

Ecography

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Supplementary material

Appendix 1: Justification for the choice of maximum body size and diet as reef fish functional attributes.

Body size

Size has a primary role in defining the ecological niche and ecological role of species, general reviews on this subject can be found in Wilson (1975) and LaBarbera (1986). More specifically the following aspects are important for reef fish:

- Energy needs: the amount of energy for metabolism increases with body size, but the amount of energy per unit of body mass decreases with body size (Munday & Jones, 1998).
- Prey selection or predator escape (Costa *et al.*, 2009): prey selection is linked to mouth gape size, which is itself a function of body size, larger fish being able to eat larger prey. Predators are also limited by the size of their prey. Therefore large fish tend to be less predated than smaller ones, all other factors being equal. In addition larger fish have higher swimming speed, which enables them to flee their predator more efficiently. Large fish have the capacity to swim over longer distances therefore increasing their foraging range compared to smaller species or smaller individuals.
- Reproductive capacity, sex ratio, size at maturity, sex reversal: the size of gonads and therefore the quantity of reproductive products is proportional to body weight, usually according to a power function. This means that larger species or larger fish will produce far more gametes than smaller species or smaller individuals. The sex ratio of many species is a function of body size, for instance small parrotfish are nearly always females, small anemone fish are nearly always males (Wong *et al.*, 2007). The size at maturity is proportional to body size, larger species being mature at relatively larger sizes than small ones. Similarly, sex reversal, which is a frequent process for reef fish, occurs at larger sizes in large species (Wong *et al.*, 2007).
- Diversity services in particular biomass production: fish weight is exponential to its body length, therefore assemblages with large species will tend to have larger biomasses than assemblages with small species, for a given diversity level. As the geographical distribution of species fish size is not random (Luiz *et al.*, 2013) this means that the biomass-diversity relationship for reef fish is not spatially homogeneous (Mora *et al.*, 2011). See also Ackerman *et al.* (2004) on the relationship between density and body size.
- Growth and production: small fish species tend to grow faster and have a higher production rate than larger species (see Paloheimo & Dickie, 1966; for general information) (there are exceptions both ways however). This means that biomass and production may not be related in the same way in reef fish assemblages dominated by small species compared to assemblages dominated by large species

- Mortality rate: small species tend to have a much higher mortality rate than larger ones (Henrique *et al.*, 2013; Munday & Jones, 1998). There are however intrinsic factors to each species. In particular mortality is linked to many other traits such as school size, mobility, level in the water column.
- PLD: large species tend to have wider geographical ranges and also longer Pelagic Larval Durations (PLD) than small species (Luiz *et al.*, 2013)
- Temperature tolerance is related to body size in reef fishes (Ospina & Mora, 2004)

Diet

Diet, as size, is an essential component of reef fish ecological niche as indicated in general reviews such as Hiatt & Strasburg (1960), Hobson (1974), Sale (1977), Bellwood *et al.* (2006). In particular diet may be important for the following:

- Trophic level and trophic niche width (for general views see Araujo *et al.*, 2011; Bearhop *et al.*, 2004): the trophic level of a species and its trophic niche width is determined by the food type it feeds on as well as the variety of food items (Floeter *et al.*, 2004; Ferreira *et al.*, 2004; Wilson *et al.*, 2008; Frederich *et al.*, 2010; Curtis-Quick *et al.*, 2012; Litsios *et al.*, 2012) For instance a species may be specialized in coral polyps but depending on where it lives it may eat polyps from different species (Lawton & Pratchett, 2012). Within the same trophic guild other species may eat only polyps from a given species or genus of *Acropora* wherever it lives.
- Habitat requirements (prey need to be present): many species having a specialized diet will restrict their habitat to areas where the food they need is present is sufficient in quantity and quality. Coral feeders are typical (Berumen & Pratchett, 2008) but there are many herbivores and plankton feeders (Frederich *et al.*, 2009; Burkepile & Hay, 2008) that live in specific habitats because of their diet.
- Feeding behavior: the way fish feed on a given item may have profound implications on the habitat and community. For instance, herbivorous fishes can be split according to several feeding behaviors such as grazers, browsers, scrapers (Bellwood & Choat, 1990). Each of these behaviors will generate different consequences on the algae/coral relationship and on many other ecological processes. The same could be said of coral feeders, of mobile invertebrate feeders.
- Home range (depending on energy requirements and type of prey and prey availability, home range will be either small or wide). For instance, large carnivorous species will necessarily have a wide home range as the resources needed to sustain their metabolism cannot be found on a restricted part of the reef. On the opposite, some small plankton feeders may stay their entire adult lives on the same spot as plankton drifts by.

References:

- Ackerman J.L., Bellwood D.R., Brown J.H. 2004 The contribution of small individuals to density-body size relationships: examination of energetic equivalence in reef fishes. *Oecologia* 139: 568-571
- Araujo M.S., Bolnick D.I., Layman C.A. (2011). The ecological causes of individual specialisation. *Ecology Letters*, 14, 948-958.
- Bearhop S., Adams C.E., Waldron S., Fuller R.A., MacLeod H. (2004). Determining Trophic Niche Width : A Novel Approach Using Stable Isotope Analysis. *Journal of Animal Ecology*, 73, 1007-1012.
- Bellwood, D. R., Wainwright, P. C., Fulton, C. J., & Hoey, A. S. 2006 Functional versatility supports coral reef biodiversity. *Proceedings of the Royal Society B: Biological Sciences*, 273(1582), 101-107.
- Bellwood, D.R. and Choat, J.H. (1990) A functional analysis of grazing in parrotfishes (family Scaridae): the ecological implications. *Environmental Biology of Fishes* 28:189-214.
- Berumen M.L. & Pratchett M.S. (2008). Trade-offs associated with dietary specialization in corallivorous butterflyfishes (Chaetodontidae: Chaetodon). *Behaviour, Ecology and Sociobiology*, 62, 989-994
- Burkepile D.E., Hay M.E. 2008 Herbivore species richness and feeding complementarity affect community structure and function on a coral reef. *PNAS*, 105 (42), 16201-16206.
- Costa GC. 2009. Predator size, prey size, and dietary niche breadth relationships in marine predators. *Ecology* 90(7):2014-2019.
- Curtis-Quick J.A., Ahmadi G.N., Smith D.J. (2012). Feeding plasticity of reef fish. *Proceedings of the 12th International Coral Reef Symposium*, Cairns, Australia, 9-13 July 2012
- Ferreira, C. E. L., Floeter, S. R., Gasparini, J. L., Joyeux, J. C. & Ferreira, B. P. 2004. Trophic structure patterns of Brazilian reef fishes: a latitudinal comparison. *Journal of Biogeography*, 31: 1093–1106.
- Floeter, S. R., Ferreira, C. E. L., Dominici-Arosemena, A. & Zalmon, I. 2004. Latitudinal gradients in Atlantic reef fish communities: trophic structure and spatial use patterns. *Journal of Fish Biology*, 64: 1680–1699.
- Frédérich B., Lehane O., Vandewalle P., Lepoint G. (2010). Trophic Niche Width, Shift, and Specialization of *Dascyllus aruanus* in Toliara Lagoon, Madagascar. *Copeia*, 2, 218-226
- Frédérich, B., Fabri, G., Lepoint, G., Vandewalle, P., & Parmentier, E. 2009 Trophic niches of thirteen damselfishes (Pomacentridae) at the Grand Récif of Toliara, Madagascar. *Ichthyological Research*, 56(1), 10-17.
- Henrique C. Giacomini, Brian J. Shuter, Nigel P. Lester, 2013. Predator bioenergetics and the prey size spectrum: Do foraging costs determine fish production? *Journal of Theoretical Biology*, 332 (), 249 – 260

- Hiatt, R.W., and D.W. Strasburg. 1960. Ecological relationships of the fish fauna on coral reefs of the Marshall islands. *Ecol. Monographs* 30(1):65-127
- Hobson, E.S. 1974. Feeding relationships of teleostean fishes on coral reefs in Kona, Hawaii. *Fish. Bull.* 72(4):915-1031
- Holt, RD, Lawton JH, Polis GA, and Martinez ND. 1999. Trophic rank and the species-area relationship. *Ecology* 80:1495–1504.
- LaBarbera M. 1986 The Evolution and Ecology of Body Size. *Patterns and Processes in the History of Life. Dahlem Workshop Reports* 36 : 69-98
- Lawton RJ and Pratchett MS (2012) Influence of dietary specialization and resource availability on geographical variation in abundance of butterflyfish. *Ecology and Evolution*, 2 (7). pp. 1347-1361
- Litsios, G., Pellissier L., Forest F., Lexer C., Pearman P.B., Zimmermann N.E., Salamin N. (2012). Trophic specialization influences the rate of environmental niche evolution in damselfishes (Pomacentridae). *Proceedings of the Royal Society*, 279, 3662-3669
- Luz, O.J., Allen, A.P., Robertson, D.R., Floeter, S.R., Kulbicki, M., Vigliola, L., Becheler, R. & Madin, J.S. 2013. Adult and larval traits as determinants of geographic range size among tropical reef fishes. *PNAS*, in press
- Munday, P.L., Jones G.P. 1998. The ecological implications of small body size among coral reef fishes. *Oceanogr. Mar. Biol. Annu. Rev.* 36: 373-411.
- Ospina A.F., Mora C. 2004 Effect of Body Size on Reef Fish Tolerance to Extreme Low and High Temperatures. *Environmental Biology of Fishes.* 70 (4): 339-343
- Paloheimo, J. E., & Dickie, L. M. 1966 Food and Growth of Fishes: III. Relations Among Food, Body Size, and Growth Efficiency. *Journal of the Fisheries Board of Canada*, 23(8), 1209-1248.
- Sale P.F. 1977 Maintenance of High Diversity in Coral Reef Fish Communities. *The American Naturalist* 111 (978) : 337-359
- Wilson, S. K., Burgess, S. C., Cheal, A. J., Emslie, M., Fisher, R., Miller, I., ... & Sweatman, H. 2008 Habitat utilization by coral reef fish: implications for specialists vs. generalists in a changing environment. *Journal of Animal Ecology*, 77(2), 220-228.
- Wong M.Y.L., Buston P.M., Munday P.L., Jones J.P. 2007. The threat of punishment enforces peaceful cooperation and stabilizes queues in a coral-reef fish. *Proc. Roy. Soc. B.* 274 (1613): 1093-1099.

Appendix 2: Sensitivity of nestedness analysis to functional group classification scheme

Table A2. Functional nestedness of reef fish assemblages across six biogeographic regions. In order to assess the sensitivity of nestedness analysis to the choice of functional group classification, two distinct functional group schemes were applied. Functional 1 corresponds to the combination of four traits (body size, trophic group, home range and schooling behaviour), while Functional 2 combines six different traits (body size, trophic group, home range, schooling behaviour, activity and level). Obs.: observed WNODF values; 95% CL: WNODF confidence limits from 1000 random matrices obtained from null model “quasiswap” (see methods); $Z\text{-score} = (X - \mu_{simul}) / \sigma_{simul}$, where X is the observed WNODF, and μ_{simul} and σ_{simul} are the mean and standard deviation, respectively, of 1000 simulated matrices. Positive Z -scores indicate higher x than expected by chance. All matrices were double sorted according to marginal richness and abundance totals.

Matrix	Functional 1			Functional 2		
Site	WNODF			WNODF		
	Obs.	Z-score	95% CL	Obs.	Z-score	95% CL
Western Atlantic	46.9	6.72	40.4–43.7	32.2	6.62	30.9–33.1
Eastern Atlantic	37.7	3.97	30.9–35.8	29.3	4.59	23.5–27.3
Tropical Eastern Pacific	45.5	9.28	34.0–37.3	30.8	8.68	25.3–27.5
Western Indo-Pacific	57.9	18.7	47.5–49.7	44.6	22.6	36.1–37.6
Central Indo-Pacific	61.7	12.7	54.6–56.7	49.7	20.4	42.3–43.7
Central Pacific	58.4	15.7	49.9–52.0	45.5	25.8	37.0–38.4

Appendix 3: The hierarchical spatial structure of reef fish assemblages

List of sites within provinces and regions, and map depicting marine biogeographic regions and its provinces (Fig. S1) (*sensu* Kulbicki *et al.*, 2013).

Table A3. List of sites embedded in provinces (scale 2) and regions (scale 1). Sites are ordered based on decreasing species richness.

Western Atlantic		Local Richness
	Southwestern Atlantic	
	Hump of Brazil	281
	São Paulo	257
	Espírito Santo	252
	Arraial do Cabo	247
	North Bahia	246
	Ilha Grande	233
	Abrolhos	187
	Santa Catarina	182
	Zumbi	167
	Manuel Luiz	133
	Fernando de Noronha	119
	Rocas' Atoll	103
	Trindade	97
	St. Paul's Rocks	57
	Atlantic Islands	
	Ascension	84
	St. Helena	72
	Caribbean	
	Cuba	452
	Bahamas	442
	Virgin Islands	436
	Florida Keys	419
	Venezuela – Tobago	404
	Pelican Cays, Belize	374
	Mexican Caribbean	360
	Martinique	290
	Guadeloupe	287
	Bonaire Island	273
	Bermuda	272
	Georgia	244
	Saba, Netherland Antilles	223
	Navassa	192
Eastern Atlantic		
	Eastern Atlantic	
	Cabo Verde	251
	São Tome	196
	Senegal	177
	Guinea-Sierra Leone	171
	Canaries	163
	Mauritania	134
	Madeira	121
Tropical Eastern Pacific		
	TEP Islands	
	Galapagos	282
	Cocos	232

	Malpelo	197
	Revillagigedos	165
	Clipperton	111
Continental TEP		
	Panama	297
	Costa Rica	277
	Colombia	267
	Nicaragua	248
	Gulf of California	246
	Honduras	236
	El Salvador	235
	Ecuador	231
	Sinaloa	216
	Tresmarías	193
	Gorgona	182
	Isla la Plata	163
	Guatemala	96
Western Indian		
	Western Indo-Pacific	1617
	Red Sea	1043
	Somali/Arabian	995
	West India and South Indian Shelf	1062
	Central Indian Ocean Islands	439
	Eastern India	431
	Andaman	
Somali/Arabian		
	Red Sea	766
	Gulf of Aqaba	681
	Gulf of Aden	629
	Oman South	527
	Gulf of Oman	441
	Arabian Gulf	319
	Erythrea-Djibouti	312
Western Indo-Pacific		
	Seychelles	1009
	Mozambique	983
	Mauritius	941
	Kenya	933
	Tanzania	928
	Maldives	896
	Comores	854
	Aldabra	821
	Madagascar	775
	Chagos	753
	La Reunion	709
	Somalia	699
	Rodrigues Island	451
	Laccadives	432
	Socotra	422
	Europa	360
	Carajos	312
Central Indo-Pacific		
	Philippines	1951
	China Sea	1728
	Solomon Islands	1688
	Sulawesi	1616
	Bali	1566
	Flores	1550
	Birds Head Peninsula	1538

Great Barrier Reef North	1499
Kalimantan	1482
Yaeyama	1460
Sumatra	1373
Java	1363
Irian Jaya	1336
Komodo	1294
Taiwan	1292
Thailand	1112
Milne Bay	1103
Ambon Islands	1052
Bismark Sea & Kimbey Bay	1039
Western Australia	994
Malay Peninsula	943
Raja Ampat	898
Pescadores	874
Timor	805
Sri Lanka	755
Ogasawara	720
Chuck	651
Halmahera	617
India – West coast	599
Christmas	580
Hong Kong	565
Dampier	544
Cocos-Keeling	538
North Sumatra	528
Gulf of Thailand	514
Vietnam	505
India – East coast	437
Andaman-Nicobar	430
Izu Islands	370
Gulf of Carpentaria	356
Central Pacific	
Easter	
Easter Island	124
Sala y Gomez	59
S. Fernandez	8
Central Pacific	
Palau	1467
Vanuatu	1458
Fiji	1445
Tonga	1061
Samoa	1051
Marshall Islands	964
South Marianas	925
Yap	816
Ifaluk	772
Pohnpei	744
Wallis Island	598
Tuvalu	589
Phoenix	582
Line Islands	579
Kosrae	545
North Marianas	491
Kapingamagari	454
Wake	438
Rotuma Island	401
Niue	366
Baker & Howland	331

Polynesia		
	Society Islands	708
	Tuamotu Islands	594
	Cook Islands	585
	Gambier	509
	Marquesas	485
	Rapa Island	393
	Pitcairn	379
	Austral Islands	351
Hawaii		
	Hawaii	512
	Jonston Atoll	292
	Midway and Northwestern Hawaii	293
Southwestern Pacific		
	New Caledonia	1324
	Capricorn bunker	1017
	Chesterfield	743
	Loyalty Islands	683
	Lord Howe	427
	Middleton-Elizabeth	415
	Norfolk	255
	Kermadec	145

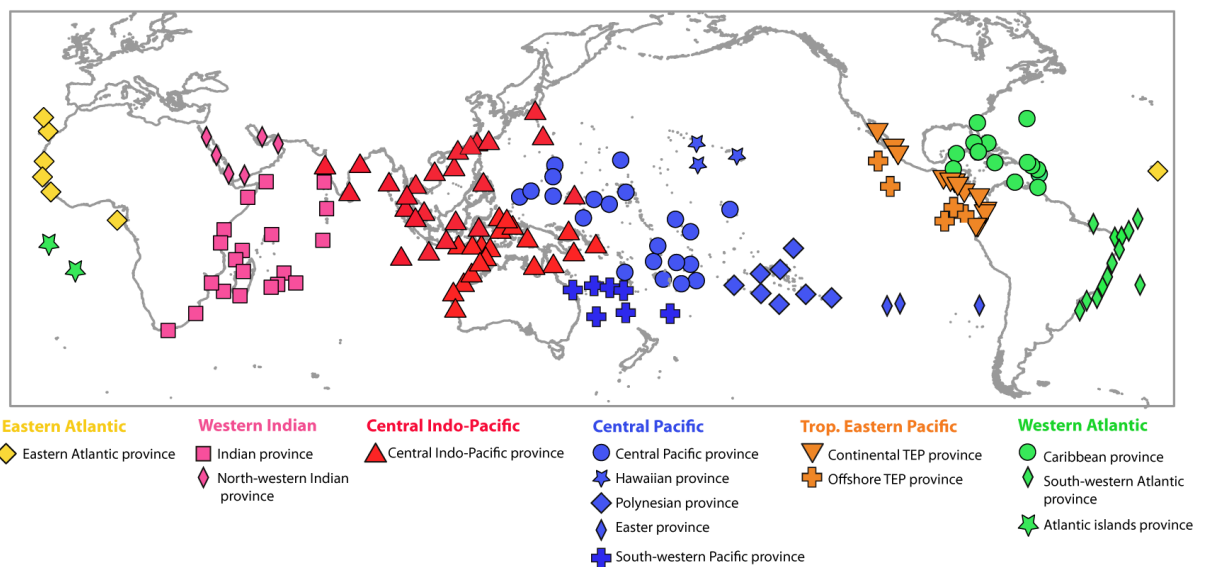


Figure A1. Map of six marine biogeographic regions and its provinces (modified from Kulbicki *et al.*, 2013). Nestedness was assessed at both scales.

Appendix 4: Model selection for the relation between taxonomic and functional nestedness with isolation gradients and plots of the model residuals vs. area gradients.

SCALE 1: Regions and Provinces (n=18)

Table A4. Model selection through analysis of variance (ANOVA) for the relation between taxonomic and functional nestedness across reef fish assemblages with isolation gradients. Nestedness (y) was estimated for regions and provinces, and its corresponding isolation value (x) refers to the mean distance from the site to the 10 nearest patches within each biogeographic region and province.

			ANOVA (model comparison)					
			F-statistic	adj R ²	p-value	Sum of squares	F-value	p-value
Taxonomic	Model 1	$y \sim x$	3.78	0.14	0.06			
	Model 2	$y \sim x + x^2$	4.99	0.49	0.02*	534.01	5.21	0.037*
Functional	Model 1	$y \sim x$	1.60	0.03	0.22			
	Model 2	$y \sim x + x^2$	0.88	0.10	0.63	41.167	0.23	0.633

* $p < 0.01$

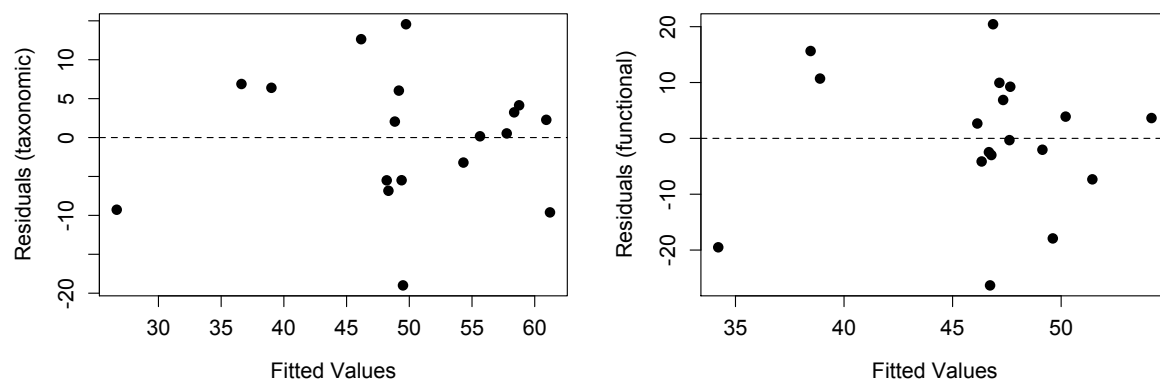


Figure A2. Residual plots of the quadratic models for taxonomic and functional nestedness contrasted against area gradients.

Appendix 5

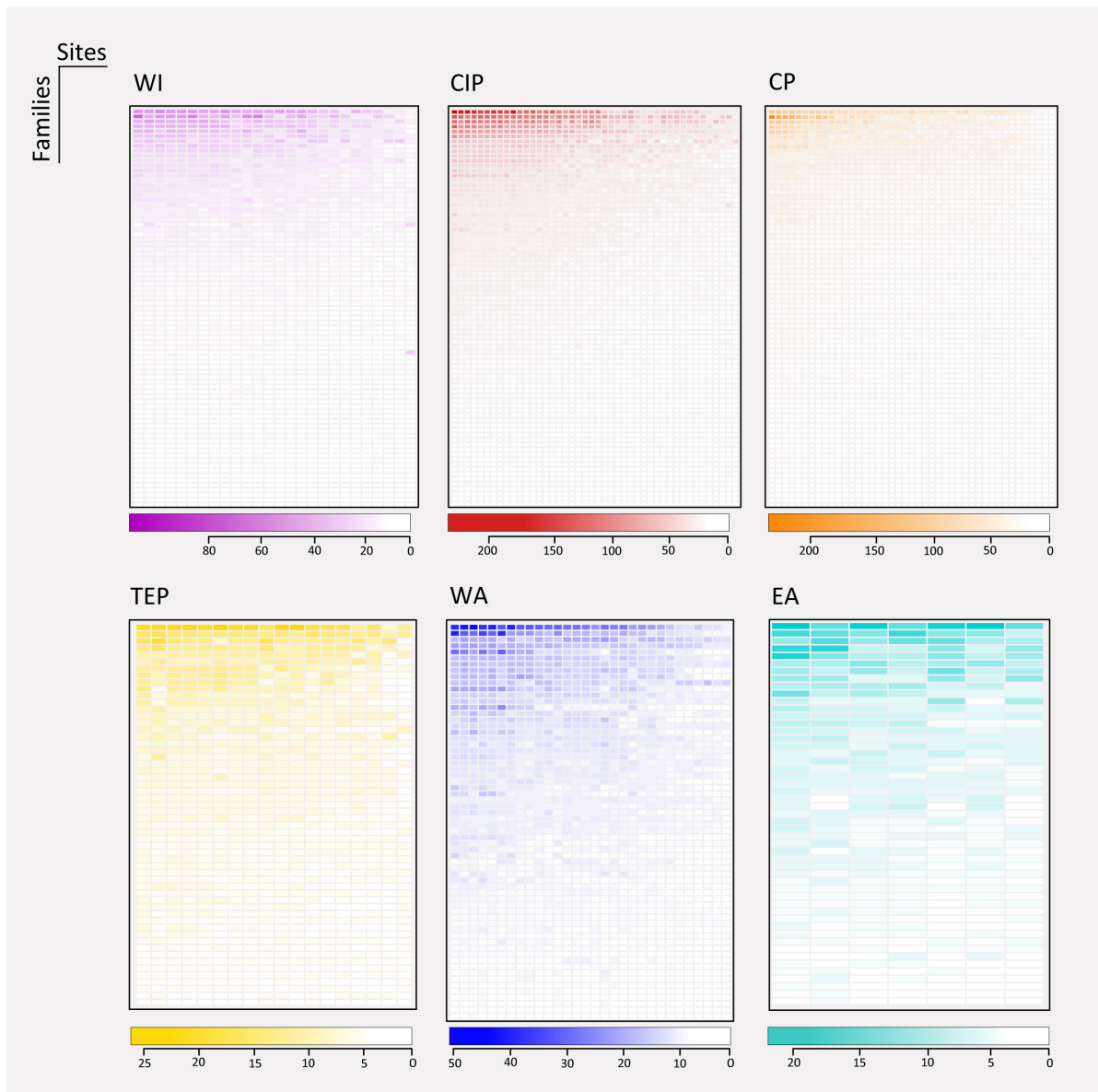


Figure A5. The taxonomic structure of global reef fish assemblages. Maximally packed matrices representing the number of species within families across sites in six biogeographic regions. From left to right, top row: Western Indian (purple), Central Indo-Pacific (red), Central Pacific (orange). Bottom row: Tropical Eastern Pacific (yellow), Western Atlantic (blue) and Eastern Atlantic (light-blue).

Appendix 6

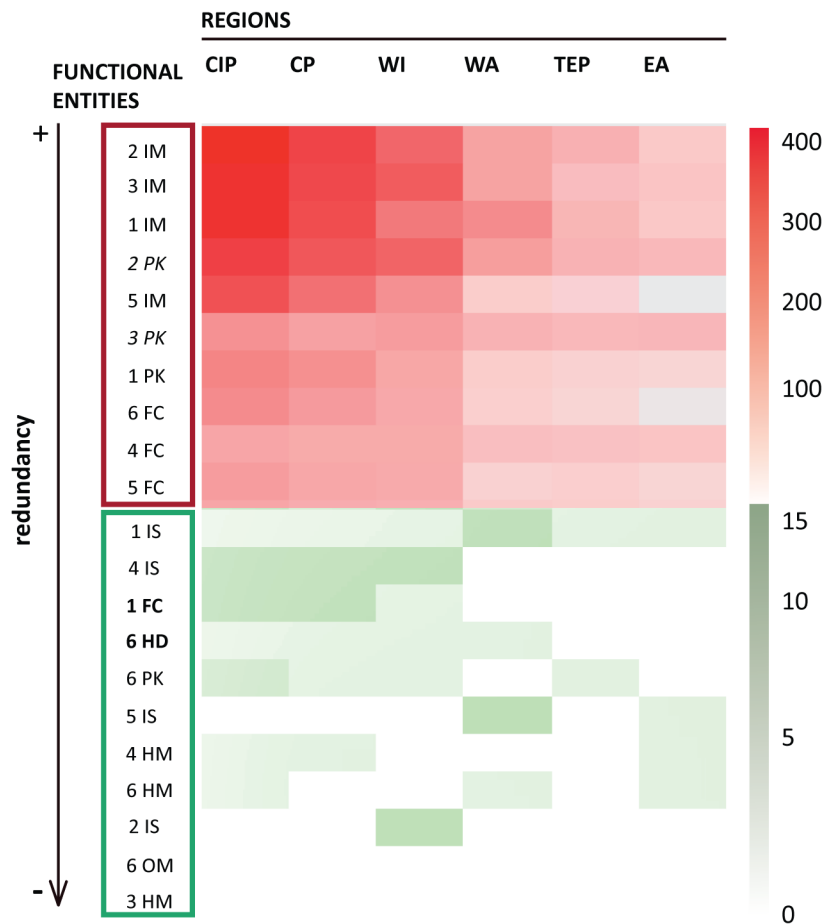


Figure A6. The nested functional structure of global reef fish assemblages. Reef fish FE that occupy the top ten positions (red portion), as well as those in the bottom ten positions (green portion) of a maximally nested matrix. FE in the red rectangle are the ten most widespread and redundant FE across the six biogeographical regions, whereas FE inside the green rectangle are those absent from certain sites and/or represented by a smaller number of species, *i.e.*, less-redundant FE. The gradients from dark-red/ dark-green to pale-red/ pale-green represent decreasing values in matrix cells. Inside the red rectangle, functional entities in italic (*2 PK*, *3 PK* = planktivores <15 cm) appear as very redundant FE in assemblages of the Indo-Pacific. Inside the green rectangle, functional entities in bold (**6 HD** = herbivore-detritivores > 80 cm; and **1 FC** = piscivores < 7 cm) are those with low redundancy across all 6 regions. CIP = Central Indo-Pacific, CP = Central Pacific, WI = Western Indian, WA = Western Atlantic, TEP = Tropical Eastern Pacific, EA = Eastern Atlantic.