

The American Naturalist

Scaling of activity space in marine organisms across latitudinal gradients

Vinay Udyawer^{a*}, Charlie Huveneers^b, Fabrice Jaine^{c,d}, Russell C. Babcock^e, Stephanie Brodie^f, Marie-Jeanne Buscot^g, Hamish A. Campbell^h, Robert G. Harcourt^{c,d}, Xavier Hoennerⁱ, Elodie J. I. Lédée^{j,k}, Colin A. Simpfendorfer^k, Matthew D. Taylor^l, Asia Armstrong^m, Adam Barnettⁿ, Culum Brown^d, Barry Bruceⁱ, Paul A. Butcher^o, Gwenael Cadiou^{l,p}, Lydie I. E. Couturier^q, Leanne Currey-Randall^r, Michael Drew^{s,t}, Christine L. Dudgeon^{u,v}, Ross G. Dwyer^w, Mario Espinoza^x, Luciana C. Ferreira^y, Anthony Fowler^t, David Harasti^l, Alastair R. Harborne^z, Nathan A. Knott^{aa}, Kate Lee^{ab,d}, Matt Lloyd^b, Michael Lowry^l, Teagan Marzullo^{ac}, Jordan Matley^{ad}, Jaime D. McAllister^{ae}, Rory McAuley^{af}, Frazer McGregor^{ag}, Mark Meekan^y, Kade Mills^{ah}, Bradley M. Norman^{ai,aj}, Beverly Oh^{ak}, Nicholas L. Payne^{ac,al}, Vic Peddemors^{am}, Toby Piddocke^{an}, Richard D. Pillans^e, Richard D. Reina^{ao}, Paul Rogers^t, Jayson M. Semmens^{ap}, Amy Smoothey^{am}, Conrad W. Speed^y, Dylan van der Meulen^{aq,ac}, Michelle R. Heupel^{ar,kr}

^a Australian Institute of Marine Science, Arafura Timor Research Facility, Darwin, NT 0810, Australia.

^b College of Science and Engineering, Flinders University, Bedford Park, Adelaide, SA 5042, Australia.

^c Integrated Marine Observing System (IMOS) Animal Tracking Facility, Sydney Institute of Marine Science, Mosman, NSW 2088, Australia

^d School of Natural Sciences, Macquarie University, North Ryde, NSW 2109, Australia.

^e CSIRO Oceans and Atmosphere, Queensland Biosciences Precinct, 306 Carmody Road St Lucia 4011 QLD Australia

^f Institute of Marine Science, University of California Santa Cruz, Santa Cruz, CA, 95064, USA.

^g Menzies Institute for Medical Research, University of Tasmania, Hobart, TAS 7001, Australia.

^h Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, NT 0909, Australia.

ⁱ CSIRO Oceans and Atmosphere, 3 - 4 Castray Esplanade, Hobart, Tasmania 7000, Australia.

^j Fish Ecology and Conservation Physiology Laboratory, Carleton University, Ottawa, ON K1S 5B6, Canada

^k College of Science and Engineering, James Cook University, Townsville, QLD 4811, Australia.

^l Port Stephens Fisheries Institute, New South Wales Department of Primary Industries, Taylors Beach, NSW 2315, Australia.

^m Project Manta, School of Biomedical Sciences, The University of Queensland, St Lucia, QLD 4072, Australia

ⁿ Marine Data Technology Hub, College of Science and Engineering, James Cook University, Townsville, QLD 4811, Australia.

^o Department of Primary Industries, New South Wales Fisheries, Coffs Harbour, NSW 2450, Australia.

^p Fish Ecology Laboratory, School of the Life Sciences, University of Technology, Sydney, NSW 2007, Australia.

^q Université de Brest, CNRS, IRD, Ifremer, UMR 6539 LEMAR, Plouzané, France

^r Australian Institute of Marine Science, Townsville, QLD 4810, Australia.

^s College of Science and Engineering, Flinders University, Bedford Park, Adelaide, SA 5042, Australia.

^t South Australian Research and Development Institute, West Beach, SA 5024, Australia.

^u School of Biomedical Sciences, The University of Queensland, St Lucia, QLD 4072, Australia.

^v School of Science, Technology and Engineering, The University of the Sunshine Coast, Moreton Bay, Petrie, Queensland 4502, Australia.

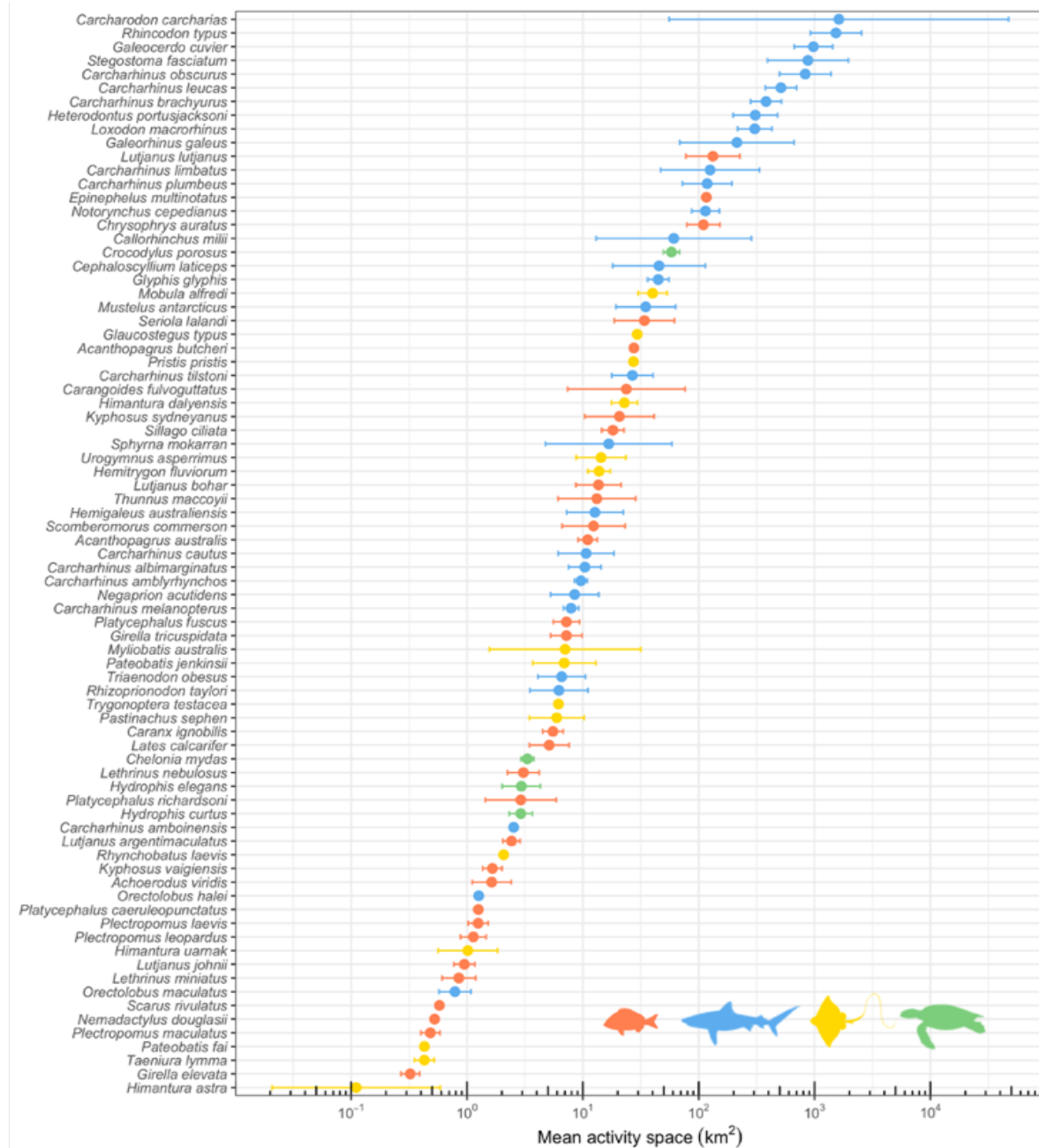
Scaling of activity space

- ^w *School of Science and Engineering, University of the Sunshine Coast, Maroochydore DC, Queensland 4558, Australia.*
- ^x *Centro de Investigación en Ciencias del Mar y Limnología & Escuela de Biología, Universidad de Costa Rica, 2060-11501 San José, Costa Rica.*
- ^y *Australian Institute of Marine Science, Indian Ocean Marine Research Centre, Crawley, WA 6009, Australia.*
- ^z *Institute of Environment and Department of Biological Sciences, Florida International University, North Miami, Florida 33181, USA.*
- ^{aa} *Marine Ecosystem Unit, New South Wales Department of Primary Industries, Huskisson, NSW 2540, Australia.*
- ^{ab} *Sydney Institute of Marine Science, Mosman, NSW 2088, Australia.*
- ^{ac} *School of Biological Earth and Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia*
- ^{ad} *Great Lakes Institute for Environmental Research, University of Windsor, Ontario N9B 9P4, Canada.*
- ^{ae} *Fisheries and Aquaculture Centre, Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS 7001, Australia.*
- ^{af} *School of Biological Sciences, University of Western Australia. Crawley, WA. 6009. Australia.*
- ^{ag} *Murdoch University Field Station, Coral Bay, WA 6701, Australia.*
- ^{ah} *Victorian National Parks Association, Carlton, Vic 3053, Australia.*
- ^{ai} *Centre for Sustainable Aquatic Ecosystems, Harry Butler Institute, Murdoch University, Murdoch, WA 6150, Australia.*
- ^{aj} *ECOCEAN Inc., Serpentine WA 6125, Australia.*
- ^{ak} *School of Biological Sciences and Oceans Institute, University of Western Australia, Crawley, WA 6009, Australia.*
- ^{al} *School of Natural Sciences, Trinity College Dublin, Dublin, Ireland.*
- ^{am} *New South Wales Department of Primary Industries, Fisheries, Mosman, NSW 2088, Australia.*
- ^{an} *Southern Cross University, National Marine Science Centre, Coffs Harbour, NSW 2450, Australia.*
- ^{ao} *School of Biological Sciences, Monash University, Clayton, VIC 3800, Australia.*
- ^{ap} *Fisheries and Aquaculture Centre, Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS 7001, Australia.*
- ^{aq} *Batemans Bay Fisheries Centre, New South Wales Department of Primary Industries, Batemans Bay NSW 2516, Australia.*
- ^{ar} *Integrated Marine Observing System, University of Tasmania, Hobart, TAS 7001, Australia.*

* Corresponding author email: v.udyawer@aims.gov.au

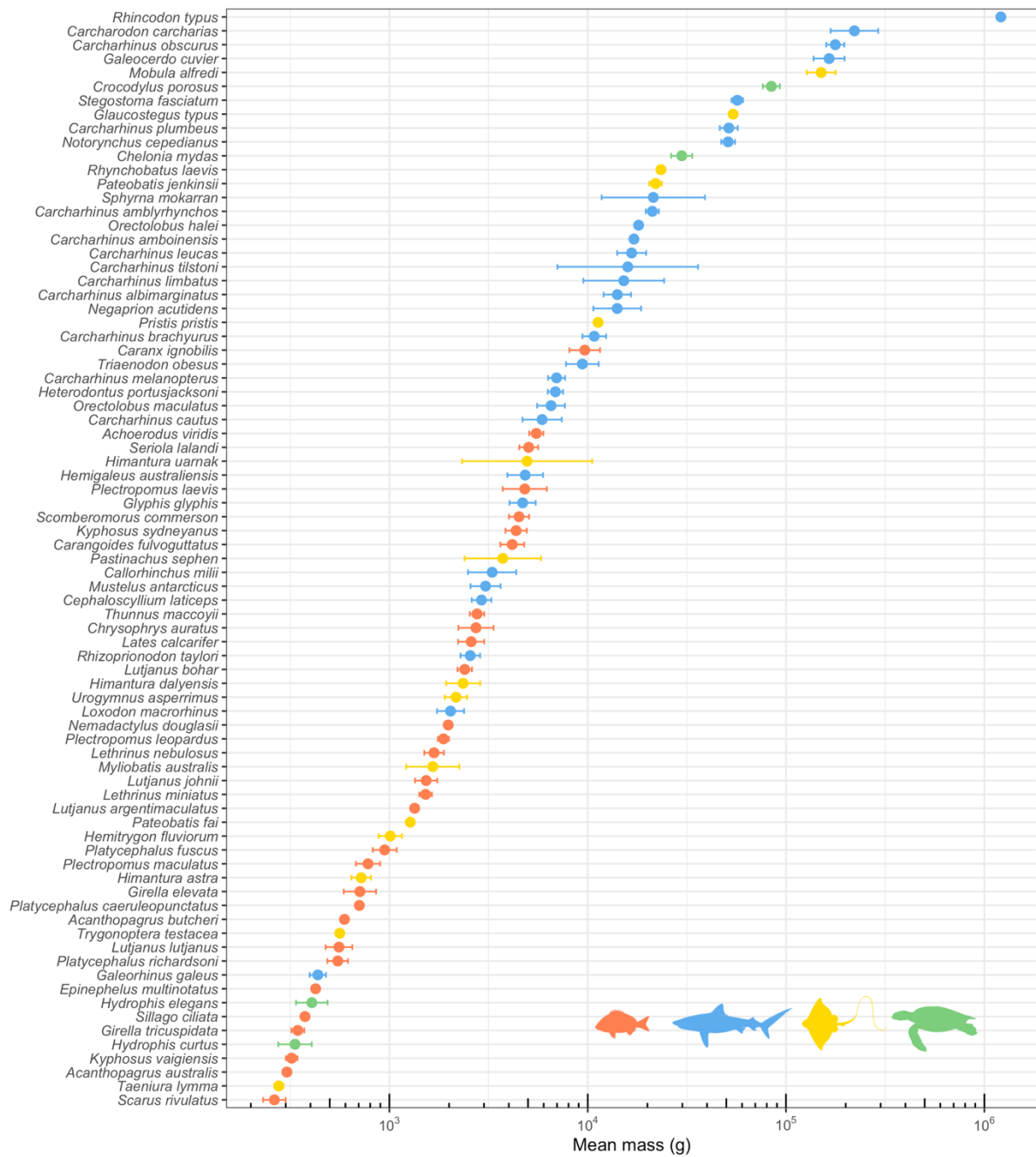
Scaling of activity space in marine organisms across latitudinal gradients

Supplementary Materials



SupFig S1a | Summary plot of log-transformed activity space metrics for each species tracked on the IMOS ATF network. Mean (points) and standard error values (error bars) summarised for each species. Colours of points represent the major marine taxa group for each species (orange: Teleost, blue: Sharks, yellow: Rays and green: Marine reptiles).

Scaling of activity space



SupFig S1b | Summary plot of log-transformed mass (g) for each species tracked on the IMOS ATF network (between 2007 – 2017). Mean (points) and standard error values (error bars) summarised for each species. Colours of points represent the major marine taxa group for each species (orange: Teleost, blue: Sharks, yellow: Rays and green: Marine reptiles).

SupTable S1 | Summary of number of individuals and variable classification used to assess allometric scaling exponents in marine ectotherms, including broad taxonomic groups (teleost fish, sharks, rays or marine reptiles), broad trophic groups (primary, secondary or tertiary consumers) and foraging habitat (benthic or pelagic forager).

Species	Common Name	Taxonomic group	Trophic group	Foraging habitat	Number of individuals	Mean \pm SE mass (g)	Mean \pm SE activity space (km ²)
<i>Acanthopagrus australis</i>	Yellowfin Bream	Teleost fish	Secondary Consumer	Benthic	71	304.05 \pm 1.05	11.01 \pm 1.21
<i>Acanthopagrus butcheri</i>	Black Bream	Teleost fish	Secondary Consumer	Benthic	1	593.36	27.57
<i>Achoerodus viridis</i>	Eastern Blue Groper	Teleost fish	Secondary Consumer	Benthic	37	5503.51 \pm 1.09	1.63 \pm 1.48
<i>Callorhynchus milii</i>	Elephantfish	Sharks	Secondary Consumer	Benthic	2	3296.04 \pm 1.32	60.93 \pm 4.68
<i>Carangoides fulvoguttatus</i>	Turrum	Teleost fish	Tertiary Consumer	Pelagic	3	4161.85 \pm 1.15	23.73 \pm 3.22
<i>Caranx ignobilis</i>	Giant Trevally	Teleost fish	Tertiary Consumer	Pelagic	7	9660.84 \pm 1.19	5.52 \pm 1.23
<i>Carcharhinus albimarginatus</i>	Silvertip Shark	Sharks	Tertiary Consumer	Pelagic	23	14099.22 \pm 1.17	10.42 \pm 1.38
<i>Carcharhinus amblyrhynchos</i>	Grey Reef Shark	Sharks	Tertiary Consumer	Pelagic	139	21171.58 \pm 1.08	9.62 \pm 1.14
<i>Carcharhinus amboinensis</i>	Pigeeye Shark	Sharks	Tertiary Consumer	Benthic	1	17101.11	2.53
<i>Carcharhinus brachyurus</i>	Bronze Whaler	Sharks	Tertiary Consumer	Pelagic	27	10786.62 \pm 1.15	381.39 \pm 1.36
<i>Carcharhinus cautus</i>	Nervous Shark	Sharks	Tertiary Consumer	Benthic	5	5885.9 \pm 1.26	10.66 \pm 1.74
<i>Carcharhinus leucas</i>	Bull Shark	Sharks	Tertiary Consumer	Pelagic	111	16651.86 \pm 1.18	512.56 \pm 1.36
<i>Carcharhinus limbatus</i>	Common Blacktip Shark	Sharks	Tertiary Consumer	Pelagic	2	15197.44 \pm 1.6	125.39 \pm 2.67
<i>Carcharhinus melanopterus</i>	Blacktip Reef Shark	Sharks	Secondary Consumer	Pelagic	153	6962.49 \pm 1.1	7.91 \pm 1.16
<i>Carcharhinus obscurus</i>	Dusky Whaler	Sharks	Tertiary Consumer	Pelagic	34	177199.58 \pm 1.11	831.51 \pm 1.67
<i>Carcharhinus plumbeus</i>	Sandbar Shark	Sharks	Tertiary Consumer	Pelagic	31	51465.36 \pm 1.11	118.24 \pm 1.64
<i>Carcharhinus tilstoni</i>	Australian Blacktip Shark	Sharks	Tertiary Consumer	Pelagic	3	15916.02 \pm 2.26	26.78 \pm 1.51
<i>Carcharodon carcharias</i>	White Shark	Sharks	Tertiary Consumer	Pelagic	2	221336.25 \pm 1.32	1622 \pm 29.19
<i>Cephaloscyllium laticeps</i>	Draughtboard Shark	Sharks	Tertiary Consumer	Benthic	8	2914.56 \pm 1.12	45.48 \pm 2.51
<i>Chelonia mydas</i>	Green Turtle	Marine reptiles	Primary Consumer	Benthic	50	29792.55 \pm 1.13	3.32 \pm 1.14
<i>Chrysophrys auratus</i>	Snapper	Teleost fish	Secondary Consumer	Benthic	50	2732.9 \pm 1.23	109.79 \pm 1.39
<i>Crocodylus porosus</i>	Saltwater Crocodile	Marine reptiles	Tertiary Consumer	Benthic	108	84318.7 \pm 1.1	58.18 \pm 1.17
<i>Dasyatis fluviorum</i>	Estuary Stingray	Rays	Secondary Consumer	Benthic	14	1009.87 \pm 1.15	13.81 \pm 1.25
<i>Epinephelus multinotatus</i>	Rankin Cod	Teleost fish	Secondary Consumer	Benthic	1	424.28	116.5
<i>Galeocerdo cuvier</i>	Tiger Shark	Sharks	Tertiary Consumer	Pelagic	25	164917.45 \pm 1.2	976.81 \pm 1.47
<i>Galeorhinus galeus</i>	School Shark	Sharks	Tertiary Consumer	Benthic	3	435.49 \pm 1.1	213.57 \pm 3.11
<i>Girella elevata</i>	Rock Blackfish	Teleost fish	Primary Consumer	Benthic	7	709.71 \pm 1.21	0.32 \pm 1.2
<i>Girella tricuspidata</i>	Luderick	Teleost fish	Primary Consumer	Benthic	23	345 \pm 1.08	7.21 \pm 1.37

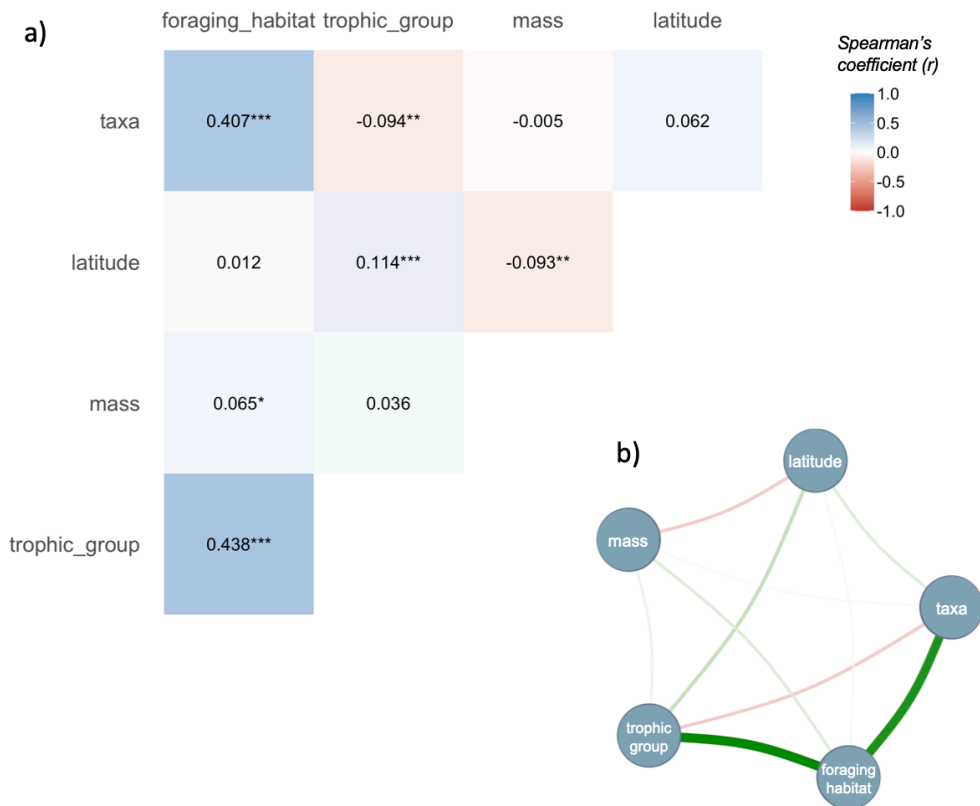
Scaling of activity space

<i>Glaucostegus typus</i>	Giant Shovelnose Ray	Rays	Secondary Consumer	Benthic	1	54115.77	29.45
<i>Glyphis glyphis</i>	Speartooth Shark	Sharks	Tertiary Consumer	Benthic	25	4697.68 ± 1.16	44.72 ± 1.24
<i>Hemigaleus australiensis</i>	Weasel Shark	Sharks	Tertiary Consumer	Benthic	5	4835.59 ± 1.23	12.71 ± 1.76
<i>Heterodontus portusjacksoni</i>	Port Jackson Shark	Sharks	Secondary Consumer	Benthic	37	6870.74 ± 1.09	307.97 ± 1.55
<i>Himantura astra</i>	Blackspotted Whipray	Rays	Secondary Consumer	Benthic	2	720.54 ± 1.12	0.11 ± 5.32
<i>Himantura dalyensis</i>	Freshwater Whipray	Rays	Secondary Consumer	Benthic	7	2353.67 ± 1.22	22.84 ± 1.29
<i>Himantura fai</i>	Pink Whipray	Rays	Secondary Consumer	Benthic	1	1274.06	0.43
<i>Himantura jenkinsii</i>	Jenkins' Whipray	Rays	Secondary Consumer	Benthic	4	21979.4 ± 1.08	6.92 ± 1.88
<i>Himantura uarnak</i>	Reticulate Whipray	Rays	Tertiary Consumer	Benthic	4	4944.62 ± 2.13	1.02 ± 1.81
<i>Hydrophis curtus</i>	Spine-bellied Sea Snake	Marine reptiles	Tertiary Consumer	Benthic	14	333.93 ± 1.21	2.91 ± 1.26
<i>Hydrophis elegans</i>	Elegant Sea Snake	Marine reptiles	Tertiary Consumer	Benthic	6	406.21 ± 1.2	2.94 ± 1.46
<i>Kyphosus sydneyanus</i>	Silver Drummer	Teleost fish	Primary Consumer	Benthic	4	4354.54 ± 1.13	20.69 ± 1.99
<i>Kyphosus vaigiensis</i>	Brassy Drummer	Teleost fish	Primary Consumer	Benthic	14	321.28 ± 1.07	1.66 ± 1.21
<i>Lates calcarifer</i>	Barramundi	Teleost fish	Secondary Consumer	Benthic	22	2583.83 ± 1.16	5.13 ± 1.49
<i>Lethrinus miniatus</i>	Redthroat Emperor	Teleost fish	Tertiary Consumer	Benthic	11	1521.44 ± 1.08	0.85 ± 1.4
<i>Lethrinus nebulosus</i>	Spangled Emperor	Teleost fish	Secondary Consumer	Benthic	20	1678.83 ± 1.12	3.06 ± 1.37
<i>Loxodon macrorhinus</i>	Sliteye Shark	Sharks	Secondary Consumer	Benthic	4	2033.16 ± 1.17	304.75 ± 1.41
<i>Lutjanus argentimaculatus</i>	Mangrove Jack	Teleost fish	Secondary Consumer	Benthic	32	1340.56 ± 1.04	2.42 ± 1.19
<i>Lutjanus bohar</i>	Red Bass	Teleost fish	Tertiary Consumer	Benthic	13	2398.68 ± 1.09	13.66 ± 1.57
<i>Lutjanus johnii</i>	Golden Snapper	Teleost fish	Tertiary Consumer	Benthic	2	1531.57 ± 1.14	0.95 ± 1.23
<i>Lutjanus lutjanus</i>	Bigeye Snapper	Teleost fish	Tertiary Consumer	Benthic	24	556.52 ± 1.17	132.65 ± 1.71
<i>Mobula alfredi</i>	Reef Manta Ray	Rays	Secondary Consumer	Pelagic	58	150316.44 ± 1.18	40.01 ± 1.33
<i>Mustelus antarcticus</i>	Gummy Shark	Sharks	Tertiary Consumer	Benthic	13	3052.32 ± 1.19	34.9 ± 1.81
<i>Myliobatis australis</i>	Southern Eagle Ray	Rays	Secondary Consumer	Benthic	4	1653.61 ± 1.36	7.03 ± 4.5
<i>Negaprion acutidens</i>	Lemon Shark	Sharks	Tertiary Consumer	Pelagic	41	14085.18 ± 1.32	8.5 ± 1.61
<i>Nemadactylus douglasii</i>	Grey Morwong	Teleost fish	Secondary Consumer	Benthic	1	1978.61	0.53
<i>Notorynchus cepedianus</i>	Broadnose Sevengill Shark	Sharks	Tertiary Consumer	Pelagic	22	51040.03 ± 1.08	114.43 ± 1.32
<i>Orectolobus halei</i>	Banded Wobbegong	Sharks	Tertiary Consumer	Benthic	1	18051.69	1.26
<i>Orectolobus maculatus</i>	Spotted Wobbegong	Sharks	Tertiary Consumer	Benthic	30	6530.15 ± 1.18	0.79 ± 1.37
<i>Pastinachus sephen</i>	Cowtail Stingray	Rays	Secondary Consumer	Benthic	11	3729.21 ± 1.56	5.95 ± 1.72
<i>Platycephalus caeruleopunctatus</i>	Bluespotted Flathead	Teleost fish	Secondary Consumer	Benthic	1	705.2	1.25
<i>Platycephalus fuscus</i>	Dusky Flathead	Teleost fish	Tertiary Consumer	Benthic	36	946.2 ± 1.15	7.21 ± 1.3
<i>Platycephalus richardsoni</i>	Tiger Flathead	Teleost fish	Secondary Consumer	Benthic	3	548.53 ± 1.13	2.91 ± 2.03
<i>Plectropomus laevis</i>	Bluespotted Coral Trout	Teleost fish	Tertiary Consumer	Benthic	4	4813.61 ± 1.29	1.25 ± 1.22
<i>Plectropomus leopardus</i>	Common Coral Trout	Teleost fish	Tertiary Consumer	Benthic	33	1872.1 ± 1.07	1.13 ± 1.29

Scaling of activity space

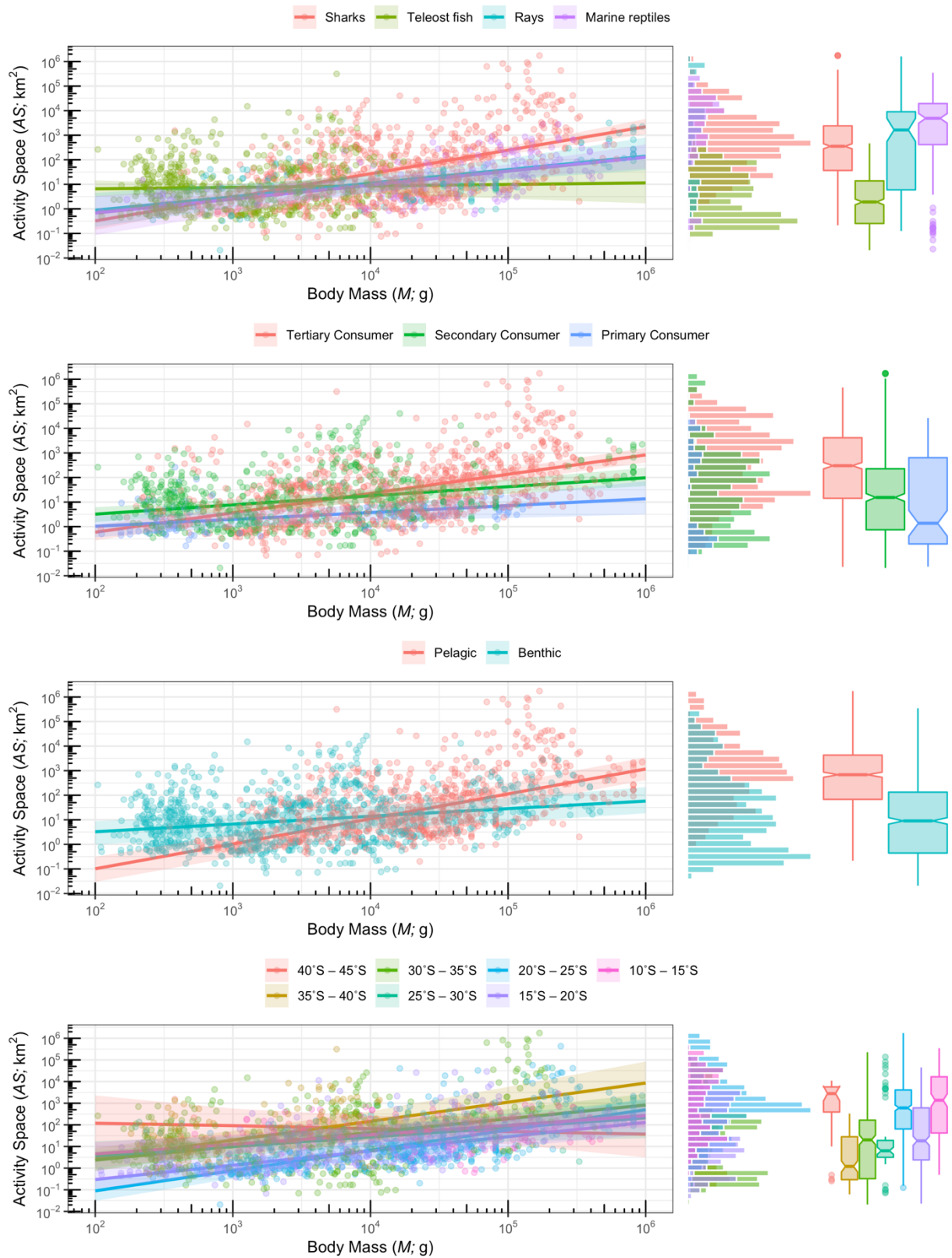
<i>Plectropomus maculatus</i>	Barcheek Coral Trout	Teleost fish	Tertiary Consumer	Benthic	8	780 ± 1.15	0.48 ± 1.21
<i>Pristis pristis</i>	Freshwater Sawfish	Rays	Secondary Consumer	Benthic	1	11280.62	27.34
<i>Rhincodon typus</i>	Whale Shark	Sharks	Secondary Consumer	Pelagic	4	1211260.41 ± 1	1529.06 ± 1.66
<i>Rhizoprionodon taylori</i>	Australian Sharpnose Shark	Sharks	Tertiary Consumer	Benthic	4	2556.39 ± 1.12	6.22 ± 1.78
<i>Rhynchobatus laevis</i>	Smoothnose Wedgefish	Rays	Secondary Consumer	Benthic	1	23398.52	2.07
<i>Scarus rivulatus</i>	Surf Parrotfish	Teleost fish	Primary Consumer	Benthic	15	262.8 ± 1.14	0.58 ± 1.05
<i>Scomberomorus commerson</i>	Spanish Mackerel	Teleost fish	Tertiary Consumer	Pelagic	12	4503.9 ± 1.12	12.37 ± 1.87
<i>Seriola lalandi</i>	Yellowtail Kingfish	Teleost fish	Tertiary Consumer	Pelagic	20	5036.83 ± 1.12	33.99 ± 1.82
<i>Sillago ciliata</i>	Sand Whiting	Teleost fish	Secondary Consumer	Benthic	51	375.09 ± 1.05	18.19 ± 1.25
<i>Sphyrna mokarran</i>	Great Hammerhead	Sharks	Tertiary Consumer	Pelagic	4	21412.76 ± 1.82	16.72 ± 3.51
<i>Stegostoma fasciatum</i>	Zebra Shark	Sharks	Secondary Consumer	Benthic	5	56798.22 ± 1.07	877.09 ± 2.24
<i>Taeniura lymma</i>	Bluespotted Fantail Ray	Rays	Secondary Consumer	Benthic	2	276.99 ± 1.05	0.43 ± 1.22
<i>Thunnus maccoyii</i>	Southern Bluefin Tuna	Teleost fish	Secondary Consumer	Pelagic	4	2765.2 ± 1.09	13.2 ± 2.16
<i>Triaenodon obesus</i>	Whitetip Reef Shark	Sharks	Tertiary Consumer	Benthic	10	9395.24 ± 1.21	6.56 ± 1.6
<i>Trygonoptera testacea</i>	Common Stingaree	Rays	Secondary Consumer	Benthic	1	561.53	6.16
<i>Urogymnus asperrimus</i>	Porcupine Ray	Rays	Secondary Consumer	Benthic	2	2165.63 ± 1.14	14.36 ± 1.64

Scaling of activity space



SupFig S3 | Multilevel correlation analysis across four covariates used in all subsequent analysis. Taxonomic group was used as a random effect within the multilevel correlation assessment using a Spearman's rank-order coefficient. a) Correlation matrix across the four covariates identify all pairwise relationships were weak (spearman coefficients $< |0.5|$; provided within the matrix). Spearman coefficient (r) displayed within the matrix with p-value significance level identified using asterisks ($p < 0.001$ ***; $p < 0.01$ **; $p < 0.5$ *). b) spoke diagram highlighting correlations ($< |0.5|$) between trophic_group, foraging_habitat and taxonomic group.

Scaling of activity space



SupFig S4 | Interaction plots for models summarised in Table 3