RELATIVE ABUNDANCE OF MACROALGAE (RAM) ON NORTHWESTERN HAWAIIAN ISLAND REEFS[1]

BY

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ABSTRACT

The Northwestern Hawaiian Islands (NWHI) represent one of the last relatively intact tropical reef ecosystems in existence, yet macroalgal community dynamics of the 10 atolls, islands, and reefs situated in the NWHI Coral Reef Ecosystem Reserve remain virtually unknown. This manuscript is the first to provide distributional maps of six common species along the NWHI chain, statistically compare sites from differing habitats and islands based on relative abundance of macroalgae (RAM), and look for temporal differences in macroalgal populations. Our findings reveal that the abundance of most macroalgal species is low, but that members of *Halimeda* and *Microdictyon* can be extremely common and in some cases form dense monotypic meadows on the reef. Other genera, such as *Stypopodium*, *Lobophora*, and *Laurencia*, become increasingly prevalent in northwesterly atolls of the Hawaiian Archipelago. The RAM across the NWHI chain as a whole remained relatively static for the years surveyed. However, slight changes occurred at Kure and Midway atolls where coral bleaching events were documented in 2002 and 2004.

INTRODUCTION

Qualitative understanding of the marine algal flora of the Northwestern Hawaiian Islands (NWHI) has improved dramatically since 2000 as the National Oceanic and Atmospheric Administration (NOAA) Pacific Island Fisheries Science Center's Coral Reef Ecosystem Division (CRED) and multi-agency Northwestern Hawaiian Islands Reef Assessment and Monitoring Program (NOWRAMP) began conducting annual research expeditions to these remote reefs. Comprehensive lists of reported algal species have been compiled (Abbott, 1989 and 1999; Abbott and Huisman, 2003), several algal species new to science described (Abbott and McDermid, 2001 and 2002; Vroom and Abbott, 2004a and b; Vroom, 2005), and reproductive processes for some algal species reported for the first time (Vroom and Smith, 2003). Yet despite this dramatic increase in phycological activity, very little quantitative research has been published to provide

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an understanding of baseline community structure on reefs surrounding these relatively unpolluted islands (Maragos and Gulko, 2002; Friedlander et al., 2004). In order to protect and conserve these valuable ecosystems in times of potential environmental change, scientists need knowledge of algal abundance and distribution in conjunction with algal diversity.

In 2002, CRED began quantitative algal monitoring of the NWHI (Fig. 1) using a rapid ecological assessment (REA) protocol developed specifically for remote island ecosystems (Preskitt et al., 2004). The species-level percent cover analyses possible through the Preskitt method (Preskitt et al., 2004) were used to successfully complete a detailed analysis of benthic cover at the French Frigate Shoals (FFS), NWHI (Vroom et al., 2005 and 2006); however photoquadrat and voucher specimen analyses proved time-consuming. An expedited method of analysis relying on the field note component of the Preskitt method was desired to quickly give a coarse-level understanding of distribution and relative abundance of macroalgae (RAM) over the entire NWHI Archipelago within a short time of returning from the field. The objectives of this study were to: (1) assess the effectiveness of field collected data for rapid post-cruise analysis (~ 1 month) of macroalgal assemblages across an entire archipelago; (2) create distributional maps of common macroalgal species; (3) determine if RAM differed significantly among sites from different habitats; (4) determine if RAM differed significantly among sites from different islands/latitudes; and (5) determine if significant differences in RAM at specific sites occurred between sampling years.

MATERIALS AND METHODS

Field Work

Benthic REA data from three research expeditions (10 September - 4 October, 2002; 14 July - 8 August, 2003; 13 September - 17 October, 2004) to the NWHI (Fig. 1) visited 59, 71, and 67 sites, respectively. The 2002 cruise marked the end of the CRED random multi-site reef assessment era, while the 2003 and 2004 cruises established and revisited long-term monitoring sites. Long-term monitoring sites were selected by a multidisciplinary group of researchers to represent a variety of habitat types at each island that could be accessed on an annual basis regardless of prevailing weather or oceanographic conditions. At each site, phycologists worked along two 25-m transect lines set in a single-file row, with each transect separated by ~10 m. With the exception of some shallower back reef and lagoonal sites, most transects were placed at a standard 10 -15 m depth. Macroalgae were identified to species in the field when possible, and rankings of macroalgal genera were observed in each quadrat (1 being the most abundant, 2 being the next most abundant, etc., with 10 being the maximum number of genera found in a single quadrat) to determine RAM. Six quadrats were located at randomly selected points along the transects (three per transect), and six quadrats were located at points 3 m perpendicular from each random point in the direction of shallower water (Vroom et al., in press). Because of difficulties with identification in the field,

macroalgae that fell within the functional groups of cyanophytes, branched coralline algae, and crustose coralline algae were lumped into their respective categories. All ranked data were collected by the same individual during each sampling year (P. Vroom 2002, 2004; K. Page 2003) to minimize the effects of observer bias.

Data Analysis

The percentage of quadrats in which each species occurred was determined for each site sampled in 2004 and used to create distributional maps of algal abundance (Figs. 2, 3). Because ratios of major algal lineages (red, brown, and green algae) have been used historically to categorize tropical and temperate ecosystems (Cheney, 1977; Schils and Coppejans, 2003), macroalgal genera also were characterized by evolutionary group, and trends among the percentage of quadrats in which each evolutionary group occurred at each island were illustrated using SigmaPlot (Fig. 4).

To test whether significant differences of RAM existed among habitats and among islands, genus ranks from quadrats surveyed in 2002 and 2003 were treated as individual replicates within a site (n = 12), and a Bray-Curtis similarity matrix of quadrats was created using PRIMER-E (Clarke and Warwick, 2001). Two rigorous analyses using two-way nested analysis of similarity (ANOSIM; 5,000 permutations) were conducted: one nesting sites within habitat type, the other nesting sites within island. Relationships among sites from different habitat types based on RAM were visually depicted using multidimensional scaling (MDS; 30 restarts). Additionally, to depict relationships among islands (latitudes) based on RAM, data within the matrices were averaged by island, and a Bray-Curtis similarity matrix of this averaged data was generated. Ordinations of relationships were created via MDS and these relationships visually compared to geographic maps of the Archipelago (Figs. 1, 5).

To determine if RAM in the NWHI changed over time, several two-way crossed ANOSIMs were conducted (Factor A = year, Factor B = site; 5,000 permutations). In the first analysis, 17 sites from across the NWHI that were sampled in 2002, 2003, and 2004 were compared. In the second analysis, 55 sites from across the chain with data for 2003 and 2004 were compared. Finally, analyses for the 17 sites with 3 years of data were conducted by island (FFS, Lisianski, Pearl and Hermes Atoll (PHR), Midway, and Kure) to determine if particular islands in the NWHI were changing more than others.

RESULTS

Distribution and Abundance

During the 2004 sampling season, 65 species of macroalgae were identified in the field (22 chlorophytes, 34 rhodophytes, 9 phaeophytes) along with branched coralline, crustose coralline, cyanophyte, and turf algal functional categories. Most species occurred in only 1-5% of the quadrats sampled. However, species of the green algal genus *Halimeda* (particularly *H. velasquezii* Taylor and *H. opuntia* Lamouroux) were

found in over 70% of quadrats at numerous islands and were major substrate occupiers across broad geographic regions and habitat types (Figs. 2, 3). Other prevalent species such as the brown algae *Lobophora variegata* Agardh, *Stypopodium flabelliforme* Weber-van Bosse, and the red alga *Laurencia galtsoffii* Howe were locally abundant across several habitat types, but on only one to several islands in the northwestern part of the NWHI chain (Figs. 2, 3). Yet other species such as the green alga *Microdictyon setchellianum* Howe were found throughout the chain, but were abundant only in forereef to backreef regions (Figs. 2, 3).

When macroalgal distributional trends were considered based on evolutionary lineage, a lower prevalence (defined as the percentage of photoquadrats at a given site in which a genus or evolutionary group occurred) of green algae was observed at Midway Atoll than other islands in the NWHI (Fig. 4a). Gardner Pinnacles exhibited a lower prevalence of red algae when compared to Maro Reef, Laysan and Lisianksi Islands, and a higher prevalence of cyanophytes than any other island in the NWHI chain (Fig. 4b, d). The French Frigate Shoals also showed a lower prevalence of red algae than Maro Reef. Midway and Kure Atolls, located at the extreme northwest end of the Hawaiian Archipelago, revealed a higher prevalence of brown algae from all other islands except Gardner Pinnacles and the French Frigate Shoals (Fig. 4c).

Relative Abundance

A two-way nested ANOSIM of ranked data from 107 sites at nine islands found a moderately low global *r*-value between sites, indicating slight differences between RAM when sites from all habitats were compared simultaneously (Table 1). However, a negative global *r*-value for tests between habitats revealed that more algal variability existed among sites within a habitat type than between habitats (Chapman and Underwood, 1999). Pairwise comparisons among the three habitat types surveyed confirmed this finding (Table 1).

A similar two-way nested ANOSIM examining RAM among latitudinally distinct islands/atolls revealed a relatively low global *r*-value between sites, indicating negligible to slight differences between RAM when sites from all islands were compared simultaneously (Table 2). However, a negative global *r*-value for tests between islands revealed that more algal variability existed among reefs within an island ecosystem than between islands as a whole (Chapman and Underwood, 1999). Pairwise comparisons between individual islands confirmed this finding, with over 80% of the *r*-values generated being negative (Table 2). The remaining island comparisons exhibited *r*-values below 0.250 (Table 2), indicating that essentially no differences existed in algal genus abundance between these islands. However, a moderate difference was revealed between Necker Island and Gardner Pinnacles ecosystems with a mid-range *r*-value.

Relationships among habitats and islands based on RAM were illustrated using MDS (Fig. 5). Clearly, sites did not segregate into distinct clusters based on habitat type (Figure 5A), and a stress value above 0.20 indicated that the relationship of sites in the MDS ordination is close to arbitrary (Clarke and Warwick, 2001). However, relationships among islands as revealed through MDS were remarkably similar to a

physical map of the NWHI island chain (Figs. 1, 5B) even though ANOSIM was not particularly successful in defining differences between islands based on rank (Table 2). Necker Island, at the southeastern end of the island chain, was located at one end of the MDS plot, while Pearl and Hermes, Midway, and Kure atolls, located at the northwestern end of the island chain, were located at the opposite corner (Figure 5B). Additionally, Lisianski Island, Laysan Island, and Maro Reef, three mid-archipelago, non-atoll-like islands and reefs, appeared clustered together in the MDS plot about halfway between Necker Island and Kure Atoll. The French Frigate Shoals, a true atoll system, appeared to be the only ecosystem whose geographic location was not accurately reflected in the MDS ordination (Figs. 1, 5B).

Comparisons BetweenYears

R-statistics around or below 0.250 from two-way crossed ANOSIMs using ranked data indicate no major difference in RAM between years at sites located in the eastern end of the NWHI chain (Table 3). However, *r*-statistics above 0.300 at both Midway and Kure atoll indicate slight to moderate differences in RAM (Clarke and Warwick, 2001) among sites located in these high latitude reefs (Table 3) and suggest that changes in the reef environment may be occurring in these areas. *R*-statistics close to 0.250 indicate that RAM has not changed significantly when the NWHI are compared as a whole.

DISCUSSION

This study provides the first quantitative data for algal genera across the entire NWHI chain and lays the groundwork for continued macroalgal monitoring studies. Field data collected via the Preskitt method (Preskitt et al., 2004) proved sufficient to create distributional species maps (Figs. 2, 3) and conduct multivariate statistical analyses of RAM among habitats, islands, and sampling periods. ANOSIM analyses revealed that percent cover data (Vroom et al., 2005) is better at detecting differences between islands than ranked abundance data. However, the field-assigned macroalgal ranks (this study) provided critical data useful for quickly interpolating seasonal or yearly differences in RAM. If a particular species "blooms" at certain times of the year, its abundance will increase in relation to other species. Similarly, if environmental changes or anthropogenic activities favor the growth of certain species over others, RAM will change over time, and these changes may be detectable through basic statistical and multivariate analyses.

Distributional maps of six common macroalgal species demonstrated a necessary leeward sampling bias in long-term monitoring sites because of weather/oceanographic constraints (Figs. 2, 3). Despite this bias, important observational trends were evident. Green algae are the most abundant macroalgal group in terms of biomass and spatial coverage in the NWHI, and calcified species play an important role in sand production (P. Vroom, personal observation). *Halimeda velasquezii*, a species that has never been recorded in the Main Hawaiian Islands (Abbott and Huisman, 2003), is the single-most

ubiquitous alga, occurring in relatively high numbers in most habitats on all islands (Figs. 2, 3). *Microdictyon setchellianum* is most abundant in terms of percent cover, especially in forereef regions on the windward sides of atolls (Vroom et al., 2005). *Halimeda opuntia* forms dense three-dimensional mats on leeward reefs and in calm lagoonal waters. Although the brown algae *Lobophora variegata* and *Stypopodium flabelliforme* are found across the entire Hawaiian island chain, distributional maps clearly show these species to be more abundant in the northwestern-most atolls (Figs. 2, 3), a phenomenon also observed by Walsh et al. (2002) in their study of shallow lagoonal reef communities at Kure Atoll. While *S. flabelliforme* was a major component of shallow-reef systems at Kure Atoll, it was a minor component of reefs at most other islands and atolls in the NWHI. Because brown algae are known to predominate over other algal lineages in cool, temperate environments (Cheney, 1977), it is possible that the cooler sea-surface temperatures found at Kure and Midway atolls during winter months (Friedlander et al., 2005) may favor a higher abundance of brown algal species (Fig. 4).

Multivariate Primer analyses testing for differences in RAM among habitats (forereef, backreef, lagoonal reefs) revealed significant variation to occur within habitat type (Table 1), a phenomenon also observed in Vroom et al. (2005) during a detailed study of benthic cover at French Frigate Shoals. Considering the amount of environmental variation present within single habitats (e.g., water motion, turbidity, light, and nutrient availability), such findings are not surprising. More revealing than significant site differences within habitats was that multivariate analyses showed no major differences among islands as a whole (Table 2) despite known temperature variation over latitude (Friedlander et al., 2005). Algal diversity appears similar across the NWHI chain even though brown algae tend to be more abundant at Midway and Kure atolls than most other islands (Fig. 4). The lower abundance of green algae at Midway may be tied to lower apex predator biomass and higher herbivorous fish densities at this atoll system, suggesting possible top-down control of the benthic habitat (DeMartini and Friedlander, 2004; E. DeMartini, personal communication).

It is remarkable that the orientation of islands based on RAM mimics the spatial patterns and geographic relationships of these island ecosystems (Figs. 1, 5B). An MDS ordination of islands based on RAM closely resembles a geographic map of the NWHI and suggests that detectable (although not significant) differences in RAM exist among islands that mirror physical distance and latitude. The placement of French Frigate Shoals away from its closest geographical neighbors and close to the three northwestern-most islands suggests similarities in RAM between these four true atoll systems (Fig. 5B). Laysan, Lisianski, and Maro, three non-atoll reefs and islands, lack broad lagoonal regions and likely exhibit a different suite of habitat types than found in true atolls. The corresponding difference in RAM is shown through MDS by these islands clustering together a slight distance away from the atolls (Fig. 5B). Gardner and Necker, the only basaltic islands, are distant from the other seven islands depicted (Fig. 5B).

Although no significant temporal differences in RAM were observed when the NWHI were compared as a whole (Table 3), slight to moderate differences in RAM at Midway and Kure may result from mass coral-bleaching events that occurred in these high-latitude reefs during 2002 and 2004 (Aeby et al., 2003; Kenyon and Brainard,

2006). Although most dead coral were anecdotally observed to be overgrown with turf algae (P. Vroom, personal observation), increased substrate availability may also affect macroalgal community dynamics by clearing space for certain species to settle and grow. Although RAM may have increased because of this additional substrate availability, it is important to consider that algae are among the fastest growing organisms in reef systems, so seasonal or oceanographic differences (e.g., El Niño events) could rapidly alter RAM for short periods. Therefore, the slight differences observed at Midway and Kure atolls in this study do not necessarily indicate permanent changes.

Overall, reefs in the NWHI are healthy, top-predator-dominated ecosystems that naturally contain a diverse and abundant algal community. Although the mix of macroalgal species is relatively similar throughout the NWHI chain, certain species (e.g., *Stypopodium flabelliforme*, *Laurencia galtsoffii*) are more abundant in the northwestern-most atolls where sea surface temperatures experience the greatest annual fluctuation (Friedlander et al., 2005). The majority of macroalgal species in the shallow (<15 m) reef habitats surveyed exhibit relatively low abundances and occurred in 1-5% of quadrats sampled for a particular island. However, species of the green algal genera *Halimeda* and *Microdictyon* often formed dense meadows with up to 100% cover in some areas. Dense meadows of algae have also been documented in deeper bank habitats not considered in this manuscript (Parrish and Boland, 2004). Future annual or biennial monitoring at established long-term sites will continue to provide understanding of normal macroalgal community dynamics and alert reef managers to permanent changes of RAM in these unique reef habitats.

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Table 1: RAM habitat comparisons: r-values of two-way nested ANOSIM (5,000 permutations).

Sample Statistic (Global R)	Sample Statistic (Global R)	Significance level of sample statistic	Number of permuted statistics > or = to Global R
Tests for differences between sites (averaged across all habitats)	0.372	0.%	0
Tests for differences between habitats (using sites as samples)	-0.346	100.%	5000
Sample statistics of pairwise tests:			
Fore-reef to backreef	-0.164		
Fore-reef to lagoonal reef	-0.463		
Back-reef to lagoonal reef	-0.233		

Table 2: RAM island comparisons: r-values of two-way nested ANOSIM. FFS = French Frigate Shoals, PHR = Pearl and Hermes Atoll (5,000 permutations).

	Sample Statistic (Global R)	Significance level of sample statistic	Number of permuted statistics > or = to Global R
Tests for differences between sites (averaged across all islands)	0.321	0.%	0
Tests for differences between islands (using sites as samples)	-0.162	100.%	5000

Sample statistics of pairwise tests:

	Kure	Midway	PHR	Lisianski	Laysan	Maro	Gardner	FFS	Necker
Necker	-0.152	-0.323	-0.089	-0.545	-0.600	-0.631	0.333	-0.621	
FFS	-0.020	0.122	-0.205	-0.115	-0.370	0.020	0.132		
Gardner	-0.435	-0.414	-0.474	-0.428	-0.364	-0.348			
Maro	-0.227	0.091	-0.179	-0.510	-0.457				
Laysan	-0.370	0.068	-0.282	-0.222					
Lisianski	-0.232	0.171	-0.185						
PHR	-0.408	-0.104							
Midway	-0.003								

Table 3: RAM year comparisons: results of two-way crossed ANOSIMs (5,000 permutations). Pairwise tests between sites not shown. FFS = French Frigate Shoals, PHR = Pearl and Hermes Atoll. One site for Laysan Island was included in the NWHI test between 2003-2004 but is not listed independently.

	Tests for differences in RAM among sites between 2002, 2003, 2004.				Tests for differences in RAM among sites between 2003 and 2004.			
Island	# sites	Sample statistic (Global R)	Significance level of sample statistic	Number of permuted statistics > or = to Global R	# sites	Sample statistic (Global R)	Significance level of sample statistic	Number of permuted statistics > or = to Global R
NWHI	17	0.277	0.%	0	55	0.229	0.%	0
FFS	3	0.253	0.%	0	11	0.217	0.%	0
Gardner	-	-	-		2	0.097	1.3%	63
Maro	-	-	-		7	0.162	0.%	0
Lisianksi	2	0.281	0.%	0	8	0.206	0.%	0
PHR	4	0.169	0.%	0	12	0.149	0.%	0
Midway	4	0.337	0.%	0	5	0.313	0.%	0
Kure	4	0.340	0.%	0	9	0.437	0.%	0

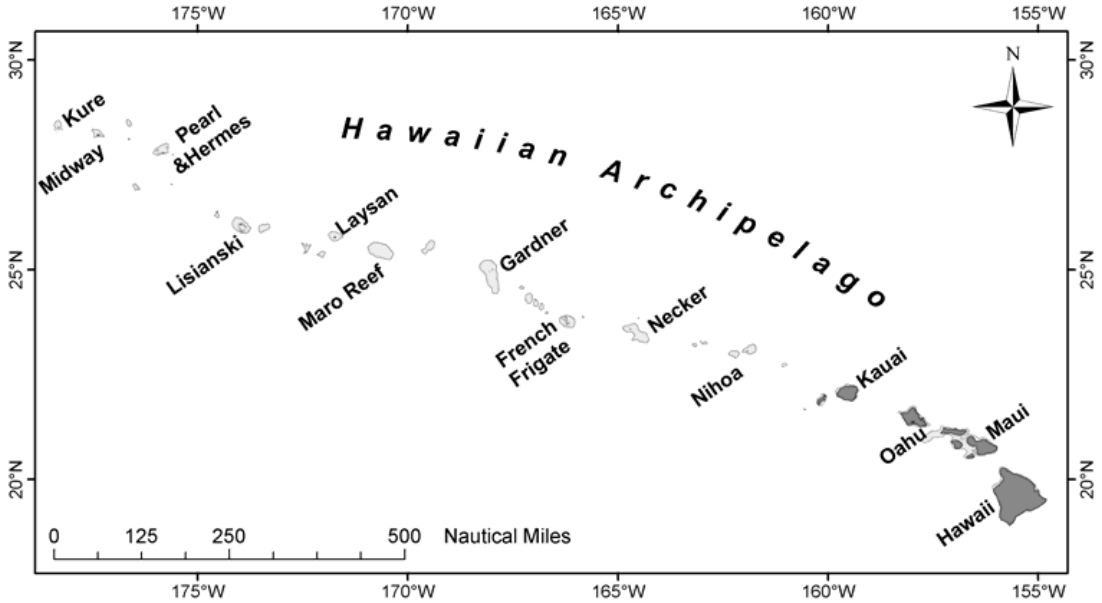

Figure 1. Map of the Hawaiian Archipelago. The 10-NWHI span from Nihoa Island to Kure Atoll.

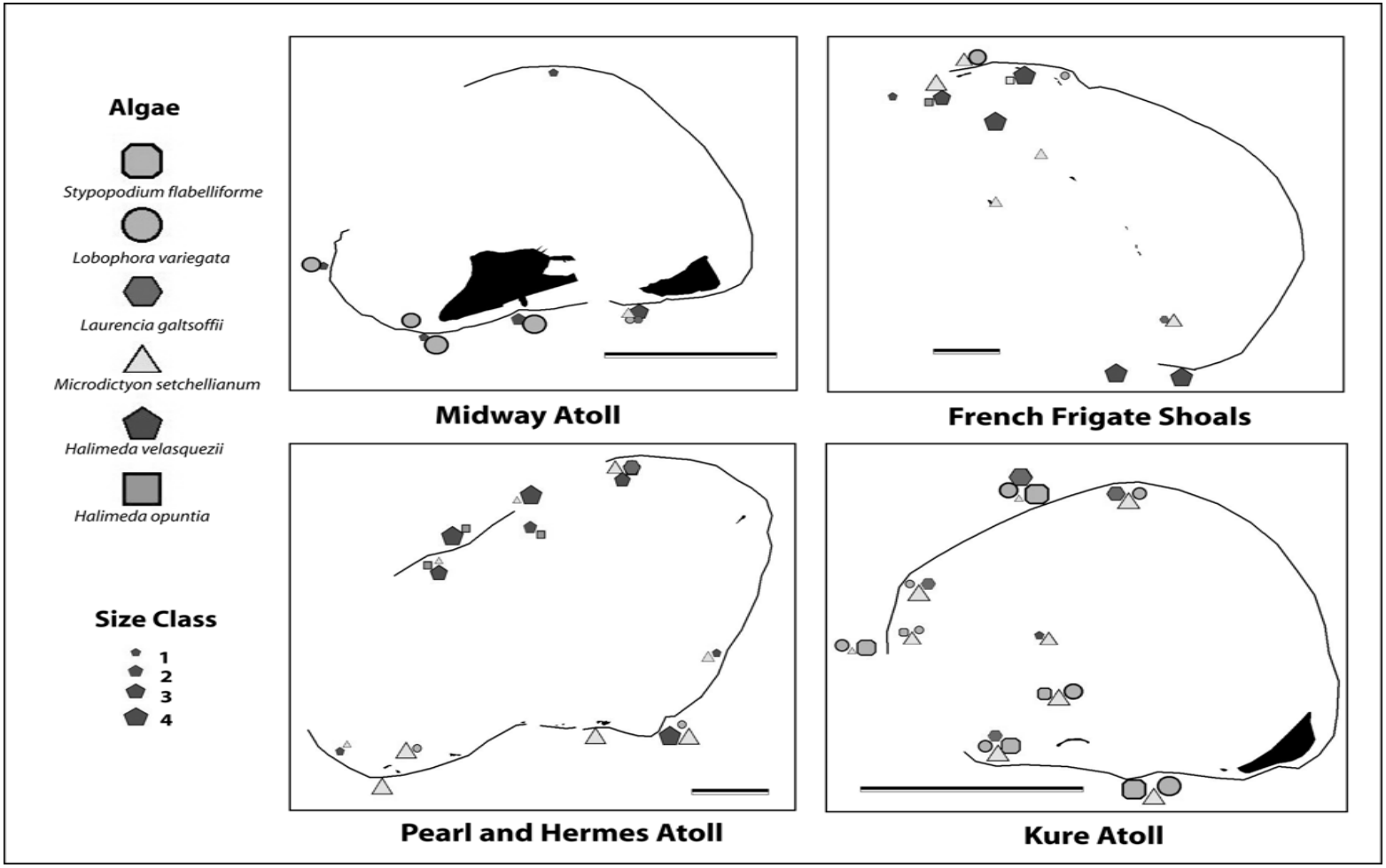

Figure 2. Outline drawings of the four atoll systems located in the Northwestern Hawaiian Islands overlaid with algal distributional maps. Solid black lines indicate position of reef crest. Scale bars = 5 km. Size classes refer to the percentage of quadrats in which an alga occurred at a given site: 1 = 1-25%, 2 = 26-50%, 3 = 51-75%, 4 = 76-100%.

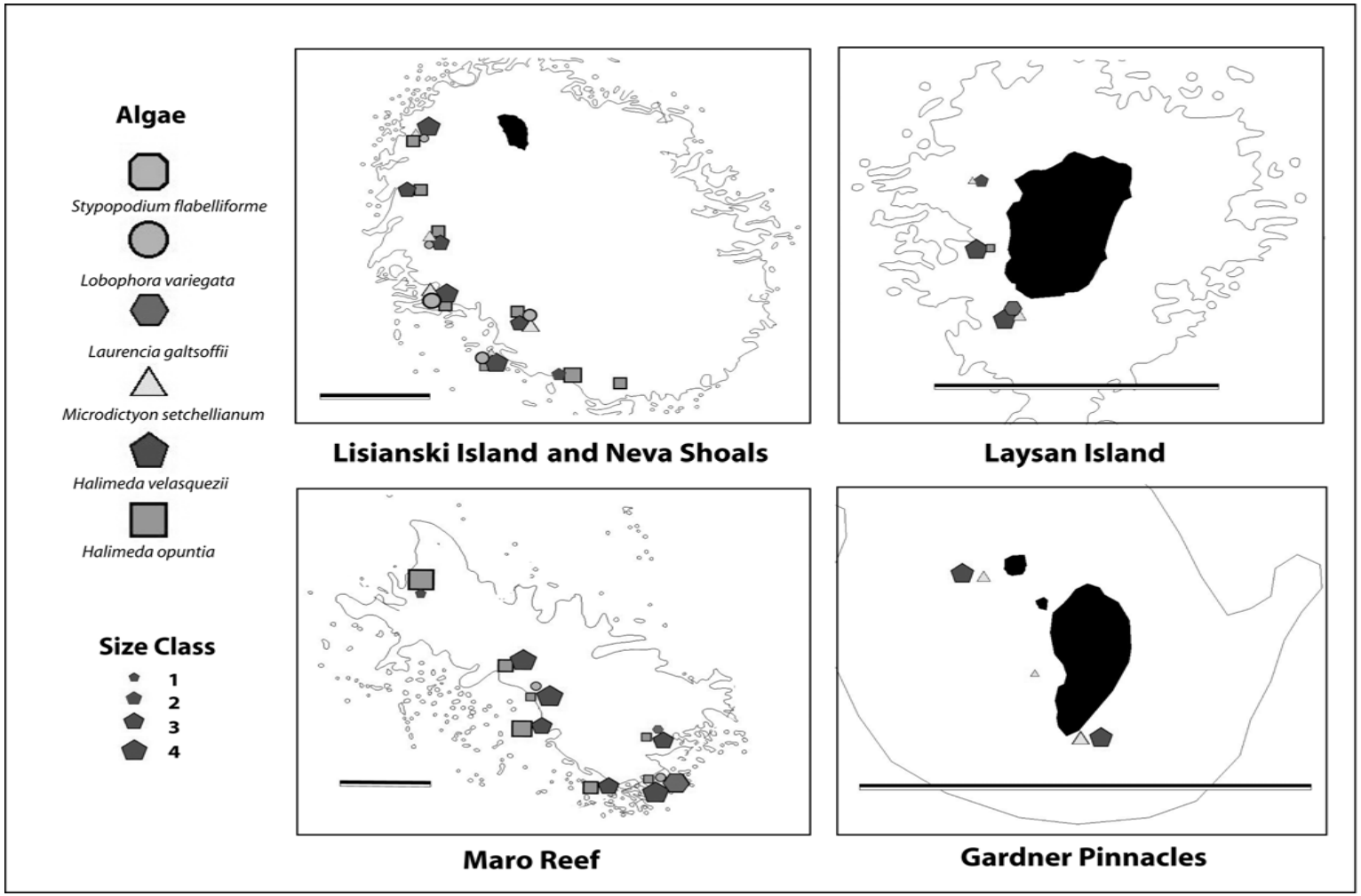

Figure 3. Outline drawings of four island reefs in the Northwestern Hawaiian Islands overlaid with algal distributional maps. Thin black lines indicate a 10-fathom isobath. Scale bar for Lisianki, Laysan, Maro = 5 km. Scale bar for Gardner = 1 km. Size classes refer to the percentage of quadrats in which an alga occurred at a give site: 1 = 1-25%, 2 = 26-50%, 3 = 51-75%, 4 = 76-100%.

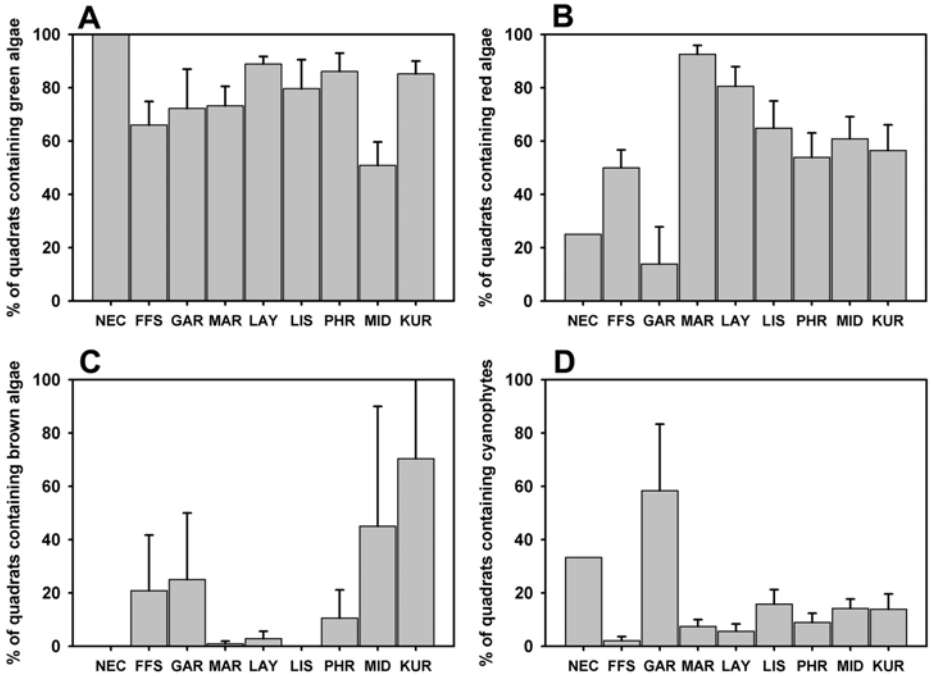

Figure 4. Prevalence of major algal lineages in the Northwestern Hawaiian Islands. Bars = standard deviation. A. Green algae; B. Red algae; C. Brown algae; D. Cyanophytes.

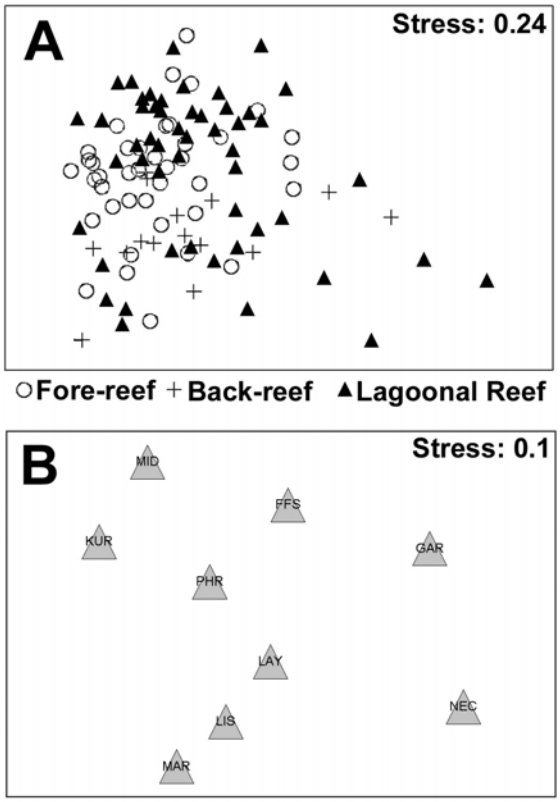

Figure 5. MDS plots. A. Relationships of 107 sites sampled throughout the NWHI based on relative abundance of macroalgae (RAM). Symbols indicate habitat type in which each site was located. B. Relationships among the NWHI based on RAM.

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