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Macroalgae exhibit diverse responses to human disturbances on coral reefs

Sara E. Cannon,[1*] Simon D. Donner,[1] Angela Liu,[1,2] Pedro C. González Espinosa,[1,3] Andrew H. Baird,[4] Julia K. Baum,[5] Andrew G. Bauman,[6] Maria Beger,[7,8,9] Cassandra E. Benkwitt,[10] Matthew J. Birt,[11] Yannick Chancerelle,[12] Joshua E. Cinner,[4] Nicole L. Crane,[13,14] Vianney Denis,[15] Martial Depczynski,[11,29] Nur Fadli,[16] Douglas Fenner,[17] Christopher J. Fulton[11],[29] Yimnang Golbuu,[18] Nicholas A. J. Graham,[10] James Guest,[19] Hugo B. Harrison,[4,20,4] Jean-Paul A. Hobbs,[21] Andrew S. Hoey,[4] Thomas H. Holmes,[22,29] Peter Houk,[23] Fraser A. Januchowski-Hartley,[24], Jamaluddin Jompa[25], Chao-Yang Kuo,[4,26] Gino Valentino Limmon,[27, 28, 29] Yuting V. Lin,[15] Timothy R. McClanahan,[30] Dominic Muenzel,[7] Michelle J. Paddack,[13,31] Serge Planes,[12] Morgan S. Pratchett,[4] Ben Radford,[11,32] James Davis Reimer,[33,34] Zoe T. Richards,[35,36] Claire L. Ross,[22,32] John Rulmal Jr.,[13,37] Brigitte Sommer,[38, 39] Gareth J. Williams,[40] Shaun K. Wilson [22,32]

*Corresponding author: s.cannon@oceans.ubc.ca; 604-789-2433

1. Department of Geography, University of British Columbia, Vancouver, BC, Canada.
2. School of Geography and the Environment, University of Oxford, Oxford, UK.
3. Institute for the Oceans and Fisheries, University of British Columbia,, Vancouver, BC, Canada.
4. Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville QLD, Australia.
5. Department of Biology, University of Victoria, Victoria, BC, Canada.
6. Department of Marine and Environmental Science, Nova Southeastern University, Dania Beach, Florida, USA.
7. School of Biology, Faculty of Biological Sciences, University of Leeds, Leeds, UK.
8. Department of Aquatic Resources Management, Faculty of Fisheries and Marine Science, Pattimura University, Indonesia.
9. Centre for Biodiversity and Conservation Science, University of Queensland, Australia.
10. Lancaster Environment Centre, Lancaster University, Lancaster, UK.
11. Australian Institute of Marine Science, Perth, Western Australia, Australia.
12. PSL Research University, CRIOBE, UAR 3278 CNRS-EPHE-UPVD, Moorea French Polynesia and the French Center for Excellence for Coral Reefs (LabEx Corail), France.
13. One People One Reef, Santa Cruz, CA, USA.
14. Department of Biology, Cabrillo College, Aptos, CA, USA.
15. Institute of Oceanography, National Taiwan University, Taipei, Taiwan.
16. Faculty of Marine and Fisheries, Universitas Syiah Kuala, Banda Aceh, Indonesia.
17. Coral Reef Consulting, Pago Pago, American Samoa.
18. Palau International Coral Reef Center, Koror, Palau.
19. School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, UK.
20. School of Biological Sciences, University of Bristol, Bristol, UK
21. School of Biological Sciences, The University of Queensland, Brisbane, QLD, Australia.
22. Marine Science Program, Biodiversity and Conservation Science, Department of Biodiversity Conservation and Attractions, Kensington WA, Australia.
23. University of Guam Marine Laboratory, UOG Station, Mangilao, Guam.
24. Department of Biosciences, Swansea University, Swansea, UK.
25. Department of Marine Science and Fisheries, Hasanuddin University, Makassar, South Sulawesi, Indonesia.
26. Biodiversity Research Center, Academia Sinica, Taipei, Taiwan.
27. Department of Marine Biology, Pattimura University, Ambon, Indonesia.
28. Maritime and Marine Science Centre of Excellence, Pattimura University, Ambon, Indonesia.
29. Centre for Collaborative Research on Aquatic Ecosystems in Eastern Indonesia.
30. Wildlife Conservation Society, Global Marine Programs, Bronx, NY, USA.

31. Santa Barbara City College, Santa Barbara, CA, USA.
32. Oceans Institute, University of Western Australia, Perth, WA, Australia.
33. Department of Marine Science, Chemistry and Biology, Faculty of Science, University of the Ryukyus, Okinawa, Japan.
34. Tropical Biosphere Research Center, University of the Ryukyus, Okinawa, Japan.
35. Coral Conservation and Research Group, School of Molecular and Life Sciences, Curtin University, Bently, WA Australia.
36. Collections and Research, Western Australian Museum, Perth, Western Australia, Australia.
37. Ulithi Falalop Community Action Program, Yap, Federated States of Micronesia.
38. School of Life and Environmental Sciences, The University of Sydney, Sydney, NSW, Australia
39. School of Life Sciences, University of Technology Sydney, Sydney, NSW 2007, Australia.
40. School of Ocean Sciences, Bangor University, Anglesey, LL59 5AB, UK.

Running Head: Macroalgae responses to local human disturbance

Abstract

Scientists and managers rely on indicator taxa such as coral and macroalgal cover to evaluate the effects of human disturbance on coral reefs, often assuming a universally positive relationship between local human disturbance and macroalgae. Despite evidence that macroalgae respond to local stressors in diverse ways, there have been few efforts to evaluate relationships between specific macroalgae taxa and local human-driven disturbance. Using genus-level monitoring data from 1,205 sites in the Indian and Pacific Oceans, we assess whether macroalgae percent cover correlates with local human disturbance while accounting for factors that could obscure or confound relationships. Assessing macroalgae at genus level revealed that no genera were positively correlated with all human disturbance metrics. Instead, we found relationships between the division or genera of algae and specific human disturbances that were not detectable when pooling taxa into a single functional category, which is common to many analyses. The convention to use percent cover of macroalgae as an indication of local human disturbance therefore likely obscures signatures of local anthropogenic threats to reefs. Our limited understanding of relationships between human disturbance, macroalgae taxa, and their responses to human disturbances impedes the ability to diagnose and respond appropriately to these threats.

Keywords: **Macroalgae, Coral Reefs, Multiple Stressors, Indian Ocean, Pacific Ocean, Local Human Disturbance, Coral Reef Health**

Introduction

Coral reefs are a highly diverse habitats within the tropical and sub-tropical seascape and provide essential services to millions of people, even as anthropogenic stressors intensify (Williams et al., 2019). Changes in the relative abundance of indicator taxa are often used to evaluate the effects of disturbances and human stressors on coral reefs, two common indicators being macroalgae and coral cover. In general, high cover of macroalgae is considered indicative of degraded reefs while high cover of hard corals indicates healthy reefs (Bruno et al., 2009; McCook, 1999; Vroom, 2011; Vroom et al., 2006). The perception that macroalgae cover is indicative of reef health is driven by the theory that local anthropogenic stressors can promote macroalgae proliferation through top-down or bottom-up processes (e.g. the Relative Dominance Model; Littler and Littler, 1984, 2007). However, macroalgae-dominated reefs are not necessarily unhealthy (Vroom, 2011; Vroom et al., 2006). Macroalgae support ecosystem functioning and services (Fulton et al., 2019), contributing to carbonate production and providing nursery habitat that supports adult fish populations (Sievers et al., 2020), including target species for tropical reef fisheries (Wilson et al., 2022). Moreover, while macroalgae and corals compete for space and macroalgae may impede coral recovery through shading, abrasion, or chemical defenses (Littler et al., 2006; Littler & Littler, 2007; Mumby et al., 2006), there are also positive interactions between corals and macroalgae. For example, macroalgae can provide refuge for corals from predation by the Crown-of-Thorns seastar, *Acanthaster planci* (Clements and Hay, 2017). Macroalgal canopies can also protect corals from bleaching by limiting exposure to high irradiance (Jompa and McCook, 1998; Smith et al., 2022).

Macroalgae is a broad term that can encompass multiple taxa with different morphology, ecology, and biology. Consequently, comparisons of studies using the percent cover of macroalgae as a proxy for local human-driven degradation often find conflicting results. For example, Smith et al (2016) reported a significant positive relationship between populated islands and macroalgae cover, concluding that human populations negatively affect reef health. Conversely, Bruno and Valdivia (2016) failed to find a relationship between human populations and macroalgae cover on reefs, concluding local signatures of degradation are being obscured by climate-driven stressors.

Differences in how macroalgae are defined may have confounded comparisons between studies. Smith et al (2016), for example, included turf algae and excluded erect, calcifying algae such as *Halimeda*, while Bruno and Valdivia (2016) excluded turf algae but included *Halimeda* and other erect, calcifying taxa. Clearly, scientists define macroalgae inconsistently, and the nature of these definitions may obscure drivers of macroalgal cover.

Furthermore, environmental factors can influence macroalgal cover on reefs, such as exposure to wind and waves (Gove et al., 2015; Page-Albins et al., 2012; Fabricius et al., 2023), seasonality (Brown et al., 2018; Fulton et al., 2014), and sea surface temperature (SST) (Graba-Landry et al., 2020; Tanaka et al., 2012). Studies endeavoring to assess links between local human disturbance and macroalgae cover should therefore consider these environmental factors in analyses. Macroalgae taxa also exhibit variability in their responses to local human and environmental stressors, including temperature (Anton et al., 2020; Fabricius et al., 2023), fishing pressure (Gilby et al., 2015), water pollution (Fabricius, 2005; McClanahan et al., 2004; McCook, 1999), and sedimentation (Fabricius, 2005; Harris et al., 2021). Research investigating these taxon-specific responses to local stressors are lacking for all but the most common macroalgae.

We re-examine the relationship between macroalgae cover and local human disturbance using data from 1,205 sites in the Indian and Pacific Oceans collected between 2004 and 2020 (Figure 1). We define macroalgae as including erect calcifying genera but excluding turf or crustose algae (Bruno et al., 2009; Steneck, 1988; Tebbet and Bellwood, 2019). We use this definition to remain consistent with past studies (e.g. Bruno et al., 2009; Bruno and Valdivia, 2016; Steneck, 1988; Tebbett and Bellwood, 2019; Tebbett et al., 2023), and to make use of pre-existing survey data in which turf algae was not identified consistently across surveys. The analyses test the hypothesis that macroalgae percent cover is correlated with local human disturbance when accounting for environmental factors that might have confounded the findings in previous studies (Bruno and Valdivia, 2016; Smith et al., 2016). For all sites and within six biogeographic realms (Costello et al., 2017; see Methods), we determined the suite of human disturbance and environmental variables (Supplementary Table 1) that best explain the genus-level macroalgae communities via canonical correspondence analysis (CCA) and stepwise ordination. Next, we fit permutational analysis of variance (PERMANOVA) models to estimate the effects of each variable on macroalgal communities. We then used Similarity Percentage Analysis (SIMPER) to determine the taxa driving differences across biogeographic realms. Finally, we fit zero-inflated generalized linear mixed models (GLMMs) to quantify the relationships between local human disturbance and the common macroalgae genera and their divisions (red, green, brown).

Materials and Methods

We collated data from genus-level macroalgae benthic surveys conducted by the authors (Supplementary Materials: Data Sources) from 1,205 individual tropical and subtropical coral reef study sites across the Indian and Pacific Oceans between 2004 and 2020, covering a period of 16 years. This dataset provides a snapshot of each site at a single time point and we did not investigate temporal changes in macroalgal communities. As discussed below, we considered temporal and methodological variables to account for differences across sites and surveys (Supplementary Table 1). Of the 1,205 sites, 1,145 identified all macroalgae to the genus level, while 60 surveys only identified macroalgae of the genus *Halimeda.* We did not include these *Halimeda*-only surveys in the investigation of community drivers of macroalgae, but we included them in the genus-specific analyses described below. All statistical modeling, figures, and plots were done using R Statistical Software version 4.4.1 (R Core Team, 2021), R Studio version 2021.09.0 Build 351 (RStudio Team, 2020), the R package ggplot2 (Wickham, 2016), and InkScape (Inkscape Project, 2020). The R code is available on GitHub (https://github.com/secanno/Cannonetal2023_Macroalgae). We created the map in QGIS version 3.24 (QGIS Development Team, 2022) using a base map from OpenStreetMap (OpenStreetMap Foundation, 2021).

To limit the ability of confounding factors to obscure potential relationships between macroalgae and local human disturbance, we identified and calculated 45 site-specific variables (in addition to 15 variables representing human disturbance), representing drivers known to influence macroalgae growth and distribution at multiple resolutions. These variables encompassed eight categories: connectivity with other reefs, heat stress, human disturbance, methodological and site descriptive variables, net primary productivity, seasonality, storms, and wind and wave exposure. Because the estimates of these variables cover a wide geographic area, we conducted the analysis for the entire dataset, and also separated the sites into marine biogeographic realms (Costello et al., 2017) to test whether the macroalgae communities within realms were explained by different variables. One of the realms, the offshore Indian Ocean, included just twelve sites, which we added to the Indo-Pacific Seas and Indian Ocean realm. We also considered data contributors and the survey methodologies as explanatory variables to account for differences in site selection and sampling methodologies. Due to spatial constraints, we are unable to detail the methods and justifications for each of the 60 explanatory variables that we considered in the main text of the manuscript. Instead, Supplementary Table 1 contains a table describing each variable, including its definition, source, spatial resolution, and justification for inclusion in the analysis.

We assessed multicollinearity during variable selection at two steps in the analysis. First, we used the R package Hmisc (Harrell, Jr., 2021) to calculate the Pearson's r correlation coefficients for all possible pairs of variables and eliminated any with r correlation values of greater than 0.7 within each of the eight covariate categories. When multiple variables were correlated within a given category, we chose those with the lowest summed Pearson's r coefficient, eliminating 33 variables (Supplementary Table 2). Then, following Borcard et al. (2011), to select variables that best explained the macroalgae community compositions, we conducted CCA and stepwise variable selection using the R package vegan (Oksanen et al., 2020) for all sites combined and independently for each of the six realms. We addressed multicollinearity in this second step by eliminating any variables with a variable inflation factor (VIF) > 10 (Table 1) (Borcard et al., 2011). We detail the variables selected by the CCAs and their VIF in Supplementary Table 3.

Using the R package vegan (Oksanen et al, 2020), we ran SIMPER (999 permutations) to identify the macroalgae taxa driving differences across biogeographic realms. We also identified variables with strong correlations to macroalgal community composition with principal component analysis and by fitting seven PERMANOVAs: one for all the data combined and for each of the six realms independently. Each PERMANOVA included the variables selected by the CCA, excluding those with VIFs > 10 (Supplementary Table 3).

Last, we evaluated how local human disturbance, represented by variables detailed in Supplementary Table 1, influenced the distribution of the most common genera of macroalgae. To estimate the effects of five categories of local human disturbance on the most common macroalgae taxa, their divisions, and for all macroalgae combined, we fit generalized linear mixed models using the R package glmmTMB (Bolker et al., 2009) for the following equation:

Percent of Macroalgae ~ cumulative human impact score + log(population density) + NDVI + nutrients + market gravity + (1|Latitude:Longitude)

We considered each of the five human disturbance variables fixed effects, the interaction between latitude and longitude a random effect to account for spatial autocorrelation across sites. The most common genera were defined as those comprising more than 1% of the total macroalgae cover, either across the entire dataset or within one of the realms. The cumulative human impact score is a metric for local human disturbance that includes small scale fishing pressure, coastal population, industrial development, tourism, and two types of water pollution (sedimentation and nitrogen from agriculture), while the normalized difference vegetation index (NDVI) is a proxy for nearby development. For more details, including methods and justifications for each of the model variables, please see Supplementary Table 1.

We compared zero and non-zero-inflated GLMM with gaussian and beta distributions. We selected zero-inflated beta regression models because they best met the assumptions that the residuals would exhibit homoscedasticity and be normally distributed, and that the data are not autocorrelated. The human population variable was log-transformed to meet the assumptions. We used diagnostic plots to test for normal distribution and equal variance of residuals with the R package DHARMA (Hartig, 2022), and Moran's tests to test for spatial autocorrelation with the package spdep (Bolker et al., 2009, Supplementary Materials 4). We also calculated the R^2 values (marginal R^2, which represents only the fixed effects, and conditional R^2, which measures the fit of the entire model) using the Nakagawa method (Nakagawa et al., 2017). Finally, to enable comparing the model results across taxa, we used the R package ggeffects to calculate the adjusted marginal effects for each of the explanatory variables (Lüdecke, 2018).

Results

Across these 1,205 sites, we identified 96 genera of macroalgae and total macroalgae cover varied from zero to 88.2% per site, with a mean of 12.8% and a median of 6.8%. The calcified green algae *Halimeda* occurred at the most sites (68.2%).

Macroalgal community compositions differed across realms (Figure 2). The genus *Halimeda* was most common in all realms except for the offshore West Pacific and northwest Pacific, where *Lobophora,* a brown fleshy alga, was the most common taxa. We describe the most common taxa within each realm in detail in Supplementary Table 5, and the full SIMPER results comparing all realms to each other in Supplementary Table 6.

The drivers of spatial differences in macroalgal community compositions differed when considering the full model (containing all sites) or within each of the realms (Table 1, Supplementary Table 7). A principal component analysis considering the potential drivers of macroalgae distribution (Supplementary Table 1) found that the first three principal components accounted for 46.32% of the variation in macroalgal communities (Supplementary Materials 8). The full equations for all the PERMANOVAs were statistically significant with p-values < 0.01 for the model containing all sites, and models for each of the realms except the mid-tropical North Pacific, which was not significant ($p = 0.08$). The explanatory power of each model varied, and each of the independent variables had R^2 values less than 0.10. For all macroalgae combined, the PERMANOVA accounted for 10% of the variation in macroalgae percent cover across sites. The model for the Mid-Tropical North Pacific had the least explanatory power for variation in macroalgal community composition ($R^2 = 0.05$), while the model for sites in the Mid-South Tropical Pacific had the greatest ($R^2 = 0.21$).

The human disturbance metrics had the largest effects of all drivers contributing to the variation in macroalgal communities in all realms. Of these human disturbance indicators, the normalized difference vegetation index (NDVI, an indicator of development on land; see Methods) and nutrients from agriculture had the greatest presence in the models, although nutrients were only significant in two of six models, while NDVI was significant in three of the six. Three of the models also included a categorical variable representing fisheries management (open-access, restricted, or closed / no access), which had greater explanatory power than the other human disturbance metrics (all of which had R^2 values less than 0.05). Of the biophysical indicators, mean wave energy was another common driver of macroalgae community composition and was significant in four out of six models. Except for fisheries management, all the variables had R^2 values that were less than or equal to 0.05.

The relationships between the percent cover and each of the human disturbance metrics varied for different macroalgae genera (Figure 3) and divisions (Figure 4, Supplementary Materials 9). The adjusted estimates indicated weak relationships between the percent cover of total macroalgae and the human disturbance metrics (Supplementary Materials 10), with effect sizes that were all less than one. When investigating potential relationships by genera or division, however, some relationships between specific taxa and human disturbance became apparent that were not evident for all macroalgae combined. Similarly, when considering the division of macroalgae (red, green, or brown), relationships with human disturbance were less apparent than they were for specific macroalgae taxa. Percent cover of all algae had a negative relationship with three out of five human disturbance variables. Within the brown macroalgae division, most taxa exhibited positive relationships with the log of the population density, and negative relationships with NDVI and nutrients from agriculture. Only two of the brown macroalgae genera exhibited strong relationships with the disturbance. The genus *Spatoglossum* was positively correlated with the cumulative human impact score (which includes sedimentation, nutrients from agriculture, tourism, industrial development, and small-scales fisheries pressure; Andrello et al., 2021), log of population density, and market gravity, but was negatively correlated with NDVI and nutrients from agriculture. By contrast, *Dictyopteris* was positively correlated with the cumulative human impact score and NDVI, but negatively correlated with market gravity and nutrients from agriculture.

Similarly, both the green and red macroalgae taxa also demonstrated weak relationships with human disturbance when considered by division, with specific taxa showing stronger positive or negative relationships. Most of the green macroalgae genera were negatively related to the log of the population density (*Microdictyon* and *Udotea* were strongly and negatively correlated*)* but were weakly related with the remaining human disturbance metrics. The red macroalgae taxa were also negatively related to the log of the population density and NDVI. By contrast, the red macroalgae genera *Ceratodictyon* and *Hypnea* were positively correlated with the population density, although these relationships were weak.

Discussion and Conclusions

The percent cover of total macroalgae is not a robust indicator for local anthropogenic disturbance in the Indian and Pacific Oceans, for two main reasons: (1) the drivers of macroalgae communities are unclear, challenging to estimate, and differ across realms, and (2) different macroalgae genera and divisions have distinct and often opposite responses to diverse types of local human disturbance.

We find that multiple environmental factors, unrelated to local anthropogenic disturbance, influenced macroalgae community compositions (connectivity, wind and wave exposure, storms, net primary production and seasonality). Accounting for these environmental factors is imperative if researchers and managers are to use macroalgae as an indicator of anthropogenic impact on reefs. Otherwise, researchers risk attributing observed patterns in macroalgal community composition to the wrong drivers. Furthermore, despite assessing 60 variables that could influence macroalgae communities, the most parsimonious models included few variables, and the PERMANOVAs all had R^2 values of less than 0.25. This indicates that the models were still unable to account for most of the variation in macroalgal communities and highlights the difficulty in identifying the drivers of ecological patterns (discussed further below).

In addition, the relative importance of the factors influencing macroalgal communities differed across the biogeographical realms. The CCA identified 17 variables influencing macroalgae distribution when considering all sites. However, each variable explained less than 3% of the variation and collectively, the full equation only accounted for 10% of the variation. Many of these variables were selected only when considering all sites collectively, but not when examining the drivers of macroalgal communities by biogeographical realm. In the Coral Sea, the CCA identified six variables as best describing the variation in macroalgal communities, half of which (nutrients from agriculture, the kurtosis of chl-a, and the standard deviation of net primary productivity) are related to nutrients, and the other half were related to storms and exposure to wind and waves (number of storms greater than type 3, cyclone score, and mean wave energy). These variables collectively accounted for 21% of the variation across sites in the Coral Sea. In the mid-South Tropical Pacific, the PERMANOVA accounted for 18% of the variation, and fisheries management and development (represented by NDVI) were important for explaining variation in macroalgal communities, along with the depth of the surveys, photosynthetic radiation, and the aspect of the site. By contrast, the heat stress metrics were not important drivers of macroalgal communities, whether considering all sites collectively or within the biogeographic realms. Collectively, the CCAs and PERMANOVA results show that macroalgal communities are influenced by different factors depending on their location. Without accounting for these factors, studies that compare the percent cover of macroalgae across broad regions may obscure differences in community compositions, rather than revealing them.

The macroalgae genera we assessed also exhibited diverse and oftentimes opposing relationships with different metrics of human disturbance. Combining all macroalgae into a single category, or into divisions, obscured ecologically important relationships. In addition, the total macroalgae cover metric was uniformly weakly explained by each of the human disturbance variables. The cumulative human impact score did not have the strongest correlation with macroalgae cover. This is most likely because this metric is a conglomeration of multiple stressors, and our analysis clearly shows that many taxa respond more strongly to a specific anthropogenic stressor. Moreover, the percent cover of many taxa will increase in response to one stressor but decline when subjected to another, somewhat nullifying any response when responses from multiple stressors are combined. This indicates that taxon-specific responses to individual human pressures should be considered when evaluating local anthropogenic impacts on coral reefs.

The individual traits of the macroalgae genera may explain their relationships with the various disturbance metrics, each of which represents a different form of localized disturbance. The genus *Halimeda* was present at almost 70% of the sites and was the most common macroalga in our dataset. As the most common calcifying alga on tropical reefs globally, *Halimeda,* produce sediment on coral reefs and play an important role in reef accretion (Hillis-Colinvaux, 1980). Our results suggest that *Halimeda* cover will increase with increasing cumulative human impacts but will decline with increasing market gravity and nutrients from agriculture. While market gravity was designed as a metric for fishing pressure (Cinner et al., 2018), it incorporates human population size, and may therefore also reflect nutrient loading present in realms with high human populations. The weak but negative correlation with nutrients from agriculture, is in contrast with past findings showing that *Halimeda* growth is stimulated by nutrients (Delgado, 1994; Teichberg et al., 2013). Increasing market gravity might increase competition with other macroalgae taxa that would otherwise be kept in check by herbivory, which could explain the negative correlation. However, coral reef herbivores show low preferences for *Halimeda* and some species are chemically defended (Hay et al., 1988; Paul and Van Alstyne, 1988). Collectively, these results reveal a complex relationship between *Halimeda* and human disturbance; it is more likely to grow where nutrients are high, but not necessarily where there is high fishing pressure.

Complex relationships may also exist for other macroalgae taxa examined here, although confirming these relationships is not possible with the current data and will require further research as well as experiments that manipulate the extent of different stressors imposed on macroalgae taxa. For example, we found that canopy-forming brown algae, which provide important habitat for fish and support small-scale fisheries (Sievers et al., 2020; Wilson et al., 2022), exhibit diverse responses to disturbance. For example, blooms of *Turbinaria* have been linked to high nutrient concentrations on the Great Barrier Reef (McCook, 1999), which is consistent with our results from across the Indian and Pacific Oceans. *Sargassum* was one of the few taxa exhibiting a negative relationship with nutrients from agriculture, which aligns with past research (e.g. McClanahan et al., 2004). However, it is in direct opposition of the Relative Dominance Model (RDM), which posits that macroalgae cover on coral reefs is dictated by human disturbance acting through top-down (e.g., fishing pressure) or bottom-up (e.g., nutrients) processes (Littler and Littler, 1984, 2007).

While past research helps explain many of the relationships between specific macroalgae taxa and our human disturbance variables, we also found unexpected relationships. The morphology of *Turbinaria,* along with its chemical defenses, make it unpalatable to many herbivores (Bittick et al., 2010) and we would not anticipate an increase in percent cover with increasing fishing pressure (Davis, 2018). However, we found a positive correlation with market gravity. Other studies have also reported that macroalgae taxa often do not respond as predicted to stressors (McClanahan et al., 2004; McCook, 1999), again, underscoring how little these interactions are understood. Unfortunately, studies investigating taxa-specific interactions with human disturbance for tropical macroalgae are lacking for all but the most common taxa and often report conflicting results (Ramseyer et al., 2021). Existing studies are primarily motivated by negative interactions between corals and macroalgae (Fulton et al., 2019; Vroom, 2011). Furthermore, because of the Relative Dominance Model's predictions, studies are usually limited to investigating the effects of fishing pressure or nutrients (e.g. Adam et al., 2021; Holbrook et al., 2022).

Our results show that the lack of correlation between total macroalgae cover and local human disturbance may be in part because of the varied interactions between disturbance and individual macroalgae taxa. Signatures of human disturbance that were undetectable using total macroalgae cover may still be evident when identifying macroalgae at the genus level. In these cases, relying on the assumption that macroalgae percent cover correlates with local disturbance may lead to maladaptive interventions; for example, if managers assume that all macroalgae will respond similarly to enhanced herbivory despite evidence to the contrary (Kelly et al., 2016), or misidentify undisturbed reefs as degraded, this approach could lead to costly and ineffective management interventions.

For reef-building corals, research has greatly improved our understanding of diverse and complex responses to disturbance. Literature has documented differences in how corals respond to bleaching, for example, because of their morphology, heterotrophic feeding ability, physiology, and several other factors (Darling et al., 2012; Loya et al., 2001; Van Woesik et al., 2011). Yet, the focus on coral in the literature demonstrates that scientists have failed to consider how genera within diverse macroalgae assemblages may also respond to disturbance differently and what this means for ecosystem function (Fulton et al., 2019). Like reef-building coral communities, some taxa of macroalgae are susceptible to climate-driven stressors (Anton et al., 2020; Graba-Landry et al., 2020). Our limited understanding of the relationships between both human and climate disturbance and macroalgae taxa, and their importance in reef ecosystem functioning, impedes our ability to respond to the many threats facing coral reef ecosystems as a whole (Vroom, 2011).

This study builds on previous research that has called the RDM and the subsequent assertions that macroalgae is correlated with local human disturbance an oversimplification (Fulton et al., 2019; McCook, 1999; Vroom, 2011) with potentially negative implications for management (McCook, 1999; Vroom, 2011), and that has criticized the widespread reliance on macroalgae as an indicator of reef health or degradation (Bruno et al., 2009; Vroom, 2011). Despite these critiques, researchers and managers continue to use total macroalgae cover to provide proxy estimates on the health of coral reefs and how they are affected by people (Bruno and Valdivia, 2016; Smith et al., 2016). A key limitation to this and other research on macroalgae distribution (Keith et al., 2014; Tebbett et al., 2023) is the lack of available survey data identifying macroalgae at the genus level. Most of the survey data we analyzed were collected to investigate the status and/or health of coral reefs, and site selection may have excluded parts of the reef with higher macroalgae cover. In addition, the sampling was uneven across realms, and the reliance on large-scale, low-resolution global databases to calculate site-specific independent variables may have affected our ability to account for local drivers of macroalgal communities because of differences in scale. Despite these limitations, this study demonstrates that the links between macroalgae cover and human disturbance are uncertain, which undermines the usefulness of total macroalgae cover as a way of estimating local, human-driven degradation.

Strategic management of coral reefs is increasingly vital as the climate continues to warm (Darling et al., 2019). Evaluating how coral reefs are being affected by disturbance is an indispensable part of research and management, but the most common metrics used in that work are based on an oversimplified and poorly tested paradigm. We have shown here that total macroalgae cover does not correlate well with local human disturbance but that evaluating macroalgae cover at the genus-level shows more promise as a management and assessment tool. Genus-level data might also provide greater understanding of the drivers of macroalgae and how they influence overall ecosystem functioning. Investments in further research on macroalgae at finer taxonomic resolutions, including genus-specific interactions with human-driven stressors, may be important for future coral reef conservation. In addition, as others have argued, testing long-standing paradigms in marine ecology will be increasingly necessary to make good predictions as climate change intensifies (Williams et al., 2019), demonstrating the need for enhanced monitoring to improve our ability to assess climate-driven changes in benthic communities. We hope that by demonstrating that total macroalgae cover is only weakly correlated with human disturbance and is not an effective way to estimate coral reef health in the Indian and Pacific Oceans, this work catalyzes much-needed consideration of how we define reef health and the effects of local human disturbance, especially under rapidly changing environmental conditions.

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Tables

Table 1. Variables that best explained macroalgal communities (CCA results) and had variable inflation factors of less than 10, shown with their pseudo-R^2 values (PERMANOVA results). Values in bold are statistically significant at α = 0.05, while those in italics are significant at α = 0.10. Empty cells indicate that variables were not selected as best explaining the macroalgal communities by the CCA and were not included in the PERMANOVAs.

Variable Type	Variable	All Data	Mid-tropical N. Pacific	Indo-Pacific seas & Indian Ocean	Coral Sea	Mid South Tropical Pacific	Offshore West Pacific	NW Pacific
	R^2 (full equation)	***0.10***	***0.05***	***0.12***	***0.21***	***0.18***	***0.07***	***0.16***
Connectivity	Reef Area (15km)			**0.05**				
	Reef Area (200km)	**0.00**		**0.01**				
Human Disturbance	Cum. Human Impact	**0.01**						
	Fisheries Management	**0.01**				**0.08**		**0.09**
	NDVI	**0.00**		**0.02**		**0.02**	**0.03**	
	Nutrients (Agriculture)	0.00	0.03		**0.04**			**0.04**
	Market Gravity							
Methodology & Sampling	Depth	**0.00**		**0.02**		**0.04**		
	Habitat	**0.02**						
	Latitude							
Net Primary Productivity	Chl-a (kurtosis)	*0.00*		**0.01**	**0.02**			0.02
	NPP (sd)	0.00			**0.05**			
Seasonality	Month of survey (by SST)	**0.03**						
	PAR average (survey mo.)	0.00				**0.04**		
	SST mean (survey mo.)			**0.01**				
Storms	# Storms ≥ Type 3	**0.00**	0.02		**0.01**			
	Cyclone Score				**0.02**			
Heat stress	MaxDHW	**0.00**						
	MMM	0.00						
	SST_{SD}	**0.00**						
Wind and Wave Exposure	Aspect	0.00				0.00	0.01	
	Wave energy (mean)	**0.00**		**0.00**	**0.04**		**0.02**	
	Wind and Wave Exposure						0.01	0.01

Figures

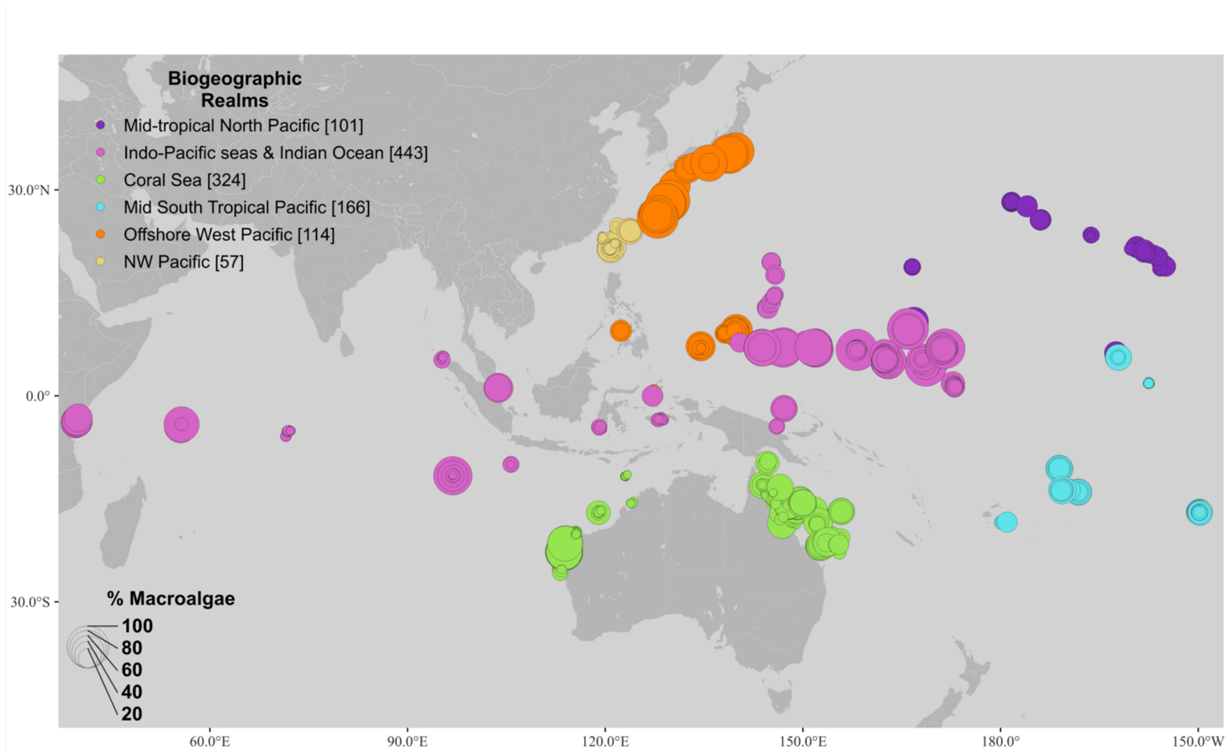
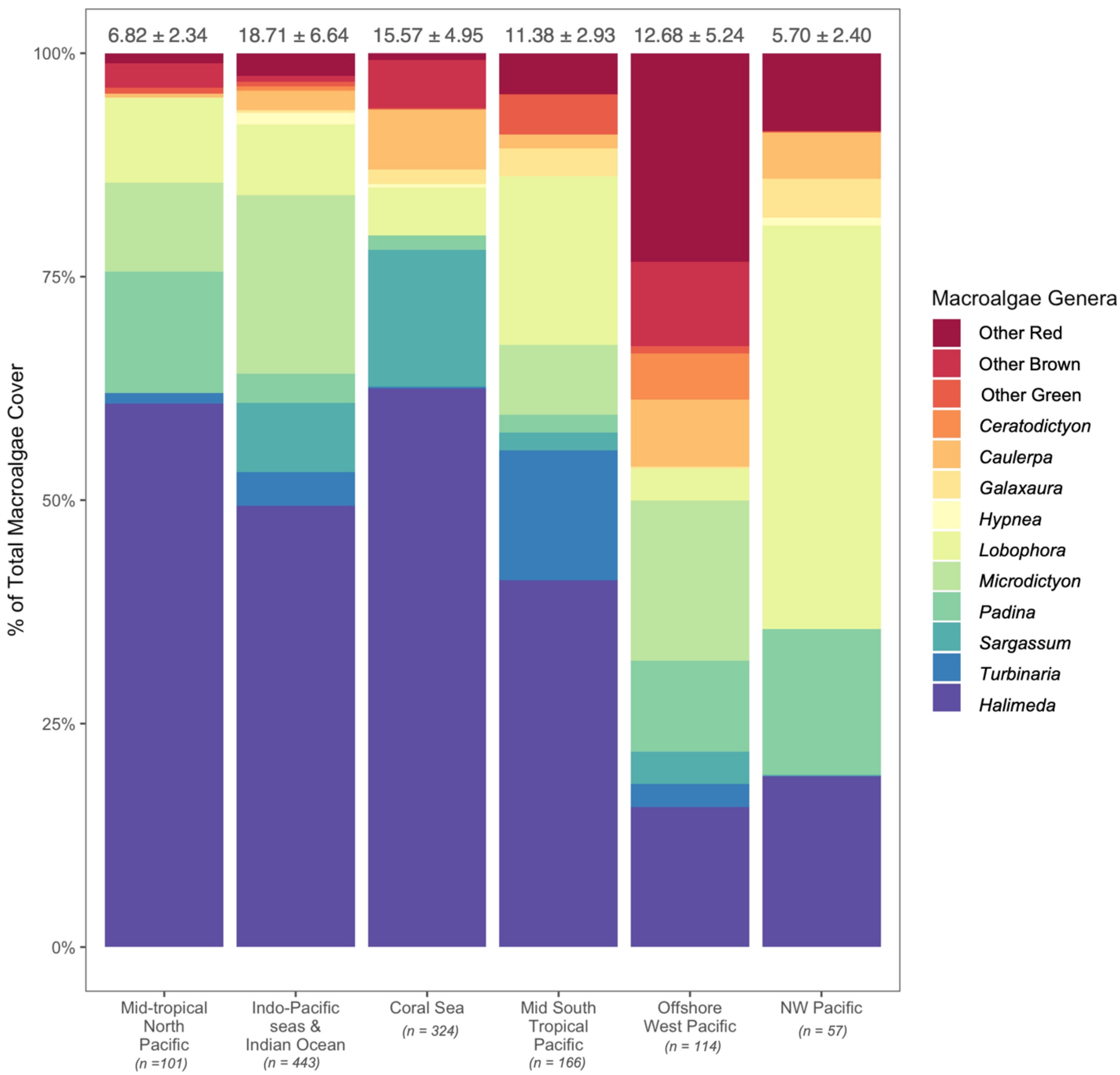
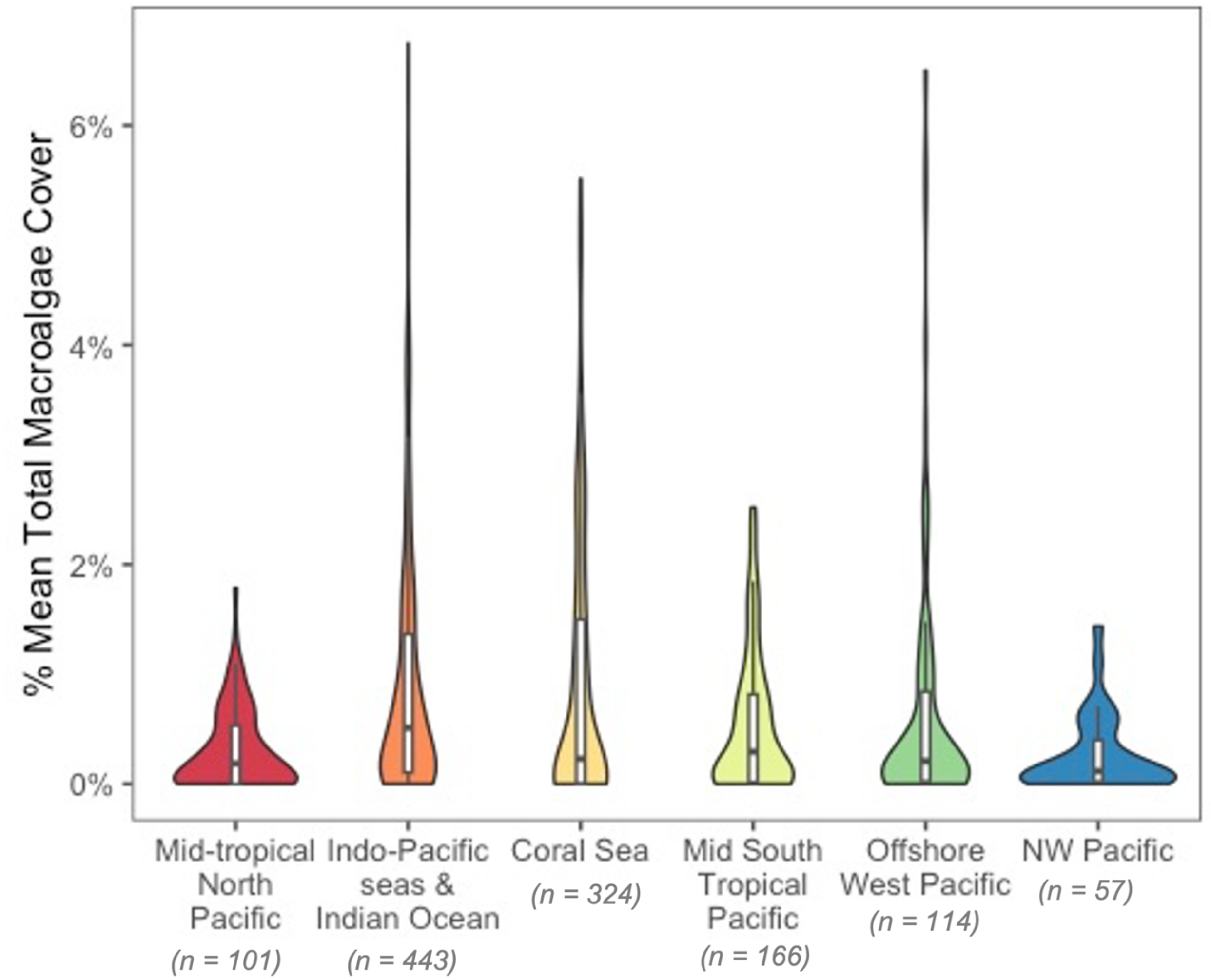


Figure 1. Map of 1,205 study sites across the Indian and Pacific Oceans, by biogeographic realm (as described in Costello et al., 2017). The size of the points represents the total percent cover of macroalgae at each site. Map lines do not necessarily depict accepted national boundaries.


6.82 ± 2.34
18.71 ± 6.64
15.57 ± 4.95
11.38 ± 2.93
12.68 ± 5.24
5.70 ± 2.40
% of Total Macroalgae Cover
100%
75%
50%
25%
0%
Mid-tropical North Pacific (n =101)
Indo-Pacific seas & Indian Ocean (n = 443)
Coral Sea (n = 324)
Mid South Tropical Pacific (n = 166)
Offshore West Pacific (n = 114)
NW Pacific (n = 57)
Macroalgae Genera
Other Red
Other Brown
Other Green
Ceratodictyon
Caulerpa
Galaxaura
Hypnea
Lobophora
Microdictyon
Padina
Sargassum
Turbinaria
Halimeda

a.



b.

Figure 2. (a) Top ten most common macroalgae taxa by biogeographic realm, with mean and standard deviation at the top of each bar. (b) Mean total macroalgae cover by site,

grouped by biogeographic realms.

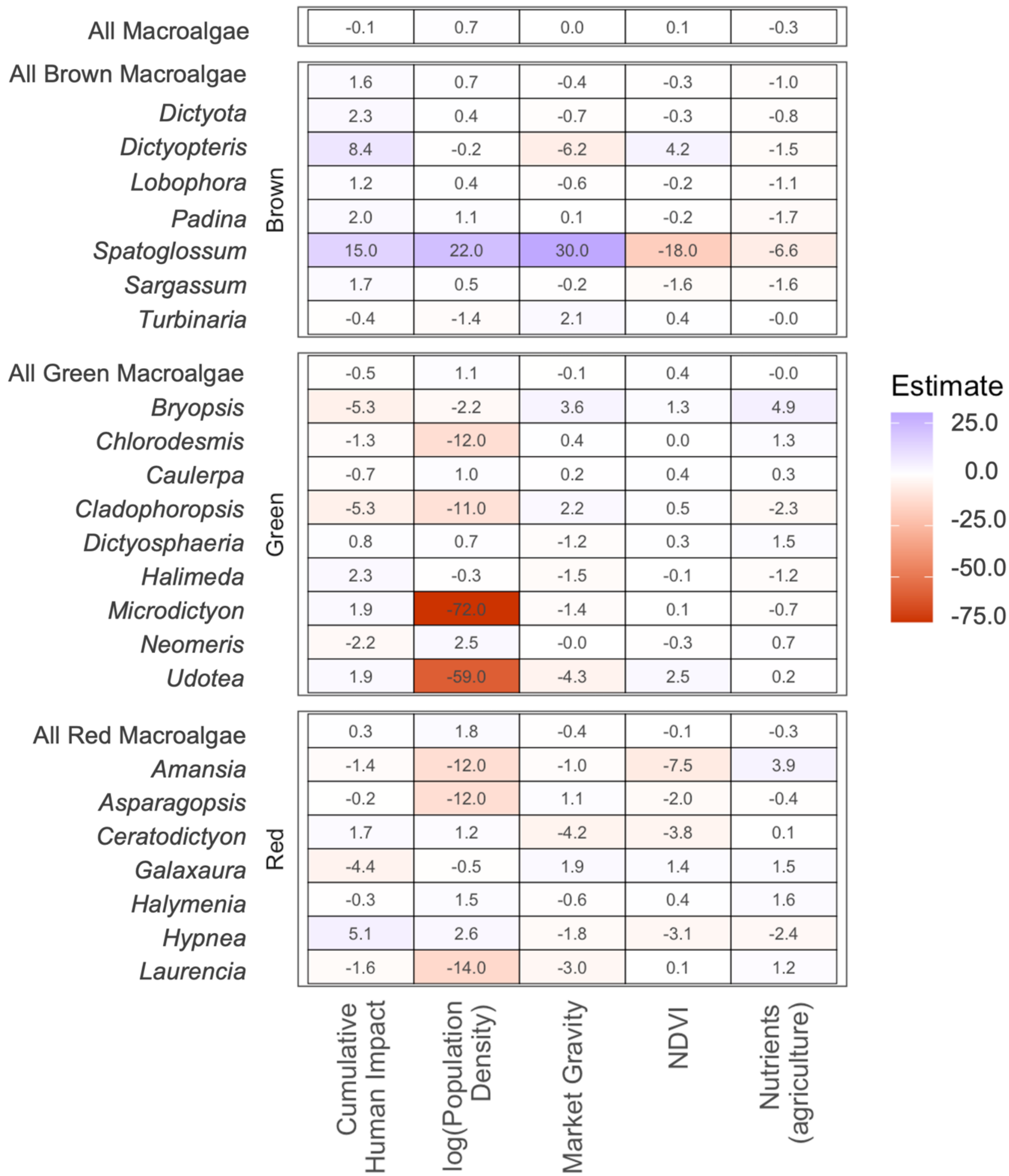


Figure 3. Estimated parameters for fixed effects from the GLMMs. *Estimates for NDVI have been multiplied by -1 to account for this variable's inverse relationship with disturbance.

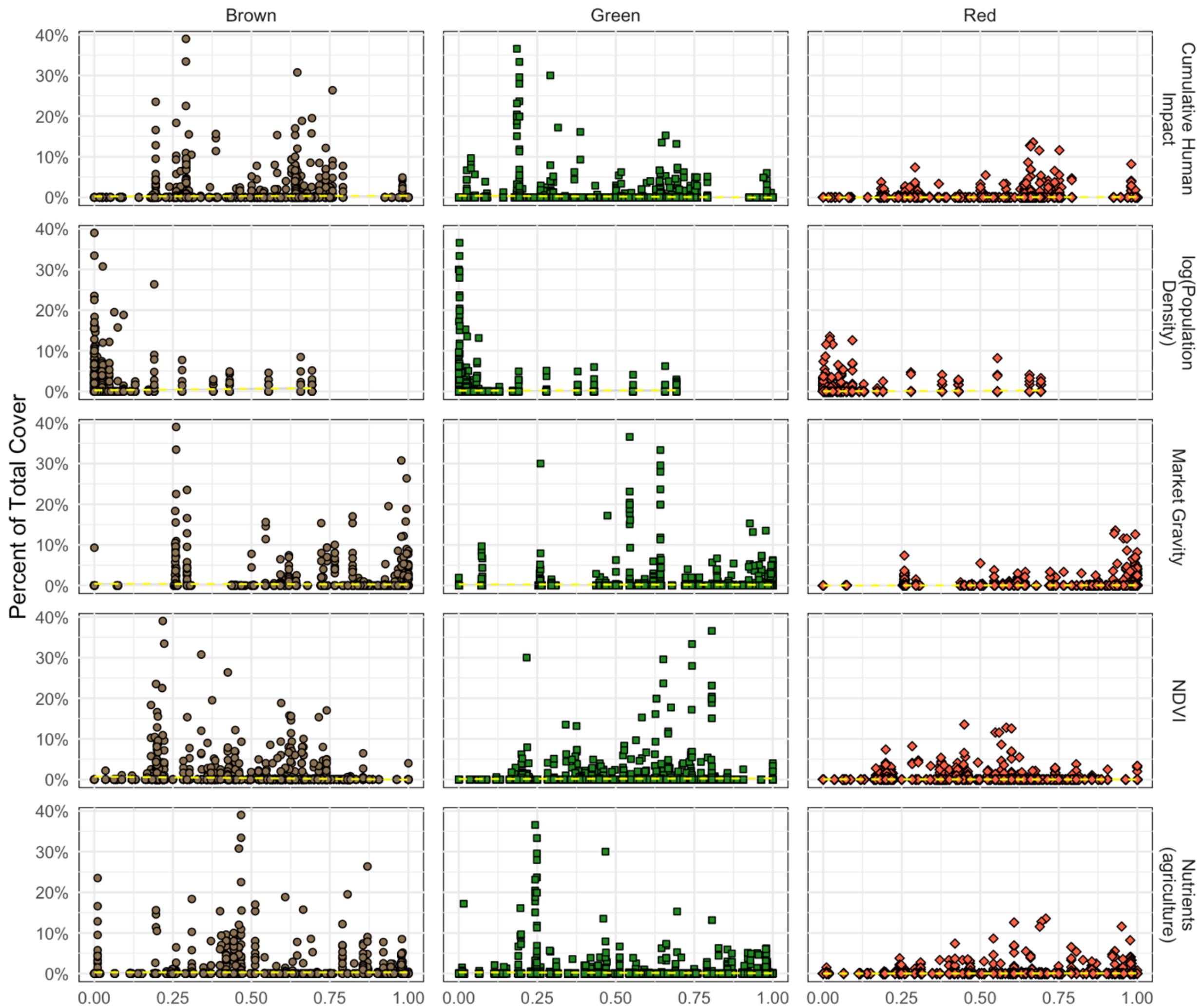


Figure 4. The percent cover of macroalgae genera grouped into three divisions (brown, green, and red), as they relate to five human disturbance variables. The dashed yellow line is the trendline. The disturbance variables have been normalized and range between zero and one (see *Methods*).

Supplementary Material: Data owners and contact information for requesting access for each dataset included in the analysis.

Site Location	Data Region(s)	Data Owner(s)	Contact Name	Contact Email
Australia	Ashmore Reef & Great Barrier Reef	Richards	Zoe Richards	zoe.richards@curtin.edu.au
Australia	Cocos (Keeling) Islands	Hobbs	J.P. Hobbs	jp.hobbs@uq.edu.au
Australia	Coral Sea	Harrison, Hobbs, Hoey, and Pratchett	Andrew Hoey	Andrew.hoey1@jcu.edu.au
Australia	Great Barrier Reef	Pratchett and Hobbs	Morgan Pratchett	morgan.pratchett@jcu.edu
Australia	Great Barrier Reef	Baird and Kuo	Andrew Baird	andrew.baird@jcu.edu.au
Australia	Ningaloo	Birt, Depczynski, Fulton, Holmes, Radford, and Wilson	Shaun Wilson	shaun.wilson@dbca.wa.gov.au

Site Location	Data Region(s)	Data Owner(s)	Contact Name	Contact Email
Australia	Ningaloo, Rowley Shoals, Shark Bay, Montebello and Barrow Islands	Ross and Holmes	Claire Ross	claire.ross@dcba.wa.gov.au
Chagos Archipelago		Benkwitt, Graham, and Wilson	Nick Graham	nick.graham@lancaster.ac.uk
Federated States of Micronesia	Chuuk, Yap, Pohnpei, Kosrae	Houk	Peter Houk	peterhouk@gmail.com
Federated States of Micronesia	Yap and Chuuk Outer Islands	Paddack, Crane, and Rulmal, Jr.	Michelle Paddack	michelle.paddack@gmail.com
Fiji	Lau	Graham, Pratchett, and Wilson	Shaun Wilson	shaun.wilson@dbca.wa.gov.au
French Polynesia	Moorea	Planes and Chancerelle	Serge Planes	planes@univ-perp.fr
Indonesia	Aceh	Baird, Fadli, and Hoey	Andrew Baird	andrew.baird@jcu.edu.au
Indonesia	Spermonde, Ambon, and Halmahera	Beger, Muenzel, Jompa, Limmon	Maria Beger	m.beger@leeds.ac.uk

Site Location	Data Region(s)	Data Owner(s)	Contact Name	Contact Email
Japan		Beger, Reimer, Sommer	Maria Beger	m.beger@leeds.ac.uk
Kenya		McClanahan	Tim McClanahan	tmcclanahan@wcs.org
Kiribati	Gilbert Islands, Tarawa and Abaiang Atolls	Cannon and Donner	Sara Cannon	s.cannon@oceans.ubc.ca
Kiribati	Kirimati	Baum	Julia Baum	baum@uvic.ca
Marshall Islands	Majuro and Arno Atolls	Cannon and Donner	Sara Cannon	s.cannon@oceans.ubc.ca
Marshall Islands	Rongelap, Ebon, Namdrik, and Wotho Atolls	Houk	Peter Houk	peterhouk@gmail.com
Palau		Golbuu	Yimnang Golbuu	ygolbuu@picrc.org
Papua New Guinea		Bauman, Cinner, and Januchowski-Hartley	Andrew Bauman	abauman@nova.edu
Philippines		Bauman and Januchowski-Hartley	Andrew Bauman	abauman@nova.edu
Seychelles		Graham and Wilson	Shaun Wilson	shaun.wilson@dbca.wa.gov.au

Site Location	Data Region(s)	Data Owner(s)	Contact Name	Contact Email
Singapore		Bauman and Guest	Andrew Bauman	abauman@nova.edu
Taiwan		Denis and Lin	Vianney Denis	vianney.denis@gmail.com
USA	American Samoa	Fenner	Douglas Fenner	douglasfennertassi@gmail.com
USA	Guam, Hawaii, Northern Marianas, American Samoa, Pacific Remote Island Areas	NOAA	Not applicable	NOAA National Centers for Environmental Information (http://ncei.noaa.gov)
USA	Pacific Remote Islands Area	Williams	Gareth Williams	g.j.williams@bangor.ac.uk

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Supplementary Table 1. Description of variables thought to influence total macroalgae percent cover on coral reefs.

	Name	Resolution and/or Units	Description and Reasoning	Source
Connectivity	*Connections between coral reefs can influence local ecological communities through larval dispersal with impacts for resilience and management* (Magris *et al.*, 2016). *Some macroalgae may travel long distances during various parts of their life cycles. Additionally, the ability of hard coral taxa to compete with macroalgae after disturbances may be influenced by coral larval supply* (Beyer *et al.*, 2018).			
1	Connectivity Score	5 km resolution, no units	A metric estimating the level of connectivity of sites to other reefs, including outgoing larval settlement (including self-recruitment) and larval export estimated via a larval connectivity model (Beyer *et al.*, 2018).	Andrello *et al.*, 2021, Beyer *et al.,* 2018
2	Reef Area (15 km)	Number of reefs cells falling within a 15-km buffer multiplied by the area of a cell (0.25 km^2).	15-km is the upper range of larval dispersion distances for most reef fishes, which can influence macroalgae percent cover through herbivory (Green *et al.*, 2015).	Yeager *et al.*, 2017
3	Reef Area (200 km)	Number of reefs cells falling within a 200-km buffer multiplied by the area of a cell (0.25 km^2).	200-km is the upper range of larval dispersal distances for large-bodied fish species (Green *et al.*, 2015). Some macroalgae can also disperse across large distances.	Yeager *et al.*, 2017
Geography	*Geography influences the oceanography and climate of a given reef. These variables will also account for geographical bias in the dataset and spatial autocorrelation across sites.*			
4	Latitude	Decimal degrees	We used the latitude and longitude to account for spatial autocorrelation in the dataset.	Data contributors
5	Longitude	Decimal degrees	We used the latitude and longitude to account for spatial autocorrelation in the dataset.	Data contributors

	Name	Resolution and/or Units	Description and Reasoning	Source
6	Land area-15	0.25 km^2 grid cell resolution, 15km radius, expressed in km^2	Land area within a 15-km radius of each site. Nutrient inputs from land-derived sources are commonly detectable within primary producers up to 15 km from shore (Lapointe and Clark 1992).	Yeager *et al.*, 2017
7	Land area-50	0.25 km^2 grid cell resolution, 50 km radius, expressed in km^2	Land area within a 50 km radius of each site. Rivers can transport nutrients from land-use activities 50 km or more from the coast.	Yeager *et al.*, 2017
8	SST_{CV}	5 km resolution, no units	The coefficient of variation for sea surface temperature represents the range of temperature values at a given site.	CRW Version 3.1 Daily Global Satellite Products (1995 – 2020) from NOAA Coral Reef Watch (2020)
9	Number of DHW > 4	5 km resolution, no units	Degree heating weeks greater than 4 represent a bleaching warning as defined by Coral Reef Watch, indicating that coral bleaching is possible.	CRW Version 3.1 Daily Global Satellite Products (1995 – 2020) from NOAA Coral Reef Watch (2020)
10	Number of DHW > 8	5 km resolution, no units	When degree heating weeks exceed 8, Coral Reef Watch issues a bleaching warning, indicating that coral bleaching is likely.	CRW Version 3.1 Daily Global Satellite Products (1995 – 2020) from NOAA Coral Reef Watch (2020)
11	SST_{kurt}	5 km resolution, no units	The kurtosis of SST is the distribution by frequency, with positive values indicating a steeper distribution than normal, and negative values indicating a broader distribution than normal.	CRW Version 3.1 Daily Global Satellite Products (1995 – 2020) from NOAA Coral Reef Watch (2020)
12	MaxDHW (all)	5 km resolution, no units	The maximum Degree Heating Weeks, a metric for cumulative heat stress, in the entire time period (between 1995 and 2020).	CRW Version 3.1 Daily Global Satellite Products (1995 – 2020) from NOAA Coral Reef Watch (2020)

	Name	Resolution and/or Units	Description and Reasoning	Source
13	Mean of annual maxDHW	5 km resolution, no units	The mean of the highest DHW from each year between 1995 and 2020.	CRW Version 3.1 Daily Global Satellite Products (1995 – 2020) from NOAA Coral Reef Watch (2020)
14	MMM	5 km resolution, expressed in °C	The Maximum Monthly Mean is the highest value among the 12 monthly mean SST climatologies at a given site. Prolonged SSTs that are 1°C greater than the MMM may induce coral bleaching (Liu et al., 2018).	CRW Version 3.1 Daily Global Satellite Products (1995 – 2020) from NOAA Coral Reef Watch (2020)
15	Overall Climate Score	5 km resolution, No units	A metric for the heat stress experienced at each site, incorporating historic, recent, and estimated future heat stress and trends (Beyer *et al.*, 2018)	Andrello *et al.*, 2021; Beyer *et al.,* 2018
16	Historic Climate Stress Score	5 km resolution, No units	A metric for the historic heat stress experienced at each site, from 1985 - 2017 (Beyer *et al.*, 2018)	Andrello *et al.*, 2021; Beyer *et al.,* 2018
17	SST_{sd}	5 km resolution, expressed in °C	The standard deviation of SST represents the amount that sea surface temperatures.	CRW Version 3.1 Daily Global Satellite Products (1995 – 2020) from NOAA Coral Reef Watch (2020)
18	SST_{skew}	5 km resolution, expressed in °C	The skewness of SST indicates whether the frequency of daily temperatures are normally distributed or skewed towards lower or higher temperature values.	CRW Version 3.1 Daily Global Satellite Products (1995 – 2020) from NOAA Coral Reef Watch (2020)
Human Disturbance	*Scientists use macroalgae as a metric for estimating reef health and may assume that coral reefs with high macroalgae percent cover are degraded (Littler and Littler, 2007). We collected a wide range of variables representing several aspects of human disturbance on coral reefs to test this assumption and whether macroalgae percent cover is useful as an indication of coral reef ecosystem health.*			

	Name	Resolution and/or Units	Description and Reasoning	Source
19	Cumulative Human Impact Score	5 km resolution, No units	An estimate of cumulative human impacts on coral reefs, including small scale fishing pressure, coastal population, industrial development, tourism, and two types of water pollution (sedimentation and nitrogen from agriculture).	Andrello *et al.*, 2021
20	Market Gravity	10 km grid cells; expressed as the number of people / (travel time to nearest market in hours)^2	The population of a major market divided by the squared travel time between a reef site and market, representing fishing pressure (Cinner et al., 2018). Fishing pressure can increase herbivory on coral reefs, which may increase macroalgae percent cover.	Andrello et al., 2021; Cinner *et al.*, 2018
21	HII-100	1 km^2 cells aggregated from 1995 – 2004	The aggregated global Human Influence Index within a 100-km radius around each site. HII incorporates population density, land use and infrastructure, and human aspects (including coastlines, roads, railroads, and rivers), which are known to predict local human impacts on coral reefs (Baumann et al., 2022).	Global Human Influence Index v2 (1995-2004) from the NASA Socioeconomic Data and Applications Center, downloaded from Baumann et al. (2022)
22	HII-10	1 km^2 cells aggregated from 1995 – 2004	The aggregated global Human Influence Index within a 10-km radius around each site.	Global Human Influence Index v2 (1995-2004) from the NASA Socioeconomic Data and Applications Center, downloaded from Baumann et al. (2022)

	Name	Resolution and/or Units	Description and Reasoning	Source
23	HII-25	1 km^2 cells aggregated from 1995 – 2004	The aggregated global Human Influence Index within a 25-km radius around each site.	Global Human Influence Index v2 (1995-2004) from the NASA Socioeconomic Data and Applications Center, downloaded from Baumann et al. (2022)
24	HII-50	1 km^2 cells aggregated from 1995 – 2004	The aggregated global Human Influence Index within a 50-km radius around each site.	Global Human Influence Index v2 (1995-2004) from the NASA Socioeconomic Data and Applications Center, downloaded from Baumann et al. (2022)
25	HII-70	1 km^2 cells aggregated from 1995 – 2004	The aggregated global Human Influence Index within a 70-km radius around each site.	Global Human Influence Index v2 (1995-2004) from the NASA Socioeconomic Data and Applications Center, downloaded from Baumann et al. (2022)
26	Population density	0.25 km^2 grid cell resolution, Number of people within a 20-km radius of each site per 1,256 km^2	As human population densities increase, associated threats, including coastal development, nutrient pollution, and fishing pressure, may also increase. A 20-km radius represents the distance travelled by most subsistence fishers (Clark et al., 2002, Chuenpagdee et al., 2006) and the scale at which land-use change has the largest impact on nutrient loading (Yeager et al., 2017).	Yeager *et al.*, 2017

	Name	Resolution and/or Units	Description and Reasoning	Source
27	Population density	0.25 km^2 grid cell resolution, Number of people within a 50-km radius of each site per 7,850 km^2	A 50-km radius represents the upper limit of small-scale or semi-commercial coastal fisheries (Chuenpagdee et al., 2006), and watershed-scale impacts of nutrient loading and sedimentation (Delvin and Brodie, 2005).	Yeager *et al.*, 2017
28	Scaled mean NDVI	1 km radius (3.14 km^2 area) resolution, no units	The mean Normalized Difference Vegetation Index of land within a 1-km radius circle around each site, and an indication of nearby development. We calculated the NDVI values using LandSat8 data from the United States Geological Survey. We scaled mean NDVI values for each site to between 0 and 1 within each of the contributed datasets to account for climate-driven variation in vegetation across sites and regions. Coastal development can influence water quality by increasing the amount of sediment and nutrients from land.	Please see Cannon et. al. (2019, 2021) for detailed methods
29	Number of Ports	5 km resolution, no units	A proxy for pressures from industrial development, including dredging. Includes all ports within 5km2 as this is the maximum likely distance of dredging impacts (Wenger *et al.*, 2020).	Andrello et al., 2021
30	Nutrients from agriculture	5 km resolution, no units	An estimate of nitrogen pollution produced via a settlement plume model. This metric will underestimate nitrogen pollution because it does not include eutrophication caused by wastewater discharge (Andrello et al., 2021).	Nitrogen delivery to coral reefs from agriculture, from Andrello et al (2021)

	Name	Resolution and/or Units	Description and Reasoning	Source
31	Population (coastal)	5 km resolution, no units	An estimate of the number of people living within a 5 km buffer of each coral reef cell using a global data layer of 2020 human populations.	Andrello et al., 2021
32	Tourism	5 km resolution, no units	The estimated number of tourist trip equivalents for global coral reefs using tourism activity from 2005 – 2012. Intensive tourist use can cause physical injury to corals, sediment-associated tissue necrosis, and disease (Lamb *et al.*, 2014), all of which may increase macroalgae percent cover.	Andrello et al., 2021
33	Sedimentation	5 km resolution, expressed as tons of sediment per km^2	Estimated sediment exposure as predicted by a sediment plume model described in Andrello et al. (2021).	Andrello et al., 2021
Methodology & Site Characteristic	*We included methodology and site characteristics here because they may account for any sampling noise associated with the data, for example from methodological differences or geographic bias. Site features such as the type of habitat and depth may also influence the benthic communities present at each site* (Magris *et al.*, 2016).			
34	Contributor	Categorical	The person(s) contributing a dataset to the analysis. We included this to account for any methodological differences driving sampling noise associated with the data.	Contributors
35	Depth	Meters	Depth of the ecological survey in meters. Depth influences the amount of light available for photosynthesis, local temperature, and exposure to wind and waves.	Contributors

	Name	Resolution and/or Units	Description and Reasoning	Source
36	Habitat	Categorical	Whether the survey site was located on a backreef, reef crest, reef flat, reef slope, or another habitat (such as terrace reefs and those in a channel). Each habitat type has different physical features that influence exposure to drivers of benthic community compositions. For example, sites on a reef crest experience higher wind and wave exposure than those on a backreef.	Contributors
37	Management	Categorical	Whether sites were open to fishing with no restrictions (open access), fishing was allowed but with restrictions (restricted access) or fishing was banned (no access) (Darling *et al.*, 2019). Fishing pressure can decrease herbivory on coral reefs and might trigger increases in some taxa of macroalgae.	Contributors
38	Methods	Categorical	Whether the survey used a point intercept transect, line intercept transect, or photo quadrat method. Methodological differences may account for potential noise in the dataset (Darling *et al.*, 2019).	Contributors
Net Primary Productivity	*Net primary productivity (NPP) on coral reefs is determined by light, water temperature, and nutrient availability* (Yeager *et al.*, 2017). *Many taxa of macroalgae may be nutrient-limited (Littler and Littler, 2007) and increasing nutrient availability (represented by NPP or* chl_a*) may drive increasing percent cover of macroalgae.*			
39	Chl_a CV	4 km^2 monthly resolution, no units	Chlorophyll-a concentration (chl_a) is widely used to indicate net primary productivity (Siegel *et al.*, 2005). The coefficient of variation (CV) represents the variation in NPP.	MODIS-Ocean Color Data from NASA (2014)

	Name	Resolution and/or Units	Description and Reasoning	Source
40	Kurtosis of chl_a	4 km^2 monthly resolution, no units	The distribution of chl_a concentration by frequency at each site, with positive values indicating a steeper distribution than normal, and negative values indicating a broader distribution than normal.	MODIS-Ocean Color Data from NASA (2014)
41	Mean chl_a	4 km^2 monthly resolution, Mg m^{-3}	The average monthly chl_a value at each site.	MODIS-Ocean Color Data from NASA (2014)
42	Chl_a SD	4 km^2 monthly resolution, no units	The standard deviation of chl_a representing the amount of variation in chl_a concentration experienced at each site.	MODIS-Ocean Color Data from NASA (2014)
43	Skewness of Chl_a	4 km^2 monthly resolution, no units	The skewness of chl_a indicates whether the frequency of daily temperatures are normally distributed or skewed towards lower or higher temperature values.	MODIS-Ocean Color Data from NASA (2014)
44	Mean Chl_a for the year of survey	4 km^2 monthly resolution, Mg m^{-3}	The average chl_a for the year of the survey.	MODIS-Ocean Color Data from NASA (2014)
45	NPP_{max}	mg C m^{-2} day^{-1}	Mean annual maximum net primary productivity of carbon	Yeager *et al.*, 2017
46	NPP_{mean}	mg C m^{-2} day^{-1}	Overall mean net primary productivity of carbon	Yeager *et al.*, 2017
47	NPP_{min}	mg C m^{-2} day^{-1}	Mean annual minimum net primary productivity of carbon	Yeager *et al.*, 2017
48	NPP_{SD}	mg C m^{-2} day^{-1}	Intra-annual standard deviation of the net primary productivity of carbon	Yeager *et al.*, 2017

	Name	Resolution and/or Units	Description and Reasoning	Source
Seasonality	*Several studies have found that macroalgae communities can be seasonal in nature, with blooms occurring at regular annual intervals, and that light and/or ocean temperatures may drive seasonal growth cycles* (Fulton *et al.*, 2014; Brown *et al.*, 2020).			
49	Mean SST of survey month	5 km	The average sea surface temperature of the month when the surveys were conducted.	CRW Version 3.1 Daily Global Satellite Products (1995 – 2020) from NOAA Coral Reef Watch (2018)
50	Mean PAR of survey month	4 km	Average photosynthetically available radiation of the survey month.	MODIS-Ocean Color Data from NASA (2014)
51	Rank of survey month by SST	Month	The month of the survey corrected by the months ranked from hottest to coldest.	CRW Version 3.1 Daily Global Satellite Products (1995 – 2020) from NOAA Coral Reef Watch (2018)
Storms and Cyclones	*Tropical storms and cyclones drive strong wind and waves that have the potential to break corals. They may also cause high storm surges that wash debris from land onto reefs, causing further damage. In some cases, macroalgae cover on coral reefs has increased immediately following storms that caused severe damage to corals.*			
52	Average number of storms	Annual	The average number of total storms per year passing within 100 km of each site. 100 km is the estimated maximum distance at which storms can cause damage to coral reefs (Fabricius *et al.*, 2008).	Storm tracks for all storms after 1989 from NOAA National Centers for Environmental Information (NCEI) International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp *et al.*, 2018) and extracted in ArcMap.

	Name	Resolution and/or Units	Description and Reasoning	Source
53	Number of storms (class tropical storms or stronger)	Total number of tropical storms or stronger passing within 100 km of each site in 10 years	The total number of tropical storms or greater passing within 100 km of each site as defined by Saffir-Simpson Hurricane Scale, in the 10 years preceding each survey.	Storm tracks were downloaded from NOAA NCEI IBTrACS (Knapp *et al.*, 2018) and extracted in ArcMap.
54	Number of storms of type 3 or stronger	Total number of Type 3 storms or stronger passing within 100 km of each site in 10 years	The total number of storms of Type 3 or greater passing within 100 km of each site as defined by the Saffir Simpson Hurricane Scale, in the 10 years preceding each survey.	Storm tracks were downloaded from NOAA NCEI IBTrACS (Knapp *et al.*, 2018) and extracted in ArcMap.
55	Number of tropical storms or stronger	Total number of tropical storms or stronger passing within 100 km of each site in 5 years	The total number of tropical storms or greater passing within 100 km of each site as defined by Saffir-Simpson Hurricane Scale, in the 5 years preceding each survey.	Storm tracks were downloaded from NOAA NCEI IBTrACS (Knapp et al., 2018) and extracted in ArcMap.
56	Number of storms of type 3 or stronger	Total number of Type 3 storms or stronger passing within 100 km of each site in 10 years	The total number of storms of Type 3 or greater passing within 100 km of each site as defined by the Saffir Simpson Hurricane Scale, in the 5 years preceding each survey.	Storm tracks were downloaded from NOAA NCEI IBTrACS (Knapp et al., 2018) and extracted in ArcMap.

	Name	Resolution and/or Units	Description and Reasoning	Source
57	Cyclone Score	5 km resolution, No units	A metric for cyclone activity from 1985 – 2014 incorporating three damaging aspects of cyclones for coral reefs: average annual days of exposure, the maximum annual number of days of explore to cyclones (winds of gale force or higher), and the inverse of the return time interval of at least one day of exposure per year (Beyer *et al.*, 2018).	Andrello *et al.*, 2021; Beyer *et al.,* 2018
Wind and wave exposure	*Wind and wave exposure can drive benthic community compositions by selecting for taxa that can withstand the local environment* (Page-Albins *et al.*, 2012).			
58	Aspect	Decimal degrees	The direction from each site to the greatest depth in the surrounding area. Because there were too many sites to measure the direction each site faced manually, we assumed that greater depths indicated the open ocean and used the direction between the site and the greatest depth in the bathymetry layer in ArcGIS. We randomly spot-checked the sites manually to ensure accuracy.	Calculated in ArcGIS.
59	Mean wave energy	3-hour temporal resolution for a span of 31 years (1979-2009). Expressed in kW m^{-1}	Wave energy flux (the power transmitted per unit of wavefront width), overall mean.	Yeager *et al.*, 2017

	Name	Resolution and/or Units	Description and Reasoning	Source
60	Wind and Wave Exposure	Decimal degrees	The angle of each site (using the Aspect) to the prevailing wind.	Calculated with data from NCDC Blended Sea Winds (Zhang, Reynolds and Bates, 2006) using the methods described in Cannon et al. (2021)

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Supplementary Table 2. Correlation Coefficients.

	aspect	WWE	NDVI	MeanChlaSurveyY4	Pop50km	Pop20km
aspect	1.00	-0.01	-0.03	-0.04	-0.06	-0.05
WWE	-0.01	1.00	0.10	-0.72	-0.75	-0.87
NDVI	-0.03	0.10	1.00	-0.09	-0.17	-0.13
MeanChlaSurveyYear	-0.04	-0.72	-0.09	1.00	0.62	0.67
Population50km	-0.06	-0.75	-0.17	0.62	1.00	0.78
Population20km	-0.05	-0.87	-0.13	0.67	0.78	1.00
MeanChlaAllYears	-0.06	-0.66	-0.07	0.97	0.59	0.59
ChlaSD	-0.04	-0.26	-0.08	0.68	0.26	0.26
ChlaKurtosis	-0.05	0.04	-0.14	0.10	-0.01	-0.02
ChlaCV	0.01	-0.06	0.00	-0.04	0.02	0.02
HII100km	-0.03	-0.38	-0.28	0.53	0.63	0.47
HII75km	-0.03	-0.44	-0.30	0.56	0.71	0.54
HII50km	-0.03	-0.48	-0.31	0.56	0.75	0.59
HII25km	-0.02	-0.36	-0.30	0.43	0.56	0.50
HII10km	0.03	-0.06	-0.29	0.08	0.27	0.21
LandArea15km	0.05	-0.07	-0.29	0.22	0.22	0.19
LandArea50km	0.01	-0.29	-0.28	0.54	0.47	0.40
NPP_max	-0.02	-0.63	-0.18	0.74	0.68	0.61
NPP_mean	-0.02	-0.70	-0.15	0.82	0.70	0.65
NPP_min	-0.04	-0.62	-0.13	0.78	0.64	0.57
NPP_sd	-0.01	-0.60	-0.17	0.61	0.63	0.60
ReefArea15km	-0.06	0.04	0.28	0.01	-0.07	-0.05
ReefArea200km	-0.04	-0.03	0.25	0.18	0.01	0.02
MeanWaveEnergy	0.05	0.09	0.00	-0.26	-0.17	-0.13
MMM	-0.14	-0.15	-0.03	-0.02	0.06	0.13
sdSST	0.06	0.05	0.17	0.28	0.11	-0.01

	aspect	WWE	NDVI	MeanChlaSurveyY4	Pop50km	Pop20km
cvSST	0.06	0.05	0.15	0.27	0.11	-0.02
kurtSST	-0.07	-0.11	-0.28	-0.08	0.04	0.09
MeanNumAnnualStorms	0.00	0.10	0.23	-0.01	0.07	-0.08
NumStorms5Yrs_TropPlus	-0.02	0.07	0.13	-0.07	-0.07	-0.08
NumStorms5Yrs_Cat3Plus	-0.02	0.04	-0.07	-0.04	0.01	-0.02
NumStorms10Yrs_TropPlus	0.00	0.07	0.16	-0.01	-0.01	-0.07
NumStorms10Yrs_Cat3Plus	-0.02	0.04	-0.01	-0.04	-0.03	-0.04
maxDHW	0.00	0.14	0.09	-0.07	-0.22	-0.17
AnnualMeanMaxDHW	0.06	0.11	0.22	-0.08	-0.15	-0.14
DHW_over_4	0.04	0.11	0.17	-0.11	-0.16	-0.13
DHW_over_8	0.00	0.06	0.02	-0.04	-0.11	-0.08
MeanSST_surveymonth	-0.01	-0.05	-0.01	-0.06	0.02	0.04
RankMonth_SST	0.01	-0.04	-0.05	-0.01	0.03	0.03
Depth	0.03	0.08	0.03	-0.23	-0.08	-0.11
MeanPARSurveyMonth	-0.09	0.05	0.16	-0.06	-0.02	-0.03
Latitude	-0.06	-0.03	-0.27	-0.15	0.17	0.08
Longitude	0.04	0.00	0.22	0.09	0.01	0.00
OverallClimateScore	-0.06	-0.11	0.03	0.15	0.13	0.15
ConnectivityScore	-0.10	0.02	0.15	0.09	0.02	0.03
CycloneScore	-0.03	-0.10	-0.09	0.10	-0.05	0.08
HistoricHeatStress	-0.04	-0.12	-0.13	0.05	0.19	0.16
MarketGravity	-0.05	-0.17	-0.30	0.20	0.34	0.26
SedimentationScore	0.02	-0.12	-0.35	0.18	0.24	0.18
NutrientScore	-0.01	-0.25	-0.30	0.37	0.43	0.32
Ports	-0.04	-0.09	-0.17	0.02	0.05	0.07
TourismValue	0.01	-0.06	-0.30	0.10	0.18	0.11
CumulativeHumanImpacts	-0.03	-0.19	-0.49	0.22	0.35	0.28

877

	MeanChlaAllYears	ChlaSD	ChlaKurtosis	ChlaCV	HII100km	HII75km	HII50km
aspect	-0.06	-0.04	-0.05	0.01	-0.03	-0.03	-0.03
WWE	-0.66	-0.26	0.04	-0.06	-0.38	-0.44	-0.48
NDVI	-0.07	-0.08	-0.14	0.00	-0.28	-0.30	-0.31
MeanChlaSurveyYear	0.97	0.68	0.10	-0.04	0.53	0.56	0.56
Population50km	0.59	0.26	-0.01	0.02	0.63	0.71	0.75
Population20km	0.59	0.26	-0.02	0.02	0.47	0.54	0.59
MeanChlaAllYears	1.00	0.75	0.11	-0.05	0.51	0.54	0.54
ChlaSD	0.75	1.00	0.42	-0.31	0.37	0.38	0.39
ChlaKurtosis	0.11	0.42	1.00	-0.44	0.15	0.17	0.21
ChlaCV	-0.05	-0.31	-0.44	1.00	-0.09	-0.09	-0.08
HII100km	0.51	0.37	0.15	-0.09	1.00	0.98	0.91
HII75km	0.54	0.38	0.17	-0.09	0.98	1.00	0.97
HII50km	0.54	0.39	0.21	-0.08	0.91	0.97	1.00
HII25km	0.42	0.38	0.27	-0.08	0.76	0.82	0.90
HII10km	0.07	0.08	0.12	0.05	0.50	0.54	0.60
LandArea15km	0.21	0.22	0.26	-0.16	0.56	0.59	0.62
LandArea50km	0.52	0.44	0.29	-0.17	0.83	0.86	0.87
NPP_max	0.71	0.44	0.14	-0.12	0.64	0.68	0.67
NPP_mean	0.80	0.43	0.09	-0.03	0.63	0.66	0.66
NPP_min	0.77	0.42	0.10	-0.01	0.59	0.62	0.61
NPP_sd	0.58	0.36	0.10	-0.14	0.53	0.57	0.58
ReefArea15km	0.03	0.00	-0.02	0.01	-0.13	-0.14	-0.17
ReefArea200km	0.20	0.13	-0.04	0.07	0.08	0.04	-0.03
MeanWaveEnergy	-0.27	-0.23	-0.13	0.13	-0.25	-0.24	-0.22
MMM	-0.01	0.00	0.07	-0.15	-0.09	-0.08	-0.07
sdSST	0.31	0.23	-0.12	0.11	0.26	0.23	0.19
cvSST	0.31	0.23	-0.11	0.11	0.27	0.24	0.20
kurtSST	-0.10	-0.05	0.22	-0.17	-0.07	-0.05	-0.01

	MeanChlaAllYears	ChlaSD	ChlaKurtosis	ChlaCV	HII100km	HII75km	HII50km
MeanNumAnnualStorms	0.00	-0.03	-0.16	0.05	0.05	0.02	0.03
NumStorms5Yrs_TropPlus	-0.06	-0.05	-0.15	0.06	-0.04	-0.06	-0.07
NumStorms5Yrs_Cat3Plus	-0.03	-0.04	-0.08	0.07	0.13	0.10	0.09
NumStorms10Yrs_TropPlus	0.01	-0.03	-0.16	0.05	0.02	0.00	-0.01
NumStorms10Yrs_Cat3Plus	-0.03	-0.06	-0.09	0.09	0.08	0.05	0.04
maxDHW	-0.06	-0.08	-0.11	0.18	-0.32	-0.33	-0.32
AnnualMeanMaxDHW	-0.06	-0.07	-0.07	0.20	-0.19	-0.20	-0.21
DHW_over_4	-0.09	-0.09	-0.09	0.15	-0.23	-0.24	-0.25
DHW_over_8	-0.04	-0.06	-0.06	0.19	-0.19	-0.18	-0.16
MeanSST_surveymonth	-0.08	-0.10	0.03	-0.14	-0.06	-0.07	-0.07
RankMonth_SST	-0.04	-0.07	0.02	-0.05	-0.02	-0.01	0.02
Depth	-0.22	-0.19	-0.09	0.16	-0.07	-0.10	-0.13
MeanPARSurveyMonth	-0.07	-0.03	-0.04	0.01	-0.06	-0.07	-0.06
Latitude	-0.16	-0.10	0.07	-0.08	0.14	0.14	0.18
Longitude	0.10	0.10	0.03	-0.19	0.04	0.01	-0.01
OverallClimateScore	0.15	0.14	0.05	-0.20	0.25	0.25	0.21
ConnectivityScore	0.10	0.10	0.05	-0.05	0.21	0.17	0.11
CycloneScore	0.09	0.09	0.14	-0.09	-0.11	-0.07	-0.09
HistoricHeatStress	0.04	0.06	0.02	-0.23	0.23	0.23	0.23
MarketGravity	0.21	0.20	0.13	-0.09	0.52	0.53	0.52
SedimentationScore	0.17	0.17	0.20	0.05	0.46	0.48	0.51
NutrientScore	0.37	0.30	0.19	-0.05	0.71	0.72	0.69
Ports	0.01	0.00	-0.01	0.02	-0.04	-0.02	0.00
TourismValue	0.10	0.11	0.03	0.03	0.37	0.38	0.38
CumulativeHumanImpacts	0.21	0.21	0.17	-0.01	0.58	0.60	0.62

878

	HII25km	HII10km	LandArea15km	LandArea50km	NPP_max	NPP_mean
aspect	-0.02	0.03	0.05	0.01	-0.02	-0.02
WWE	-0.36	-0.06	-0.07	-0.29	-0.63	-0.70
NDVI	-0.30	-0.29	-0.29	-0.28	-0.18	-0.15
MeanChlaSurveyYear	0.43	0.08	0.22	0.54	0.74	0.82
Population50km	0.56	0.27	0.22	0.47	0.68	0.70
Population20km	0.50	0.21	0.19	0.40	0.61	0.65
MeanChlaAllYears	0.42	0.07	0.21	0.52	0.71	0.80
ChlaSD	0.38	0.08	0.22	0.44	0.44	0.43
ChlaKurtosis	0.27	0.12	0.26	0.29	0.14	0.09
ChlaCV	-0.08	0.05	-0.16	-0.17	-0.12	-0.03
HII100km	0.76	0.50	0.56	0.83	0.64	0.63
HII75km	0.82	0.54	0.59	0.86	0.68	0.66
HII50km	0.90	0.60	0.62	0.87	0.67	0.66
HII25km	1.00	0.79	0.79	0.81	0.52	0.49
HII10km	0.79	1.00	0.76	0.52	0.20	0.16
LandArea15km	0.79	0.76	1.00	0.76	0.38	0.32
LandArea50km	0.81	0.52	0.76	1.00	0.62	0.61
NPP_max	0.52	0.20	0.38	0.62	1.00	0.94
NPP_mean	0.49	0.16	0.32	0.61	0.94	1.00
NPP_min	0.43	0.11	0.29	0.59	0.85	0.96
NPP_sd	0.46	0.19	0.31	0.48	0.94	0.81
ReefArea15km	-0.17	-0.19	-0.12	-0.14	-0.10	-0.07
ReefArea200km	-0.11	-0.23	-0.19	0.02	0.07	0.11
MeanWaveEnergy	-0.21	-0.07	-0.25	-0.27	-0.20	-0.17
MMM	-0.04	-0.05	-0.10	-0.18	0.03	-0.05
sdSST	0.13	0.04	0.08	0.23	0.25	0.29
cvSST	0.14	0.05	0.10	0.24	0.24	0.29
kurtSST	0.03	0.00	0.09	-0.02	-0.03	-0.07

	HII25km	HII10km	LandArea15km	LandArea50km	NPP_max	NPP_mean
MeanNumAnnualStorms	0.04	0.07	0.00	-0.03	-0.10	-0.06
NumStorms5Yrs_TropPlus	-0.01	0.07	-0.06	-0.11	-0.14	-0.13
NumStorms5Yrs_Cat3Plus	0.12	0.14	0.03	0.03	-0.07	-0.06
NumStorms10Yrs_TropPlus	0.01	0.07	-0.02	-0.05	-0.07	-0.05
NumStorms10Yrs_Cat3Plus	0.06	0.08	-0.02	-0.01	-0.08	-0.07
maxDHW	-0.27	-0.21	-0.15	-0.22	-0.20	-0.16
AnnualMeanMaxDHW	-0.17	-0.16	-0.11	-0.15	-0.12	-0.06
DHW_over_4	-0.21	-0.17	-0.14	-0.19	-0.15	-0.10
DHW_over_8	-0.12	-0.10	-0.10	-0.11	-0.08	-0.04
MeanSST_surveymonth	-0.06	-0.08	-0.02	-0.07	-0.04	-0.09
RankMonth_SST	0.01	-0.04	-0.04	-0.01	0.01	-0.02
Depth	-0.10	0.01	-0.21	-0.25	-0.17	-0.19
MeanPARSurveyMonth	-0.05	0.01	-0.13	-0.15	0.00	-0.05
Latitude	0.26	0.31	0.19	0.04	-0.11	-0.17
Longitude	0.02	-0.03	0.14	0.08	-0.07	-0.05
OverallClimateScore	0.10	0.03	0.02	0.19	0.22	0.18
ConnectivityScore	0.06	-0.07	-0.05	0.12	0.08	0.06
CycloneScore	-0.16	-0.24	-0.07	0.02	0.17	0.15
HistoricHeatStress	0.17	0.16	0.08	0.13	0.13	0.07
MarketGravity	0.48	0.40	0.34	0.39	0.44	0.36
SedimentationScore	0.55	0.53	0.51	0.47	0.28	0.25
NutrientScore	0.62	0.45	0.47	0.61	0.54	0.51
Ports	0.02	0.11	0.05	-0.03	0.05	0.02
TourismValue	0.35	0.40	0.32	0.32	0.20	0.16
CumulativeHumanImpacts	0.62	0.61	0.53	0.51	0.41	0.34

879

	NPP_min	NPP_sd	ReefArea15km	ReefArea200km	MeanWaveEnergy	MMM
aspect	-0.04	-0.01	-0.06	-0.04	0.05	-0.14
WWE	-0.62	-0.60	0.04	-0.03	0.09	-0.15
NDVI	-0.13	-0.17	0.28	0.25	0.00	-0.03
MeanChlaSurveyYear	0.78	0.61	0.01	0.18	-0.26	-0.02
Population50km	0.64	0.63	-0.07	0.01	-0.17	0.06
Population20km	0.57	0.60	-0.05	0.02	-0.13	0.13
MeanChlaAllYears	0.77	0.58	0.03	0.20	-0.27	-0.01
ChlaSD	0.42	0.36	0.00	0.13	-0.23	0.00
ChlaKurtosis	0.10	0.10	-0.02	-0.04	-0.13	0.07
ChlaCV	-0.01	-0.14	0.01	0.07	0.13	-0.15
HII100km	0.59	0.53	-0.13	0.08	-0.25	-0.09
HII75km	0.62	0.57	-0.14	0.04	-0.24	-0.08
HII50km	0.61	0.58	-0.17	-0.03	-0.22	-0.07
HII25km	0.43	0.46	-0.17	-0.11	-0.21	-0.04
HII10km	0.11	0.19	-0.19	-0.23	-0.07	-0.05
LandArea15km	0.29	0.31	-0.12	-0.19	-0.25	-0.10
LandArea50km	0.59	0.48	-0.14	0.02	-0.27	-0.18
NPP_max	0.85	0.94	-0.10	0.07	-0.20	0.03
NPP_mean	0.96	0.81	-0.07	0.11	-0.17	-0.05
NPP_min	1.00	0.67	-0.03	0.14	-0.16	-0.11
NPP_sd	0.67	1.00	-0.17	-0.03	-0.13	0.12
ReefArea15km	-0.03	-0.17	1.00	0.51	-0.36	0.12
ReefArea200km	0.14	-0.03	0.51	1.00	-0.23	-0.12
MeanWaveEnergy	-0.16	-0.13	-0.36	-0.23	1.00	-0.30
MMM	-0.11	0.12	0.12	-0.12	-0.30	1.00
sdSST	0.29	0.17	-0.03	0.36	0.02	-0.56
cvSST	0.30	0.16	-0.04	0.35	0.03	-0.60
kurtSST	-0.09	0.00	0.04	-0.35	-0.28	0.55

	NPP_min	NPP_sd	ReefArea15km	ReefArea200km	MeanWaveEnergy	MMM
MeanNumAnnualStorms	-0.08	-0.09	0.01	-0.08	-0.09	-0.07
NumStorms5Yrs_TropPlus	-0.15	-0.10	-0.04	-0.03	0.03	0.01
NumStorms5Yrs_Cat3Plus	-0.08	-0.07	0.01	0.17	-0.07	-0.04
NumStorms10Yrs_TropPlus	-0.07	-0.05	-0.08	-0.02	0.02	-0.06
NumStorms10Yrs_Cat3Plus	-0.08	-0.08	-0.01	0.22	-0.06	-0.07
maxDHW	-0.14	-0.24	0.09	-0.07	0.01	-0.13
AnnualMeanMaxDHW	-0.05	-0.15	0.06	0.02	0.09	-0.16
DHW_over_4	-0.09	-0.17	0.03	-0.08	0.12	-0.14
DHW_over_8	-0.05	-0.11	0.06	-0.09	0.01	-0.16
MeanSST_surveymonth	-0.11	-0.02	0.11	0.01	-0.23	0.26
RankMonth_SST	-0.04	0.02	-0.05	0.12	-0.06	-0.23
Depth	-0.22	-0.10	-0.12	-0.01	0.32	-0.08
MeanPARSurveyMonth	-0.07	0.04	0.07	0.06	0.08	0.15
Latitude	-0.21	-0.06	0.05	-0.27	-0.38	0.44
Longitude	-0.04	-0.13	0.44	0.28	-0.63	0.14
OverallClimateScore	0.17	0.22	0.06	0.36	-0.05	0.16
ConnectivityScore	0.06	0.03	0.23	0.60	-0.29	0.11
CycloneScore	0.18	0.15	0.03	0.08	0.06	0.09
HistoricHeatStress	0.04	0.17	-0.03	0.07	-0.07	0.21
MarketGravity	0.32	0.44	-0.08	0.05	-0.12	0.12
SedimentationScore	0.22	0.24	-0.17	-0.12	-0.03	0.05
NutrientScore	0.47	0.47	-0.17	0.03	-0.12	-0.01
Ports	0.00	0.09	-0.07	-0.13	0.10	0.12
TourismValue	0.12	0.21	-0.15	-0.04	-0.07	-0.04
CumulativeHumanImpacts	0.29	0.41	-0.21	-0.16	-0.08	0.13

	sdSST	cvSST	kurtSST	MeanNumAnnualStorms	NumStorms5Yrs_TropPlus
aspect	0.06	0.06	-0.07	0.00	-0.02
WWE	0.05	0.05	-0.11	0.10	0.07
NDVI	0.17	0.15	-0.28	0.23	0.13
MeanChlaSurveyYear	0.28	0.27	-0.08	-0.01	-0.07
Population50km	0.11	0.11	0.04	0.07	-0.07
Population20km	-0.01	-0.02	0.09	-0.08	-0.08
MeanChlaAllYears	0.31	0.31	-0.10	0.00	-0.06
ChlaSD	0.23	0.23	-0.05	-0.03	-0.05
ChlaKurtosis	-0.12	-0.11	0.22	-0.16	-0.15
ChlaCV	0.11	0.11	-0.17	0.05	0.06
HII100km	0.26	0.27	-0.07	0.05	-0.04
HII75km	0.23	0.24	-0.05	0.02	-0.06
HII50km	0.19	0.20	-0.01	0.03	-0.07
HII25km	0.13	0.14	0.03	0.04	-0.01
HII10km	0.04	0.05	0.00	0.07	0.07
LandArea15km	0.08	0.10	0.09	0.00	-0.06
LandArea50km	0.23	0.24	-0.02	-0.03	-0.11
NPP_max	0.25	0.24	-0.03	-0.10	-0.14
NPP_mean	0.29	0.29	-0.07	-0.06	-0.13
NPP_min	0.29	0.30	-0.09	-0.08	-0.15
NPP_sd	0.17	0.16	0.00	-0.09	-0.10
ReefArea15km	-0.03	-0.04	0.04	0.01	-0.04
ReefArea200km	0.36	0.35	-0.35	-0.08	-0.03
MeanWaveEnergy	0.02	0.03	-0.28	-0.09	0.03
MMM	-0.56	-0.60	0.55	-0.07	0.01
sdSST	1.00	1.00	-0.87	0.46	0.35
cvSST	1.00	1.00	-0.86	0.45	0.34
kurtSST	-0.87	-0.86	1.00	-0.41	-0.37

	sdSST	cvSST	kurtSST	MeanNumAnnualStorms	NumStorms5Yrs_TropPlus
MeanNumAnnualStorms	0.46	0.45	-0.41	1.00	0.77
NumStorms5Yrs_TropPlus	0.35	0.34	-0.37	0.77	1.00
NumStorms5Yrs_Cat3Plus	0.35	0.34	-0.31	0.43	0.64
NumStorms10Yrs_TropPlus	0.49	0.48	-0.47	0.84	0.95
NumStorms10Yrs_Cat3Plus	0.44	0.43	-0.39	0.47	0.61
maxDHW	-0.02	-0.01	0.10	0.00	-0.05
AnnualMeanMaxDHW	0.17	0.16	-0.11	-0.01	-0.04
DHW_over_4	0.07	0.07	-0.02	-0.07	-0.10
DHW_over_8	0.03	0.03	0.09	-0.10	-0.12
MeanSST_surveymonth	-0.25	-0.26	0.30	-0.07	-0.10
RankMonth_SST	0.09	0.10	-0.08	-0.01	-0.09
Depth	0.08	0.07	-0.18	0.07	0.12
MeanPARSurveyMonth	0.02	0.00	-0.11	0.02	-0.01
Latitude	-0.43	-0.42	0.54	0.14	0.02
Longitude	0.07	0.08	0.03	0.26	0.06
OverallClimateScore	0.04	0.03	-0.16	-0.14	-0.07
ConnectivityScore	0.19	0.18	-0.17	-0.09	-0.09
CycloneScore	-0.42	-0.42	0.38	-0.83	-0.63
HistoricHeatStress	-0.07	-0.07	-0.03	0.06	0.07
MarketGravity	0.15	0.14	-0.04	-0.17	-0.12
SedimentationScore	-0.04	-0.02	0.11	-0.08	-0.01
NutrientScore	0.20	0.21	-0.05	-0.09	-0.06
Ports	-0.11	-0.12	0.09	-0.06	0.02
TourismValue	0.15	0.15	-0.13	0.08	0.11
CumulativeHumanImpacts	0.00	0.00	0.10	-0.12	-0.04

881

	NumStorms5Yrs_Cat3Plus	NumStorms10Yrs_TropPlus	NumStorms10Yrs_Cat3Plus
aspect	-0.02	0.00	-0.02
WWE	0.04	0.07	0.04
NDVI	-0.07	0.16	-0.01
MeanChlaSurveyYear	-0.04	-0.01	-0.04
Population50km	0.01	-0.01	-0.03
Population20km	-0.02	-0.07	-0.04
MeanChlaAllYears	-0.03	0.01	-0.03
ChlaSD	-0.04	-0.03	-0.06
ChlaKurtosis	-0.08	-0.16	-0.09
ChlaCV	0.07	0.05	0.09
HII100km	0.13	0.02	0.08
HII75km	0.10	0.00	0.05
HII50km	0.09	-0.01	0.04
HII25km	0.12	0.01	0.06
HII10km	0.14	0.07	0.08
LandArea15km	0.03	-0.02	-0.02
LandArea50km	0.03	-0.05	-0.01
NPP_max	-0.07	-0.07	-0.08
NPP_mean	-0.06	-0.05	-0.07
NPP_min	-0.08	-0.07	-0.08
NPP_sd	-0.07	-0.05	-0.08
ReefArea15km	0.01	-0.08	-0.01
ReefArea200km	0.17	-0.02	0.22
MeanWaveEnergy	-0.07	0.02	-0.06
MMM	-0.04	-0.06	-0.07
sdSST	0.35	0.49	0.44
cvSST	0.34	0.48	0.43
kurtSST	-0.31	-0.47	-0.39

	NumStorms5Yrs_Cat3Plus	NumStorms10Yrs_TropPlus	NumStorms10Yrs_Cat3Plus
MeanNumAnnualStorms	0.43	0.84	0.47
NumStorms5Yrs_TropPlus	0.64	0.95	0.61
NumStorms5Yrs_Cat3Plus	1.00	0.59	0.87
NumStorms10Yrs_TropPlus	0.59	1.00	0.64
NumStorms10Yrs_Cat3Plus	0.87	0.64	1.00
maxDHW	-0.13	-0.06	-0.14
AnnualMeanMaxDHW	-0.10	-0.02	-0.09
DHW_over_4	-0.13	-0.09	-0.11
DHW_over_8	-0.11	-0.13	-0.14
MeanSST_surveymonth	-0.01	-0.13	-0.01
RankMonth_SST	0.09	-0.07	0.14
Depth	0.19	0.11	0.19
MeanPARSurveyMonth	-0.14	-0.02	-0.09
Latitude	0.21	-0.04	0.12
Longitude	0.05	0.10	0.06
OverallClimateScore	0.06	-0.07	0.07
ConnectivityScore	0.16	-0.08	0.21
CycloneScore	-0.56	-0.68	-0.58
HistoricHeatStress	0.18	0.06	0.16
MarketGravity	0.17	-0.08	0.16
SedimentationScore	0.16	-0.04	0.08
NutrientScore	0.16	-0.04	0.10
Ports	-0.05	0.00	-0.06
TourismValue	0.27	0.12	0.24
CumulativeHumanImpacts	0.20	-0.05	0.12

882

	maxDHW	AnnualMeanMaxDHW	DHW_over_4	DHW_over_8	MeanSST_surveymonth
aspect	0.00	0.06	0.04	0.00	-0.01
WWE	0.14	0.11	0.11	0.06	-0.05
NDVI	0.09	0.22	0.17	0.02	-0.01
MeanChlaSurveyYear	-0.07	-0.08	-0.11	-0.04	-0.06
Population50km	-0.22	-0.15	-0.16	-0.11	0.02
Population20km	-0.17	-0.14	-0.13	-0.08	0.04
MeanChlaAllYears	-0.06	-0.06	-0.09	-0.04	-0.08
ChlaSD	-0.08	-0.07	-0.09	-0.06	-0.10
ChlaKurtosis	-0.11	-0.07	-0.09	-0.06	0.03
ChlaCV	0.18	0.20	0.15	0.19	-0.14
HII100km	-0.32	-0.19	-0.23	-0.19	-0.06
HII75km	-0.33	-0.20	-0.24	-0.18	-0.07
HII50km	-0.32	-0.21	-0.25	-0.16	-0.07
HII25km	-0.27	-0.17	-0.21	-0.12	-0.06
HII10km	-0.21	-0.16	-0.17	-0.10	-0.08
LandArea15km	-0.15	-0.11	-0.14	-0.10	-0.02
LandArea50km	-0.22	-0.15	-0.19	-0.11	-0.07
NPP_max	-0.20	-0.12	-0.15	-0.08	-0.04
NPP_mean	-0.16	-0.06	-0.10	-0.04	-0.09
NPP_min	-0.14	-0.05	-0.09	-0.05	-0.11
NPP_sd	-0.24	-0.15	-0.17	-0.11	-0.02
ReefArea15km	0.09	0.06	0.03	0.06	0.11
ReefArea200km	-0.07	0.02	-0.08	-0.09	0.01
MeanWaveEnergy	0.01	0.09	0.12	0.01	-0.23
MMM	-0.13	-0.16	-0.14	-0.16	0.26
sdSST	-0.02	0.17	0.07	0.03	-0.25
cvSST	-0.01	0.16	0.07	0.03	-0.26
kurtSST	0.10	-0.11	-0.02	0.09	0.30

	maxDHW	AnnualMeanMaxDHW	DHW_over_4	DHW_over_8	MeanSST_surveymonth
MeanNumAnnualStorms	0.00	-0.01	-0.07	-0.10	-0.07
NumStorms5Yrs_TropPlus	-0.05	-0.04	-0.10	-0.12	-0.10
NumStorms5Yrs_Cat3Plus	-0.13	-0.10	-0.13	-0.11	-0.01
NumStorms10Yrs_TropPlus	-0.06	-0.02	-0.09	-0.13	-0.13
NumStorms10Yrs_Cat3Plus	-0.14	-0.09	-0.11	-0.14	-0.01
maxDHW	1.00	0.71	0.67	0.85	0.06
AnnualMeanMaxDHW	0.71	1.00	0.94	0.78	-0.05
DHW_over_4	0.67	0.94	1.00	0.75	-0.03
DHW_over_8	0.85	0.78	0.75	1.00	0.01
MeanSST_surveymonth	0.06	-0.05	-0.03	0.01	1.00
RankMonth_SST	-0.09	-0.26	-0.27	-0.12	0.41
Depth	-0.02	0.09	0.10	0.04	-0.04
MeanPARSurveyMonth	-0.05	0.00	-0.03	0.02	0.05
Latitude	0.02	-0.21	-0.15	0.02	0.28
Longitude	0.01	-0.02	-0.05	-0.06	0.20
OverallClimateScore	-0.78	-0.67	-0.66	-0.78	-0.02
ConnectivityScore	-0.26	-0.10	-0.16	-0.23	0.08
CycloneScore	0.04	0.06	0.10	0.11	0.00
HistoricHeatStress	-0.82	-0.91	-0.85	-0.84	0.04
MarketGravity	-0.46	-0.23	-0.21	-0.20	-0.03
SedimentationScore	-0.23	-0.18	-0.20	-0.16	-0.05
NutrientScore	-0.34	-0.19	-0.23	-0.19	-0.06
Ports	-0.01	-0.08	-0.07	-0.02	0.06
TourismValue	-0.31	-0.28	-0.27	-0.24	-0.03
CumulativeHumanImpacts	-0.40	-0.33	-0.31	-0.23	-0.02

883

	RankMonth_SST	Depth	MeanPARSurveyMonth	Latitude	Longitude
aspect	0.01	0.03	-0.09	-0.06	0.04
WWE	-0.04	0.08	0.05	-0.03	0.00
NDVI	-0.05	0.03	0.16	-0.27	0.22
MeanChlaSurveyYear	-0.01	-0.23	-0.06	-0.15	0.09
Population50km	0.03	-0.08	-0.02	0.17	0.01
Population20km	0.03	-0.11	-0.03	0.08	0.00
MeanChlaAllYears	-0.04	-0.22	-0.07	-0.16	0.10
ChlaSD	-0.07	-0.19	-0.03	-0.10	0.10
ChlaKurtosis	0.02	-0.09	-0.04	0.07	0.03
ChlaCV	-0.05	0.16	0.01	-0.08	-0.19
HII100km	-0.02	-0.07	-0.06	0.14	0.04
HII75km	-0.01	-0.10	-0.07	0.14	0.01
HII50km	0.02	-0.13	-0.06	0.18	-0.01
HII25km	0.01	-0.10	-0.05	0.26	0.02
HII10km	-0.04	0.01	0.01	0.31	-0.03
LandArea15km	-0.04	-0.21	-0.13	0.19	0.14
LandArea50km	-0.01	-0.25	-0.15	0.04	0.08
NPP_max	0.01	-0.17	0.00	-0.11	-0.07
NPP_mean	-0.02	-0.19	-0.05	-0.17	-0.05
NPP_min	-0.04	-0.22	-0.07	-0.21	-0.04
NPP_sd	0.02	-0.10	0.04	-0.06	-0.13
ReefArea15km	-0.05	-0.12	0.07	0.05	0.44
ReefArea200km	0.12	-0.01	0.06	-0.27	0.28
MeanWaveEnergy	-0.06	0.32	0.08	-0.38	-0.63
MMM	-0.23	-0.08	0.15	0.44	0.14
sdSST	0.09	0.08	0.02	-0.43	0.07
cvSST	0.10	0.07	0.00	-0.42	0.08
kurtSST	-0.08	-0.18	-0.11	0.54	0.03

	RankMonth_SST	Depth	MeanPARSurveyMonth	Latitude	Longitude
MeanNumAnnualStorms	-0.01	0.07	0.02	0.14	0.26
NumStorms5Yrs_TropPlus	-0.09	0.12	-0.01	0.02	0.06
NumStorms5Yrs_Cat3Plus	0.09	0.19	-0.14	0.21	0.05
NumStorms10Yrs_TropPlus	-0.07	0.11	-0.02	-0.04	0.10
NumStorms10Yrs_Cat3Plus	0.14	0.19	-0.09	0.12	0.06
maxDHW	-0.09	-0.02	-0.05	0.02	0.01
AnnualMeanMaxDHW	-0.26	0.09	0.00	-0.21	-0.02
DHW_over_4	-0.27	0.10	-0.03	-0.15	-0.05
DHW_over_8	-0.12	0.04	0.02	0.02	-0.06
MeanSST_surveymonth	0.41	-0.04	0.05	0.28	0.20
RankMonth_SST	1.00	-0.02	0.06	0.07	0.03
Depth	-0.02	1.00	0.10	0.04	-0.18
MeanPARSurveyMonth	0.06	0.10	1.00	-0.10	-0.06
Latitude	0.07	0.04	-0.10	1.00	0.30
Longitude	0.03	-0.18	-0.06	0.30	1.00
OverallClimateScore	0.16	-0.11	0.11	-0.20	0.05
ConnectivityScore	0.15	-0.01	0.13	-0.11	0.24
CycloneScore	-0.16	-0.21	0.04	-0.36	-0.23
HistoricHeatStress	0.24	-0.04	0.07	0.20	0.09
MarketGravity	0.03	0.08	0.08	0.14	-0.02
SedimentationScore	-0.06	-0.04	-0.18	0.16	-0.26
NutrientScore	-0.02	-0.06	-0.04	0.05	-0.13
Ports	-0.06	0.07	0.02	0.13	-0.02
TourismValue	0.19	0.00	-0.05	0.11	-0.09
CumulativeHumanImpacts	0.02	-0.01	-0.06	0.27	-0.19

	OverallClimateScore	ConnectivityScore	CycloneScore	HistoricHeatStress	MarketGravity
aspect	-0.06	-0.10	-0.03	-0.04	-0.05
WWE	-0.11	0.02	-0.10	-0.12	-0.17
NDVI	0.03	0.15	-0.09	-0.13	-0.30
MeanChlaSurveyYear	0.15	0.09	0.10	0.05	0.20
Population50km	0.13	0.02	-0.05	0.19	0.34
Population20km	0.15	0.03	0.08	0.16	0.26
MeanChlaAllYears	0.15	0.10	0.09	0.04	0.21
ChlaSD	0.14	0.10	0.09	0.06	0.20
ChlaKurtosis	0.05	0.05	0.14	0.02	0.13
ChlaCV	-0.20	-0.05	-0.09	-0.23	-0.09
HII100km	0.25	0.21	-0.11	0.23	0.52
HII75km	0.25	0.17	-0.07	0.23	0.53
HII50km	0.21	0.11	-0.09	0.23	0.52
HII25km	0.10	0.06	-0.16	0.17	0.48
HII10km	0.03	-0.07	-0.24	0.16	0.40
LandArea15km	0.02	-0.05	-0.07	0.08	0.34
LandArea50km	0.19	0.12	0.02	0.13	0.39
NPP_max	0.22	0.08	0.17	0.13	0.44
NPP_mean	0.18	0.06	0.15	0.07	0.36
NPP_min	0.17	0.06	0.18	0.04	0.32
NPP_sd	0.22	0.03	0.15	0.17	0.44
ReefArea15km	0.06	0.23	0.03	-0.03	-0.08
ReefArea200km	0.36	0.60	0.08	0.07	0.05
MeanWaveEnergy	-0.05	-0.29	0.06	-0.07	-0.12
MMM	0.16	0.11	0.09	0.21	0.12
sdSST	0.04	0.19	-0.42	-0.07	0.15
cvSST	0.03	0.18	-0.42	-0.07	0.14
kurtSST	-0.16	-0.17	0.38	-0.03	-0.04

	OverallClimateScore	ConnectivityScore	CycloneScore	HistoricHeatStress	MarketGravity
MeanNumAnnualStorms	-0.14	-0.09	-0.83	0.06	-0.17
NumStorms5Yrs_TropPlus	-0.07	-0.09	-0.63	0.07	-0.12
NumStorms5Yrs_Cat3Plus	0.06	0.16	-0.56	0.18	0.17
NumStorms10Yrs_TropPlus	-0.07	-0.08	-0.68	0.06	-0.08
NumStorms10Yrs_Cat3Plus	0.07	0.21	-0.58	0.16	0.16
maxDHW	-0.78	-0.26	0.04	-0.82	-0.46
AnnualMeanMaxDHW	-0.67	-0.10	0.06	-0.91	-0.23
DHW_over_4	-0.66	-0.16	0.10	-0.85	-0.21
DHW_over_8	-0.78	-0.23	0.11	-0.84	-0.20
MeanSST_surveymonth	-0.02	0.08	0.00	0.04	-0.03
RankMonth_SST	0.16	0.15	-0.16	0.24	0.03
Depth	-0.11	-0.01	-0.21	-0.04	0.08
MeanPARSurveyMonth	0.11	0.13	0.04	0.07	0.08
Latitude	-0.20	-0.11	-0.36	0.20	0.14
Longitude	0.05	0.24	-0.23	0.09	-0.02
OverallClimateScore	1.00	0.60	0.13	0.81	0.38
ConnectivityScore	0.60	1.00	0.03	0.22	0.30
CycloneScore	0.13	0.03	1.00	-0.14	0.02
HistoricHeatStress	0.81	0.22	-0.14	1.00	0.35
MarketGravity	0.38	0.30	0.02	0.35	1.00
SedimentationScore	0.14	0.09	-0.05	0.14	0.34
NutrientScore	0.31	0.24	0.01	0.23	0.49
Ports	-0.01	-0.14	0.02	0.07	0.21
TourismValue	0.29	0.15	-0.24	0.33	0.45
CumulativeHumanImpacts	0.29	0.12	-0.06	0.36	0.73

885

	SedimentationScore	NutrientScore	Ports	TourismValue	CumulativeHumanImpacts
aspect	0.02	-0.01	-0.04	0.01	-0.03
WWE	-0.12	-0.25	-0.09	-0.06	-0.19
NDVI	-0.35	-0.30	-0.17	-0.30	-0.49
MeanChlaSurveyYear	0.18	0.37	0.02	0.10	0.22
Population50km	0.24	0.43	0.05	0.18	0.35
Population20km	0.18	0.32	0.07	0.11	0.28
MeanChlaAllYears	0.17	0.37	0.01	0.10	0.21
ChlaSD	0.17	0.30	0.00	0.11	0.21
ChlaKurtosis	0.20	0.19	-0.01	0.03	0.17
ChlaCV	0.05	-0.05	0.02	0.03	-0.01
HII100km	0.46	0.71	-0.04	0.37	0.58
HII75km	0.48	0.72	-0.02	0.38	0.60
HII50km	0.51	0.69	0.00	0.38	0.62
HII25km	0.55	0.62	0.02	0.35	0.62
HII10km	0.53	0.45	0.11	0.40	0.61
LandArea15km	0.51	0.47	0.05	0.32	0.53
LandArea50km	0.47	0.61	-0.03	0.32	0.51
NPP_max	0.28	0.54	0.05	0.20	0.41
NPP_mean	0.25	0.51	0.02	0.16	0.34
NPP_min	0.22	0.47	0.00	0.12	0.29
NPP_sd	0.24	0.47	0.09	0.21	0.41
ReefArea15km	-0.17	-0.17	-0.07	-0.15	-0.21
ReefArea200km	-0.12	0.03	-0.13	-0.04	-0.16
MeanWaveEnergy	-0.03	-0.12	0.10	-0.07	-0.08
MMM	0.05	-0.01	0.12	-0.04	0.13
sdSST	-0.04	0.20	-0.11	0.15	0.00
cvSST	-0.02	0.21	-0.12	0.15	0.00
kurtSST	0.11	-0.05	0.09	-0.13	0.10

	SedimentationScore	NutrientScore	Ports	TourismValue	CumulativeHumanImpacts
MeanNumAnnualStorms	-0.08	-0.09	-0.06	0.08	-0.12
NumStorms5Yrs_TropPlus	-0.01	-0.06	0.02	0.11	-0.04
NumStorms5Yrs_Cat3Plus	0.16	0.16	-0.05	0.27	0.20
NumStorms10Yrs_TropPlus	-0.04	-0.04	0.00	0.12	-0.05
NumStorms10Yrs_Cat3Plus	0.08	0.10	-0.06	0.24	0.12
maxDHW	-0.23	-0.34	-0.01	-0.31	-0.40
AnnualMeanMaxDHW	-0.18	-0.19	-0.08	-0.28	-0.33
DHW_over_4	-0.20	-0.23	-0.07	-0.27	-0.31
DHW_over_8	-0.16	-0.19	-0.02	-0.24	-0.23
MeanSST_surveymonth	-0.05	-0.06	0.06	-0.03	-0.02
RankMonth_SST	-0.06	-0.02	-0.06	0.19	0.02
Depth	-0.04	-0.06	0.07	0.00	-0.01
MeanPARSurveyMonth	-0.18	-0.04	0.02	-0.05	-0.06
Latitude	0.16	0.05	0.13	0.11	0.27
Longitude	-0.26	-0.13	-0.02	-0.09	-0.19
OverallClimateScore	0.14	0.31	-0.01	0.29	0.29
ConnectivityScore	0.09	0.24	-0.14	0.15	0.12
CycloneScore	-0.05	0.01	0.02	-0.24	-0.06
HistoricHeatStress	0.14	0.23	0.07	0.33	0.36
MarketGravity	0.34	0.49	0.21	0.45	0.73
SedimentationScore	1.00	0.67	0.05	0.45	0.76
NutrientScore	0.67	1.00	-0.04	0.31	0.67
Ports	0.05	-0.04	1.00	0.14	0.36
TourismValue	0.45	0.31	0.14	1.00	0.73
CumulativeHumanImpacts	0.76	0.67	0.36	0.73	1.00

886

Supplementary Table 3. Variable inflation scores used to select variables included in the PERMANOVAs, for variables selected by the CCA. We excluded those with VIF > 10 (shaded). For categorical variables with multiple levels (e.g. Contributor, Habitat, Management, Month by SST, and Methods), we show the maximum VIF. The descriptions of each variable are in Supplementary Table 1.

All Sites	
Variable	VIF
Contributor	305.18
Latitude	22.64
Month (ranked by SST)	4.98
Storms within 5 years (Type 3 Plus)	3.95
maxDHW	8.44
Cumulative human impact	8.71
Habitat	4.15
Nutrients (agriculture)	5.00
Mean wave energy	4.31
Longitude	10.93
Cyclone score	11.51
NPP_{SD}	7.16
Climate score	16.54
SST_{SD}	7.16
Market gravity	13.34
MMM	2.15
Depth	2.65
Reef area (200 km)	3.29
SST (kurtosis)	67.29
Connectivity score	11.86
Management	6.77
NDVI	1.96
Mean PAR (survey month)	5.00
WWE	457.30
Aspect	3.12
Chl_a (kurtosis)	1.87

Realm 9. Mid-tropical North Pacific	
Variable	VIF
Month (ranked by SST)	39.86
sdSST	1399.22
Mean PAR (survey month)	17.98
Cyclone score	27.09
Mean wave energy	53.88
MMM	87.97
Connectivity score	12.84
Contributor	2243.78
Latitude	12401.24
SST (kurtosis)	948.99
Storms within 5 years (type 3 plus)	2.97
Nutrients (agriculture)	7.98

Realm 13. Indo-Pacific seas & Indian Ocean	
Variable	VIF
Contributor	323.15
SST_{SD}	57.29
Month (ranked by SST)	13.86
Longitude	414.91
Cumulative human impacts	12.36
Chl_a (kurtosis)	2.12
Latitude	89.97
Reef area (200 km)	7.31
Depth	1.98
Market gravity	20.75
Management	10.20
NPP_{SD}	14.22
NDVI	1.49
Mean SST (month of survey)	2.09
Reef area (15km)	3.61
Nutrients (agriculture)	11.63
SST (kurtosis)	44.96
Mean wave energy	3.31
Climate score (overall)	41.52
Connectivity score	15.41

Realm 16. Coral Sea	
Variable	VIF
Contributor (max)	19113.93
Human population (20 km)	1535.29
MaxDHW	11.29
Nutrients (agriculture)	4.79
NDVI	4.42
Connectivity score	38.02
Climate score (overall)	35.05
Latitude	50.24
Chl_a (kurtosis)	5.67
Mean wave energy	4.42
Storms within 5 years (Type 3 plus)	1.49
Mean PAR (survey month)	15.71
Month (ranked by SST)	553.32
Mean SST (survey month)	104.94
Reef area (200 km)	13.76
Management	10.09
Cyclone score	16.87
NPP_{SD}	1.99

Realm 17. Mid South Tropical Pacific	
Variable	VIF
Contributor (max)	19113.93
Cyclone score	109.21
Management	3.79
Aspect	1.26
Depth	1.40
Market Gravity	14.57
NDVI	1.65
Mean PAR (survey month)	3.83
Latitude	1356.94
MaxDHW	99.48

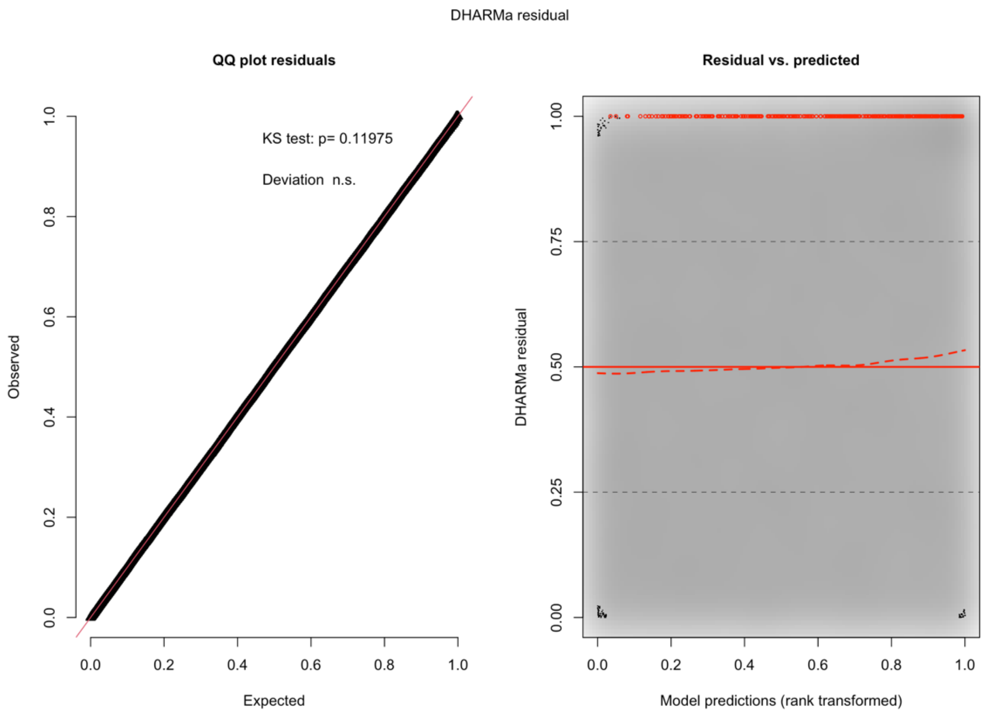
Realm 20. Offshore West Pacific	
Variable	VIF
Contributor	662.17
Month (ranked by SST)	6177.86
Longitude	513.55
MaxDHW	86.85
Mean SST (survey month)	3401.77
Reef area (200 km)	901.62
Connectivity score	163.17
NDVI	5.86
WWE	5.34
Aspect	5.39
Market gravity	357.29
Mean wave energy	3.62
Storms within 5 years (Type 3 Plus)	161.77
SST_{SD}	1443.77
MMM	116.86
Latitude	8939.16
SST (kurtosis)	5442.84
Cumulative human impacts	46.51
Habitat	11.85
Human population (20 km)	22.96
Mean PAR (survey month)	39.86
Cyclone score	1808.99
Climate score (overall)	1476.10

Realm 29. NW Pacific	
Variable	VIF
Contributor	60.62
Depth	10.38
Chl_a (kurtosis)	4.38
Connectivity score	11.38
Nutrients (agriculture)	3.27
Management	8.51
WWE	1.91
Reef area (15 km)	17.82

Supplementary Materials 4. Diagnostic plots for beta-distributed zero-inflated GLMMS

All Macroalgae.

***a.* Residual Plots**



b. **Moran's Test**

Moran I statistic standard deviate = -0.27834, p-value = 0.6096

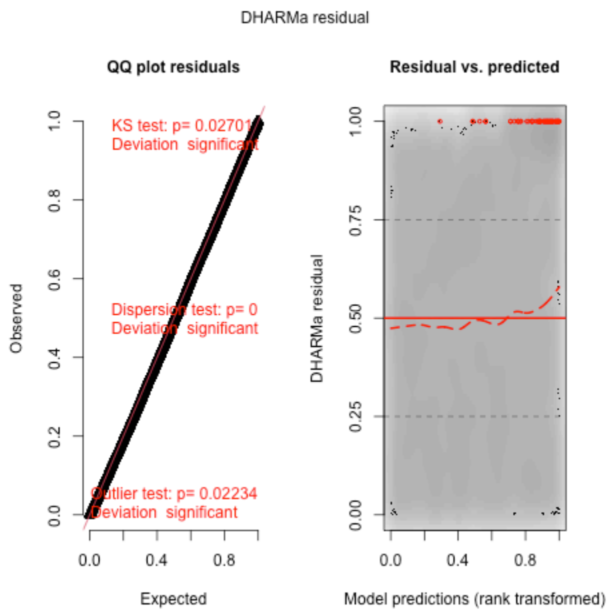
alternative hypothesis: greater

sample estimates:

Moran I statistic	Expectation	Variance
-8.623524e-04	-9.254718e-06	9.394231e-06

All Brown Macroalgae.

a. Residual Plots



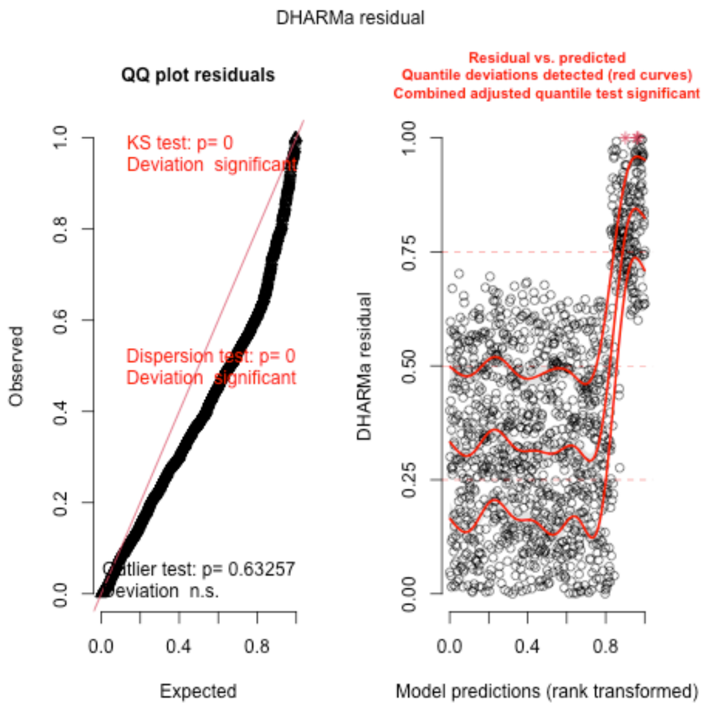
b. Moran's Test

Moran I statistic standard deviate = -0.94013, p-value = 0.8264
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-6.742769e-03	-4.736418e-05	5.071978e-05

Dictyota.

a. Residual Plots



b. **Moran's Test**

Moran I statistic standard deviate = 2.511, p-value = 0.006019

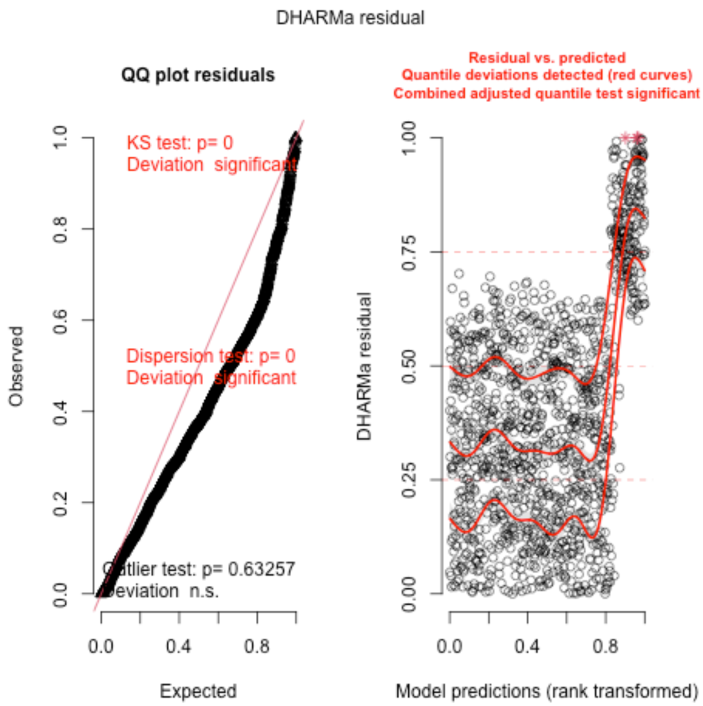
alternative hypothesis: greater

sample estimates:

Moran I statistic	Expectation	Variance
0.0897219292	-0.0008058018	0.0012997689

Dictyopteris.

a. Residual plots



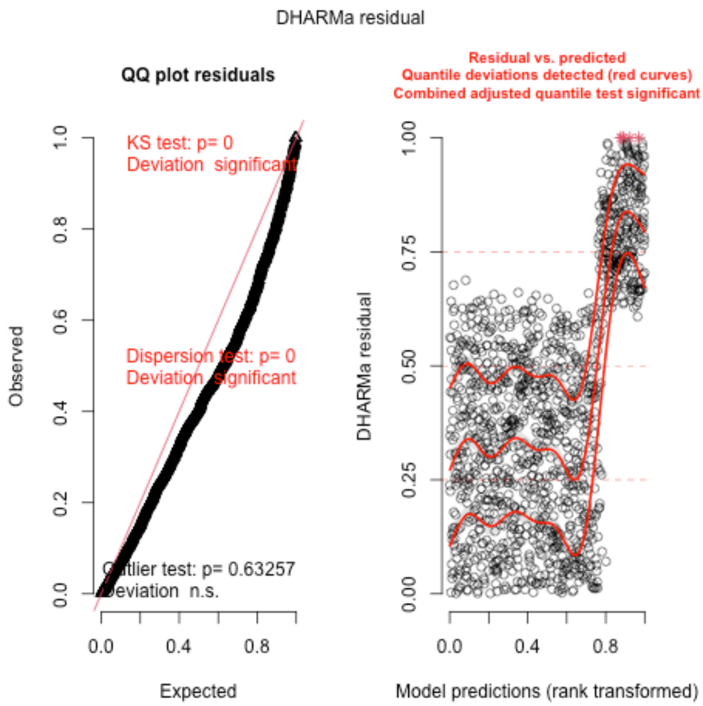
b. Moran's test

Moran I statistic standard deviate = 2.511, p-value = 0.006019
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
0.0897219292	-0.0008058018	0.0012997689

Lobophora.

a. Residual Plots



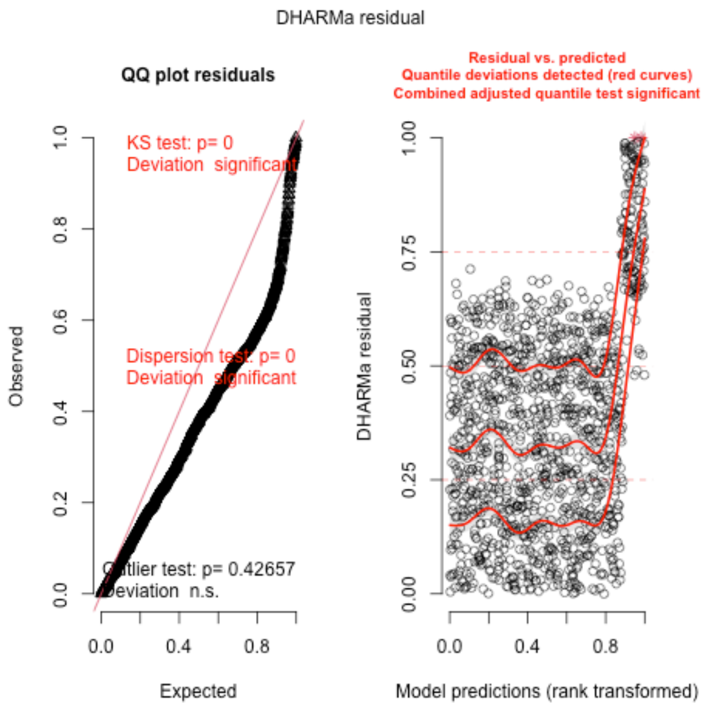
b. Moran's Test

Moran I statistic standard deviate = 2.4397, p-value = 0.007349
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
0.0804870752	-0.0008058018	0.0011102454

Padina.

a. Residual Plots



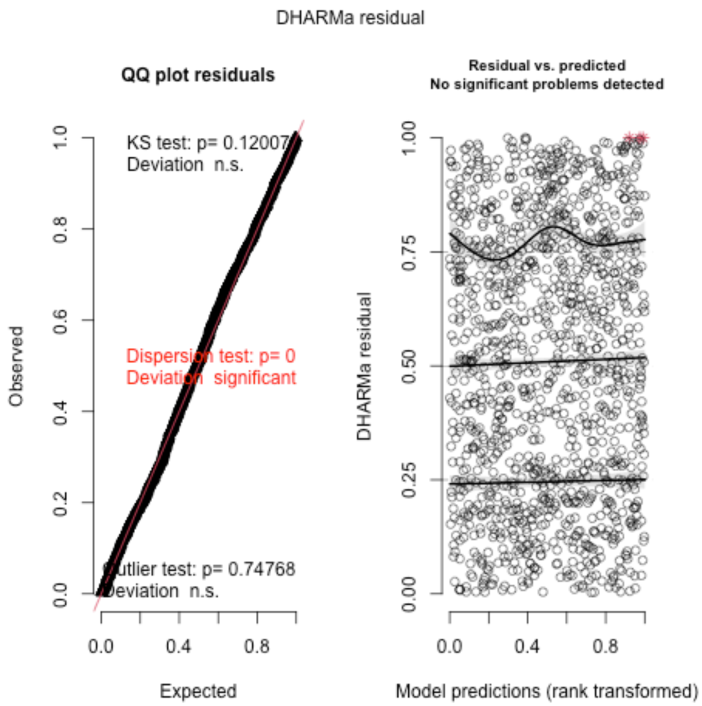
b. Moran's Test

Moran I statistic standard deviate = 6.3323, p-value = 1.208e-10
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
0.2277455693	-0.0008058018	0.0013026996

Spatoglossum.

a. Residual Plots



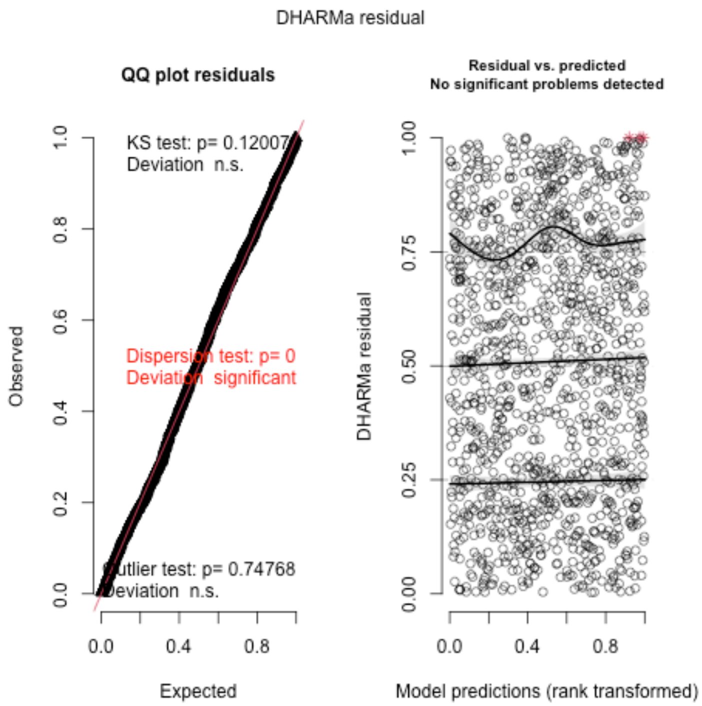
b. Moran's Test

Moran I statistic standard deviate = -2.332, p-value = 0.9901
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-0.0433821098	-0.0008058018	0.0003333396

Sargassum.

a. Residual Plots



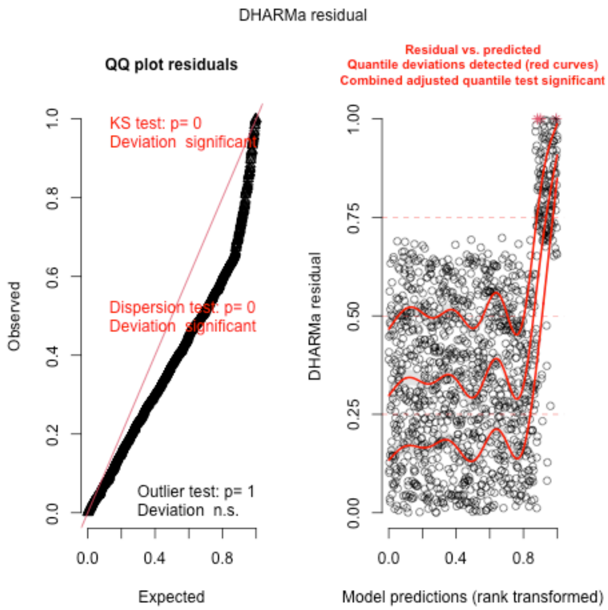
b. Moran's Test

Moran I statistic standard deviate = 3.7477, p-value = 8.923e-05
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
0.1339887139	-0.0008058018	0.0012936429

Turbinaria.

a. **Residual Plots**



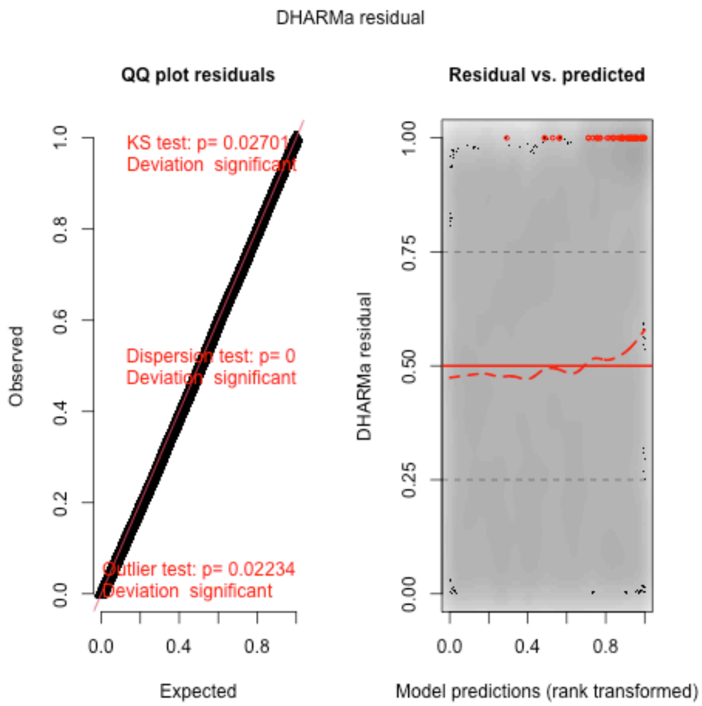
b. **Moran's Test**

Moran I statistic standard deviate = -29.869, p-value = 1
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-0.9648241706	-0.0008058018	0.0010416729

All Green Macroalgae.

a. Residual Plots



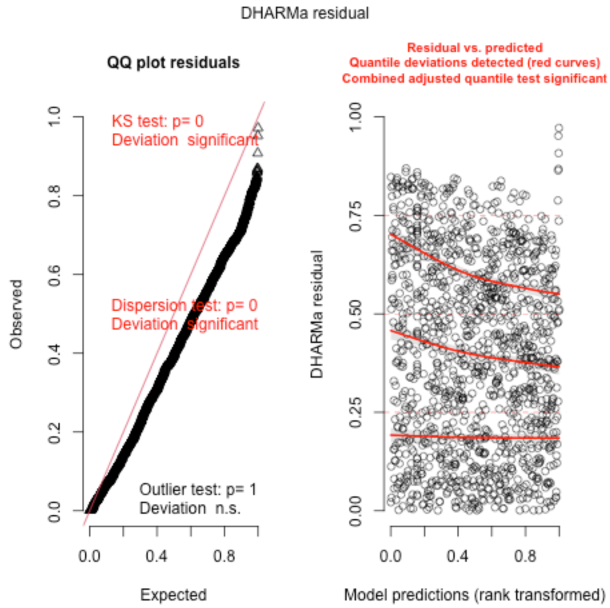
b. Moran's Test

Moran I statistic standard deviate = 0.2079, p-value = 0.4177
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
1.297462e-03	-3.834209e-05	4.128299e-05

Bryopsis.

a. Residual Plots



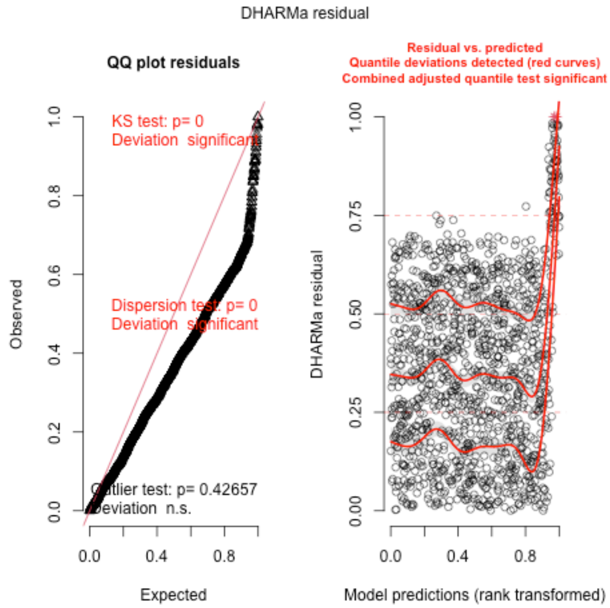
b. Moran's Test

Moran I statistic standard deviate = -6.5094, p-value = 1
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-0.1960915596	-0.0008058018	0.0009000443

Chlorodesmis.

a. Residual Plots



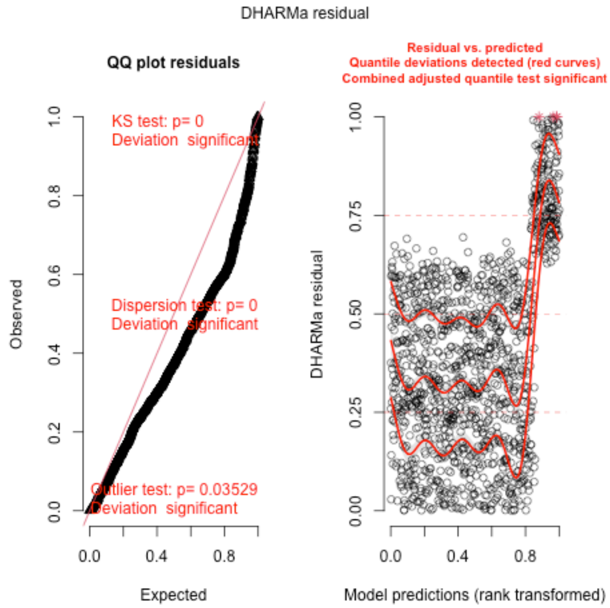
b. Moran's Tests

Moran I statistic standard deviate = -19.767, p-value = 1
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-0.7246005841	-0.0008058018	0.0013407505

Caulerpa.

a. Residual Plots



b. Moran's Test

Moran I statistic standard deviate = 8.4404, p-value < 2.2e-16

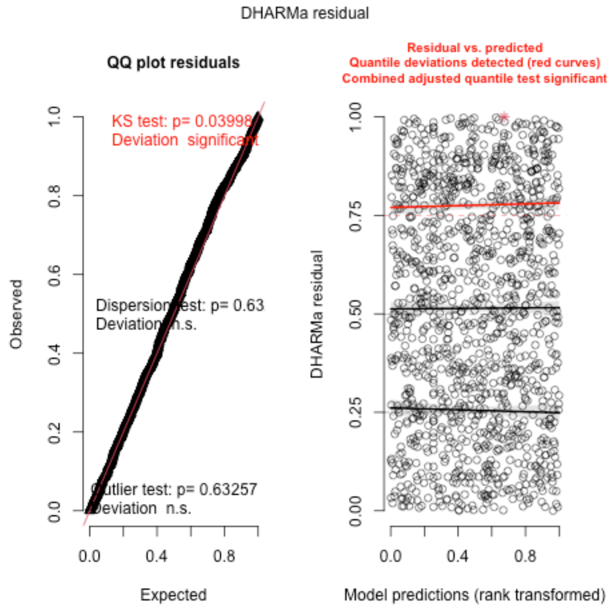
alternative hypothesis: greater

sample estimates:

Moran I statistic	Expectation	Variance
0.2959883933	-0.0008058018	0.0012364874

Cladophoropsis.

a. Residual Plots



b. Moran's Test

Moran I statistic standard deviate = 13.674, p-value < 2.2e-16

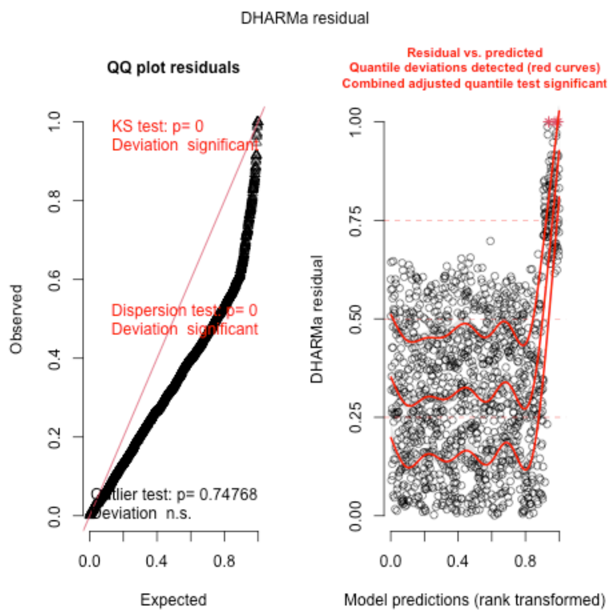
alternative hypothesis: greater

sample estimates:

Moran I statistic	Expectation	Variance
0.4489339689	-0.0008058018	0.0010817439

Dictyosphaeria.

a. Residual Plots



b. Moran's Test

Moran I statistic standard deviate = 1.5434, p-value = 0.06137
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
0.0514275036	-0.0008058018	0.0011453833

Halimeda.

a. **Residual Plots**

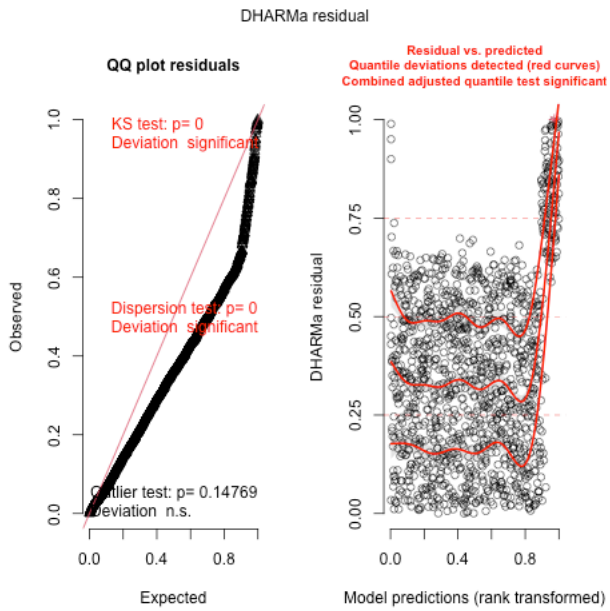
b. **Moran's Test**

Moran I statistic standard deviate = 5.1213, p-value = 1.517e-07
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
0.273599174	-0.001680672	0.002889309

Microdictyon.

a. Residual Plots



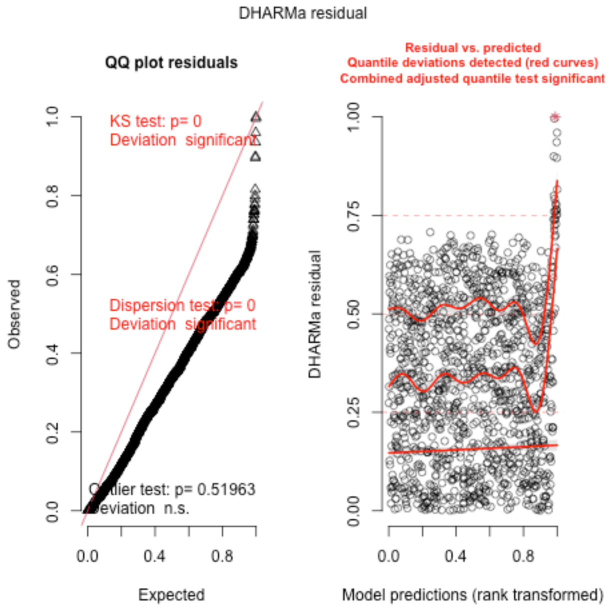
b. Moran's Test

Moran I statistic standard deviate = -0.52639, p-value = 0.7007
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-0.0199539804	-0.0008058018	0.0013232546

Neomeris.

a. **Residual Plots**



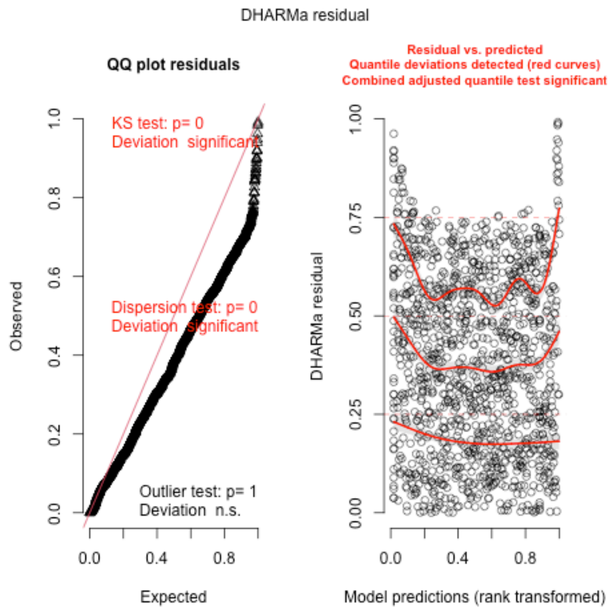
b. **Moran's Test**

Moran I statistic standard deviate = 14.933, p-value < 2.2e-16
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
0.3849908498	-0.0008058018	0.0006674577

Udotea.

a. Residual Plots



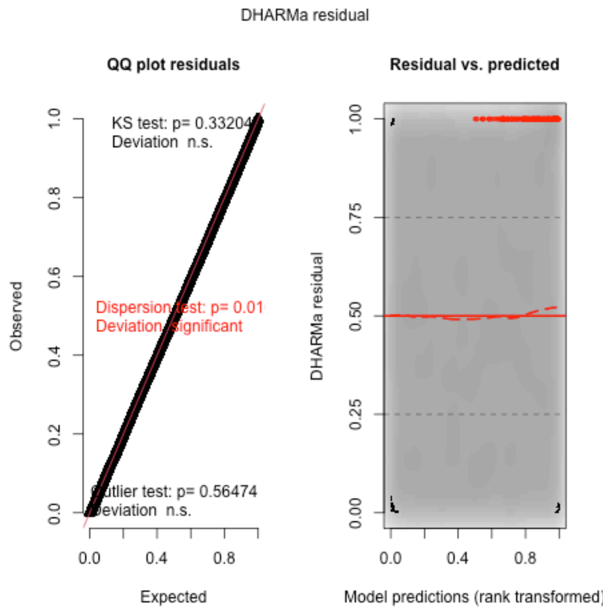
b. Moran's Test

Moran I statistic standard deviate = -31.969, p-value = 1
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-0.9915109931	-0.0008058018	0.0009603581

All Red Macroalgae.

a. Residual Plots



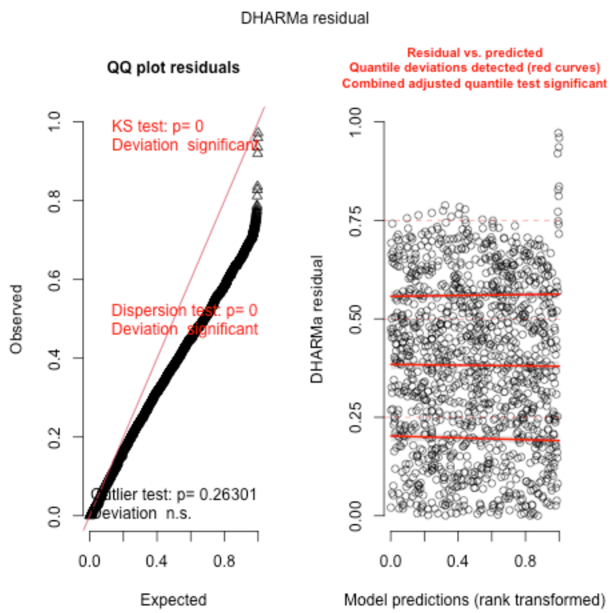
b. Moran's Test

Moran I statistic standard deviate = -0.28934, p-value = 0.6138
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-1.185480e-03	-1.677430e-05	1.631486e-05

Amansia.

a. Residual Plots



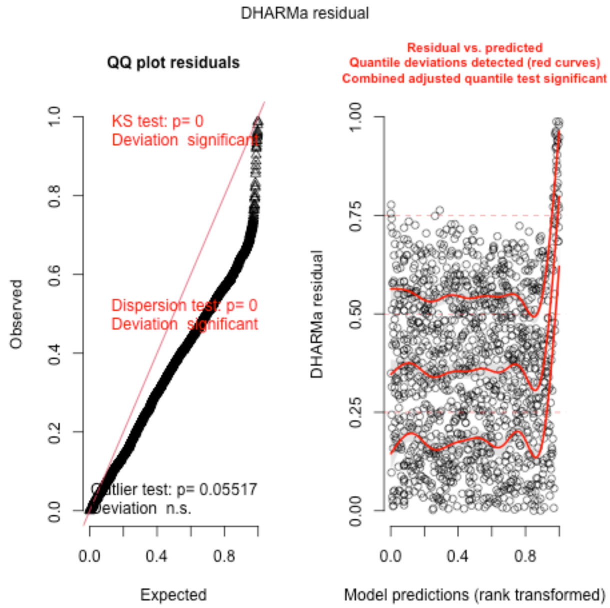
b. Moran's Test

Moran I statistic standard deviate = 4.8454, p-value = 6.319e-07
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
0.1566480591	-0.0008058018	0.0010559787

Asparagopsis.

a. Residual Plots



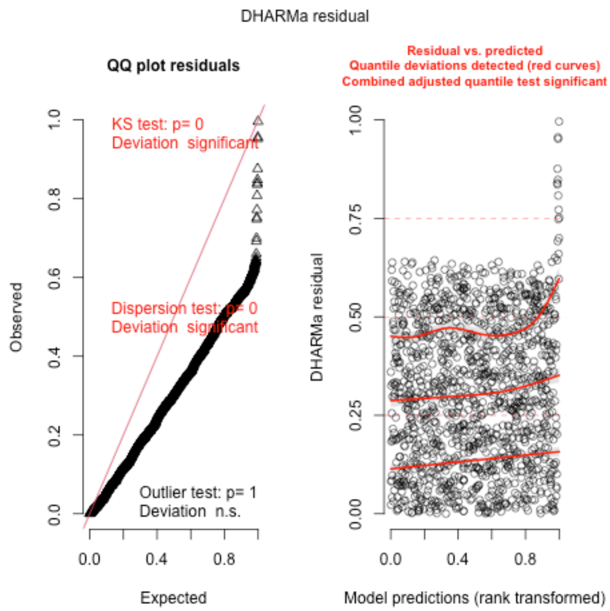
b. Moran's Test

Moran I statistic standard deviate = 5.1317, p-value = 1.436e-07
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
0.1789781895	-0.0008058018	0.0012274012

Ceratodictyon.

a. Residual Plots



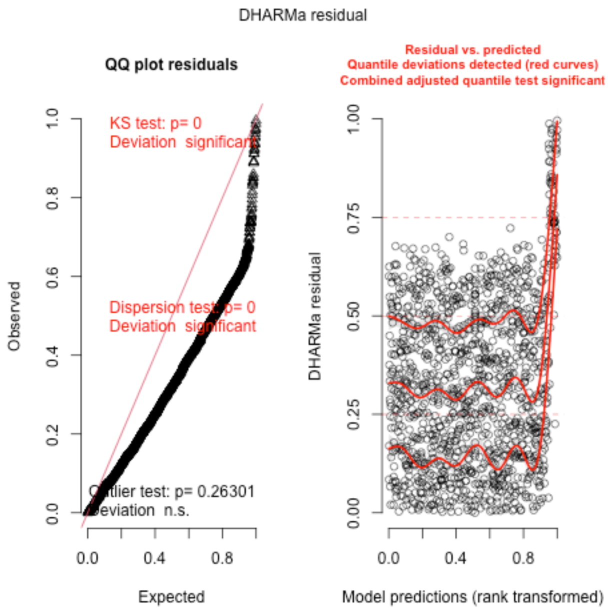
b. Moran's Test

Moran I statistic standard deviate = -15.611, p-value = 1
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-0.5042586961	-0.0008058018	0.0010400224

Galaxaura.

a. Residual Plots



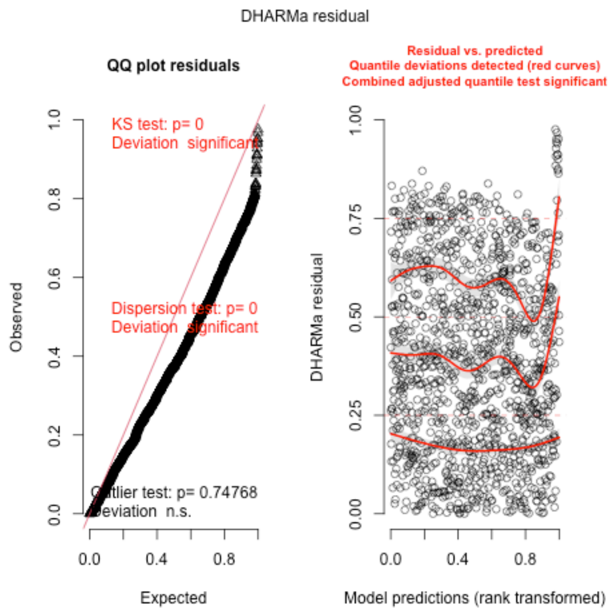
b. Moran's Test

Moran I statistic standard deviate = 19.188, p-value < 2.2e-16
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
0.4802926162	-0.0008058018	0.0006286597

Halymenia.

a. **Residual Plots**



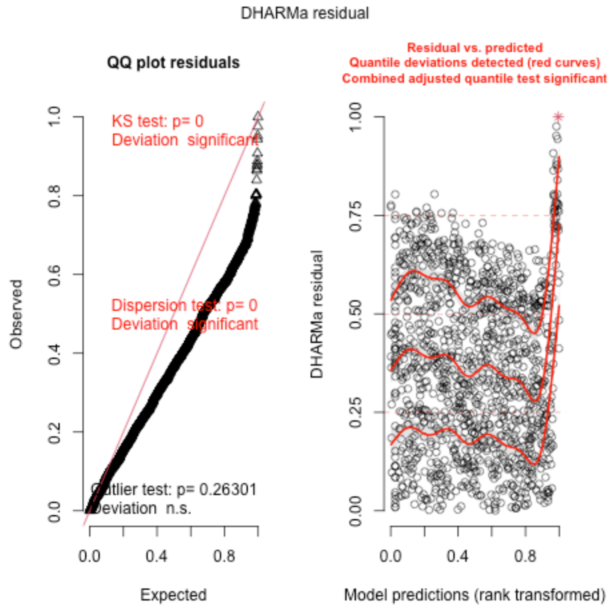
b. Moran's I

Moran I statistic standard deviate = -13.839, p-value = 1
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-0.4858614635	-0.0008058018	0.0012284550

Hypnea.

a. Residual Plots



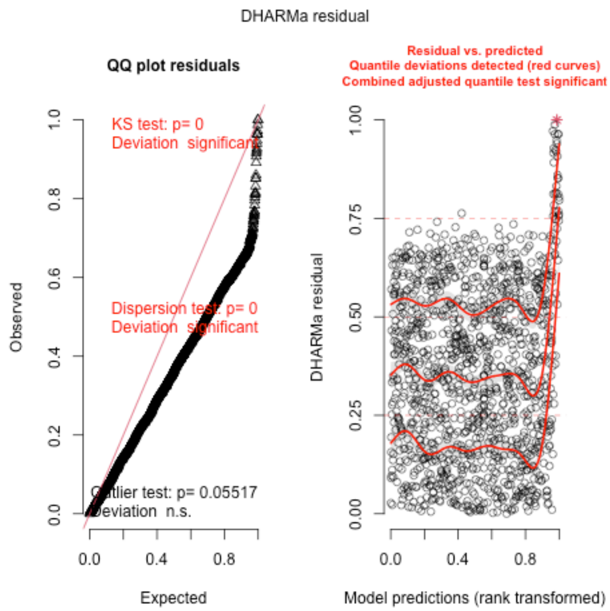
b. Moran's I

Moran I statistic standard deviate = -4.0611, p-value = 1
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-0.0774534269	-0.0008058018	0.0003562212

Laurencia.

a. Residual Plots



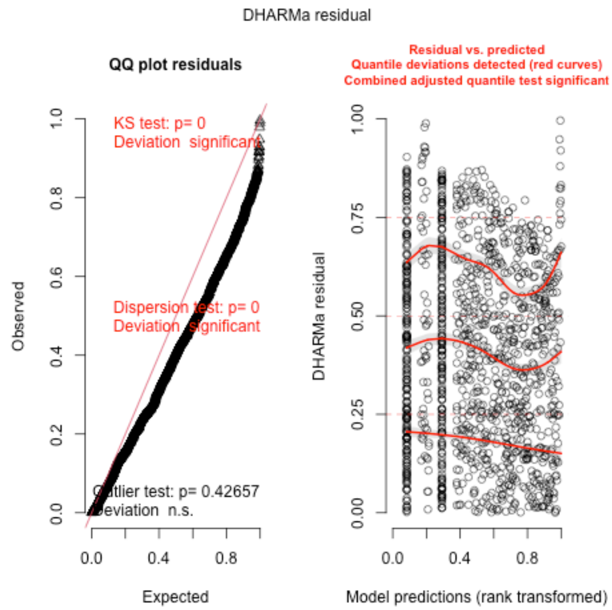
b. Moran's Test

Moran I statistic standard deviate = -33.023, p-value = 1
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-0.9841853743	-0.0008058018	0.0008867521

Neurymenia.

a. Residual Plots



b. Moran's Test

Moran I statistic standard deviate = -32.351, p-value = 1
alternative hypothesis: greater
sample estimates:

Moran I statistic	Expectation	Variance
-0.9150749293	-0.0008058018	0.000798700

Supplementary Table 5. Ten most common macroalgae taxa by average value, across all sites and within biogeographic realms.

All Sites (1205 Total)				
Genus	**Division**	**Mean**	**Maximum**	**Median**
All Macroalgae	--	12.80	88.20	6.79
Sargassum	Brown	13.00	62.00	6.25
Microdictyon	Green	12.00	69.70	5.00
Halimeda	Green	8.02	77.30	4.44
Amansia	Red	6.34	13.50	4.96
Cladophoropsis	Green	4.76	9.30	4.51
Dictyopteris	Brown	4.60	14.60	4.00
Ceratodictyon	Red	4.44	20.00	1.23
Lobophora	Brown	3.89	82.70	1.31
Padina	Brown	3.21	24.40	2.08
Spatoglossum	Brown	3.17	12.20	0.53

9. Mid-tropical North Pacific (101)				
Genus	**Division**	**Mean**	**Maximum**	**Median**
All Macroalgae	--	6.83	24.40	5.13
Padina	Brown	5.41	11.60	4.82
Halimeda	Green	5.16	21.60	4.39
Microdictyon	Green	3.98	12.60	2.43
Asparagopsis	Red	3.09	3.33	3.09
Neomeris	Green	3.08	3.35	3.08
Lobophora	Brown	2.24	9.30	1.99
Liagora	Red	1.68	1.68	1.68
Turbinaria	Brown	1.53	3.33	0.93
Dictyota	Brown	1.27	5.83	0.31
Caulerpa	Green	0.22	0.51	0.17

13. Indo-Pacific seas & Indian Ocean				
Genus	**Division**	**Mean**	**Maximum**	**Median**
All Macroalgae	--	18.40	88.20	14.80
Microdictyon	Green	12.80	69.70	3.66
Sargassum	Brown	10.10	62.00	4.92
Halimeda	Green	8.16	77.30	4.94
Cystoseiria	Brown	7.12	26.40	3.53
Lobophora	Brown	4.50	82.67	0.68
Cladophoropsis	Green	4.12	6.23	4.10
Jania	Red	3.56	6.54	3.66
Turbinaria	Brown	3.00	29.50	1.07
Padina	Brown	2.91	12.40	1.64
Spyridia	Red	2.46	2.46	2.46

16. Coral Sea [324]

Genus	Division	Mean	Maximum	Median
All Macroalgae	**--**	**15.60**	**78.50**	**9.74**
Galaxaura	**Red**	**26.10**	**35.20**	**26.10**
Sargassum	**Brown**	**22.40**	**59.10**	**19.70**
Halimeda	**Green**	**14.10**	**44.60**	**11.20**
Sargassopsis	**Brown**	**8.20**	**37.20**	**4.25**
Hydroclathrus	**Brown**	**5.59**	**13.60**	**5.75**
Dictosphaeria	**Green**	**5.04**	**14.10**	**0.76**
Dictyopteris	**Brown**	**4.75**	**10.20**	**4.25**
Caulerpa	**Green**	**4.50**	**30.00**	**1.43**
Lobophora	**Brown**	**3.07**	**23.60**	**0.69**
Laurencia	**Brown**	**3.05**	**13.70**	**1.67**

17. Mid South Tropical Pacific [166]

Genus	Division	Mean	Maximum	Median
All Macroalgae	**--**	**11.40**	**37.90**	**9.07**
Microdictyon	**Green**	**9.11**	**12.30**	**9.31**
Lobophora	**Brown**	**6.33**	**28.50**	**4.52**
Turbinaria	**Brown**	**5.67**	**26.10**	**4.50**
Padina	**Brown**	**4.73**	**6.00**	**5.00**
Chlorodesmis	**Green**	**4.58**	**8.33**	**4.17**
Halimeda	**Green**	**4.26**	**22.80**	**2.38**
Sargassum	**Brown**	**3.83**	**6.00**	**4.00**
Asparagopsis	**Red**	**3.81**	**8.00**	**3.33**
Galaxaura	**Red**	**3.58**	**7.48**	**4.45**
Dictyota	**Brown**	**3.31**	**15.30**	**1.71**

20. Offshore West Pacific [114]

Genus	Division	Mean	Maximum	Median
All Macroalgae	**--**	**12.70**	**85.40**	**4.70**
Eckloniopsis	**Brown**	**31.50**	**40.80**	**31.50**
Ptilophora	**Red**	**25.00**	**37.90**	**25.00**
Microdictyon	**Green**	**16.10**	**43.90**	**15.40**
Ventricaria	**Green**	**15.70**	**15.70**	**15.70**
Vanvoorstia	**Red**	**12.80**	**12.80**	**12.80**
Corallina	**Red**	**11.80**	**20.50**	**11.80**
Ceratodictyon	**Red**	**11.50**	**20.00**	**10.50**
Prionitis	**Red**	**11.40**	**11.40**	**11.40**
Cladophoropsis	**Green**	**9.30**	**9.30**	**9.30**
Amansia	**Red**	**9.06**	**13.50**	**9.12**

29. NW Pacific [57]				
Genus	**Division**	**Mean**	**Maximum**	**Median**
All Macroalgae	**--**	**5.70**	**22.10**	**2.66**
Padina	**Brown**	**8.54**	**17.00**	**8.54**
Caulerpa	**Green**	**5.40**	**5.40**	**5.40**
Amansia	**Red**	**3.63**	**11.60**	**1.45**
Spatoglossum	**Brown**	**3.17**	**12.20**	**0.53**
Neomeris	**Green**	**2.93**	**11.50**	**1.45**
Gracilaria	**Red**	**2.41**	**2.41**	**2.41**
Lobophora	**Brown**	**1.97**	**8.53**	**0.99**
Actinotrichia	**Red**	**1.68**	**1.68**	**1.68**
Halimeda	**Green**	**1.43**	**11.00**	**0.27**
Dudresnaya	**Red**	**1.20**	**1.20**	**1.20**

Supplementary Table 6. SIMPER results.

Realm 16 vs Realm 13

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.428	0.314	1.365	8.928	7.092	0.536	0.001	***
MIC	0.066	0.188	0.352	0.131	3.078	0.619	0.833	
SRG	0.060	0.168	0.354	2.139	1.031	0.694	0.001	***
LPA	0.060	0.151	0.393	0.751	1.055	0.768	1.000	
CLP	0.038	0.114	0.331	0.953	0.317	0.815	0.264	
PAD	0.034	0.107	0.319	0.261	0.447	0.858	0.998	
TRB	0.020	0.079	0.257	0.026	0.543	0.883	1.000	
CHL	0.017	0.077	0.217	0.191	0.029	0.904	0.152	
DIC	0.015	0.061	0.248	0.146	0.237	0.923	1.000	
DCT	0.012	0.048	0.245	0.062	0.238	0.938	0.843	
GLA	0.009	0.074	0.127	0.213	0.043	0.950	0.811	
ASP	0.008	0.058	0.145	0.018	0.131	0.961	0.971	
HYP	0.007	0.048	0.153	0.053	0.173	0.970	0.218	
LAU	0.007	0.031	0.221	0.287	0.006	0.978	0.006	**
UDO	0.005	0.035	0.132	0.162	0.000	0.984	0.001	***
DPT	0.003	0.018	0.152	0.155	0.000	0.988	0.997	
HLA	0.003	0.020	0.134	0.011	0.047	0.991	0.721	
CLS	0.002	0.016	0.123	0.000	0.071	0.994	0.549	
CER	0.002	0.013	0.148	0.000	0.062	0.996	0.998	
VAL	0.001	0.019	0.071	0.000	0.010	0.998	0.838	
NEO	0.001	0.014	0.070	0.000	0.010	0.999	0.994	
BRY	0.001	0.008	0.107	0.000	0.027	1.000	0.827	

Contrast: 16_9

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p
HA	0.454	0.310	1.464	8.928	3.736	0.564	0.001 ***
PAD	0.078	0.204	0.384	0.261	0.833	0.661	0.002 **
LPA	0.074	0.157	0.474	0.751	0.600	0.753	0.774
SRG	0.043	0.148	0.288	2.139	0.000	0.806	0.451
MIC	0.036	0.128	0.281	0.131	0.612	0.851	0.994
CLP	0.033	0.109	0.302	0.953	0.027	0.891	0.567
DIC	0.026	0.097	0.264	0.146	0.258	0.923	0.754
CHL	0.017	0.073	0.229	0.191	0.000	0.944	0.328
TRB	0.008	0.042	0.196	0.026	0.071	0.954	1.000
LAU	0.008	0.034	0.223	0.287	0.000	0.963	0.106
GLA	0.006	0.070	0.090	0.213	0.000	0.971	0.843
NEO	0.006	0.036	0.154	0.000	0.095	0.978	0.113
ASP	0.005	0.031	0.171	0.018	0.095	0.984	0.940
UDO	0.005	0.037	0.142	0.162	0.000	0.991	0.090 .
DPT	0.003	0.020	0.155	0.155	0.000	0.995	0.875
DCT	0.002	0.022	0.083	0.062	0.000	0.997	1.000
HYP	0.002	0.009	0.163	0.053	0.000	0.999	0.986
HLA	0.001	0.014	0.071	0.011	0.000	1.000	0.949

1278

Contrast: 16_17

Column1	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.403	0.312	1.290	8.928	3.721	0.477	0.005	**
LPA	0.107	0.187	0.570	0.751	2.115	0.604	0.005	**
TRB	0.056	0.136	0.407	0.026	1.202	0.669	0.001	***
DIC	0.054	0.141	0.386	0.146	1.080	0.734	0.001	***
SRG	0.045	0.144	0.316	2.139	0.153	0.787	0.346	
MIC	0.041	0.157	0.257	0.131	0.607	0.835	0.999	
CLP	0.039	0.119	0.329	0.953	0.129	0.882	0.257	
CHL	0.023	0.097	0.242	0.191	0.122	0.909	0.003	**
PAD	0.023	0.093	0.242	0.261	0.158	0.936	1.000	
ASP	0.019	0.094	0.198	0.018	0.229	0.958	0.053	.
GLA	0.015	0.082	0.187	0.213	0.243	0.976	0.135	
LAU	0.007	0.032	0.219	0.287	0.000	0.985	0.059	.
UDO	0.005	0.037	0.132	0.162	0.000	0.991	0.038	*
DPT	0.003	0.019	0.153	0.155	0.000	0.994	0.967	
DCT	0.003	0.024	0.108	0.062	0.021	0.997	1.000	
HYP	0.001	0.008	0.160	0.053	0.000	0.999	0.999	
HLA	0.001	0.017	0.060	0.011	0.000	1.000	0.993	

1279

Contrast: 16_20

Column1	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.372	0.330	1.127	8.928	1.528	0.415	0.448	
LPA	0.073	0.180	0.406	0.751	0.679	0.496	0.855	
CLP	0.070	0.145	0.481	0.953	1.437	0.574	0.001	***
PAD	0.066	0.150	0.440	0.261	1.780	0.647	0.006	**
SRG	0.056	0.166	0.338	2.139	0.344	0.710	0.065	.
MIC	0.047	0.159	0.298	0.131	1.548	0.762	0.973	
CHL	0.032	0.096	0.332	0.191	0.583	0.798	0.001	***
CER	0.028	0.116	0.243	0.000	0.996	0.829	0.001	***
TRB	0.027	0.082	0.325	0.026	0.301	0.859	0.898	
DPT	0.026	0.088	0.292	0.155	1.232	0.888	0.001	***
DCT	0.023	0.061	0.374	0.062	0.989	0.913	0.008	**
AMA	0.015	0.070	0.210	0.000	0.876	0.929	0.001	***
DIC	0.013	0.064	0.208	0.146	0.213	0.944	1.000	
GLA	0.009	0.079	0.118	0.213	0.019	0.955	0.647	
LAU	0.008	0.035	0.225	0.287	0.004	0.963	0.031	*
HLA	0.006	0.030	0.215	0.011	0.098	0.971	0.007	**
NEO	0.006	0.033	0.196	0.000	0.370	0.978	0.016	*
UDO	0.005	0.040	0.126	0.162	0.000	0.983	0.088	.
VAL	0.004	0.025	0.166	0.000	0.333	0.988	0.036	*
VEN	0.003	0.023	0.123	0.000	0.212	0.991	0.009	**
BRY	0.002	0.019	0.130	0.000	0.130	0.994	0.040	*
CLS	0.002	0.016	0.134	0.000	0.159	0.996	0.449	
HYP	0.002	0.011	0.166	0.053	0.001	0.998	0.984	
ASP	0.002	0.009	0.183	0.018	0.029	1.000	0.999	

Contrast: 16_29

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.413	0.376	1.100	8.928	0.633	0.439	0.035	*
LPA	0.160	0.233	0.686	0.751	2.017	0.609	0.001	***
NRM	0.055	0.135	0.410	0.000	0.933	0.668	0.001	***
CLP	0.046	0.148	0.308	0.953	0.129	0.716	0.151	
SRG	0.046	0.155	0.294	2.139	0.005	0.764	0.378	
PAD	0.043	0.158	0.270	0.261	0.408	0.809	0.499	
GLA	0.032	0.100	0.319	0.213	0.179	0.843	0.010	**
SPT	0.029	0.098	0.293	0.000	0.582	0.874	0.001	***
CHL	0.025	0.116	0.220	0.191	0.002	0.901	0.066	.
LAU	0.021	0.060	0.349	0.287	0.141	0.923	0.001	***
AMA	0.019	0.075	0.248	0.000	0.401	0.943	0.008	**
TRB	0.011	0.075	0.143	0.026	0.001	0.954	1.000	
DPT	0.009	0.056	0.167	0.155	0.045	0.964	0.199	
MIC	0.009	0.079	0.112	0.131	0.000	0.973	1.000	
DIC	0.007	0.032	0.223	0.146	0.038	0.981	1.000	
HYP	0.007	0.033	0.211	0.053	0.057	0.989	0.294	
UDO	0.006	0.047	0.129	0.162	0.003	0.995	0.072	.
DCT	0.002	0.023	0.085	0.062	0.000	0.997	1.000	
HLA	0.002	0.024	0.062	0.011	0.000	0.999	0.786	
VAL	0.001	0.005	0.116	0.000	0.004	0.999	0.831	
ASP	0.001	0.006	0.095	0.018	0.000	1.000	1.000	
NEO	0.000	0.001	0.220	0.000	0.003	1.000	0.989	

Contrast: 13_9

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p
HA	0.365	0.272	1.340	7.092	3.736	0.486	0.670
MIC	0.092	0.211	0.435	3.078	0.612	0.608	0.117
PAD	0.077	0.185	0.413	0.447	0.833	0.710	0.002 **
LPA	0.073	0.160	0.455	1.055	0.600	0.807	0.841
DIC	0.032	0.097	0.330	0.237	0.258	0.850	0.428
SRG	0.025	0.116	0.217	1.031	0.000	0.883	0.960
TRB	0.021	0.074	0.277	0.543	0.071	0.911	0.979
CLP	0.014	0.062	0.226	0.317	0.027	0.930	1.000
ASP	0.013	0.062	0.212	0.131	0.095	0.947	0.432
DCT	0.011	0.045	0.254	0.238	0.000	0.962	0.641
HYP	0.007	0.049	0.134	0.173	0.000	0.971	0.317
NEO	0.006	0.036	0.175	0.010	0.095	0.980	0.041 *
GLA	0.004	0.037	0.111	0.043	0.000	0.985	0.979
CHL	0.002	0.019	0.124	0.029	0.000	0.988	1.000
CLS	0.002	0.018	0.129	0.071	0.000	0.991	0.408
CER	0.002	0.014	0.157	0.062	0.000	0.994	0.972
HLA	0.002	0.013	0.151	0.047	0.000	0.997	0.768
VAL	0.001	0.013	0.091	0.010	0.000	0.998	0.701
BRY	0.001	0.009	0.112	0.027	0.000	1.000	0.498
LAU	0.000	0.004	0.056	0.006	0.000	1.000	1.000

1280

Contrast: 13_17

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.337	0.279	1.210	7.092	3.721	0.422	0.999	
LPA	0.102	0.183	0.555	1.055	2.115	0.549	0.015	*
MIC	0.092	0.220	0.421	3.078	0.607	0.664	0.017	*
TRB	0.062	0.135	0.459	0.543	1.202	0.742	0.001	***
DIC	0.059	0.138	0.430	0.237	1.080	0.816	0.001	***
SRG	0.028	0.114	0.250	1.031	0.153	0.852	0.980	
PAD	0.024	0.080	0.306	0.447	0.158	0.882	1.000	
ASP	0.024	0.100	0.244	0.131	0.229	0.913	0.001	***
CLP	0.020	0.081	0.248	0.317	0.129	0.938	0.999	
GLA	0.013	0.060	0.218	0.043	0.243	0.954	0.273	
DCT	0.012	0.046	0.253	0.238	0.021	0.969	0.811	
CHL	0.009	0.055	0.163	0.029	0.122	0.980	0.989	
HYP	0.006	0.049	0.132	0.173	0.000	0.988	0.393	
CLS	0.002	0.017	0.126	0.071	0.000	0.991	0.455	
CER	0.002	0.014	0.153	0.062	0.000	0.993	0.996	
HLA	0.002	0.013	0.142	0.047	0.000	0.996	0.926	
VAL	0.001	0.019	0.073	0.010	0.001	0.997	0.745	
NEO	0.001	0.014	0.073	0.010	0.000	0.999	0.962	
BRY	0.001	0.008	0.110	0.027	0.000	1.000	0.701	
LAU	0.000	0.004	0.055	0.006	0.000	1.000	1.000	

Contrast: 13_20

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.321	0.292	1.102	7.092	1.528	0.370	1.000	
MIC	0.098	0.221	0.443	3.078	1.548	0.483	0.020	*
LPA	0.067	0.173	0.388	1.055	0.679	0.560	0.973	
PAD	0.065	0.134	0.481	0.447	1.780	0.635	0.006	**
CLP	0.053	0.116	0.456	0.317	1.437	0.696	0.009	**
SRG	0.039	0.139	0.278	1.031	0.344	0.741	0.641	
TRB	0.034	0.088	0.385	0.543	0.301	0.780	0.502	
DCT	0.030	0.069	0.433	0.238	0.989	0.814	0.001	***
CER	0.029	0.111	0.264	0.062	0.996	0.848	0.001	***
DPT	0.023	0.086	0.268	0.000	1.232	0.875	0.001	***
DIC	0.023	0.085	0.267	0.237	0.213	0.901	0.943	
CHL	0.017	0.048	0.358	0.029	0.583	0.921	0.225	
AMA	0.015	0.068	0.212	0.000	0.876	0.937	0.001	***
ASP	0.010	0.060	0.159	0.131	0.029	0.948	0.793	
NEO	0.007	0.036	0.207	0.010	0.370	0.957	0.002	**
GLA	0.007	0.054	0.132	0.043	0.019	0.965	0.883	
HLA	0.007	0.025	0.272	0.047	0.098	0.973	0.001	***
HYP	0.007	0.050	0.136	0.173	0.001	0.981	0.306	
VAL	0.006	0.032	0.173	0.010	0.333	0.987	0.003	**
CLS	0.004	0.023	0.183	0.071	0.159	0.992	0.038	*
BRY	0.003	0.018	0.168	0.027	0.130	0.996	0.004	**
VEN	0.003	0.023	0.123	0.000	0.212	0.999	0.019	*
LAU	0.001	0.012	0.083	0.006	0.004	1.000	1.000	

Contrast: 13_29

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.399	0.329	1.214	7.092	0.633	0.424	0.111	
LPA	0.145	0.218	0.667	1.055	2.017	0.578	0.001	***
MIC	0.070	0.202	0.349	3.078	0.000	0.653	0.506	
NRM	0.052	0.126	0.413	0.000	0.933	0.708	0.001	***
PAD	0.041	0.137	0.299	0.447	0.408	0.751	0.569	
SRG	0.027	0.123	0.222	1.031	0.005	0.780	0.846	
SPT	0.027	0.094	0.289	0.000	0.582	0.809	0.001	***
GLA	0.026	0.074	0.349	0.043	0.179	0.836	0.038	*
CLP	0.025	0.106	0.238	0.317	0.129	0.863	0.845	
DIC	0.020	0.078	0.257	0.237	0.038	0.885	0.909	
TRB	0.020	0.082	0.243	0.543	0.001	0.906	0.967	
AMA	0.018	0.072	0.248	0.000	0.401	0.925	0.012	*
DCT	0.013	0.055	0.246	0.238	0.000	0.939	0.450	
HYP	0.013	0.063	0.202	0.173	0.057	0.953	0.060	.
LAU	0.012	0.044	0.271	0.006	0.141	0.965	0.022	*
ASP	0.011	0.072	0.150	0.131	0.000	0.977	0.538	
DPT	0.006	0.045	0.122	0.000	0.045	0.983	0.465	
CHL	0.004	0.038	0.104	0.029	0.002	0.987	0.999	
VAL	0.003	0.029	0.093	0.010	0.004	0.990	0.196	
CER	0.002	0.016	0.155	0.062	0.000	0.992	0.914	
CLS	0.002	0.019	0.128	0.071	0.000	0.995	0.311	
HLA	0.002	0.016	0.141	0.047	0.000	0.997	0.596	
NEO	0.002	0.018	0.087	0.010	0.003	0.999	0.646	
BRY	0.001	0.009	0.110	0.027	0.000	1.000	0.368	
UDO	0.000	0.001	0.178	0.000	0.003	1.000	0.997	

Contrast: 9_17

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.316	0.264	1.195	3.736	3.721	0.406	0.999	
LPA	0.124	0.193	0.644	0.600	2.115	0.565	0.008	**
DIC	0.076	0.159	0.480	0.258	1.080	0.663	0.001	***
PAD	0.069	0.192	0.363	0.833	0.158	0.752	0.009	**
MIC	0.066	0.181	0.367	0.612	0.607	0.838	0.636	
TRB	0.060	0.136	0.440	0.071	1.202	0.914	0.003	**
ASP	0.025	0.095	0.258	0.095	0.229	0.946	0.035	*
GLA	0.011	0.053	0.206	0.000	0.243	0.960	0.462	
CLP	0.011	0.055	0.192	0.027	0.129	0.974	1.000	
CHL	0.008	0.055	0.144	0.000	0.122	0.984	0.925	
SRG	0.006	0.031	0.189	0.000	0.153	0.991	1.000	
NEO	0.006	0.036	0.161	0.095	0.000	0.999	0.086	.
DCT	0.001	0.013	0.080	0.000	0.021	1.000	1.000	

Signif. codes: 0 ,Äò***,Äô 0.001 ,Äò**,Äô 0.01 ,Äò*,Äô 0.05 ,Äò.,Äô 0.1 ,Äò ,Äô 1

1282

Contrast: 9_20

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.289	0.279	1.035	3.736	1.528	0.340	1.000	
PAD	0.113	0.221	0.513	0.833	1.780	0.474	0.001	***
LPA	0.087	0.184	0.472	0.600	0.679	0.576	0.424	
MIC	0.073	0.186	0.394	0.612	1.548	0.662	0.488	
CLP	0.051	0.110	0.466	0.027	1.437	0.723	0.068	.
DIC	0.035	0.118	0.298	0.258	0.213	0.764	0.309	
CER	0.032	0.122	0.259	0.000	0.996	0.801	0.001	***
DPT	0.026	0.095	0.274	0.000	1.232	0.832	0.001	***
TRB	0.026	0.065	0.399	0.071	0.301	0.862	0.814	
DCT	0.023	0.060	0.389	0.000	0.989	0.890	0.026	*
SRG	0.019	0.097	0.192	0.000	0.344	0.912	0.967	
CHL	0.017	0.043	0.390	0.000	0.583	0.932	0.340	
AMA	0.016	0.075	0.216	0.000	0.876	0.951	0.005	**
NEO	0.013	0.050	0.252	0.095	0.370	0.966	0.003	**
ASP	0.006	0.032	0.197	0.095	0.029	0.973	0.825	
HLA	0.006	0.024	0.252	0.000	0.098	0.980	0.051	.
VAL	0.005	0.027	0.172	0.000	0.333	0.986	0.084	.
GLA	0.003	0.035	0.096	0.000	0.019	0.990	0.918	
VEN	0.003	0.025	0.124	0.000	0.212	0.993	0.074	.
CLS	0.002	0.017	0.135	0.000	0.159	0.996	0.429	
BRY	0.002	0.016	0.144	0.000	0.130	0.999	0.127	
LAU	0.001	0.010	0.083	0.000	0.004	1.000	0.979	
HYP	0.000	0.003	0.077	0.000	0.001	1.000	1.000	

Contrast: 9_29

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.378	0.333	1.136	3.736	0.633	0.410	0.426	
LPA	0.172	0.224	0.767	0.600	2.017	0.596	0.001	***
PAD	0.103	0.258	0.398	0.833	0.408	0.707	0.003	**
NRM	0.062	0.138	0.449	0.000	0.933	0.774	0.001	***
MIC	0.037	0.132	0.276	0.612	0.000	0.814	0.939	
DIC	0.036	0.125	0.288	0.258	0.038	0.853	0.324	
SPT	0.032	0.103	0.305	0.000	0.582	0.887	0.001	***
GLA	0.024	0.054	0.442	0.000	0.179	0.912	0.096	.
AMA	0.021	0.079	0.265	0.000	0.401	0.935	0.013	*
CLP	0.015	0.085	0.175	0.027	0.129	0.951	0.974	
LAU	0.013	0.046	0.291	0.000	0.141	0.966	0.022	*
NEO	0.007	0.043	0.169	0.095	0.003	0.974	0.064	.
DPT	0.006	0.046	0.141	0.000	0.045	0.981	0.421	
ASP	0.006	0.036	0.167	0.095	0.000	0.987	0.775	
HYP	0.006	0.030	0.194	0.000	0.057	0.993	0.420	
TRB	0.004	0.028	0.158	0.071	0.001	0.998	1.000	
SRG	0.001	0.005	0.138	0.000	0.005	0.999	0.999	
VAL	0.001	0.004	0.138	0.000	0.004	1.000	0.702	
CHL	0.000	0.002	0.138	0.000	0.002	1.000	1.000	
UDO	0.000	0.001	0.191	0.000	0.003	1.000	0.797	

Contrast: 17_20

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.244	0.255	0.957	3.721	1.528	0.278	1.000	
LPA	0.115	0.205	0.560	2.115	0.679	0.409	0.006	**
MIC	0.076	0.204	0.373	0.607	1.548	0.496	0.375	
TRB	0.069	0.140	0.497	1.202	0.301	0.575	0.001	***
DIC	0.064	0.155	0.413	1.080	0.213	0.648	0.001	***
CLP	0.056	0.122	0.463	0.129	1.437	0.712	0.006	**
PAD	0.055	0.127	0.433	0.158	1.780	0.775	0.092	.
CER	0.029	0.117	0.251	0.000	0.996	0.809	0.001	***
DPT	0.024	0.090	0.272	0.000	1.232	0.837	0.001	***
DCT	0.023	0.060	0.384	0.021	0.989	0.863	0.008	**
SRG	0.023	0.098	0.231	0.153	0.344	0.889	0.969	
CHL	0.022	0.066	0.340	0.122	0.583	0.914	0.048	*
ASP	0.021	0.098	0.210	0.229	0.029	0.938	0.076	.
AMA	0.015	0.072	0.214	0.000	0.876	0.955	0.001	***
GLA	0.013	0.065	0.206	0.243	0.019	0.971	0.281	
NEO	0.007	0.034	0.198	0.000	0.370	0.978	0.020	*
HLA	0.006	0.023	0.240	0.000	0.098	0.985	0.035	*
VAL	0.004	0.026	0.169	0.001	0.333	0.990	0.040	*
VEN	0.003	0.024	0.124	0.000	0.212	0.993	0.002	**
BRY	0.003	0.022	0.118	0.000	0.130	0.996	0.050	*
CLS	0.002	0.017	0.135	0.000	0.159	0.999	0.435	
LAU	0.001	0.013	0.069	0.000	0.004	1.000	0.994	

Contrast: 17_29

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.289	0.290	0.997	3.721	0.633	0.310	1.000	
LPA	0.203	0.239	0.849	2.115	2.017	0.528	0.001	***
DIC	0.070	0.170	0.414	1.080	0.038	0.604	0.002	**
TRB	0.063	0.153	0.414	1.202	0.001	0.672	0.008	**
NRM	0.057	0.134	0.427	0.000	0.933	0.733	0.001	***
MIC	0.044	0.175	0.250	0.607	0.000	0.780	0.909	
GLA	0.036	0.086	0.417	0.243	0.179	0.819	0.003	**
SPT	0.030	0.101	0.299	0.000	0.582	0.851	0.001	***
CLP	0.028	0.116	0.244	0.129	0.129	0.882	0.722	
ASP	0.025	0.116	0.212	0.229	0.000	0.908	0.063	.
PAD	0.022	0.113	0.196	0.158	0.408	0.932	0.977	
AMA	0.019	0.076	0.256	0.000	0.401	0.953	0.007	**
LAU	0.014	0.052	0.267	0.000	0.141	0.968	0.009	**
CHL	0.009	0.062	0.147	0.122	0.002	0.978	0.823	
SRG	0.007	0.034	0.203	0.153	0.005	0.985	0.999	
DPT	0.006	0.050	0.125	0.000	0.045	0.992	0.466	
HYP	0.006	0.031	0.182	0.000	0.057	0.998	0.449	
DCT	0.001	0.014	0.079	0.021	0.000	0.999	1.000	
VAL	0.001	0.005	0.125	0.001	0.004	1.000	0.790	
NEO	0.000	0.001	0.232	0.000	0.003	1.000	0.929	
UDO	0.000	0.001	0.183	0.000	0.003	1.000	0.899	

1285

Contrast: 20_29

Genus	Average	SD	Ratio	Average (Group A)	Average (Group B)	Cumulative Sum	p	
HA	0.184	0.251	0.733	1.528	0.633	0.195	1.000	
LPA	0.177	0.252	0.701	0.679	2.017	0.382	0.001	***
PAD	0.077	0.180	0.426	1.780	0.408	0.463	0.009	**
CLP	0.068	0.156	0.433	1.437	0.129	0.534	0.007	**
NRM	0.059	0.140	0.419	0.000	0.933	0.596	0.001	***
MIC	0.048	0.167	0.291	1.548	0.000	0.647	0.868	
AMA	0.036	0.107	0.333	0.876	0.401	0.685	0.001	***
CER	0.034	0.135	0.253	0.996	0.000	0.721	0.002	**
DPT	0.033	0.112	0.300	1.232	0.045	0.757	0.001	***
GLA	0.032	0.090	0.354	0.019	0.179	0.790	0.021	*
SPT	0.031	0.102	0.298	0.000	0.582	0.823	0.001	***
TRB	0.029	0.084	0.343	0.301	0.001	0.853	0.681	
DCT	0.026	0.066	0.388	0.989	0.000	0.880	0.023	*
SRG	0.023	0.115	0.203	0.344	0.005	0.905	0.891	
CHL	0.018	0.048	0.385	0.583	0.002	0.924	0.249	
DIC	0.018	0.081	0.227	0.213	0.038	0.944	0.890	
LAU	0.016	0.055	0.286	0.004	0.141	0.960	0.003	**
NEO	0.008	0.036	0.210	0.370	0.003	0.968	0.072	.
HLA	0.007	0.028	0.245	0.098	0.000	0.976	0.040	*
HYP	0.007	0.035	0.192	0.001	0.057	0.983	0.318	
VAL	0.005	0.028	0.196	0.333	0.004	0.989	0.066	.
BRY	0.004	0.032	0.114	0.130	0.000	0.992	0.035	*
VEN	0.003	0.026	0.124	0.212	0.000	0.996	0.057	.
CLS	0.002	0.017	0.135	0.159	0.000	0.998	0.370	
ASP	0.001	0.009	0.167	0.029	0.000	1.000	0.976	
UDO	0.000	0.001	0.177	0.000	0.003	1.000	0.851	

Supplementary Table 7. PERMANOVA results.

Variables significant at α = 0.05 are bolded and those significant at α = are italicized.

All sites.				
Formula = percent ~ Month of survey (ranked by SST) + storms within 5 years (Type 3+) + maxDHW + cumulative human impacts + habitat + nutrients (agriculture) + mean wave energy + NPP_{SD} + SST_{SD} + MMM + Depth + reef area (200 km) + management + NDVI + mean PAR (survey month) + aspect + Chl_a (kurtosis)				
	Sum of Squares	**R^2**	**Pseudo-F**	**p-value**
Model	**29.08**	**0.10**	**2.62**	**< 0.01**
Residual	266.23	0.90		
Total	295.30	1.00		
Variables				
Month (ranked by SST)	**9.26**	**0.03**	**2.16**	**< 0.01**
Storms within 5 years (Type 3+)	**0.79**	**0.00**	**2.21**	**0.02**
MaxDHW	**0.99**	**0.00**	**2.79**	***< 0.01***
Cumulative human impacts	**1.72**	**0.01**	**4.81**	**< 0.01**
Habitat	**5.52**	**0.02**	**5.14**	**< 0.01**
Nutrients (agriculture)	0.37	0.00	1.02	0.42
Mean wave energy	**0.72**	**0.00**	**1.99**	**0.03**
NPP_{SD}	0.43	0.00	1.19	0.28
Reef area (200km)	**1.46**	**0.00**	**4.06**	**< 0.01**
Management	**3.27**	**0.01**	**4.56**	**< 0.01**
NDVI	**0.90**	**0.00**	**2.51**	**< 0.01**
Mean PAR (survey month)	**0.79**	**0.00**	**2.22**	**0.02**
Aspect	0.23	0.00	0.65	0.81
Chl_a (kurtosis)	*0.67*	*0.00*	*1.87*	*0.05*
Residual	424.38	0.96		
Total	443.18	1.00		

b. Mid-tropical North Pacific				
Formula = percent ~ Storms within 5 years (Type 3+) + nutrients (agriculture)				
	Sum of Squares	R^2	Pseudo-F	p-value
Model	*9.97*	*0.05*	*1.63*	*0.08*
Residual	19.30	0.94		
Total	19.27	1.00		
Variables				
Population (20 km)	**0.38**	**0.02**	**3.94**	**< 0.01**
Depth	**0.59**	**0.01**	**2.21**	**0.03**
Residual	18.30	0.94		
Total	19.27	1.00		

Indo-Pacific seas & Indian Ocean				
Formula = percent ~** Chl$_a$ **(kurt) + reef area (200 km) + depth + NDVI + mean SST (survey month) + reef area (15 km) + mean wave energy				
	Sum of Squares	**R^2**	**Pseudo-F**	**p-value**
Model	**23.54**	**0.18**	**7.60**	**< 0.01**
Residual	110.02	0.82		
Total	133.56	1.00		
Variables				
Reef area (200 km)	**1.56**	**0.01**	**5.55**	**< 0.01**
Mean wave energy	**1.14**	**0.01**	**4.06**	**< 0.01**
Depth	**2.89**	**0.02**	**10.27**	**< 0.01**
Mean SST (survey month)	**1.29**	**0.01**	**4.59**	**< 0.01**
Chl$_a$ (kurtosis)	**1.26**	**0.01**	**4.49**	**< 0.01**
Reef area (15 km)	**4.58**	**0.03**	**16.27**	**0.04**
Mean PAR (survey month)	**1.94**	**0.01**	**6.88**	
Cumulative Human Impact	**4.92**	**0.04**	**17.50**	
Aspect	**0.66**	**0.01**	**2.35**	**0.02**
Residual	110.02	0.82		
Total	133.56	1.00		

Coral Sea.

Formula = percent ~ nutrients (agriculture) + NDVI + *chl_a* ***(kurtosis) + mean wave energy + storms within 5 years (type 3+) + NPP_{SD}***

	Sum of Squares	**R^2**	**Pseudo-F**	**p-value**
Model	**16.28**	**0.21**	**9.88**	**< 0.01**
Residual	60.13	0.79		
Total	76.41	1.00		
Variables				
Nutrients (agriculture)	**4.58**	**0.06**	**16.66**	**< 0.01**
NDVI	**3.05**	**0.04**	**11.12**	**< 0.01**
Chl_a **(kurtosis)**	**1.26**	**0.02**	**4.59**	**< 0.01**
Mean wave energy	**2.97**	**0.04**	**10.81**	**< 0.01**
Storms within 5 years (Type 3+)	**0.92**	**0.01**	**3.36**	**< 0.01**
NPP_{SD}	**3.50**	**0.05**	**12.76**	**< 0.01**
Residual	60.13	0.79		
Total	76.41	1.00		

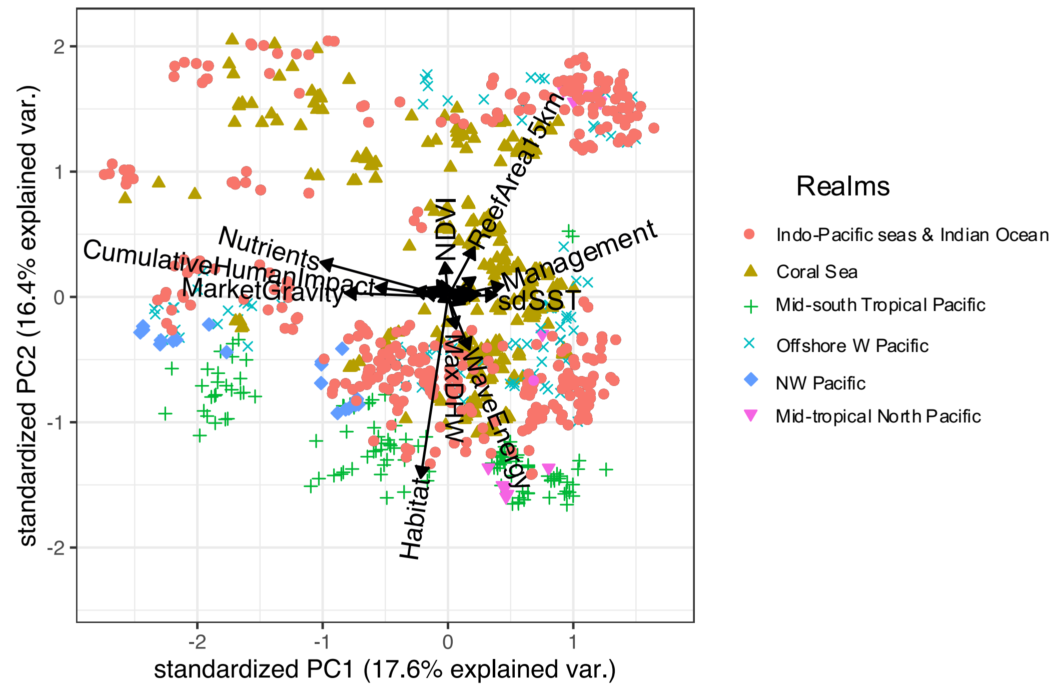
Mid South Tropical Pacific				
Formula = percent ~ management + aspect + depth + NDVI + mean PAR (survey month)				
	Sum of Squares	**R^2**	**Pseudo-F**	**p-value**
Model	**10.76**	**0.18**	**5.80**	**< 0.01**
Residual	48.26	0.82		
Total	59.02	1.00		
Variables				
Management	**5.00**	**0.08**	**8.08**	**< 0.01**
Aspect	0.17	0.02	0.54	0.83
Depth	**2.57**	**0.04**	**8.29**	**< 0.01**
NDVI	**0.89**	**0.02**	**2.87**	**< 0.01**
Mean PAR (survey month)	**2.14**	**0.04**	**6.91**	**< 0.01**
Residual	48.26	0.82		
Total	59.02	1.00		

Offshore West Pacific				
Formula = percent ~ NDVI + WWE + aspect + mean wave energy				
	Sum of Squares	**R^2**	**Pseudo-F**	**p-value**
Model	**3.28**	**0.07**	**1.99**	**< 0.01**
Residual	46.62	0.93		
Total	49.90	1.00		
Variables				
NDVI	**1.31**	**0.03**	**3.16**	**< 0.01**
WWE	**0.49**	**0.01**	**1.19**	**0.26**
Aspect	**0.42**	**0.01**	**1.01**	**0.42**
Mean wave energy	1.06	0.02	2.58	< 0.01
Residual	46.62	0.93		
Total	49.90	1.00		

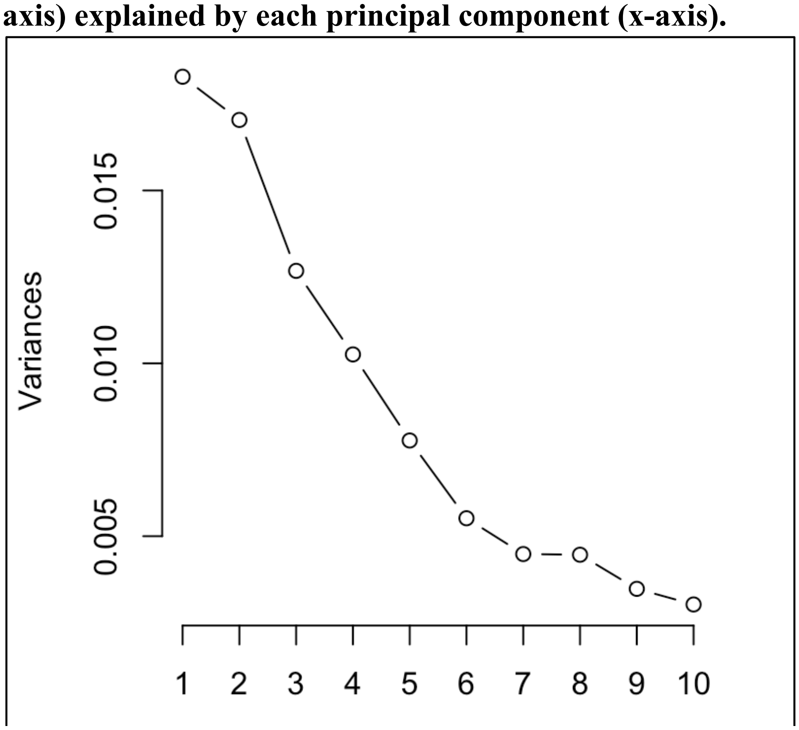
NW Pacific				
Formula = percent ~ chl_a (kurtosis) + nutrients + management + WWE				
	Sum of Squares	**R^2**	**Pseudo-F**	**p-value**
Model	**0.54**	**0.02**	**1.36**	**< 0.01**
Residual	19.74	0.84		
Total	23.57	1.00		
Variables				
Chl_a (kurtosis)	0.54	0.02	1.36	0.12
Nutrients (agriculture)	**0.85**	**0.04**	**2.16**	**< 0.01**
Management	**2.09**	**0.09**	**2.65**	**< 0.01**
WWE	0.35	0.01	0.88	0.62
Residual	19.74	0.86		
Total	23.57	1.00		

SuppMaterials 8. Principle Component Analysis of environmental variables as (a) a biplot and (b) scree plot.

a. **Biplot of Principal Component Analysis.**



b. **Scree plot of Principal Component Analysis, showing the amount of variation (y-axis) explained by each principal component (x-axis).**



Supplementary Table 9. Full results for the Zero-Inflated Generalized Linear Mixed Effects Models. For ease of interpretation, we multiplied the estimates for NDVI by -1 because the variables have inverse relationships with disturbance. In the table below, positive values indicate that macroalgae percent cover increases as disturbance increases, and negative values indicate that the percent cover decreases as disturbance increases.

Genus / Category	R^2		Cumulative Human Impacts		Log (Population 20km)		Market Gravity		NDVI		Nutrients	
	Marg	Cond	Est	p	Est	p	Est	p	Est	p	Est	p
All Macroalgae	0.01	0.13	0.96	0.85	**0.09**	**< 0.01**	**1.59**	**< 0.01**	**1.57**	**< 0.01**	**0.51**	**< 0.01**
All Brown Macroalgae	0.07	0.10	1.91	0.14	**0.05**	**<0.01**	0.92	0.74	**2.14**	**<0.01**	**0.30**	**<0.01**
Dictyota	0.13	NA	2.21	0.79	0.05	0.54	1.07	0.97	1.76	0.66	0.17	0.27
Dictyopteris	0.84	NA	2.72	0.93	2.67	0.97	7.13	0.76	3.29	0.43	0.29	0.84
Lobophora	0.06	NA	11.60	0.38	0.01	0.51	0.43	0.62	2.02	0.55	0.28	0.41
Padina	0.17	0.34	1.43	0.93	**0.00**	**< 0.01**	5.65	0.46	6.29	0.31	0.13	0.34
Spatoglossum	0.99	NA	4.95	0.94	0.03	0.87	0.00	0.71	15.86	0.86	1.78	0.95
Sargassum	0.35	NA	0.08	0.62	**0.00**	**< 0.01**	1.10	0.98	7.88	0.55	4.78	0.56
Turbinaria	0.19	0.93	0.21	0.62	0.00	0.54	1.67	0.79	0.57	0.71	0.63	0.79
All Green Macroalgae	0.06	NA	**1.24**	**0.03**	**0.27**	**<0.01**	**1.31**	**0.07**	**1.98**	**<0.01**	**0.57**	**<0.01**
Bryopsis	0.94	1.00	0.29	1.00	0.26	1.00	*0.00*	*0.05*	1.27	1.00	0.12	0.00
Chlorodesmis	0.24	0.91	0.31	0.60	0.03	0.99	0.12	0.50	0.36	0.64	0.09	0.38
Caulerpa	0.03	NA	4.53	0.64	0.38	0.87	3.82	0.50	1.98	0.59	0.13	0.25
Cladophoropsis	0.07	1.00	0.15	0.11	0.00	0.99	0.11	0.64	0.36	0.47	0.42	0.91
Dictosphaeria	0.22	NA	0.69	0.92	0.19	0.87	1.91	0.81	3.33	0.49	3.63	0.64
Halimeda	0.01	NA	**10.11**	**< 0.01**	1.54	0.83	**0.22**	**< 0.01**	0.90	0.76	**0.29**	**< 0.01**
Microdictyon	0.95	NA	1.21	0.29	0.84	0.82	0.19	0.54	5.47	0.28	0.87	0.96
Neomeris	0.11	NA	17.66	0.77	5.94	0.90	0.24	0.79	2.66	0.80	0.06	0.57
Udotea	0.94	1.00	0.08	0.72	0.04	0.42	1.72	0.91	0.62	0.89	0.58	0.89
All Red Macroalgae	0	--	--	--	**--**	**--**	--	--	**--**	**--**	**--**	**--**
Amansia	0.93	NA	2.94	0.94	5.07	0.91	0.19	0.85	16.39	0.76	0.04	0.69
Asparagopsis	0.53	0.73	1.29	0.96	Inf	0.78	0.56	0.87	12.54	0.41	0.50	0.82
Ceratodictyon	0.88	0.95	31.89	0.81	0.00	0.41	0.35	0.90	3.84	0.83	0.06	0.72
Galaxaura	0.42	NA	0.21	0.76	7.32	0.88	0.26	0.68	0.57	0.83	1.20	0.95
Halymenia	0.27	0.58	0.10	0.84	**0.00**	**0.01**	33.76	0.53	0.08	0.57	0.00	0.43
Hypnea	0.71	NA	0.00	0.12	**0.00**	**< 0.01**	1.29	0.97	*Inf*	*0.08*	8.26	0.53
Laurencia	0.69	0.99	0.33	0.85	84.81	0.83	0.92	0.98	18.89	0.42	0.65	0.88
Neurymenia	1.00	1.00	952.82	0.78	Inf	0.71	0.00	0.60	0.36	0.89	0.02	0.66

Supplementary Materials 10. Estimated parameters for GLMM models. P-values computed using a Wald z-distribution approximation. Values significant at a α = 0.05 are in bold, while those significant at α are in italics.

Taxa	**NDVI**			**Log(Population)**			**Market Gravity**			**Cumulative Human Impacts**			**Nutrients from agriculture**		
	Est	z	p	Est	z	p	Est	z	p	Est	z	p	Est	z	P
All Macroalgae	**0.15**	**2.13**	**0.03**	**0.71**	**2.42**	**0.02**	-0.09	-0.85	0.40	0.02	0.11	0.91	**-0.34**	**-3.33**	**<0.01**
All Brown Macroalgae	**-0.31**	**-2.74**	**<0.01**	**0.74**	**2.14**	**0.03**	**-0.36**	**-2.07**	**0.04**	**1.55**	**4.86**	**<0.01**	**-0.98**	**-6.15**	**<0.01**
Dictyota	-0.29	-1.22	0.22	0.41	0.49	0.63	**-0.72**	**-2.22**	**0.03**	**2.33**	**3.77**	**<0.01**	**-0.85**	**-2.73**	**<0.01**
Dictyopteris	*4.17*	*1.90*	*0.06*	-0.20	-0.04	0.97	**-6.21**	**-2.35**	**0.02**	**8.37**	**2.42**	**0.02**	-1.48	-1.34	0.18
Lobophora	-0.21	-1.12	0.26	0.40	0.50	0.62	*-0.55*	*-1.70*	*0.09*	**1.22**	**2.06**	**0.04**	**-1.05**	**-3.60**	**<0.01**
Padina	-0.21	-0.69	0.49	1.06	1.57	0.12	0.10	0.24	0.81	**2.05**	**2.86**	**<0.01**	**-1.67**	**-4.18**	**<0.01**
Spatoglossum	-18.42	-1.29	0.20	22.17	0.57	0.57	*29.59*	*1.80*	*0.07*	**14.77**	**1.80**	**0.07**	*-6.56*	*-1.88*	*0.06*
Sargassum	**-1.57**	**-3.15**	**<0.01**	0.53	0.72	0.47	-0.19	-0.37	0.71	1.67	1.64	0.10	**-1.59**	**-3.60**	**<0.01**
Turbinaria	0.37	0.89	0.37	-1.35	-1.20	0.23	**2.12**	**3.00**	**<0.01**	**-0.44**	**0.35**	**0.73**	-0.02	-0.03	0.98
All Green Macroalgae	**0.36**	**4.10**	**<0.01**	**1.11**	**2.72**	**<0.01**	-0.15	-1.22	0.22	**-0.54**	**-2.42**	**0.02**	-0.05	-0.40	0.70
Bryopsis	1.30	0.83	0.41	**-2.19**	**-2.99**	**<0.01**	3.61	1.61	0.11	**-5.31**	**-4.21**	**<0.01**	**4.91**	**7.14**	**<0.01**
Chlorodesmis	0.00	0.01	0.99	-12.05	-0.67	0.50	0.39	0.41	0.68	-1.26	-0.75	0.45	1.32	1.83	0.07
Caulerpa	*0.44*	*1.81*	*0.07*	1.02	0.94	0.35	0.18	0.40	0.69	-0.69	-0.99	0.32	0.34	0.47	0.48
Cladophoropsis	0.52	0.18	0.86	**-11.47**	**-3.53**	**<0.01**	2.23	0.68	0.50	-5.27	-0.97	0.33	-2.30	-0.62	0.54
Dictyosphaeria	0.35	1.19	0.24	0.70	0.29	0.77	**-1.18**	**-3.68**	**<0.01**	0.82	1.21	0.23	**1.52**	**3.11**	**<0.01**
Halimeda	-0.11	-0.30	0.76	-0.35	0.21	0.83	**-1.50**	**-2.85**	**<0.01**	**2.31**	**2.60**	**< 0.01**	**-1.23**	**-2.60**	**< 0.01**
Microdictyon	0.12	0.33	0.74	-71.56	-1.27	0.21	**-1.41**	**-2.36**	**0.02**	1.86	1.05	0.30	-0.73	-1.02	0.31
Neomeris	-0.33	-0.32	0.75	2.46	0.34	0.73	-0.03	-0.03	0.97	-2.20	-1.28	0.20	0.66	0.79	0.43
Udotea	**2.51**	**3.71**	**< 0.01**	**-58.79**	**-58.00**	**< 0.01**	**-4.26**	**-6.30**	**<0.01**	1.93	0.87	0.38	0.18	0.11	0.92
All Red Macroalgae	-0.11	-0.63	0.53	**1.77**	**4.76**	**<0.01**	*-0.37*	*-1.70*	*0.09*	0.35	1.01	0.31	*-0.33*	*-1.70*	*0.09*
Amansia	-7.52	-1.39	0.16	-11.65	-1.05	0.29	-1.00	-0.27	0.90	-1.43	-0.12	0.90	3.86	0.48	0.63
Asparagopsis	**-2.05**	**-2.25**	**0.03**	-11.51	-0.56	0.58	1.15	1.63	0.11	-0.16	-0.12	0.90	-0.42	-0.68	0.50
Ceratodictyon	-3.79	-1.55	0.12	1.25	0.91	0.37	**-4.20**	**-2.49**	**<0.01**	1.66	0.66	0.51	0.08	0.06	0.96
Galaxaura	**1.41**	**2.83**	**<0.01**	-0.52	-0.16	0.87	*1.85*	*1.82*	*0.07*	**-4.43**	**-2.24**	**0.03**	*1.53*	*2.00*	*0.05*
Halymenia	0.45	0.43	0.67	1.47	1.10	0.27	-0.64	0.33	0.74	-0.30	-0.18	0.86	1.64	1.06	0.29
Hypnea	**-3.07**	**2.52**	**0.01**	**2.59**	**3.43**	**<0.01**	**-1.80**	**-2.27**	**0.02**	**5.14**	**2.86**	**0.01**	**-2.36**	**-3.70**	**<0.01**
Laurencia	0.10	0.14	0.89	**-14.49**	**-3.04**	**<0.01**	**-2.99**	**-2.60**	**0.01**	-1.63	-0.74	0.46	1.18	1.45	0.15