University of Guam – Marine Laboratory
For the Micronesia Conservation Trust
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Background for Micronesia Challenge Monitoring Protocols and Assessment Framework

From 2011 and 2014 the Micronesia Conservation Trust and its partners, including the University of Guam Marine Laboratory, implemented a Cooperative Agreement for the *Building sustainable coral reef monitoring and management capacity for the Micronesia Challenge, and Beyond.* This project had the following objectives:

- Gaps in coral reef management and monitoring capacity in the Federated States of Micronesia, the Republic of Palau, and the Republic of the Marshall islands are identified, and recommendations developed to address them

- Each jurisdiction has trained and well coordinated coral reef monitoring teams

- All monitoring teams are conducting standardized monitoring protocols, and established databases are functional and accessible to all resource owners

- Local jurisdictional teams are effectively providing ongoing training and mentoring in community-based observation, compliance, and enforcement for protected areas in at least two new jurisdictions

- The Micronesia Sustainable Financing Plan is adopted by all jurisdictions and at least one internal income generation strategy is being implemented in the Federated States of Micronesia and the Republic of the Marshall Islands

This project supported the Micronesia Challenge, an overarching regional conservation effort. Recognizing the need to work together at the regional level to confront environmental and sustainable development issues, in a rapidly changing world, the Chief Executives of the Federated States of Micronesia, the Republic of the Marshall Islands, the Republic of Palau, the U.S. Commonwealth of the Northern Mariana Islands, and the U.S. Territory of Guam, collectively committed to the Micronesia Challenge (MC), with a declared goal to: *Effectively conserve at least 30% of the near-shore marine resources and 20% of the terrestrial resources across Micronesia by 2020.*

To advance the goals of the MC, partners developed marine monitoring protocols and an assessment framework during several MC Measures Working Group meetings conducted between 2011 and 2014. Under the Cooperative Agreement referenced above, project partners used the MC protocols to collect standardized datasets that serve as inputs into the evolving assessment framework. Current project partners are finalizing the assessment framework and formally assessing the MC. The following document contains standardized monitoring protocols and a first draft of this assessment framework.

MC Monitoring Protocols and Assessment Framework

The reef-assessment protocol was designed to address the highest priority management questions at both local and regional scales (Figure 1). Accordingly, sites were stratified across (i) management regimes, (ii) wave exposure, (iii) islands, and (iv) major reef habitats, to be representative of each island. Cumulatively, Appendix 1 reports upon data from 78 sites across the Marshall Islands, Federated States of Micronesia, and Commonwealth of the Northern Mariana Islands, which were examined between 2012 and 2014 (Table 1). However, these protocols are employed by the Palau International Coral Reef Research Institute as well. With the exception of Palau, data were collected by local monitoring teams in collaborative partnerships with Dr. Peter Houk's research lab at the University of Guam (names listed in the body of final NOAA report). These organizations are responsible for coral-reef monitoring activities and have the legislative authority to conduct research. Further, non-invasive research was conducted which included photographs and visual estimates described below. Given the non-invasive nature of research, no further permits were required. Table 1 contains the GPS coordinates for all research sites.

MC field protocols were designed with high-statistical power (80%) to detect a relative change of 25% for all the benthos, with absolute abundances of 20% or greater at the site level [1]. At each site, five 50-m transects were used to measure fishes, corals, and other benthic assemblages between 8–10 m on outer reefs, and at 3–5 m for inner lagoon reefs. A single depth was selected to maximize the number of monitoring sites across the region, while keeping within logistical constraints. Depths were selected to match zones of optimal coral growth.

Benthic substrates were evaluated using a photo-quadrat technique. Fifty photos were taken at 1-m intervals along each 50-m transect line. Within each photo the benthic substrates were evaluated under five randomly allocated crosses. Benthic-assemblage metrics were derived from data aggregated across the 50 photographs, to the transect level (n=5). Metrics included coral and macroalgal cover, coral-genus richness, and a benthic substrate ratio defined by the percentage cover of heavily calcifying (corals and CCA) versus non-or-low calcifying (turf, encrusting, and macroalgae) substrates.

Coral-assemblage data represent an optional component of MC monitoring (as defined in 3rd MC measures report) that is performed whenever individuals with the necessary skillsets exist. For FSM, RMI, and CNMI, coral assemblage data were collected by a single observer (PH) in all of the jurisdictions except CNMI, where a calibrated observer (SJ) also collected data. During each survey, 10 replicate 1 m^2 quadrats were haphazardly tossed at equal intervals along the transect lines. On the reefs of CNMI, 16 tosses of a 0.5 m^2 were alternatively used to account for inherent difference in coral-assemblage demography. Sampling intensity was selected in accordance with multivariate data saturation points, whereby individual quadrats were sequentially incorporated into principle component ordinations until a saturation point was exceeded [1,2]. For each quadrat, all coral colonies with their center points within the quadrat boundary were measured for maximum diameter (x), and for the diameter perpendicular to the maximum (y). Surface area was calculated assuming colonies were elliptical. Coral taxonomy followed [3].

The size and abundance of fishes that are consumed by people (hereinafter food-fish) were collected by four calibrated observers, with individual observers being consistent across jurisdictions. Fish assemblages were estimated from 12 stationary-point counts (SPCs) conducted at equal intervals along the transect lines. At each SPC, the observer recorded the species name and the size of all food-fish within a 5 m circular radius for a period of 3 minutes. Food-fish were defined as acanthurids, scarids, serranids, carangids, labrids, lethrinids, lutjanids, balistids, kyphosids, mullids, holocentrids, and sharks. The sizes of fishes were binned into 5 cm categories, and converted to biomass using coefficients from regional fishery-dependent data when available, or from FishBase (www.fishbase.org).

MC Assessment Protocol

Classification of reef habitats

The major reef habitats were distinguished using principle component analyses, ordination plots, and multivariate tests of comparison using the benthic-substrate data [4] (Figure 2). Subsequent analyses of 'ecosystem condition' were nested within both jurisdictions and major-reef habitats. The reef habitats differed in accordance with island geology, however some habitats were common throughout the region, including outer reefs, inner reefs, patch reefs, and channel reefs. In the case of CNMI, previous work had already identified the main reef types, including spur-and-groove reefs, interstitial-framework reefs, and Rota-island reefs with limited Holocene framework [5]. Notably, these reef types had a non-uniform distribution across CNMI. Only outer reefs were evident on Namdrik and Kosrae.

'Effective management' and 'ecological condition'

In order to assess 'effective management' and 'ecological condition', latent variables were generated from each of the biological data outlined above (Figure 3). Latent variables were comprised of several biological metrics that originated from working groups across the jurisdictions. Metrics were associated with ecological processes and principles central to ecosystem function and maintenance (Table 2). While attention was given to omit highly correlated metrics, sensitivity analyses were performed to assess their relative contributions. Both the diversity of latent variables and stratification by major habitat within each jurisdiction were used to reduce anomalous influences of past disturbances on estimates of ecological condition. Major disturbances have not been observed on the study islands since 2009 with the exception of Kosrae, where a moderate bleaching event occurred in 2013 (personal observation, PH), one year prior to data collection. Elsewhere, data were collected before recent thermal-stress anomalies in CNMI and Marshall Islands.

Latent variables associated with coral assemblages were derived from coral-colony surveys: (i) assemblage heterogeneity, (ii) size-frequency skewness, (iii) species richness, and (iv) Shannon-Weaver evenness. Heterogeneity was measured by multivariate Bray-Curtis dissimilarities, which were highest with species composition differences among replicate coral quadrats. The skewness of size-frequency distributions was an approximate measure of the dominance of specific coral-colony sizes. Latent variables associated with benthic substrates were derived from photo-quadrat surveys: (v) coral cover, (vi) benthic-substrate ratio, (vii) coral evenness, and (viii) macroalgal cover. Latent variables associated with the food-fish assemblages were: (ix) assemblage heterogeneity, (x) fish-assemblage size, (xi) fish-assemblage biomass, and (xii) apex-predator biomass.

All metrics were sorted from low-to-high and standardized by reef type within each jurisdiction. Ecosystem-condition scores were calculated using the following equation:

$$\sum_{i=1}^{n} \frac{\left(\frac{c_i+b_i}{2}\right)+f_i}{2} \quad (1),$$

where c_i, b_i, and f_i, represent latent-variable scores for corals, the benthic substrate, and food-fish, respectively, across *n* sites within each jurisdiction and reef habitat. Reef habitats within each jurisdiction are hereafter referred to as strata. These calculations provided equal weighting to the mobile and sessile components of the ecosystem. Ecosystem-condition scores were normalized to the maximum value, and 'effective conservation' was attributed to all sites that were within one standard deviation (mean SD = 30%) of the maximum score. Effective conservation for the Micronesia Challenge was then calculated by taking the number of sites that exceeded the 70% threshold. The logic behind establishing a cutoff threshold was to facilitate a regional comparison that highlighted the relative differences among jurisdictions and habitats. In addition, complementary investigations between ecosystem-condition scores and localized stressors were conducted.

Literature Cited

1. Houk P, Van Woesik R (2013) Progress and Perspectives on Question-Driven Coral-Reef Monitoring. BioScience 63: 297-303.
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3. Veron JEN (2000) Corals of the World; Stafford-Smith M, editor. Townsville.
4. Anderson M, Gorley R, Clarke K (2008) PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods. Plymouth.
5. Houk P, van Woesik R (2010) Coral assemblages and reef growth in the Commonwealth of the Northern Mariana Islands (Western Pacific Ocean). Mar Ecol 31: 318-329.

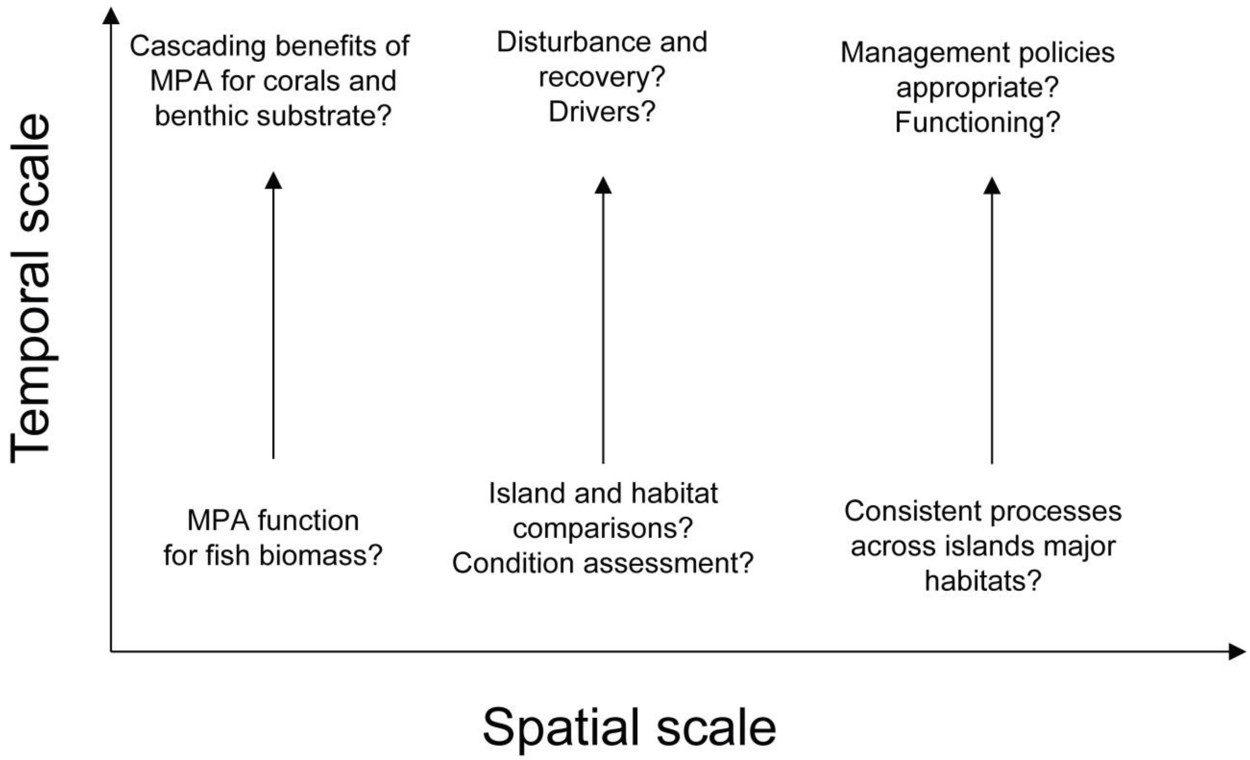

Figure 1. Examples of pressing questions driving monitoring designs for collaborative coral-reef monitoring across Micronesia, and their spatial and temporal scales of operation.

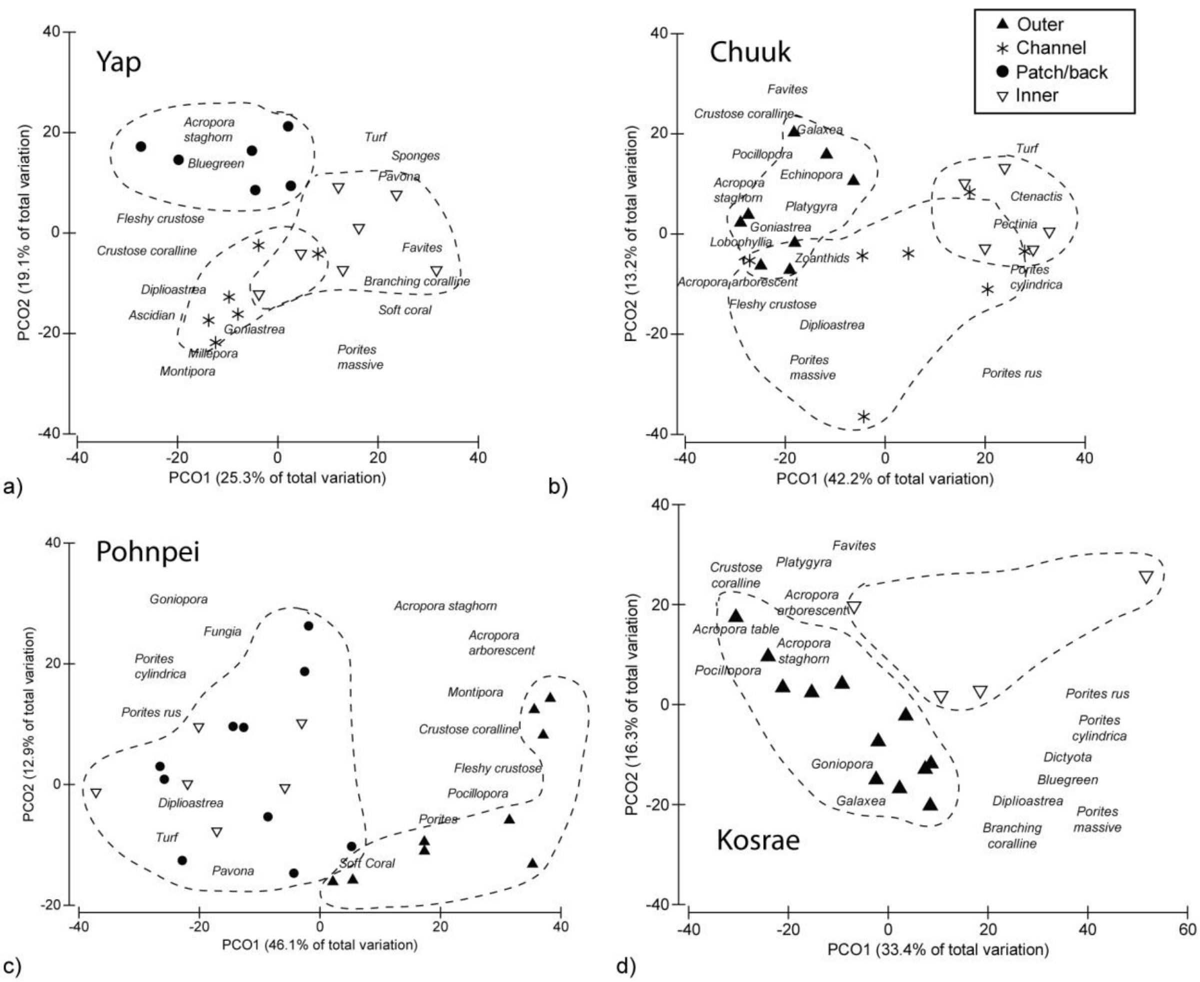

Figure 2. Principle components ordination plots of benthic substrate abundances across jurisdiction-reeftypes in Micronesia. Dashed lines indicate significant differences based upon permutational multivariate analyses of comparisons. Influential substrate categories are shown on the plots, with their location depicting their affinity with major reeftypes. Locations of substrates categories on the plots were derived from spearman rank correlation coefficients with PCO axes ($\rho > 0.5$).

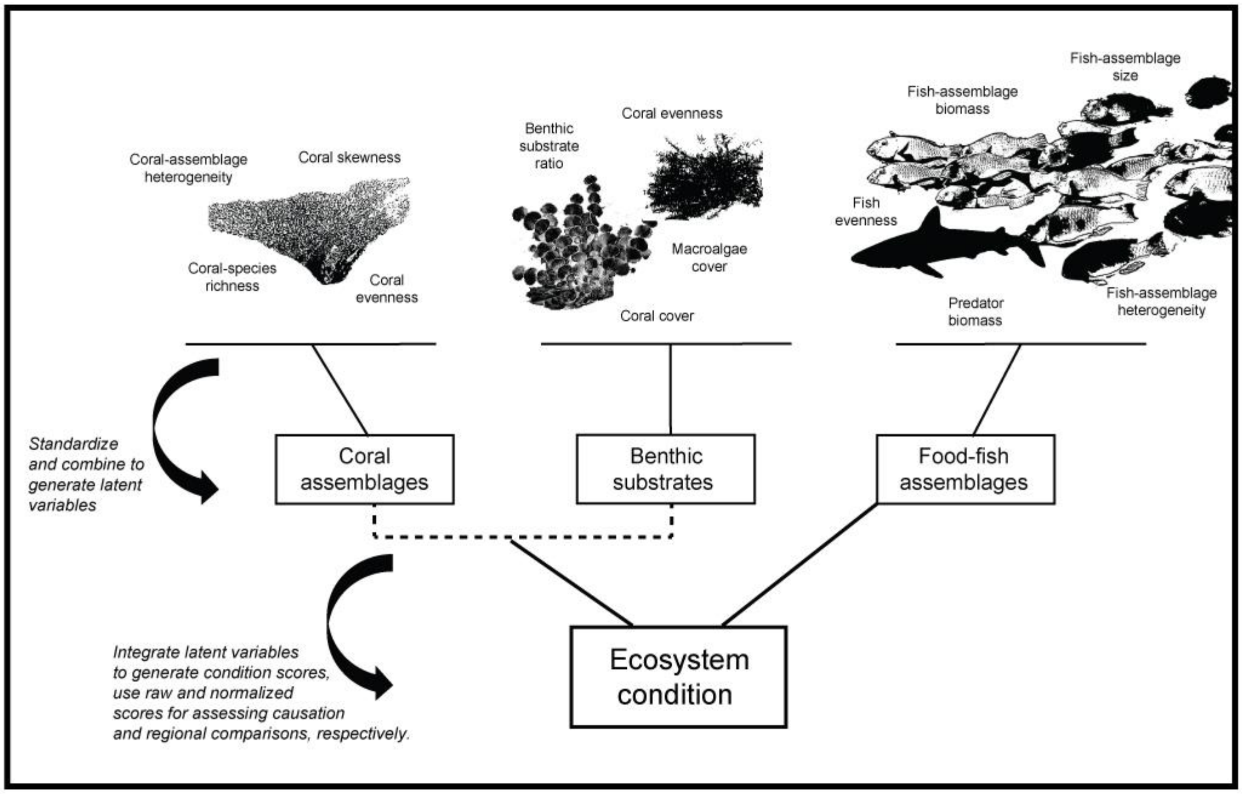

Figure 3. Ecosystem condition evaluation process depicting the contribution of individual biological metrics on their respective latent variables, and the weighting of latent variables on overall condition scores. Latent variables were generated from independent datasets. Biological metrics were established by a working group of regional scientists, and linked with key processes required for ecosystem function and maintenance (Table 2).

Table 1. Site-based characteristics and biological metrics generated from MC Protocols.

Jurisdiction	Island	Site	Local name	GPS X	GPS Y	Reef type	MPA Status	Wave Exposure (J/m3)	Distance from major fishing port (km)	Fishing proxy (standardized by strata and combined)	Disturbed land in watershed (km2)	Distance from discharge (km)	Pollution proxy (standardized by strata and combined)
Commonwealth of the Northern Mariana Islands	Aguijan	CNMI-1	AGU_12	342807	1642480	Spur-and-groove	No	629.8	38.6	4.37	0.04	0.12	4.65
Commonwealth of the Northern Mariana Islands	Rota	CNMI-10	ROT-6_12	300459	1566145	Rota raised Holocene	No	365.4	3.4	12.61	0.19	0.18	4.01
Commonwealth of the Northern Mariana Islands	Rota	CNMI-11	RR_12	308740	1570072	Rota raised Holocene	No	965.3	12.8	3.79	0.29	0.12	6.51
Commonwealth of the Northern Mariana Islands	Rota	CNMI-12	SAHY_12	299569	1563743	Rota raised Holocene	No	161.1	0.5	14.37	0.11	0.18	3.03
Commonwealth of the Northern Mariana Islands	Rota	CNMI-13	TALK_12	305271	1561044	Rota raised Holocene	No	584.0	7.2	3.56	0.56	0.22	7.21
Commonwealth of the Northern Mariana Islands	Rota	CNMI-14	WHB_12	298271	1563772	Rota raised Holocene	No	407.0	0.6	13.63	0.09	0.39	0.38
Commonwealth of the Northern Mariana Islands	Saipan	CNMI-2	BI_12	372724	1687351	Spur-and-groove	Yes	501.2	25.6	7.88	0.09	0.21	3.96
Commonwealth of the Northern Mariana Islands	Saipan	CNMI-3	COP_12	360977	1670710	Spur-and-groove	No	128.7	7.42	13.91	0.29	0.15	6.22
Commonwealth of the Northern Mariana Islands	Saipan	CNMI-4	LLB#1_12	366425	1676402	Spur-and-groove	No	224.3	21.4	10.11	0.09	0.21	3.99
Commonwealth of the Northern Mariana Islands	Saipan	CNMI-5	OBY_12_2	364397	1670287	Spur-and-groove	No	127.8	10.9	13.33	0.13	0.17	4.78
Commonwealth of the Northern Mariana Islands	Saipan	CNMI-6	OGND_12	359633	1676634	Spur-and-groove	No	304.0	1.7	15.65	N/A	N/A	0.45
Commonwealth of the Northern Mariana Islands	Saipan	CNMI-7	TANK_12	369943	1678305	Spur-and-groove	Yes	2530.1	27.4	1.86	1.16	0.25	9.54
Commonwealth of the Northern Mariana Islands	Saipan	CNMI-8	WB_11	370155	1688934	Spur-and-groove	No	360.5	15.2	11.31	N/A	N/A	0.45
Commonwealth of the Northern Mariana Islands	Tinian	CNMI-9	TIN - 1 (12)	355222	1662018	Spur-and-groove	No	2215.9	14.8	5.15	0.04	0.24	3.35
Federated States of Micronesia	Chuuk	CHK-1	Puwe	837023	377259	Patch	No	247.0	12.6	8.94	N/A	N/A	N/A
Federated States of Micronesia	Chuuk	CHK-10	Fourupw	806821	341489	Channel	No	262.3	37.4	13.76	N/A	N/A	N/A
Federated States of Micronesia	Chuuk	CHK-11	Wininen	793255	384328	Patch	No	426.5	36.2	1.68	N/A	N/A	N/A
Federated States of Micronesia	Chuuk	CHK-12	Oun	836404	354517	Channel	No	2021.6	21.6	3.06	N/A	N/A	N/A
Federated States of Micronesia	Chuuk	CHK-13	Moch	831950	386042	Channel	No	195.6	13.8	14.00	N/A	N/A	N/A
Federated States of Micronesia	Chuuk	CHK-14	Sapuk	824304	379043	Inner	No	40.0	7.8	12.50	0.04	0.58	2.67
Federated States of Micronesia	Chuuk	CHK-15	Apichun	819913	378854	Patch	No	59.9	12.2	13.44	N/A	N/A	N/A
Federated States of Micronesia	Chuuk	CHK-16	Manukun	808363	375577	Inner	No	117.9	18.2	7.06	0.04	0.29	4.31
Federated States of Micronesia	Chuuk	CHK-17	Fanangal	833887	368737	Patch	No	195.0	9.9	10.90	N/A	N/A	N/A
Federated States of Micronesia	Chuuk	CHK-18	Och	817621	361795	Inner	No	318.8	13.1	6.62	0.01	0.81	1.31
Federated States of Micronesia	Chuuk	CHK-19	none yet	806077	356745	Inner	No	665.1	24.7	1.56	N/A	N/A	4.34
Federated States of Micronesia	Chuuk	CHK-2	Truk Stop	822864	371782	Inner	No	229.7	2.9	12.20	0.71	0.33	10.60
Federated States of Micronesia	Chuuk	CHK-3	Sanat	800230	390961	Channel	No	157.3	32.3	6.71	N/A	N/A	N/A
Federated States of Micronesia	Chuuk	CHK-4	Aroch	800578	378381	Patch	No	144.5	28.5	7.60	N/A	N/A	N/A
Federated States of Micronesia	Chuuk	CHK-5	Oranu	826638	344641	Channel	No	136.7	28.7	6.59	N/A	N/A	N/A
Federated States of Micronesia	Chuuk	CHK-6	Parem	814354	365876	Inner	No	11.4	11.2	11.30	0.07	0.20	5.14
Federated States of Micronesia	Chuuk	CHK-7	Piis	848755	365095	Channel	No	228.0	25.3	9.21	N/A	N/A	N/A
Federated States of Micronesia	Chuuk	CHK-8	Falos	833313	363960	Patch	No	0.2	11.8	15.00	N/A	N/A	N/A
Federated States of Micronesia	Chuuk	CHK-9	Nematon	814047	343125	Inner	No	2.7	40.2	15.54	0.07	0.92	0.87
Federated States of Micronesia	Kosrae	KOS-1	Buoy-16	582358	276178	Outer	No	127.5	13.8	7.85	0.11	0.25	4.77
Federated States of Micronesia	Kosrae	KOS-2	Buoy-8	584519	281554	Outer	No	2382.2	6.9	5.29	0.20	1.27	4.00
Federated States of Micronesia	Kosrae	KOS-4	Buoy-TS	591012	272464	Outer	No	122.0	2.1	15.82	0.47	1.49	5.65
Federated States of Micronesia	Kosrae	KOS-5	Buoy-44	553424	167286	Outer	No	813.0	4.1	11.90	0.36	0.63	8.50
Federated States of Micronesia	Kosrae	KOS-6	Buoy-50	553002	278247	Outer	No	2372.3	6.1	5.55	0.09	0.35	4.88
Federated States of Micronesia	Kosrae	KOS-7	Buoy-20	582503	273344	Outer	No	239.8	16.8	5.65	N/A	N/A	0.84
Federated States of Micronesia	Kosrae	KOS-2	Buoy-27	585054	267521	Outer	No	156.8	12.5	8.67	N/A	N/A	0.84
Federated States of Micronesia	Pohnpei	PNI-1	Sapwitik MPA Inner Reef	774869	414498	Inner	Yes	33.6	5.74	7.44	4.64	5.16	4.55
Federated States of Micronesia	Pohnpei	PNI-9	Pearem patch reef	773142	419563	Inner	No	39.3	12.9	5.20	0.18	3.55	2.16
Federated States of Micronesia	Pohnpei	PNI-10	Black Coral	751750	401833	Outer	Yes	151.4	31.1	9.99	N/A	N/A	N/A
Federated States of Micronesia	Pohnpei	PNI-11	Laiap Island	749443	410766	Inner	Yes	6.8	37.8	7.21	0.30	2.74	2.74
Federated States of Micronesia	Pohnpei	PNI-2	Palikir Channel	771437	403790	Inner	No	23.9	11.2	9.24	0.71	6.84	0.62
Federated States of Micronesia	Pohnpei	PNI-12	Nahtik Inner	749411	413314	Inner	No	2.2	40.9	7.03	0.39	2.12	3.23
Federated States of Micronesia	Pohnpei	PNI-13	Nan Mwokil	748516	417939	Inner	No	0.3	45.3	6.07	0.43	4.14	2.11
Federated States of Micronesia	Pohnpei	PNI-14	Nan Pwin	751234	424215	Outer	No	2403.0	53.1	2.38	0.35	2.48	N/A
Federated States of Micronesia	Pohnpei	PNI-15	Nan Wap Outer	759729	429066	Outer	Yes	2367.0	32.9	4.87	2.78	7.63	N/A
Federated States of Micronesia	Pohnpei	PNI-16	Nan Wap Inner	759707	427638	Inner	Yes	2.8	35.7	8.28	2.78	5.30	3.04
Federated States of Micronesia	Pohnpei	PNI-17	Madamken	768932	426178	Outer	No	2367.9	23.6	6.00	N/A	N/A	N/A
Federated States of Micronesia	Pohnpei	PNI-3	Palikir Inner Reef (Mwahng)	769443	405093	Inner	No	5.2	11.7	13.85	0.07	2.03	2.76
Federated States of Micronesia	Pohnpei	PNI-4	Main Channel (Sokehs)	773711	409658	Outer	No	24.4	5.4	16.56	4.59	5.23	N/A
Federated States of Micronesia	Pohnpei	PNI-5	Nan Mweli Outer Reef	779036	414985	Outer	No	288.1	9.9	14.58	N/A	N/A	N/A
Federated States of Micronesia	Pohnpei	PNI-6	Pwukihn Dawahk Outer Reef	768618	399166	Outer	No	220.5	18.8	12.72	N/A	N/A	N/A
Federated States of Micronesia	Pohnpei	PNI-7	Pehleng Channel	758640	401697	Inner	No	29.9	24.1	5.97	2.52	5.51	2.62
Federated States of Micronesia	Pohnpei	PNI-8	Mwahnd MPA Inner Reef	774875	422339	Inner	Yes	1.7	14.1	14.10	0.18	6.23	0.79
Federated States of Micronesia	Yap	YAP-1	Atliw	1058744	181245	Outer	No	839.5	19.9	10.26	0.14	1.23	N/A
Federated States of Micronesia	Yap	YAP-9	Gafnuw Channel	1059013	192630	Channel	No	202.4	19.6	5.30	1.61	3.20	1.77
Federated States of Micronesia	Yap	YAP-10	M'il Inner Reef	1063528	185988	Inner	No	19.0	11.4	4.77	0.19	1.56	2.10
Federated States of Micronesia	Yap	YAP-11	Pakel	1054712	184646	Inner	No	1.1	3.1	14.10	1.32	1.67	3.60
Federated States of Micronesia	Yap	YAP-12	Toruw	1063860	191153	Outer	No	1772.1	22.6	4.42	N/A	N/A	N/A
Federated States of Micronesia	Yap	YAP-14	Nimpal Channel	1056509	179732	Channel	Yes	243.2	21.2	4.09	0.18	0.94	1.21
Federated States of Micronesia	Yap	YAP-2	Gachug	1053766	178195	Channel	No	6.6	23.7	7.48	0.98	1.39	4.86
Federated States of Micronesia	Yap	YAP-3	N'ef Blue Hole	1048969	176663	Inner	No	8.1	26.1	4.69	0.02	0.72	4.06
Federated States of Micronesia	Yap	YAP-4	Reey Outer Reef	1048630	175506	Outer	Yes	808.8	24.1	7.83	N/A	N/A	N/A
Federated States of Micronesia	Yap	YAP-5	Af Blue Hole	1052437	186614	Inner	No	2.1	3.1	13.66	0.00	0.71	4.02
Federated States of Micronesia	Yap	YAP-6	Gabach Channel	1049852	183837	Channel	No	0.9	5.2	16.44	1.33	2.45	3.57
Federated States of Micronesia	Yap	YAP-7	Garim	1045326	179338	Outer	No	1830.4	11.6	7.39	N/A	N/A	N/A
Federated States of Micronesia	Yap	YAP-8	Pelak Channel	1053411	190363	Channel	No	1.8	10.7	13.78	1.14	1.64	5.02
Federated States of Micronesia	Yap	Yap-15	Rumong outer reef	1067126	186067	Outer	No	1064.4	16.26	11.02	N/A	N/A	N/A
Federated States of Micronesia	Yap	Yap-13	Af outer reef	1050819	187756	Outer	Yes	1647.0	7.1	10.44	N/A	N/A	N/A
Republic of the Marshall Islands	Namdrik	NAM-1	Nam-1	618775	178446	Outer	No	253.3	1.6	15.66	0.00	0.46	1.02
Republic of the Marshall Islands	Namdrik	NAM-2	Nam-2	618469	180888	Outer	No	785.2	3.9	11.12	0.00	0.30	-0.04
Republic of the Marshall Islands	Namdrik	NAM-3	Nam-3	623866	180412	Outer	No	2270.6	9.1	3.17	0.00	0.74	-0.66

Republic of the Marshall Islands	Namdrik	NAM-4	Nam-4	623966	177201	Outer	No	63.6	4.6	12.39	N/A	N/A	-0.19
Republic of the Marshall Islands	Namdrik	NAM-5	Nam-6	621759	182159	Outer	No	2659.0	8.3	3.03	0.00	0.24	0.32
Republic of the Marshall Islands	Namdrik	NAM-6	Nam-7	618506	180399	Outer	No	288.9	3.5	13.14	0.00	0.25	0.73

Island	Site	fish assem size (cm)	fish ass biomass (kg/SPC)	predator biomass (kg/SPC)	fish heterogeneity (% dissimilarity)	fish evenness (Shannon H)
Aguijan	CNMI-1	15.98	2.71	0.51	45.81	2.80
Rota	CNMI-10	11.98	0.95	0.07	47.56	2.21
Rota	CNMI-11	14.23	7.44	0.12	54.34	0.78
Rota	CNMI-12	14.69	2.57	1.26	45.31	2.23
Rota	CNMI-13	13.44	1.78	0.03	51.49	2.71
Rota	CNMI-14	11.84	1.00	0.04	41.09	1.88
Saipan	CNMI-2	14.24	2.27	0.11	43.26	2.62
Saipan	CNMI-3	10.15	0.51	0.00	41.52	1.95
Saipan	CNMI-4	10.02	0.84	0.68	38.92	1.80
Saipan	CNMI-5	11.02	2.44	0.05	41.95	2.40
Saipan	CNMI-6	8.92	0.42	0.00	32.87	1.66
Saipan	CNMI-7	14.60	0.90	0.06	30.04	0.98
Saipan	CNMI-8	10.91	2.80	0.10	38.23	2.22
Tinian	CNMI-9	13.67	0.78	0.01	38.75	1.56
Chuuk	CHK-1	12.36	1.32	2.22	47.18	2.09
Chuuk	CHK-10	13.18	2.89	5.69	51.18	1.90
Chuuk	CHK-11	21.64	10.91	4.36	49.01	2.79
Chuuk	CHK-12	22.84	16.67	82.01	36.16	2.39
Chuuk	CHK-13	18.70	5.75	3.01	52.63	2.73
Chuuk	CHK-14	16.60	4.04	0.10	48.50	2.68
Chuuk	CHK-15	14.72	4.73	2.58	50.60	2.56
Chuuk	CHK-16	14.41	2.01	0.01	57.93	2.42
Chuuk	CHK-17	18.75	9.43	68.23	34.43	1.83
Chuuk	CHK-18	14.77	4.04	3.99	49.84	2.22
Chuuk	CHK-19	19.22	8.48	29.98	51.31	2.27
Chuuk	CHK-2	9.54	0.45	0.00	36.21	1.81
Chuuk	CHK-3	14.83	3.47	0.18	53.59	2.64
Chuuk	CHK-4	12.49	1.19	0.97	46.27	1.98
Chuuk	CHK-5	18.87	6.66	45.83	17.11	2.16
Chuuk	CHK-6	9.76	0.48	0.00	34.04	1.66
Chuuk	CHK-7	13.17	3.86	9.08	56.31	2.11
Chuuk	CHK-8	14.25	2.39	1.41	59.59	2.43
Chuuk	CHK-9	17.01	5.78	19.44	47.36	2.22
Kosrae	KOS-1	16.56	3.66	0.17	41.75	2.79
Kosrae	KOS-2	17.27	9.64	0.31	41.23	2.93
Kosrae	KOS-4	17.58	12.21	0.29	36.77	2.80
Kosrae	KOS-5	17.40	11.42	1.19	34.81	2.83
Kosrae	KOS-6	16.23	8.38	0.25	25.93	2.36
Kosrae	KOS-7	15.80	6.20	0.26	36.20	2.78
Kosrae	KOS-2	16.26	4.54	0.27	46.29	3.02
Pohnpei	PNI-1	11.97	1.54	0.01	42.67	2.54
Pohnpei	PNI-9	15.89	2.76	0.38	39.43	2.65
Pohnpei	PNI-10	17.83	6.36	0.28	43.07	2.81
Pohnpei	PNI-11	14.31	1.72	0.17	38.85	2.57
Pohnpei	PNI-2	12.48	1.84	1.22	50.61	2.70
Pohnpei	PNI-12	17.60	3.20	0.43	50.54	3.13
Pohnpei	PNI-13	15.00	1.64	0.00	41.72	2.46
Pohnpei	PNI-14	17.44	12.31	0.14	38.49	2.46
Pohnpei	PNI-15	21.94	34.70	1.71	42.22	2.74
Pohnpei	PNI-16	19.85	7.92	0.40	51.18	2.62
Pohnpei	PNI-17	17.79	8.73	0.51	40.46	2.71
Pohnpei	PNI-3	13.08	1.45	0.09	48.47	2.77
Pohnpei	PNI-4	11.28	2.11	0.02	45.30	2.45
Pohnpei	PNI-5	12.16	2.77	0.04	33.09	2.46
Pohnpei	PNI-6	12.72	5.21	0.18	44.96	2.97
Pohnpei	PNI-7	13.50	2.68	0.32	49.33	2.05
Pohnpei	PNI-8	12.11	1.32	0.04	46.68	2.76
Yap	YAP-1	11.36	2.14	0.14	43.65	2.08
Yap	YAP-9	14.00	1.80	0.22	55.21	2.22
Yap	YAP-10	10.33	0.65	0.00	37.85	1.75
Yap	YAP-11	7.86	0.37	0.13	55.85	1.73
Yap	YAP-12	11.22	1.75	0.39	54.83	2.35
Yap	YAP-14	14.29	2.02	0.93	50.00	2.13
Yap	YAP-2	13.15	1.46	0.06	40.56	2.33
Yap	YAP-3	9.85	0.34	0.02	53.40	2.05
Yap	YAP-4	13.10	2.15	0.80	47.19	1.96
Yap	YAP-5	9.71	0.51	0.07	36.02	1.73
Yap	YAP-6	12.87	3.66	0.40	52.43	2.58
Yap	YAP-7	13.11	4.79	1.23	48.72	2.66
Yap	YAP-8	10.87	1.09	0.40	34.45	1.90
Yap	Yap-15	14.98	2.52	0.36	57.59	2.93
Yap	Yap-13	13.28	4.81	0.48	46.86	2.93
Namdrik	NAM-1	19.24	4.23	1.82	53.13	2.46

Namdrik	NAM-2	19.48	6.27	2.78	56.19	2.89
Namdrik	NAM-3	19.04	5.77	7.52	48.34	2.74
Namdrik	NAM-4	22.41	8.58	4.75	52.60	2.61
Namdrik	NAM-5	17.24	3.75	1.56	49.72	2.91
Namdrik	NAM-6	16.46	2.95	5.29	44.79	1.99

Island	site	benthic ratio	coral evenness (Shannon H)	coral cover	macroalgae cover
Aguijan	CNMI-1	1.29	2.29	35.28	2.72
Rota	CNMI-10	0.50	1.74	9.04	20.34
Rota	CNMI-11	0.86	1.03	9.14	20.39
Rota	CNMI-12	0.42	1.92	6.73	13.36
Rota	CNMI-13	0.46	1.84	6.32	7.17
Rota	CNMI-14	0.22	1.75	5.64	6.73
Saipan	CNMI-2	1.27	2.48	36.60	6.00
Saipan	CNMI-3	0.79	2.23	30.32	1.79
Saipan	CNMI-4	0.31	2.06	5.76	6.46
Saipan	CNMI-5	1.74	2.16	24.28	3.91
Saipan	CNMI-6	1.55	2.40	24.06	6.80
Saipan	CNMI-7	1.20	2.61	38.39	0.74
Saipan	CNMI-8	0.88	2.02	21.46	6.40
Tinian	CNMI-9	1.60	2.38	35.36	2.16
Chuuk	CHK-1	1.00	0.77	31.04	24.30
Chuuk	CHK-10	1.71	1.50	38.52	17.73
Chuuk	CHK-11	0.79	1.05	19.49	31.38
Chuuk	CHK-12	2.07	1.70	35.10	15.92
Chuuk	CHK-13	1.20	1.25	27.36	9.52
Chuuk	CHK-14	2.48	0.42	32.82	5.31
Chuuk	CHK-15	0.51	0.59	4.08	39.97
Chuuk	CHK-16	1.71	1.20	30.42	6.42
Chuuk	CHK-17	1.43	1.58	32.40	18.32
Chuuk	CHK-18	1.88	1.25	24.16	4.65
Chuuk	CHK-19	2.00	1.26	28.75	19.67
Chuuk	CHK-2	1.44	0.66	26.48	17.78
Chuuk	CHK-3	2.27	0.53	27.62	12.90
Chuuk	CHK-4	1.31	0.96	30.00	9.04
Chuuk	CHK-5	3.11	1.54	38.90	2.37
Chuuk	CHK-6	0.70	0.61	21.28	30.16
Chuuk	CHK-7	1.94	1.31	38.88	16.62
Chuuk	CHK-8	1.06	1.41	17.60	21.68
Chuuk	CHK-9	1.00	1.14	28.40	32.40
Kosrae	KOS-1	3.73	1.90	65.30	2.98
Kosrae	KOS-2	3.59	1.69	56.64	1.28
Kosrae	KOS-4	3.49	1.47	51.51	0.89
Kosrae	KOS-5	1.59	2.18	15.88	1.13
Kosrae	KOS-6	3.46	1.85	47.82	3.38
Kosrae	KOS-7	1.48	1.94	34.91	5.95
Kosrae	KOS-2	3.61	1.85	63.68	4.96
Pohnpei	PNI-1	3.33	1.42	44.24	0.00
Pohnpei	PNI-9	1.91	1.49	42.46	0.64
Pohnpei	PNI-10	2.50	1.26	15.68	15.92
Pohnpei	PNI-11	0.50	1.44	23.50	1.92
Pohnpei	PNI-2	1.38	1.40	35.52	1.68
Pohnpei	PNI-12	1.17	1.89	25.76	1.04

Pohnpei	PNI-13	2.88	2.42	53.99	1.92
Pohnpei	PNI-14	3.86	1.86	18.72	19.04
Pohnpei	PNI-15	3.00	1.52	8.72	19.60
Pohnpei	PNI-16	1.76	1.32	57.68	5.92
Pohnpei	PNI-17	1.29	1.74	23.60	9.36
Pohnpei	PNI-3	3.72	1.51	39.28	0.72
Pohnpei	PNI-4	1.30	1.65	8.53	29.44
Pohnpei	PNI-5	1.97	1.84	12.80	0.48
Pohnpei	PNI-6	1.94	1.48	21.76	6.56
Pohnpei	PNI-7	2.85	1.60	36.72	2.88
Pohnpei	PNI-8	4.63	1.64	52.88	0.08
Yap	YAP-1	3.60	1.87	49.04	0.64
Yap	YAP-9	5.17	1.73	61.76	0.00
Yap	YAP-10	3.14	1.06	63.20	0.00
Yap	YAP-11	3.39	1.14	54.48	0.00
Yap	YAP-12	2.58	2.25	25.04	0.00
Yap	YAP-14	5.65	1.63	54.16	0.08
Yap	YAP-2	5.75	1.59	65.52	1.36
Yap	YAP-3	5.51	0.82	64.16	0.00
Yap	YAP-4	1.95	2.21	31.04	0.32
Yap	YAP-5	4.15	0.58	43.84	0.08
Yap	YAP-6	2.60	0.99	48.48	3.44
Yap	YAP-7	2.55	1.80	29.68	0.48
Yap	YAP-8	3.00	1.96	49.60	0.00
Yap	Yap-15	3.59	1.62	30.53	0.17
Yap	Yap-13	1.38	1.95	12.16	0.00
Namdrik	NAM-1	5.29	1.86	48.24	10.08
Namdrik	NAM-2	5.12	2.10	35.68	4.88
Namdrik	NAM-3	13.78	1.37	58.53	1.06
Namdrik	NAM-4	2.87	1.78	37.71	21.61
Namdrik	NAM-5	9.43	1.79	65.02	4.81
Namdrik	NAM-6	4.91	2.06	28.42	11.50

Island	Site	coral skewness	coral heterogeneity (% dissimilarity)	species richness	coral evenness (Shannon H)
Aguijan	CNMI-1	2.53	65.91	6.50	3.30
Rota	CNMI-10	4.37	54.56	6.94	2.53
Rota	CNMI-11	2.72	50.84	5.27	1.22
Rota	CNMI-12	1.73	59.93	5.88	2.63
Rota	CNMI-13	2.43	62.13	4.38	2.41
Rota	CNMI-14	1.68	61.10	5.88	2.82
Saipan	CNMI-2	4.14	56.79	10.00	3.14
Saipan	CNMI-3	2.34	56.78	8.75	3.04
Saipan	CNMI-4	2.74	58.27	7.19	2.91
Saipan	CNMI-5	2.99	60.25	8.56	2.96
Saipan	CNMI-6	3.91	64.19	5.81	3.10
Saipan	CNMI-7	3.74	61.02	6.56	2.88
Saipan	CNMI-8	2.60	59.50	7.44	3.00
Tinian	CNMI-9	2.68	61.90	8.13	3.30
Chuuk	CHK-1	3.86	54.80	4.20	1.70
Chuuk	CHK-10	3.17	45.94	7.90	2.00
Chuuk	CHK-11	NA	NA	NA	NA
Chuuk	CHK-12	NA	NA	NA	NA
Chuuk	CHK-13	NA	NA	NA	NA
Chuuk	CHK-14	NA	NA	NA	NA
Chuuk	CHK-15	NA	NA	NA	NA
Chuuk	CHK-16	NA	NA	NA	NA
Chuuk	CHK-17	NA	NA	NA	NA
Chuuk	CHK-18	NA	NA	NA	NA
Chuuk	CHK-19	NA	NA	NA	NA
Chuuk	CHK-2	2.30	55.06	2.40	1.22
Chuuk	CHK-3	3.60	50.99	6.80	1.45
Chuuk	CHK-4	6.60	60.99	7.20	1.99
Chuuk	CHK-5	4.12	51.77	9.20	2.31
Chuuk	CHK-6	4.20	50.33	2.50	1.15
Chuuk	CHK-7	2.54	54.25	6.00	2.09
Chuuk	CHK-8	3.30	61.20	4.40	1.81
Chuuk	CHK-9	3.00	53.39	2.60	1.36
Kosrae	KOS-1	3.43	60.08	5.40	2.59
Kosrae	KOS-2	1.86	57.67	3.10	2.16
Kosrae	KOS-4	4.97	45.82	6.70	1.91
Kosrae	KOS-5	3.19	54.94	7.90	2.31
Kosrae	KOS-6	2.84	56.92	4.50	2.19
Kosrae	KOS-7	2.92	55.89	4.80	2.11
Kosrae	KOS-2	4.11	55.74	7.50	2.40
Pohnpei	PNI-1	3.32	51.72	5.70	1.66
Pohnpei	PNI-9	4.40	29.60	6.20	1.84
Pohnpei	PNI-10	4.65	48.99	7.90	1.73
Pohnpei	PNI-11	2.58	48.19	4.70	1.75
Pohnpei	PNI-2	4.50	52.13	5.30	1.49
Pohnpei	PNI-12	4.84	53.27	5.40	1.61
Pohnpei	PNI-13	2.55	58.86	9.90	3.01
Pohnpei	PNI-14	2.58	60.11	5.50	2.26
Pohnpei	PNI-15	1.37	61.38	6.60	2.61
Pohnpei	PNI-16	2.39	29.16	3.90	1.34
Pohnpei	PNI-17	2.50	56.73	7.40	2.08
Pohnpei	PNI-3	4.73	40.04	3.60	1.20
Pohnpei	PNI-4	3.20	50.00	5.60	1.63
Pohnpei	PNI-5	2.79	46.61	9.70	2.15
Pohnpei	PNI-6	2.70	42.39	8.80	1.48

Pohnpei	PNI-7	5.16	44.84	7.20	1.60
Pohnpei	PNI-8	4.37	40.34	6.70	1.68
Yap	YAP-1	1.45	51.71	8.20	2.60
Yap	YAP-9	4.45	56.56	7.25	2.48
Yap	YAP-10	4.92	45.70	6.50	1.68
Yap	YAP-11	3.80	48.91	4.13	1.67
Yap	YAP-12	4.50	55.02	9.50	2.20
Yap	YAP-14	6.54	51.73	9.40	1.95
Yap	YAP-2	3.60	54.22	5.75	2.36
Yap	YAP-3	4.33	39.53	3.88	1.16
Yap	YAP-4	3.69	55.59	11.00	2.63
Yap	YAP-5	2.44	34.22	2.13	1.04
Yap	YAP-6	2.78	24.91	4.50	1.04
Yap	YAP-7	3.56	53.34	9.63	2.16
Yap	YAP-8	3.47	49.78	5.25	2.11
Yap	Yap-15	4.46	35.13	12.20	1.80
Yap	Yap-13	2.29	58.15	8.00	2.56
Namdrik	NAM-1	2.99	50.72	5.80	1.87
Namdrik	NAM-2	3.19	56.51	4.20	2.29
Namdrik	NAM-3	2.03	42.39	7.60	2.39
Namdrik	NAM-4	4.33	52.56	5.60	1.75
Namdrik	NAM-5	2.44	53.47	8.60	2.20
Namdrik	NAM-6	1.89	49.62	4.80	2.61

Table 2. Biological metrics used to evaluate coral-reef ecosystem conditions that were related reef processes and ecological principles.

METRIC	KEY PROCESSES	FOUNDATIONAL PRINCIPLES	SUPPORTING CITATIONS
FISH ASSEMBLAGE SIZE	Grazing, disturbance resistance, recovery potential, distribution of diversity across trophic guilds, sustainable provisioning	Allometry, reproduction, niche partitioning, distribution of biomass across fast/slow energy pathways in food webs, size-based fishery regulations	[1] [2] [3] [4] [5] [6] [7] [8] [9] [10,11]
FISH ASSEMBLAGE BIOMASS	Disturbance resistance, recovery potential, carbon sequestration, sustainable provisioning	Food web stability, Nutrient cycling, harvesting quotas,	[11-17]
PREDATOR BIOMASS	Competitive dominance in lower trophic guilds, carbon sequestration, ecosystem function	Predation, competition, diversity maintenance, trophic cascades, food web stability	[13,14,18-20]
FISH ASSEMBLAGE HETEROGENEITY AND EVENNESS	Disturbance resistance, recovery potential	Response diversity, functional redundancy, food web stability	[18,21-27]
BENTHIC SUBSTRATE RATIO[1]	Reef calcification and accretion, carbon sequestration	Competition, slow energy pathways in food webs	[10,16,28-30]
CORAL COVER	Habitat formation and complexity, reef calcification and accretion, carbon sequestration	Nutrient cycling, fundamental niche creation, slow energy pathways in food webs	[31-34]
MACROALGAL COVER	Competition, grazing, carbon recycling	Nutrient cycling, herbivore response, fast energy pathways in food webs	[16,28-30]
CORAL EVENNESS, SPECIES RICHNESS, AND ASSEMBLAGE HETEROGENEITY	Habitat complexity, disturbance resistance, recovery potential	Response diversity, functional diversity, food web stability	[4, 31-35]
CORAL ASSEMBLAGE SKEWNESS	Recruitment, habitat complexity, habitat formation	Allometry, fundamental niche creation, fast/slow energy pathways in food	[16,33,36,37]

		webs, population dynamics	

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