

Sea urchins, macroalgae and coral reef decline: a functional evaluation of an intact reef system, Ningaloo, Western Australia

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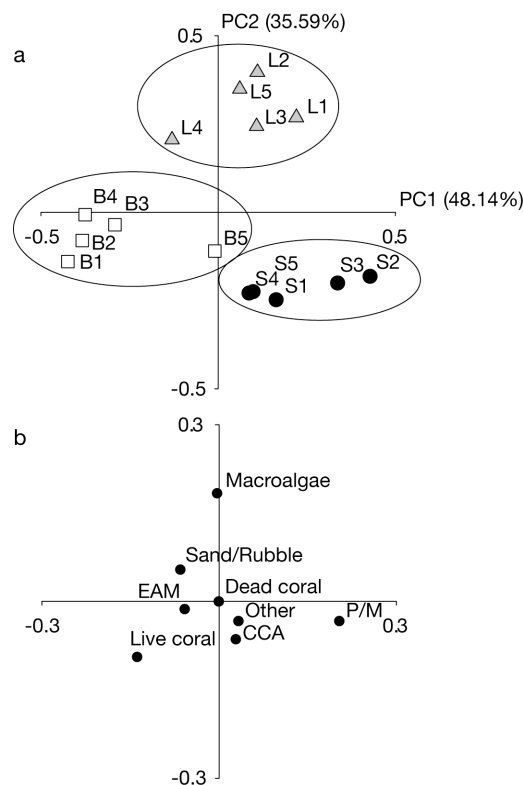


Fig. S1. Principal component analysis (PCA) of benthic cover illustrating the grouping of 15 sites across 3 clearly defined habitats (slope [S], back reef [B] and lagoon [L]) on Ningaloo Reef. (a) Ordination plot showing the relationship between sites. Ellipses show groupings detected in the cluster analysis. (b) Vector plot identifying the major benthic categories characterising the 3 habitats. The first 2 components in the PCA explained 83.7% (48.1 and 35.6%, respectively) of the variation in benthic cover between sites. The 3 habitats appeared well separated from each other. The partitioning of the back reef and slope was explained by PC1, whilst the lagoonal characteristics were distinguished by PC2. PC1 was mainly driven by pavement/matrix (P/M) dominating the slope. High live coral cover and epilithic algal matrix (EAM) were abundant on the back reef. Macroalgae was the distinguishing characteristic for the lagoon on PC2

Table S1. Length–weight relationships collected from specimens in the Philippines during 1988 (D. R. Bellwood unpubl. data). For each species, the estimation parameters (a and b) and the number of specimens used (n) are given, as well as minimum and maximum length of sampled individuals and what relationship was measured; weight (WT) against total (TL) or standard (SL) length

Species	n	r ²	a	b	Min	Max	Relationship
<i>Calotomus carolinus</i>	9	0.9764	0.0197	3.209	127	278	WT:TL
	9	0.9609	0.0179	3.280	106	230	WT:SL
<i>Chlorurus gibbus</i>	10	0.9834	0.0221	3.337	308	490	WT:TL
	10	0.9724	0.0183	3.252	253	410	WT:SL
<i>Chlorurus sordidus</i>	14	0.9819	0.0200	3.249	165	268	WT:TL
	14	0.978	0.0179	3.300	135	215	WT:SL
<i>Hipposcarus longiceps</i>	21	0.9637	0.0020	2.618	250	590	WT:TL
	21	0.9806	0.0170	3.129	210	400	WT:SL
<i>Scarus bleekeri</i>	28	0.9875	0.0176	3.020	48	348	WT:TL
	28	0.9938	0.0147	2.999	38	280	WT:SL
<i>Scarus chameleon</i>	5	0.9984	0.0244	3.566	189	290	WT:TL
	5	0.9979	0.0222	2.604	160	245	WT:SL
<i>Scarus dimidiatus</i>	52	0.9686	0.0162	2.913	152	330	WT:TL
	52	0.9604	0.0129	2.843	124	280	WT:SL
<i>Scarus flavipectoralis</i>	7	0.9798	0.0169	2.981	147	290	WT:TL
	7	0.9956	0.0164	3.116	122	240	WT:SL
<i>Scarus forsteni</i>	11	0.9149	0.0215	3.301	150	235	WT:TL
	11	0.9036	0.0160	3.072	122	195	WT:SL
<i>Scarus ghobban</i>	18	0.9951	0.0176	3.005	103	512	WT:TL
	18	0.9925	0.0149	2.992	83	435	WT:SL
<i>Scarus niger</i>	68	0.9823	0.0018	3.077	21	315	WT:TL
	68	0.9786	0.0015	3.063	18	260	WT:SL
<i>Scarus prasiognathus</i>	17	0.9968	0.0195	3.187	62	422	WT:TL
	17	0.9959	0.0161	3.140	50	355	WT:SL
<i>Scarus psittacus</i>	35	0.986	0.0166	2.998	133	287	WT:TL
	35	0.9908	0.0139	2.968	109	235	WT:SL
<i>Scarus quoyi</i>	25	0.9657	0.0166	2.959	116	300	WT:TL
	25	0.9666	0.0133	2.909	87	245	WT:SL
<i>Scarus rivulatus</i>	21	0.9779	0.0197	3.196	139	370	WT:TL
	21	0.9843	0.0183	3.301	115	290	WT:SL
<i>Scarus rubroviolaceus</i>	25	0.9879	0.0189	3.111	150	450	WT:TL
	25	0.9796	0.0149	3.006	116	380	WT:SL
<i>Scarus spinus</i>	11	0.9884	0.0179	3.109	160	238	WT:TL
	11	0.9837	0.0152	3.106	130	196	WT:SL
<i>Scarus tricolor</i>	64	0.9201	0.0224	3.359	135	295	WT:TL
	64	0.9121	0.0177	3.191	112	245	WT:SL

Table S2. Functional group identity and total counts of roving fish herbivores on Ningaloo Reef

Functional group/species	Slope	Back reef	Lagoon	Total
Browsers	83	208	199	490
Acanthuridae	40	58	39	137
<i>Naso annulatus</i>	1	12	31	44
<i>Naso brevirostris</i>	2	1	0	3
<i>Naso lituratus</i>	12	5	0	17
<i>Naso unicornis</i>	25	40	8	73
Kyphosidae	42	30	10	82
<i>Kyphosus cornelii</i>	0	2	0	2
<i>Kyphosus</i> sp.	42	28	10	80
Siganidae	1	120	150	271
<i>Siganus fuscescens</i>	1	120	150	271
Excavators	23	109	40	172
Labridae (Scarinae)	23	109	40	172
<i>Chlorurus microrhinos</i>	4	2	8	14
<i>Chlorurus sordidus</i>	19	107	32	158
Grazers/Detritivores	324	480	63	867
Acanthuridae	313	467	56	836
<i>Acanthurus dussumeri</i>	91	15	32	138
<i>Acanthurus grammoptilus</i>	3	0	0	3
<i>Acanthurus nigricans</i>	1	1	0	2
<i>Acanthurus nigricauda</i>	11	0	0	11
<i>Acanthurus nigrofuscus</i>	6	4	7	17
<i>Acanthurus olivaceus</i>	38	0	0	38
<i>Acanthurus</i> sp.	0	0	1	1
<i>Acanthurus triostegus</i>	138	410	7	555
<i>Ctenochaetus striatus</i>	16	21	5	42
<i>Ctenochaetus strigosus</i>	0	1	0	1
<i>Zebrasoma scopas</i>	6	11	4	21
<i>Zebrasoma veliferum</i>	3	4	0	7
Siganidae	11	13	7	31
<i>Siganus</i> sp.	0	0	4	4
<i>Siganus trispilos</i>	0	3	0	3
<i>Siganus virigatus</i>	9	9	2	20
<i>Siganus laqueus</i>	2	1	1	4
Scrapers	136	222	16	374
Labridae (Scarinae)	136	222	16	374
<i>Hipposcarus longiceps</i>	0	3	0	3
<i>Scarus chameleon</i>	9	13	1	23
<i>Scarus dimidiatus</i>	2	2	0	4
<i>Scarus frenatus</i>	14	47	1	62
<i>Scarus ghobban</i>	6	9	0	15
<i>Scarus globiceps</i>	0	1	0	1
<i>Scarus oviceps</i>	0	5	0	5
<i>Scarus prasiognathus</i>	34	23	1	58

<i>Scarus psittacus</i>	6	2	0	8
<i>Scarus rivulatus</i>	5	16	1	22
<i>Scarus rubroviolaceus</i>	34	2	0	36
<i>Scarus schlegeli</i>	26	58	12	96
<i>Scarus sp.</i>	0	41	0	41
Total	566	1019	318	1903

Table S3. Proportion of benthic cover for the 3 distinct habitats on Ningaloo Reef. CCA: crustose coralline algae; P/M: pavement/matrix; EAM: epilithic algal matrix. Macroalgae are those species ≥ 15 mm in length

Benthic cover	Slope	Back reef	Lagoon
CCA	0.18	0.05	0.01
Dead coral	0.00	0.00	0.00
P/M	0.49	0.10	0.30
EAM	0.04	0.12	0.05
Live coral	0.17	0.38	0.03
Macroalgae	0.01	0.10	0.42
Other	0.10	0.00	0.00
Sand/Rubble	0.02	0.26	0.18
Total	1.00	1.00	1.00

Table S4. Result from 2-way ANOVA comparing the inferred cross-shelf impact for: (a) macroalgae, CCA and live coral; (b) total abundance and biomass of fish and echinoids; and (c) scraping, fish bioerosion and sea urchin bioerosion. Data were $^4\sqrt{}$ - and $^5\sqrt{}$ -transformed. Significant results ($\alpha = 0.05$) are in **bold**

Source of variation	df	MS	F	p
(a) Macroalgae, CCA and live coral				
Macroalgae				
Site	4	1.992	1.460	0.300
Habitat	2	50.738	37.185	<0.001
Site × Habitat	8	1.367	8.684	<0.001
Error	204	0.157		
CCA				
Site	4	0.332	0.096	0.981
Habitat	2	26.862	7.802	0.013
Site × Habitat	8	3.450	31.712	<0.001
Error	204	0.109		
Live coral				
Site	4	3.000	1.950	0.195
Habitat	2	39.001	25.352	<0.001
Site × Habitat	8	1.541	19.003	<0.001
Error	204	0.081		
(b) Fish/echinoid abundance and biomass				
Abundance				
Excavators				
Site	4	1.092	0.795	0.56
Habitat	2	7.449	5.427	0.034
Site × Habitat	8	1.373	10.119	<0.001
Error	60	0.136		
Scrapers				
Site	4	0.09	0.134	0.965
Habitat	2	14.083	20.938	<0.001
Site × Habitat	8	0.673	4.331	<0.001
Error	60	0.155		
Browsers				
Site	4	2.131	0.881	0.516
Habitat	2	1.869	0.773	0.493
Site × Habitat	8	2.419	5.187	<0.001
Error	60	0.466		
Grazers/Detritivores				
Site	4	0.295	0.143	0.961
Habitat	2	9.825	4.773	0.043
Site × Habitat	8	2.059	5.282	<0.001
Error	60	0.39		
Echinoids				
Site	4	0.341	0.248	0.903
Habitat	2	102.129	74.139	<0.001
Site × Habitat	8	1.378	4.955	<0.001
Error	60	0.278		

Total abundance fish				
Site	4	4.214	0.295	0.873
Habitat	2	105.855	7.369	0.015
Site × Habitat	8	14.366	9.227	<0.001
Error	60	1.557		
Biomass				
Excavators				
Site	4	34.613	1.063	0.434
Habitat	2	174.86	5.371	0.033
Site × Habitat	8	32.555	7.36	<0.001
Error	60	4.423		
Scrapers				
Site	4	8.647	0.455	0.767
Habitat	2	408.225	21.499	<0.001
Site × Habitat	8	18.988	4.535	<0.001
Error	60	4.187		
Browsers				
Site	4	87.321	1.154	0.398
Habitat	2	53.998	0.714	0.519
Site × Habitat	8	75.667	4.965	<0.001
Error	60	15.241		
Grazers/Detritivores				
Site	4	13.825	0.437	0.779
Habitat	2	144.489	4.566	0.048
Site × Habitat	8	31.648	4.141	<0.001
Error	60	7.641		
Total biomass fish				
Site	4	168.960	0.506	0.733
Habitat	2	2331.090	6.984	0.018
Site × Habitat	8	333.770	47.790	<0.001
Error	60	47.790		

c) Physical impact

Scrapers				
Site	4	0.547	0.115	0.974
Habitat	2	109.109	22.919	<0.001
Site × Habitat	8	4.761	4.973	<0.001
Error	60	0.957		
Excavators				
Site	4	11.487	1.288	0.351
Habitat	2	30.977	3.474	0.082
Site × Habitat	8	8.917	8.78	<0.001
Error	60	1.016		
Echinoids				
Site	4	0.192	0.734	0.594
Habitat	2	29.426	112.716	<0.001
Site × Habitat	8	0.261	2.94	0.008
Error	60	0.089		

Table S5. Tukey's HSD post hoc test comparing the proportion of (a) benthic cover between the slope, back reef and lagoon habitats on Ningaloo Reef. Also shown are the post hoc results from (b) abundance, (c) biomass and (d) physical impact across the shelf for 4 functional groups of herbivores: grazers/detritivores, browsers, scrapers and excavators. Significant values are in **bold**

Factor	Interaction		
	Back reef/Lagoon	Lagoon/Slope	Slope/Back reef
a) Benthic			
Macroalgae	< 0.001	< 0.001	< 0.001
Live coral	< 0.001	< 0.001	< 0.001
CCA	< 0.001	< 0.001	< 0.001
b) Abundance			
Grazers/detritivores	< 0.001	< 0.001	0.876
Browsers	0.022	0.758	0.117
Scrapers	< 0.001	< 0.001	0.09
Excavators – fish	< 0.001	0.213	< 0.001
Excavators – urchins	< 0.001	< 0.001	< 0.001
Total fish	< 0.001	< 0.001	0.213
c) Biomass			
Grazers/detritivores	< 0.001	< 0.001	0.573
Browsers	0.03	0.648	0.204
Scrapers	< 0.001	< 0.001	0.978
Excavators – fish	< 0.001	0.107	< 0.001
Total	< 0.001	0.042	< 0.001
d) Function			
Scrapers	< 0.001	< 0.001	0.133
Excavators – fish	< 0.001	0.368	< 0.001
Excavators – urchins	< 0.001	< 0.001	< 0.001

Table S6. Scraping and excavating rates for fish and echinoids in the 3 investigated habitats on Ningaloo Reef

Process/species	Slope	Back reef	Lagoon
Scraping (% yr ⁻¹)	619.67	841.56	43.00
Excavation (kg m ⁻² yr ⁻¹)	1.73	2.31	1.41
Fish			
<i>Chlorurus microrhinos</i>	0.64	0.32	1.29
<i>Chlorurus sordidus</i>	0.54	1.98	0.12
Total	1.18	2.30	1.41
Echinoids			
<i>Diadema</i> sp.	0.15	0.00	0.00
<i>Echinometra mathaei</i>	0.40	0.01	0.00
Total	0.55	0.01	0.00