected and its body length (total length in cm) estimated. After a ~30 second acclimation period, each individual was followed for a minimum of 3 minutes during which the number of bites and the feeding substratum was recorded (minimum n=xx individuals per species, per site, per location).

We estimated the average feeding rate (bites per minute) for each observed fish. For scrapers, we also estimated the bite scar size of each individual.

*Ecological variable processing*

Grazing species were categorised as croppers or scrapers according to their morphology and feeding behaviour (Green and Bellwood 2009). While both groups of grazing fishes feed primarily on the epilithial algal matrix (EAM) covered substrata, they differ in the amount of material/substratum that is removed during the feeding action. Croppers remove the upper portions of the algae and associated detritus and microbes leaving the basal portions of the algae intact on the substratum, while scraping parrotfishes remove shallow pieces of the substratum together with the EAM, leaving distinct bite scars (Choat et al. 2002; Wilson et al. 2003, Hoey and Bellwood 2008) (Table S1).

We used feeding observations to convert UVC biomass estimates into the total grazing potential of croppers and scrapers. We defined grazing functions separately for each functional group whereby cropping function was measured as feeding intensity (bite rate data) and scraping function was measured as area grazed (bite rate and bite area data). We used a Bayesian hierarchical modelling framework that estimates species- and genera-level functional rates. This method allowed us to estimate grazing rates for UVC species which were not observed in feeding surveys (n = 63). Cropper function was quantified in terms of potential feeding intensity, the total number of bites per minute, and derived from a predictive model which accounted for species- and genera-specific bite rates (Eqs. 1,2). In our cropper feeding data, bite rates were weakly correlated with TL (Pearson’s r = -0.18), and so we assumed bite rates were unrelated to body size.

 Eq. 1

 +DATASTE Eq. 2

From this model, we generated species- and genera- level posterior predictions of grazing rates and assigned to each individual cropping fish observed in UVCs. We then used allometric relationships to convert bite rates into grams of carbon removed through EAM consumption (Marshell and Mumby 2015). Following Van Rooij et al. (1998), daily carbon intake was linked to body mass as

 Eq. 3

which we then divided by the predicted number of bites per day to produce an estimate of grams carbon consumed per minute by each individual cropping fish. We summed estimates within UVC replicates (i.e. point count or transect) and averaged across replicates to give site-level estimates of potential cropping function.

For scrapers, we defined the potential scraping function in terms of area of substrata cleared per minute. Feeding observations provided estimates of bite rates, which we modelled as a function of body size (TL, cm) according to species- and genera-specific grazing rates, for gamma distributed errors (Eqs. 4, 5).

 Eq. 4

 Eq. 5

To account for potential differences in scraping action among species and across body sizes, we used a second underwater feeding observation dataset of scraper bite areas. Bite scar area (cm2) was modelled as a function of body size (TL, cm), for Gamma distributed errors (Eqs. 6,7).

 Eq. 6

 Eq. 7

By including size (TL) as an explanatory covariate, our model accounted for scar area increasing with body size (Fig. S2A) and bite rates decreasing with body size (Fig. S2B). For each observed scraper in the UVC dataset, we generated posterior predictions for bite rate and scar size according to its species identity and body size. Species which were not observed in feeding observations were assigned genera-level bite rates. These predictions were converted to area scraped per minute (bite rate \* scar size = area scraped) (m2 minute-1 hectare-1), summed within surveys and averaged to give site-level estimates of potential scraping function.

All models fitted to feeding data were fitted with weakly informative priors (Table S2) using Markov Chain Monte Carlo sampling implemented in Stan. We sampled three chains of 3,000 iterations (warmup = 1,500) each for model checks, and one long chain of 5,000 iterations (warmup =1,500) for generating grazing predictions. Model convergence was assessed by inspecting posterior predictions, Gelman-Rubin diagnostic (), and the number of effective samples (Table S2).

*Statistical modelling*

We modelled variation in herbivore functioning according to 1) gradients in benthic habitat composition and exploitation pressure and 2) grazer biomass and assemblage size structure. Explanatory covariates were derived from fish and benthic surveys. First, to account for fishing effects ranging from the remote and protected Chagos archipelago to heavily-exploited reefs in Seychelles, we estimated total fish community biomass as a proxy for exploitation pressure. This proxy, hereafter fishable biomass, is highly sensitive to exploitation pressure and, in the Indian Ocean, is predicted by human population size, access to markets, and fisheries management (McClanahan et al. 2016). Reefs were also assigned a categorical fishing pressure covariate to distinguish between protected (i.e. no-take areas), exploited, and remote reefs.

Second, benthic surveys provided site-level estimates of benthic composition. We estimated the site-level cover for four major habitat-forming groups (live hard coral, macroalgae, available substrate, and rubble) and structural complexity by averaging across replicates at each site. Available substrate was the total cover of rock, bare substrate, and turf algae, and represents the area of substrate available for EAM growth. To understand the range of benthic habitat types across the dataset, we categorised reefs according to their benthic regime, using a correlation-based PCA and K-means clustering (Jouffray et al. 2015). The optimal number of clusters was found using an elbow method with k=2-15 range, and then applied to the K-means clustering. For reefs in Seychelles which were surveyed in multiple years, we estimated regimes at each site by averaging cover values over time.

Third, we estimated the biomass of each functional group (kg ha-1) and a large fish indicator (LFI) as a measure of size structure. We defined large fish separately for each group as the length at the 75% quantile of the size distribution in the full dataset, where the LFI was the relative abundance of fish greater than 15 cm for croppers and 30 cm for scrapers. Biomass and the LFI were estimated for each replicate and averaged at each reef.

Prior to statistical modelling, we scaled and centered all continuous covariates to a mean of zero and standard deviation of one, and converted the categorical fishing status covariate into two dummy variables (fished - protected, fished - pristine) (Schielzeth 2010). We used multimodel inference to assess parameter effect sizes. For each function, we fitted a global linear mixed effects model with five benthic fixed effects (hard coral, macroalgae, sand, rubble and structural complexity) and four exploitation fixed effects (fishable biomass, pristine reef, protected reef and mean size), for gamma distributed errors (). Potential covariance among reefs in the same dataset and year was modelled using nested random intercept terms where, for each observation *i* at each reef *j* in dataset *k*:

[](https://www.codecogs.com/eqnedit.php?latex=grazing_%7bijk%7d%20%3D%20A%20%2B%20B*hardcoral_%7bijk%7d%20%2B%20C*macroalgae_%7bijk%7d%20%2B%20D*sand_%7bijk%7d%20%2B%20E*rubble_%7bijk%7d%20%2B%20F*complexity_%7bijk%7d%20%2B%20G*fishablebiomass_%7bijk%7d%20%2B%20H*pristine.fished_%7bijk%7d%20%2B%20I*fished.protected_%7bijk%7d%20%2B%20%2B%20J*mean.size_%7bijk%7d%20%2B%20reef_j%20%2B%20dataset_k%20%2B%20\epsilon_%7bijk%7d%250) Eq. 8

From the global model, we fitted all possible subset models (Bartoń 2013) and assessed their support using Akaike’s Information Criterion (AIC), where the top-ranked model had the lowest AIC score (Burnham and Anderson 2003). Initial modelling indicated support for multiple competing models (i.e. ∆AIC < 2), so we visualised relative covariate effect sizes by extracting standardised t-values for all models within 7 AIC units of the top-ranked model and, for each model, rescaling t-values so that 1 is the strongest predictor in a given model, and weighing that value by the models’ AIC weight (Cade 2015). These scaled t-values represent the relative effect size of each covariate between 0 (unimportant) and 1 (important). Next we generated model predictions to visualise the effect of each covariate with scaled t-value > 0.4, excluding remaining fixed effects and random effects and correcting predictions by each models’ AIC weight, with prediction uncertainty represented by the AIC-weighted sample variance (Robinson et al. 2017). Our multi-model approach accounts for uncertainty in the ‘best’ fitted model when AIC scores indicate several models are equally valid (Burnham and Anderson 2003). We avoid potential biases in model-averaged coefficient sizes by presenting effect sizes as standardised t-values, which are more informative measures of covariate importance than sums of AIC weights (Cade 2015).

We examined the dependency of grazing function on grazing biomass and size structure, without modelling benthic and fishing effects. For each function, we fitted a generalized linear mixed effects model for each observation *i* at each reef *j* in dataset *k*, for Gamma distributed errors:

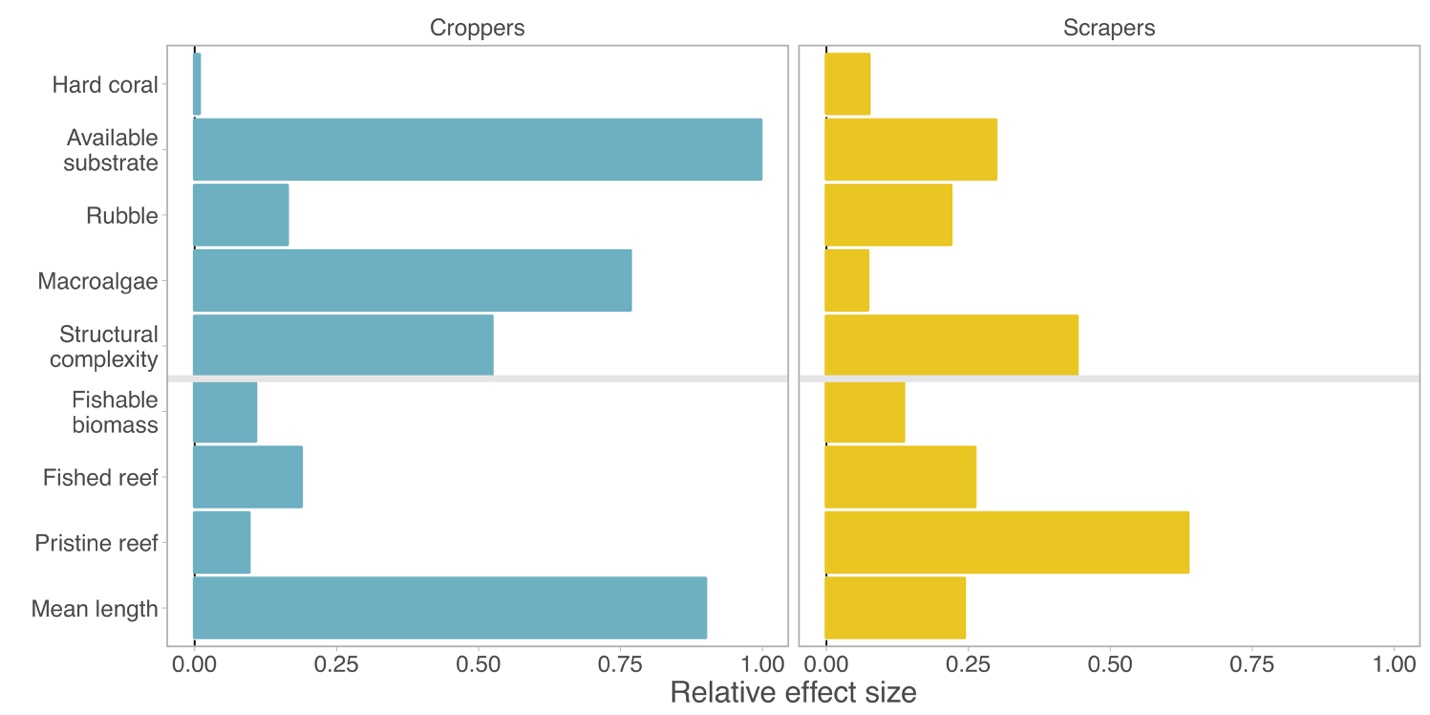
 Eq. 9

Here, by modelling the observed data and omitting benthic and fishing covariates, we aim to use the variation in function caused by bottom-up and top-down effects to assess the dependence of grazing potential on grazer biomass and size structure. We weighed model support for each covariate and the interaction between biomass and the LFI with AIC (Burnham and Anderson 2003).

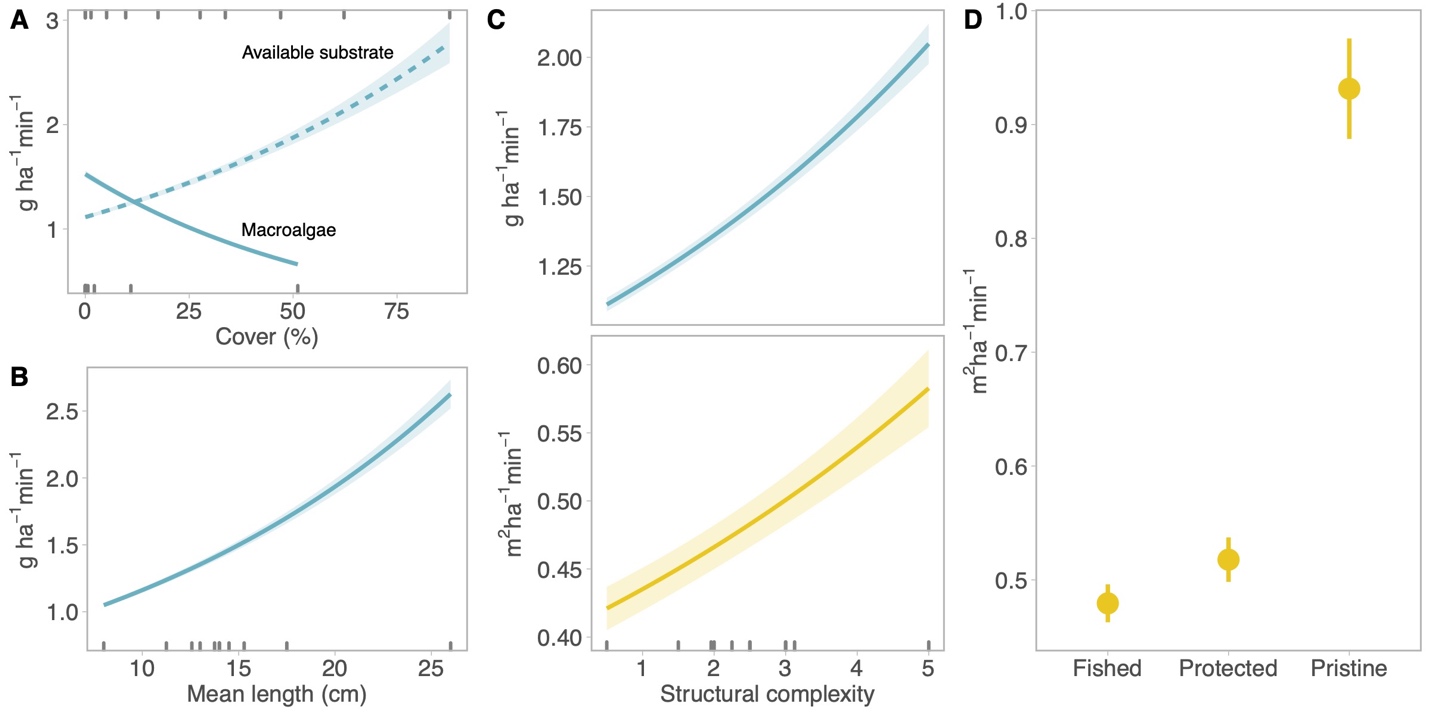
All data were analysed in R (R Core Team 2018), using packages *lme4* (linear mixed effect models; Bates et al. 2015), *MuMIn* (multimodel inference; Bartoń 2013), *rethinking* (Bayesian models; McElreath 2017), and *vegan* (diversity estimates; Oksanen et al. 2017).

**Results**

Visual census data were integrated with *in situ* feeding observations for 131 reefs in four Indo-Pacific archipelagos. For cropping fishes, 9 species were assigned individual bite rates (32.9% of UVC biomass), and remaining species were assigned genera-specific (54.4%) or an average cropper bite rate (12.6%). Combined with herbivore biomass, bite rates corresponded with modelled assemblage-level algal consumption rates ranging from 0.04 to 5.52 g ha-1 min-1, with grazing highest on GBR and Chagos reefs (Fig. S3A). Irrespective of region, algal consumption was maximised in complex habitats with high substrate availability and low macroalgal densities, while hard coral or rubble cover were weak influences (Fig. 1, 2A). Algal consumption rates were unaffected by fishing intensity, with remote, protected and fished reefs hosting similar cropping function potential (Fig. 1). Algal consumption did increase with average cropper size, indicating that reefs with cropper assemblages dominated by larger fishes had a higher grazing potential (Fig. 2B).

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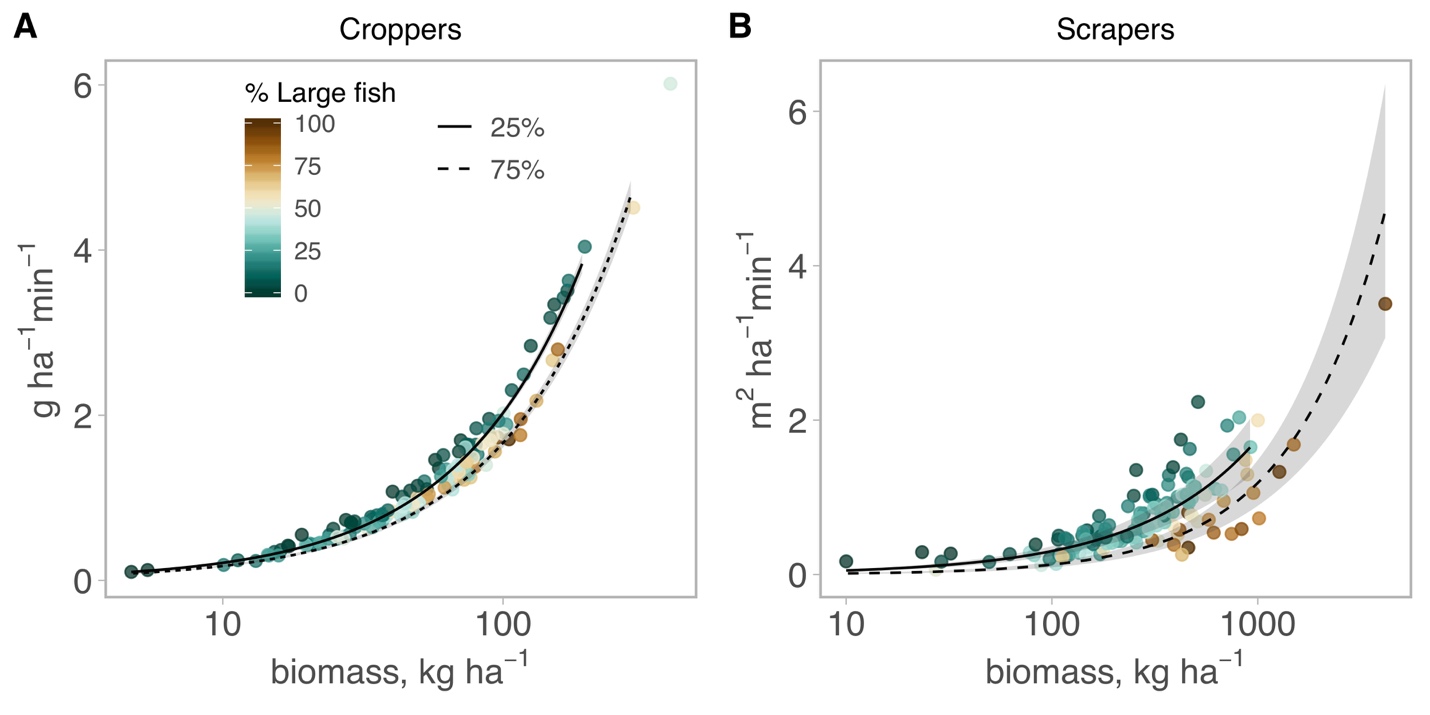
**Figure 1. Relative effect of benthic composition and fishing pressure on cropping and scraping rates.** Bars are relative effect size ratios of each covariate for top-ranking model sets (models ≤ 7 AIC units of top-ranked model), scaled to indicate very weak (0) or very important (1) drivers of grazing rates.



**Figure 2. Predicted effects of benthic and fishing drivers on cropper (A,B,C) and scraper (C,D) function.** Lines and points are herbivore functions as predicted by top model sets (≤ 7 AIC units from top-ranking model) holding other covariates to their means, with each model prediction weighted by its AIC weight and error represented as sample variance. All selected covariates had relative effect size ratios > 0.4 (Fig. 1). Decile rugs indicate the spread of observed data (in A, top rug is available substrate and bottom rug is macroalgae).

Feeding data were more highly resolved for scraping herbivores, with all fishes assigned size-based bite areas, and either species- (27 of 35 species, 80.9% of UVC) or genera-specific bite rates (19.1%). Potential area scraped was greatest on GBR reefs (> 1 m2 min-1 ha-1) and lowest on Maldives reefs (< 0.3 m2 min-1 ha-1) (Figure S4B). Scraping rates increased with structural complexity (Fig. 2C) but, in contrast to croppers, were relatively invariant across benthic cover covariates (Fig. 1). Remote reefs had the greatest scraping rates, which were considerably lower on fished reefs than protected ones (Figs. 1, 2D). After accounting for these coarse protection effects, scraping was only weakly associated with total fishable biomass and mean fish length (Fig. 1).

Fish biomass is often used as a proxy for the magnitude of their function, but the relationship between biomass and function is rarely tested. Here, cropping potential was strongly and positively correlated with cropper biomass (R2 = 0.98, Fig. 3A), indicating that the drivers of biomass variation would match tightly to the modelled drivers of cropper function. Scraping function potential also increased with scraper biomass, but with greater levels of unexplained variation in area scraped (m2 min-1 ha-1) (R2 = 0.82) which occurred across the full biomass gradient (Fig. 3B). Size structure (LFI; the proportion of large-bodied individuals in each assemblage) modified function ~ biomass relationships, with potential grazing function increasing as assemblages became dominated by smaller-bodied individuals (Fig. 3, Table 1). Although the LFI covariate was retained in both cropper and scraper models, size structure effects were stronger for scrapers (parameter coefficient = XX) than croppers (XX). For example, at average grazer biomass levels(croppers = 65 kg ha-1; scrapers = 370 kg ha-1), potential scraping function was 21% higher in small-bodied assemblages (LFI = 25%) than in large-bodied assemblages (LFI = 75%) whereas cropping function was 15% higher.



**Figure 3. Association between grazing function, grazer biomass, and assemblage size structure.** Reef-level estimates of cropper algal consumption (A) and scraper area grazed (B) plotted against UVC biomass (log10 scale), coloured by the LFI. Lines are model fits of grazing ~ biomass relationships for small-bodied assemblages (solid line: 25% large fish) and large-bodied assemblages (dashed line: 75% large fish), shaded with two standard errors. Large fishes are defined as ≥ 15 cm for croppers and ≥ 30 cm for scrapers.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Intercept** | **Biomass** | **LFI** | **LFI\*biomass** | **AICc** | **∆AIC** | **AIC weight** |
| *Croppers* |  |  |  |  |  |  |
| **0.024** | **0.728** | **-0.087** | **-** | **-296.935** | **0.000** | **0.748** |
| 0.025 | 0.727 | -0.086 | -0.002 | -294.759 | 2.176 | 0.252 |
| 0.077 | 0.681 | 0.000 | - | -208.064 | 88.871 | 0.000 |
| 0.414 | 0.000 | 0.183 | - | 226.190 | 523.125 | 0.000 |
| *Scrapers* |  |  |  |  |  |  |
| **-0.581** | **0.693** | **-0.317** | **0.084** | **-117.791** | **0.000** | **1.000** |
| -0.542 | 0.654 | -0.306 | - | -100.337 | 17.454 | 0.000 |
| -0.526 | 0.522 | 0.000 | - | -45.345 | 72.446 | 0.000 |
| -0.445 | 0.000 | 0.000 | - | 97.598 | 215.389 | 0.000 |
| -0.446 | 0.000 | 0.074 | - | 98.559 | 216.350 | 0.000 |

**Table 1. AIC selection for grazing function ~ grazer biomass + LFI models, showing parameter coefficients, AICc and AIC weights.**

**Discussion**

Herbivore functioning varied substantially across the Indo-Pacific in accordance with top-down (i.e. fishing pressure) and bottom-up (i.e. benthic habitat) drivers which were specific to each functional group. Small-bodied croppers were primarily controlled by bottom-up influences, with function maximised in complex habitats with high substrate availability and low macroalgae cover. Conversely, for parrotfishes, scraping was maximised on remote reefs in the Chagos archipelago which is isolated from fishing pressures, and was weakly associated with benthic habitat. Benthic and fishing influences were underpinned by the strong dependence of grazing on fish biomass, although we also demonstrated that reefs with greater dominance of small-bodied fishes exert moderately greater grazing rates.

Cropping potential was primarily mediated by benthic habitat type, in particular structural complexity, macroalgae cover, and substrate availability. Our results emphasize the strong dependence of small-bodied reef fishes on benthic composition (Munday and Jones 1998; Wilson et al. 2010), and demonstrate that potential cropping is not affected by top-down fishing effects, likely because cropping assemblages are dominated by small-bodied fishes which are not targeted in many reef-associated fisheries (Hicks & McClanahan 2012). Strong relationships between benthic composition and the grazing function of small-bodied reef fish may reflect the importance of resource availability, which has been shown to have stronger control on cropping surgeonfishes than fishing pressure (Russ et al. 2018). For example, the decrease in function with increasing macroalgae is likely because turf algae are less accessible to croppers under macroalgal canopies (Roff et al. 2015) whereas, on reefs with high substrate availability and limited macroalgae, expansive and easily accessible turf mats tend to support large grazer populations (Williams & Polunin 2001). Strong benthic effects imply that cropper functioning will respond more strongly to habitat disturbances, such as coral bleaching, habitat destruction or enrichment of algal communities, than to fishing. For example, disturbances which increase substrate availability for turf algal growth, such as coral mortality from heat stress (Gilmour et al. 2013), might therefore be expected to stimulate an increase in cropping function. However, since structural complexity was also shown to be a strong driver, any positive rebound of cropping function may be negated if disturbances also erode structural complexity (Graham et al. 2006).

Scraping function was strongly influenced by fishing pressure, which suppressed grazing rates far below those supported at remote wilderness reefs in the Chagos Archipelago. Our results further indicate that exploitation of large-bodied scrapers has compromised scraping functions on coral reefs (Bellwood et al. 2012). This effect superseded influences of benthic cover and small-scale fishing protection, suggesting that bottom-up control of scraping assemblages on reefs leads to minimal variation in their function, and that small-scale fishing protection does not conserve wilderness levels of scraping function. Movement of fish across reserve boundaries (Green et al. 2014) and poor compliance (Bergseth et al. 2018) likely limited the effectiveness of these small MPAs, many of which are adjacent to fishing grounds. Despite weak benthic cover effects, scraping rates increased moderately with structural complexity, further underlining the importance of coral reef structure in supporting herbivory (Nash et al. 2016).

Although total herbivore biomass was the strongest predictor of function for both croppers and scapers, remaining unexplained variation in function ~ biomass relationships was partially attributable to biodiversity effects. Positive effects of species richness on grazing rates, particularly for scrapers, are broadly consistent with recent coral reef studies which have uncovered positive biodiversity effects on herbivory (Lefcheck et al. 2019, Topor et al. 2019). The mechanisms underlying our results are, however, entirely different to those in small-scale experiments where biodiversity has been suggested to lead to feeding complementarity (Burkepile and Hay 2008, 2011) and intensifies grazing of individual fishes (Lefcheck et al. 2019, Topor et al. 2019). By focusing on benthic plots, these studies do not necessarily extrapolate to entire reefscapes where grazing pressure is dependent on the size of the resident fish assemblage, which itself is controlled by the availability of benthic habitat and historic fishing levels. Therefore, our approach of integrating feeding rates with UVC data enabled us to generate reef-level estimates of potential grazing pressure across a gradient of grazing biomass. At this scale, we confirm that more diverse reefs have higher potential grazing pressure. Here, however, β patterns contradict Lefcheck et al.’s (2019) finding that high species turnover raised grazing rates, likely because our LCBD estimates assessed turnover of species among distinct regional pools rather than among connected habitats. Across regional pools, we suggest that assemblages dominated by widely-distributed species have a lower grazing potential than those dominated by endemic species.

Biodiversity effects partially explained why grazing function decoupled from grazing biomass. Decoupling was strongest in scrapers, likely because all fishes were assigned species-, genera- and size-specific bite rates (Lokrantz et al. 2008) and so scraping estimates were more sensitive to changes in species diversity. In contrast, croppers were more tightly coupled to biomass levels, due to the absence of bite size data and to the high proportion of individual fishes which were assigned average grazing rates. Indeed, we note that our definitions of grazing functions were limited by our generalisation across species with similar functions but different feeding modes. This may have been particularly problematic for cropping species which have well-documented differences in morphology, diet (e.g. detritivores or turf), and feeding behaviours (Choat et al. 2002, Wilson et al. 2003, Brandl et al. 2015, Tebbett et al. 2017). The modelling framework we used to generate grazing estimates is a significant improvement on the procedure employed by previous macroscale grazing studies (e.g. Bellwood et al. 2012). By modelling genera- and species-specific bite rates from observations collected in several regions, we were able to leverage observational data in a hierarchical framework which predicts grazing rates of new, related species, given uncertainties in species, genera and body sizes. For example, we were able to assign bite rates to species observed in UVC but not observed in feeding surveys, with estimates that were informed by the feeding behaviour of closely related congeners. Such models could be further improved with additional feeding data on other herbivore species in different regions, and could even be developed to account for temperature effects on grazing rates (Bruno et al. 2015) that might confound comparisons of herbivory across temperature regimes.

The random intercepts in our predictive models indicated that regional similarities in grazing rates were unexplained by benthic, fishing and biodiversity covariates, which is likely due to unmeasured processes that control herbivore biomass. For example, herbivore biomass variation (and thus grazing function) has been linked to differences in oceanic productivity (Heenan et al. 2016) while video observations indicate that grazing intensity is constrained by wave exposure (Bejarano et al. 2017). Similarly, long-term studies of frequently perturbed coral reefs indicate that grazing assemblages continually reorganize in response to disturbance (Han et al. 2016), implying that grazing intensity will respond in similar non-linear trajectories. Temporal analyses linking habitat suitability, primary productivity, and herbivory would greatly develop our understanding of how herbivory rates influence long-term changes in reef state.

Our study demonstrates how benthic habitat, fishing pressure and biodiversity influence the functional potential of herbivore assemblages at scales which are relevant for understanding ecosystem-level responses to disturbances such as bleaching (Nash et al. 2016). Cropping pressure is likely to increase in response to stressors which clear substrate space for turf growth. Intact reef structure will be critical for maintenance of scraping functions, though reefs in close proximity to human populations are unlikely to return to wilderness levels of grazing pressure, even with protection from fishing. For a given level of biomass, protection of biodiversity will enhance grazing, but differences in regional pools mean that grazing potential of fish assemblages may vary naturally among reefs. We stress that biomass was by far the most important predictor of scraping function, and recovery or protection of fish biomass will help ensure herbivory processes are functionally intact on degraded coral reefs (Williams et al. 2016).

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[**Supplementary Material**](https://github.com/jpwrobinson/grazing-gradients/blob/master/writing/ms/supp-material.pdf)

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