The following supplements accompany the article

Comparative application of trophic ecosystem models to evaluate drivers of endangered Hawaiian monk seal populations

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Marine Ecology Progress Series 582: 215–229 (2017)

Supplement 1. Monk seal foraging area used to determine model domain

We designated the study area around Laysan Island based on monk seal foraging ranges and dive depths (habitat designations for FFS were taken from Parrish et al. 2012). For Laysan, these foraging ranges came from satellite tag data from 27 seals (Stewart et al. 2006). Stewart et al. (2006) showed no visits to Lisianski, a nearby island with significant foraging area, by Laysan animals (n=20). Given the low frequency of Laysan seals foraging at Lisianski and confounding factors associated with tracking biomass for a second monk seal population, Lisianski was excluded from the Laysan study area (Fig S1). It should be noted, however, that Lisianski tagged seals visited Laysan frequently (this is accounted for in biomass estimates below). The Stewart et al. (2006) data showed 30%-40% of seals visited Raita bank (~222 km from Laysan), thus it was included in the study area. Maro Reef and the Northampton Sea Mounts (~120 km and ~74 km from Laysan, respectively) were also commonly visited and hence included in the study area. The total area encompassing the included features was approximately 327km x 93km, ~30,000km^2. Areas deeper than 500m were considered out of range of normal monk seal foraging dives and were excluded from the study area. Monk seal habitat was divided in depth categories per divisions previously presented in Parrish et al. (2012).

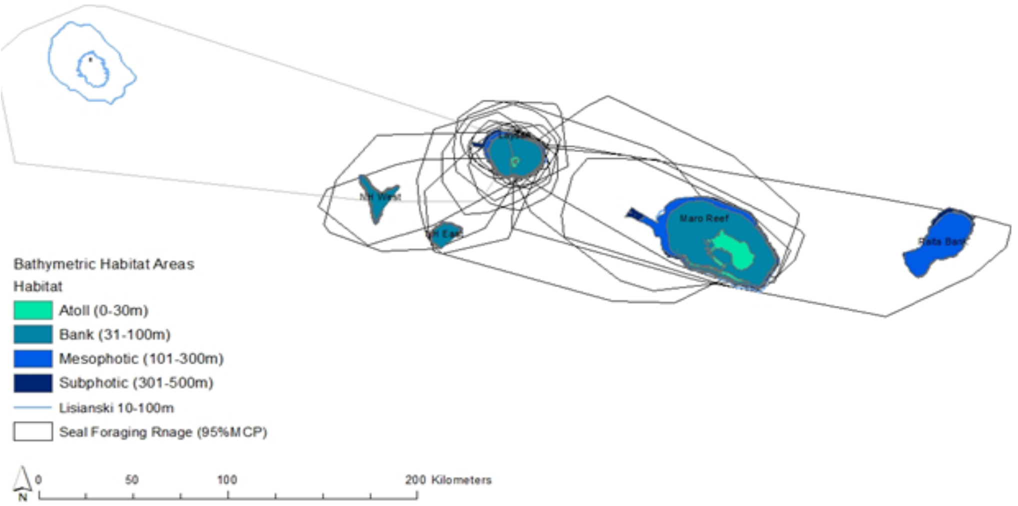

Fig S1. Foraging ranges of 27 monk seals from Laysan Island.

Supplement 2. Species and common name for the most frequently encountered taxa in field surveys for the model groups.

Little is known about the species composition of lower trophic level groups (heterotrophic benthos and lower) thus those groups are omitted from this table. When there were more than 10 species per group, only those species that contributed to >1% of the total biomass for that group were included. All groups are updated from Parrish et al. (2012) when data were available.

Model component	Species (common name)
Sea birds	*Anous stolidus pileatus* (brown noddy) *Phoebastria immutabilis* (Laysan albatross) *Phoebastria nigripes* (black-footed albatros) *Pterodroma hypoleuca* (Bonin petrel) *Gygis alba rothschildi* (white tern) *Fregata minor palmerstoni* (great frigatebirds) *Puffinus nativitatis* (Christmas shearwater) *Puffinus pacificus* (wedge-tailed shearwater) *Sterna fuscata oahuensis* (Sooty tern) *Sula dactylatra personata* (brown booby)
Tiger shark	*Galeocerdo cuvier*
Monk seal	*Monachus schauinslandi*
Reef & Bank Sharks	*Carcharhinus amblyrhynchos* (gray reef shark) *Carcharhinus galapagensis* (galapagos shark) *Triaenodon obesus* (whitetip reef shark)
Reef & Bank Jacks	*Caranx ferdau* (blue trevally) *Caranx ignobilis* (giant trevally) *Caranx lugubris* (black trevally) *Caranx melanpygus* (bluefin trevally) *Caranx orthogrammus* (island jack) *Carangoides ferdau* (black jack) *Pseudocaranx dentex* (thicklipped jack) *Seriola dumerili* (greater amberjack)
Turtles	*Chelonia mydas* (green turtle)
Benthic Bottomfish	*Epinephelus quernus* (Hawaiian grouper) *Etelis carbunculus* (squirrelfish snapper) *Etelis coruscans* (flame snapper) *Pristipomoides zonatus* (flower snapper)
Demersal Bottomfish	*Aprion virescens* (green jobfish) *Pristipomoides auricilla* (goldflag snapper) *Pristipomoides filamentosus* (pink snapper)

Model component	**Species (common name)**
Small Pelagics	*Decapterus macarellus* (mackerel scad) *Spratelloides delicatulus* (sprat)
Reef & Bank Fish Piscivores	*Aphareus furca* (small tooth jobfish) *Aphareus rutilans* (rusty jobfish) *Aulostomus chinensis* (trumpetfish) *Gymnothorax flavimarginatus* (yellowmargin moray) *Oxycheilinus unifasciatus* (ringtal maori wrasse) *Paracirrhites forsteri* (blackside hawkfish) *Parupeneus cyclostomus* (goldsaddle goatfish)
Reef & Bank Fish Planktivores	*Abudefduf abdominalis* (Hawaiian sergeant) *Chaetodon miliaris* (milletseed butterflyfish) *Chromis ovalis* (oval chromis) *Chromis verator* *Cirrhilabrus jordani* (flame wrasse) *Dascyllus albisella* (Hawaiian dascyllus) *Heniochus diphreutes* (pennantfish) *Melichthys niger* (black triggerfish) *Naso brevirostris* (short-nosed unicornfish) *Naso hexacanthus* (sleek unicornfish) *Pseudanthias thompsoni* (Hawaiian anthias)
Reef & Bank Fish Herbivores	*Acanthurus dussumieri* (eyestripe surgeonfish) *Acanthurus nigrofuscus* (lavender tang) *Acanthurus nigroris* (bluelined surgeonfish) *Acanthurus olivaceus* (orange band surgeonfish) *Acanthurus triostegus* (convict tang) *Centropyge fisheri* (orange angelfish) *Centropyge potteri* (potter's angelfish) *Chlorurus perspicillatus* (spectacled parrotfish) *Chlorurus sordidus* (bullethead parrotfish) *Ctenochaetus strigosus* (goldring surgeonfish) *Kyphosus sp* (chub) *Melichthys vidua* (pink tail triggerfish) *Naso lituratus* (orangespine unicornfish) *Naso unicornis* (bluespine unicornfish) *Scarus dubius* (regal parrotfish) *Stegastes fasciolatus* (Pacific gregory)
Reef & Bank Fish Benthic Carnivores	*Anampses cuvier* (pearl wrasse) *Bodianus bilunulatus* (tarry hogfish) *Cantherhines dumerilii* (whitespotted filefish) *Chaetodon multicinctus* (peddled butterflyfish) *Coris venusta* (elegant coris) *Coris flavovittata* (yellowstriped coris) *Gunnellichthys curiosus* (curious wormfish) *Monotaxis grandoculis* (humpnose bigeye bream)

Model component	**Species (common name)**
	Oplegnathus punctatus (spoted knifejaw) *Paracirrhites arcatus* (arc-eye hawkfish) *Parapercis schauinslandii* (redspotted sandperch) *Pseudojuloides cerasinus* (smalltail wrasse) *Sufflamen bursa* (lei triggerfish) *Sufflamen fraenatum* (masked triggerfish) *Thalassoma ballieui* (blacktail wrasse) *Thalassoma duperrey* *Thalassoma purpureum* (surge wrasse) *Zanclus cornutus* (Moorish idol)
Mesophotic Fish Piscivores	*Ariosoma marginatum* (big-eye conger) *Ophichthus kunaloa* (snake eel) *Ophidion muraenolepis* (black edged cusk eel)
Mesophotic Fish Planktivores	*Odontanthias elizabethae* (elizabeth's anthias) *Plectranthias kelloggi* (threadfin perchlet) *Pseudoanthias bicolor* (bicolor anthias) *Pseudoanthias thompsoni* (thompson's anthias) *Symphysanodon maunaloae* (slope fish)
Mesophotic Fish Benthic Carnivores	*Bothus pantherinus* (panther flounder) *Bothus thompsoni* (thompson's flounder) *Callionymus decorates* (longtail dragonet) *Canthigaster coronate* (crown toby) *Canthigaster rivulata* (maze toby) *Malacanthus brevirostris* (flagtail tilefish) *Parapercis schauinslandii* (redspotted sandperch) *Sebastapistes ballieui* (spotfin scorpionfish)
Mesophotic forage fish	*Luzonichthys earli* (Splitfin anthias)
Subphotic Fish Piscivores	*Chaunax* sp. (sea toad) *Chlorophtalmus* sp. (green eyes) *Chrionema* sp. *Meadia abyssalis* (Abyssal cut-throat eel) *Pontinus macrocephalus* (largeheaded scorpionfish) *Squalus mitskurii* (dogfish)
Subphotic Fish Planktivores	*Antigonia eos* (boar fish) *Antigonia capros* (boar fish) *Caelorinchus spilonotus* (spotted rattail) *Decapterus tabl* (redtail scad) *Grammicolepis* sp. *Hollardia goslinei* (white-spotted spikefish) *Myctophidae* *Pseudopentaceros wheeleri* (armorhead) *Zenopsis nubulosus* (john dory)

Model component	Species (common name)
Subphotic Fish Benthic Carnivore	*Bembrops filifera* (duck-billed bembropsid) *Polymixia berndti* (Berndt's beard fish) *Satyrichthys* sp. (orange rakefish)
Macros Heterotrophs	*Calappa bicornis* (two-horned box crab) *Calappa calappa* (smooth box crab) *Carpilius convexus* (convex pebble crab) *Charybdis hawaiiensis* (Hawaiian swimming crab) *Heterocarpus ensifer* (two-spined shrimp) *Heterocarpus laevigatus* (red-tipped shrimp) *Panulirus marginatus* (spiny lobster) *Scyllarides squammosus* (common slipper lobster)
Cephalopods	*Octopus cyanea* (Hawaiian day octopus) *Octopus ornatus* (ornate octopus) *Sthenoteuthis oualaniensis* (neon flying squid)

Supplement 3 - Source for parameters for Laysan Ecopath

Biomass estimates

Biomass estimates (in metric tons per square kilometer, t/km^2) came from 1998, when available, the initial year of the Ecosim simulation. Groups for which no information was available, we used the biomass estimates from Parrish et al. (2012) corrected for habitat area in Laysan, or used Ecopath-derived estimates.

Production, Consumption and Ecotrophic efficiency

For the groups with existing data, the production to biomass (P/B) and consumption to biomass (C/B) ratio were recalculated based on biomass-weighted means of the taxa comprising the functional groups. C/B was calculated using the empirical formula of Pauly (1986) and Palomares & Pauly (1998). P/B was determined based on the sum of the natural mortality rate (M), estimated using the empirical formula of Pauly (1980), and for the exploited species, we added the fishing mortality rate (F) to M. The ecotrophic efficiency (EE) of monk seals was based on the loss of juvenile monk seals which differs between these regions. We estimated the EE to be 0.11 based on a loss of half as many juveniles compared to the FFS area for which Parrish et al. (2012) estimated an EE of 0.225. For the groups with limited or no existing data, (meso and subphotic groups and lower functional groups), we assumed that the parameters for P/B, C/B and EE were the same as FFS. All parameters had associated uncertainty estimates, with the greatest confidence being assigned to those parameters from Laysan surveys. These ranks or ‘pedigree’ (Pauly et al. 2000) were used for uncertainty analyses.

Details per functional group

Seabirds: Coastal seabirds include the Laysan and black-footed albatross, Christmas and wedge-tailed shearwater, great frigatebird, brown booby, white and sooty tern, brown noddy, and Bonin petrel (www.fws.gov). Most of these seabirds catch their prey (juvenile or small fish such as mackerel scad, juvenile goatfish, flying fish, squid) from the subsurface, some in association with large groups of apex predators that corral the fish and bring them to the surface in offshore areas. Diet and vital rates were taken from Parrish et al. (2012) and biomass was model derived assuming an EE of 0.45.

Tiger sharks: The biomass of tiger sharks at any given island in the Northwestern Hawaiian Islands archipelago is in constant flux because of emigration and immigration. We used the same biomass (0.007-0.01 t·km^2) and diet information as given in Parrish et al. (2012). The daily ratio required to sustain average growth of tiger sharks in Hawaii is about 200 grams of food per day (C. Meyer and K. Holland Pers Comm. 1/6/2016). We multiplied this value by 1.5 to account for juvenile somatic growth and for reproduction of mature animals, and divided it by the average weight of a 2 m tiger shark of 115 kg, which gave us a Q/B of 0.9. P/B was obtained from FISHBASE (Froese & Pauly 2008).

Monk Seals: Biomass and other life history parameters were estimated from NMFS field survey data from the Northwest Hawaiian Islands (National Marine Fisheries Service 2016, 1998 data for Laysan Island (LAY) queried directly from original databases for the analysis here). Wherever possible we used methods identical to Parrish et al. (2012) to ensure comparability between the LAY and FFS ecosystem models.

Biomass - Biomass was model derived with an EE of 0.11 and compared with survey data as a validation tool. To estimate biomass from surveys we queried the HMSRP Population Assessment database for "all seen" seals on LAY each year from 1998-2015. Note, by including all animals seen on LAY in a given year we expect to include all resident animals as well as some migrant animals, for example those from Lisianski Island that only make occasional foraging trips to LAY. This was determined to be a valuable inclusion because telemetry data (Stewart et al. 2006) and sightings data (as used by National Marine Fisheries Service 2016) suggest that as many as 5% of Lisianski animals might make a foraging trip to LAY in a year thus adding to the seal biomass relying on the local ecosystem. Age specific biomass for seals were the same as those used by Parrish et al. (2012), derived from growth curve estimates from FFS demographic data (Baker et al. 2014). We queried the database for additional/updated mass data and found evidence that generally supported use of the previously established mass estimates (Table S3.1). Seals in the youngest age class fit the estimate very closely. Subadults were seldom directly weighed, but with little data, it appears that this age group may be poorly described by the estimated mass of 125kg (but note that data were only available for 3 year olds, and we might expect rapid growth toward adult size in the 3-4 year age range). Adult masses showed wide variation that spanned the estimated values. Given the range in masses, especially for subadults and adults, it will be important to incorporate uncertainty for biomass measures.

Table S3.1. Population Assessment Database (NWHI seals)

Age class	Sample Size	Avg Mass	Model Estimate
0-2	1104	58kg	60kg
3-4	26 (3 yrs only)	74kg	125kg
5+	1	202kg	170kg
MHI Veterinary Records			
0-2	4 ("yearlings")	51kg	
3-4	3 ("juveniles")	81kg	
5+	5	160kg	

Diet Matrix - Diet items were based on species identified by scat analysis from Goodman-Lowe 1998, and proportions of prey reflected in diet composition was based on fatty analysis by Iverson et al. (2011). Diet composition analysis based on fatty acid models indicated that animals across the southern half of the NWHI (FFS, LAY, and LIS) exhibited nearly identical distribution of diet items (see figure 48 in Iverson et al. 2011). Thus, we were comfortable using the diet matrix developed by Parrish et al. (2012) for the FFS population.

Consumption Q/B - Consumption rates were estimated based on caloric need to fuel monk seals' basal metabolic rates (Olesiuk 1993). Olesiuk calculated that captive monk seals required 1.5kg of herring per day to meet their caloric needs, and then estimated that a seal in the wild would need to consume 3kg of fish per day. We used this estimate of 1095 kg/year for each seal in the population (thus accounting for higher consumption/kg in smaller growing seals vs adults that would be larger but have lower energetic needs/kg). Q/B was estimated as 1095 x #seals / total biomass.

Production P/B - Age-specific mortality rates were derived from HMSRP Population Assessment survival analysis (Baker & Thompson 2007, National Marine Fisheries Service 2016). We estimated the number of mortalities per year as 1-survival (at age) X #seals (at age), then multiplied by age-specific mass to get the mortality rate per biomass (P/B).

Reef & Bank sharks: Biomass of reef and bank sharks was derived by the model with an assumed EE of 0.23 and 0.40 respectively. Reef shark biomass was compared with biomass estimates from towed-diver surveys of reef habitat conducted between 2000 and 2008 (PIFSC CREP unpublished data). Reef sharks were only observed around Maro (2.7 g/m^2) from the towed diver surveys. Adjusted for the entire reef area, the biomass was estimated to be ~0.8 g/m^2. Results from the pre-balance check suggested it should be around 0.3 g/m^2 (Supplement 6) which is more comparable to the model derived estimate (0.1 g/m^2). Diet data were assumed the same as published in Parrish et al. (2012) where it was obtained from DeCrosta et al. (1984), Vatter (2000), and FISHBASE (Froese & Pauly 2008). P/B and Q/B were obtained from FISHBASE and weighted by biomass of the shark species.

Reef & Bank jacks: Biomass was derived from surveys of bank habitat (Parrish & Boland 2004), providing 0.05 t/km^2 for bank jacks and from towed-diver survey of reef habitat conducted between 2000 and 2008 (PIFSC CREP unpublished data), providing 1.24 t/km^2 for reef jacks. Diet, P/B, and Q/B for bank jacks were taken from Parrish et al. (2012) (obtained from Sudekum et al. 1991) and for reef jacks from FISHBASE based on weighted biomass of jack taxa.

Turtles: The resident population of Hawaiian green turtles is made up of juveniles (80%) and subadults (20%) with between 100 and 200 individuals total (G. Balazs pers comm Dec 23, 2015). For this reason, published vital rate estimates for green turtles from areas with resident populations in Hawaii (Wabnitz et al. 2010, Parrish et al. 2012, Weijerman et al. 2013) were scaled back to reflect the lower amount of turtle hatchlings with high mortality rates. P/B was set to 0.109, and Q/B was set at 6.76. Biomass was model derived with an EE of 0.40.

Small Pelagics: Biomass was model derived with an EE of 0.95; diet, P/B, and Q/B were taken from FISHBASE (Froese & Pauly 2008).

Bottomfish: We followed the Parrish et al. (2012) approach to calculate the biomass of bottomfish: mean annual stock biomass (1024.1 t) for the Ho'omalu area in the NWHI in 1998, reported by Brodziak et al. (2009), was divided by the mesophotic area in the Ho'omalu area NWHI (3148.2 km^2) (Parrish & Boland 2004) and entered in ECOPATH for the mesophotic fraction of the model at 0.32 t/km^2. Based on their diet, we divided this group into 'demersal bottomfish', eating mostly zooplankton, and 'benthic bottomfish' eating mostly fish (Haight et al. 1993). We used the same proportion of demersal to benthic bottomfish as Parrish et al. (2012), giving us 0.14 t/km^2 and 0.18 t/km^2, respectively. P/B, Q/B, and diet were obtained from FISHBASE (Froese & Pauly 2008) and Haight et al. (1993). During tuning, we adjusted the biomass upward to 0.215 t/km^2 for the benthic bottomfish group.

Reef fish: Reef fish biomass came from 45 stationary point count (SPC) surveys conducted at random stratified sites around Laysan by NOAA Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Program (CREP) from 2009 to 2015, and biomass was assumed to be the same for 1998. Species were aggregated into functional groups based on their diet. Species specific P/B and Q/B came from FISHBASE (www. fishbase.org) and were average per functional group based on weighted biomass per taxa.

Bank, mesophotic & subphotic fish: Bank and mesophotic biomass data came from Parrish and Boland (2004) and surveys conducted by the Papahanaumokuakea Marine National Monument in depths from 50-90 m (PMNM unpublished data). Biomass for the subphotic zone was assumed to be the same as in the French Frigate Shoals area reported in Parrish et al. (2012). Vital rates came from FISHBASE and were averaged per functional group based on weighted biomass. Diet data came from Parrish et al (2012).

Macro-heterotrophs & heterotrophic benthos: Biomass was derived by the model using an EE of 0.92 and 0.972 respectively. Vital rates came from the literature (MacDonald 1984, Parrish et al. 1985, Opitz 1993, Defelice 1997, Parrish et al. 2012).

Cephalopods: Biomass was derived by the model using an EE of 0.78. Vital rates came from the literature (Wells & Wells 1970, Van Heukelem 1973, Opitz 1993, Mather 1995).

Low level production: Biomass was derived by the model using an EE of 0.88 and vital rates came from NWHI published studies (Odum & Odum 1955, Atkinson & Grigg 1984, Polovina 1984).

Fishery Removals: Catch landings were taken from Hawaii State Commercial reporting zones (16925, 17025, 17125, 17225), which include both the reef around Laysan and neighboring reefs and banks in the Laysan region encompassed by the model.

Supplement 4. Input parameter values, pedigree (uncertainty estimates) and diet matrix

Ecopath input parameters for Laysan. Bold values are model derived.

Group nr	Group name	Trophic level	Habitat area (fraction)	Biomass (t/km²)	Production / biomass (/year)	Consumption / biomass (/year)	Ecotrophic efficiency
1	Seabirds	4.19	0.33	**0.001**	0.19	111.00	0.45
2	Tiger Sharks	4.26	0.33	0.003	0.21	0.90	**0.06**
3	Monk Seals	4.37	1.00	**0.008**	0.09	8.61	0.11
4	Reef Sharks	4.32	0.33	**0.034**	0.19	1.82	0.23
5	Bank Sharks	4.35	0.25	**0.007**	0.20	1.82	0.40
6	Reef Jacks	4.02	0.33	0.409	0.26	3.41	**0.01**
7	Bank Jacks	4.19	0.25	0.013	0.90	3.41	**0.03**
8	Turtles	2.10	0.33	**0.169**	0.11	6.76	0.40
9	Benthic BF	3.52	0.20	0.043	1.18	4.00	**0.99**
10	Demersal BF	3.29	0.20	0.034	1.18	4.00	**0.30**
11	Small Pelagics	3.10	1.00	**0.718**	0.48	6.92	0.95
12	Reef Piscivores	3.79	0.33	1.103	0.30	6.12	**0.85**
13	Reef Planktivores	3.00	0.33	2.640	0.91	8.25	**0.88**
14	Reef Herbivores	2.14	0.33	6.729	0.66	21.42	**0.71**
15	Reef Benth. Carniv.	3.42	0.33	3.739	0.68	6.20	**0.91**
16	Bank Piscivores	4.04	0.26	0.021	1.26	7.93	**0.42**
17	Bank Planktivores	3.00	0.26	1.131	3.54	15.73	**0.10**
18	Bank Herbivores	2.14	0.26	2.696	1.01	26.55	**0.11**
19	Bank Benth. Carniv.	3.42	0.26	2.346	1.76	10.31	**0.03**
20	Meso Piscivores	4.14	0.20	0.013	1.38	3.13	**0.36**
21	Meso Planktivores	3.00	0.20	0.114	2.40	6.03	**0.10**
22	Meso Benth Carniv.	3.79	0.20	0.004	2.06	4.53	**0.59**
23	Meso Forage Fish	3.00	0.20	0.147	4.18	7.23	**0.99**
24	Sub Piscivores	4.48	0.22	0.003	0.92	8.37	**0.58**
25	Sub Benth. Carniv.	3.56	0.22	0.008	1.39	3.77	**0.59**
26	Sub Planktivores	3.00	0.22	0.012	1.42	4.04	**0.93**
27	Macro Heterotroph	2.81	1.00	**8.714**	3.79	9.10	0.92
28	Cephalopods	3.81	1.00	**1.974**	3.31	11.30	0.78
29	Heterotr. Benthos	2.25	1.00	**3.058**	81.50	224.04	0.97
30	Zooplankton	2.00	1.00	0.800	58.67	177.34	**0.98**
31	Phytoplankton	1.00	1.00	1.228	130.00	0.00	**0.89**
32	Benthic Algae	1.00	0.59	**46.121**	12.28	0.00	0.88
33	Detritus	1.00	1.00	1000.00			**0.76**

Ecopath input parameters for French Frigate Shoals. Bold values are model derived.

Group nr	Group name	Trophic level	Habitat area (fraction)	Biomass (t/km²)	Production / biomass (/year)	Consumption / biomass (/year)	Ecotrophic efficiency
1	Seabirds	4.23	0.08	**0.000**	0.19	111.00	0.45
2	Tiger Sharks	4.27	0.08	0.001	0.25	3.00	**0.18**
3	Monk Seals	4.37	1.00	0.005	0.10	8.00	**1.00**
4	Reef Sharks	4.41	0.08	0.002	0.20	2.20	**0.35**
5	Bank Sharks	4.35	0.49	0.004	0.20	2.20	**0.50**
6	Reef Jacks	4.04	0.08	0.020	0.90	4.40	**0.01**
7	Bank Jacks	4.21	0.49	0.025	0.90	4.40	**0.01**
8	Turtles	2.10	1.00	**0.128**	0.17	6.76	0.04
9	Benthic BF	3.52	0.16	0.026	1.18	4.00	**0.69**
10	Demersal BF	3.29	0.16	0.021	1.18	4.00	**0.08**
11	Small Pelagics	3.15	1.00	**0.132**	0.55	6.50	0.80
12	Reef Piscivores	3.97	0.08	0.282	1.30	7.02	**0.55**
13	Reef Planktivores	3.00	0.08	0.338	3.24	15.15	**0.60**
14	Reef Herbivores	2.14	0.08	0.631	1.50	23.34	**0.59**
15	Reef Benth. Carniv.	3.42	0.08	0.409	1.86	9.10	**0.74**
16	Bank Piscivores	4.04	0.49	0.044	1.30	7.00	**0.85**
17	Bank Planktivores	3.00	0.49	0.735	3.23	15.15	**0.11**
18	Bank Herbivores	2.14	0.49	0.647	1.00	23.34	**0.28**
19	Bank Benth. Carniv.	3.42	0.49	1.171	1.86	9.11	**0.08**
20	Meso Piscivores	4.14	0.16	0.008	1.60	3.50	**0.28**
21	Meso Planktivores	3.00	0.16	0.107	3.00	7.00	**0.05**
22	Meso Benth. Carniv.	3.79	0.16	0.003	2.00	4.00	**0.48**
23	Meso Forage Fish	3.00	0.16	0.094	4.00	7.00	**0.51**
24	Sub Piscivores	4.48	0.27	0.004	0.80	8.30	**0.57**
25	Sub Benth. Carniv.	3.56	0.27	0.009	1.70	3.40	**0.65**
26	Sub Planktivores	3.00	0.27	0.016	1.75	4.50	**0.66**
27	Macro Heterotroph	2.81	1.00	**3.100**	3.40	9.00	0.94
28	Cephalopods	3.81	1.00	**0.587**	3.50	12.01	0.76
29	Heterotro. Benthos	2.25	1.00	**0.600**	97.77	200.00	0.92
30	Zooplankton	2.00	1.00	**0.398**	49.84	165.96	0.94
31	Phytoplankton	1.00	1.00	1.046	130.00	0.00	**0.49**
32	Benthic Algae	1.00	0.57	**9.157**	13.68	0.00	0.69
33	Detritus	1.00	1.00	1000.00			**0.27**
35	Detritus	1.00	1.00	1000.00			

Pedigree for input parameters used in Monte Carlo simulations. Values are confidence intervals in percentages

Group name	Biomass in habitat area	P/B	Q/B	Diet	Catch
Searbirds Near Shore	30	10	10	20	
Tiger Sharks	50	50	50	30	
Monk Seals	10	10	10	20	
Reef Sharks	80	50	50	30	30
Bank Sharks	80	50	50	30	30
Reef Jacks	30	30	30	30	30
Bank Jacks	30	30	30	30	30
Turtles	60	40	40	20	
Benthic bottomfish	30	50	50	30	30
Demersl bottomfish	30	50	50	30	30
Small Pelagics	50	50	50	30	
RF Pisc	30	50	50	30	
RF Plank	30	50	50	30	
RF Herb	30	50	50	30	
RF BC	30	50	50	30	
Bank Pisc	30	50	50	30	
Bank Plank	30	50	50	30	
Bank Herb	30	50	50	30	
Bank BC	30	50	50	30	
Meso Pisc	30	50	50	30	
Meso Plank	30	50	50	30	
Meso BC	30	50	50	30	
Meso Forage Fish	80	50	50	30	
Sub Pisc	30	50	50	30	
Sub BC	30	50	50	30	
Sub Plank	30	50	50	30	
Macro Heterotrophs	80	20	20	30	30
Cephalopods	80	20	20	20	
Heterotrophic Benthos	80	20	20	30	
Zooplankton	80	20	20	20	
Phytoplankton	80	20			
Benthic Algae	80	20			
Detritus	80				

Criteria for setting uncertainty estimates through Confidence Intervals (CI):

Biomass	**CI (%)**
Estimated by Ecopath	80
From other model	70
Guesstimate	50
Indirect method	30
Local, low precision	20
Local, high precision	10

P/B & C/B	**CI (%)**
Estimated by Ecopath	80
From other model	80
Guesstimate	80
Empirical relationship	50
Similar species, similar system, low precision	40
Similar species, same system, low precision	30
Same species, similar system, high precision	20
Same species, same system, high precision	10

Diet	**CI (%)**
General knowledge of related group/species	80
From other model	80
General knowledge of same group/species	60
Qualitative diet composition study	40
Quantitative but limited study	30
Quantitative, detailed study	20

Catch	**CI (%)**
For all groups set to 30	

Monte Carlo Simulation

We applied the Monte Carlo routine in Ecosim to select the best model considering the uncertainty in Ecopath input parameters. Confidence intervals for each parameter were increased or decreased from the input values within the Monte Carlo module. We set the number of trials to 50. Each trial represented an Ecosim run of the best fit model (1998-2015) with a randomly-selected set of Ecopath parameters (B, P/B, C/B, EE) for each group. Parameters were drawn from a uniform distribution centered on the mean with the coefficient of variation defined, and only the runs that end in a balanced model were kept for that trial, hence, one trial can have 100 or more simulations. The best fit model was determined by minimizing the residuals between predicted and observed time series using a least-square fitting criterion which gave us a measure of fit as the Sum of Squared deviations (SS).

Diet Composition

	Prey\predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Seabirds	0	0.005	0	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Tiger Sharks	0	0.015	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Monk Seals	0	0.03	0	0.006	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Reef Sharks	0	0.016	0	0.024	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Bank Sharks	0	0.043	0	0	0.034	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Reef Jacks	0	0.01	0	0.025	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Bank Jacks	0	0.04	0	0	0.025	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Turtles	0	0.163	0	0	0	0.005	0	0	0	0	0	0	0	0	0	0	0	0
9	Benthic BF	0	0	0.495	0.1	0.1	0.005	0.005	0	0	0	0	0	0	0	0	0	0	0
10	Demersal BF	0	0	0.005	0.06	0.06	0.005	0.005	0	0	0	0	0	0	0	0	0	0	0
11	Small Pelagics	0.259	0	0	0.006	0.006	0.205	0.3	0	0.02	0	0	0	0	0	0	0	0	0
12	Reef Pisc	0.158	0.008	0	0.07	0	0.066	0	0	0	0	0	0.092	0	0	0.003	0	0	0
13	Reef Plank	0.113	0.007	0	0.087	0	0.062	0	0	0.014	0	0	0.3	0	0	0.014	0	0	0
14	Reef Herb	0.126	0.009	0.025	0.150	0	0.249	0	0	0.001	0	0	0.25	0	0	0.011	0	0	0
15	Reef BC	0.344	0.037	0	0.12	0	0.348	0	0	0.001	0	0	0.262	0	0	0.001	0	0	0
16	Bank Pisc	0	0.03	0	0	0.07	0	0.066	0	0	0	0	0	0	0	0	0.03	0	0
17	Bank Plank	0	0.029	0	0	0.087	0	0.062	0	0.056	0	0	0	0	0	0	0.3	0	0
18	Bank Herb	0	0.034	0.048	0	0.150	0	0.079	0	0.004	0	0	0	0	0	0	0.174	0	0
19	Bank BC	0	0.15	0	0	0.120	0	0.348	0	0.004	0	0	0	0	0	0	0.4	0	0
20	Meso Pisc	0	0	0.06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	Meso Plank	0	0	0.137	0	0	0	0.05	0	0.036	0	0	0	0	0	0	0	0	0
22	Meso BC	0	0	0.036	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	Meso For. Fish	0	0	0.005	0	0	0.01	0.03	0	0.35	0.005	0.15	0	0	0	0	0	0	0
24	Sub Pisc	0	0	0.004	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	Sub BC	0	0	0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	Sub Plank	0	0	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	Macro Hetero	0	0.173	0.04	0.065	0.065	0.02	0.03	0	0.014	0.255	0	0	0	0	0	0	0	0
28	Cephalopods	0	0.201	0.1	0.232	0.281	0.025	0.025	0	0.01	0.01	0	0.04	0	0	0.1	0.04	0	0
29	Heter Benthos	0	0	0.003	0	0	0	0	0	0	0.23	0	0.056	0	0.111	0.871	0.056	0	0.111
30	Zooplankton	0	0	0	0	0	0	0	0.1	0.49	0.5	0.85	0	1	0	0	0	1	0
31	Phytoplankt.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	Benthic Algae	0	0	0	0	0	0	0	0.9	0	0	0	0	0	0.889	0	0	0	0.889
33	Detritus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Continuation of Diet Composition

	Prey \ predator	19	20	21	22	23	24	25	26	27	28	29	30
1	Seabirds	0	0	0	0	0	0	0	0	0	0	0	0
2	Tiger Sharks	0	0	0	0	0	0	0	0	0	0	0	0
3	Monk Seals	0	0	0	0	0	0	0	0	0	0	0	0
4	Reef Sharks	0	0	0	0	0	0	0	0	0	0	0	0
5	Bank Sharks	0	0	0	0	0	0	0	0	0	0	0	0
6	Reef Jacks	0	0	0	0	0	0	0	0	0	0	0	0
7	Bank Jacks	0	0	0	0	0	0	0	0	0	0	0	0
8	Turtles	0	0	0	0	0	0	0	0	0	0	0	0
9	Benthic BF	0	0	0	0	0	0	0	0	0	0	0	0
10	Demersal BF	0	0	0	0	0	0	0	0	0	0	0	0
11	Small Pelagics	0	0	0	0	0	0	0	0	0	0	0	0
12	Reef Piscivores	0	0	0	0	0	0	0	0	0	0	0	0
13	Reef Planktivore	0	0	0	0	0	0	0	0	0	0	0	0
14	Reef Herbivores	0	0	0	0	0	0	0	0	0	0	0	0
15	Reef Benth.Carniv.	0	0	0	0	0	0	0	0	0	0	0	0
16	Bank Piscivores	0.003	0	0	0	0	0	0	0	0	0	0	0
17	Bank Planktivore	0.014	0	0	0	0	0	0	0	0	0	0	0
18	Bank Herbivores	0.011	0	0	0	0	0	0	0	0	0	0	0
19	Bank Benth.Carniv.	0.001	0	0	0	0	0	0	0	0	0	0	0
20	Meso. Piscivores	0	0.05	0	0	0	0	0	0	0	0	0	0
21	Meso. Planktivore	0	0.1	0	0	0	0	0	0	0	0	0	0
22	Meso. Benth.Carniv.	0	0.05	0	0	0	0	0	0	0	0	0	0
23	Meso. Forage Fish	0	0.75	0	0.3	0	0	0	0	0	0	0	0
24	Sub Piscivores	0	0	0	0	0	0.05	0	0	0	0	0	0
25	Sub Benth.Carniv.	0	0	0	0	0	0.3	0	0	0	0	0	0
26	Sub Planktivore	0	0	0	0	0	0.35	0.2	0	0	0	0	0
27	Macro Heterotrops	0	0	0	0	0	0	0	0	0.1	1	0	0
28	Cephalopods	0.1	0.05	0	0.2	0	0.3	0.1	0	0	0	0	0
29	Heterotr. Benthos	0.871	0	0	0.5	0	0	0.7	0	0.5	0	0.2	0
30	Zooplankton	0	0	1	0	1	0	0	1	0	0	0	0
31	Phytoplankton	0	0	0	0	0	0	0	0	0	0	0	1
32	Benthic Algae	0	0	0	0	0	0	0	0	0.4	0	0.4	0
33	Detritus	0	0	0	0	0	0	0	0	0	0	0.4	0

Differences from the above diet matrix for the Laysan model after tuning are:

Predator:	Reef sharks,	Prey:	Monk seal = 0.0001; RF Herb = 0.156
Predator:	Small pelagics	Prey	Meso.Forage fish = 0.1; Zooplankton = 0.9
Predator:	RF Piscivores,	Prey:	RF Piscivores = 0.015; RF Planktivores = 0.25; RF Herbivores = 0.377
Predator:	Bank BC	Prey:	Bank Piscivores = 0.0001; Macro Hetrotrophs = 0.003
Predator	Meso. Pisc.	Prey	Meso PLanktivore = 0.2; Meso Forage fish = 0.65

Supplement 5. Principal Component Analyses (PCA)

Using PCA, we determined how the apex predators are clustered based on their diet and which groups drive the differences between these functional species groups. Based on the eigenvalue, differences in the variation are not easily captured by just a couple of principal components (PC; Fig. S5.1), and four PCs explain about 70% of the variance (scree plot on right below).

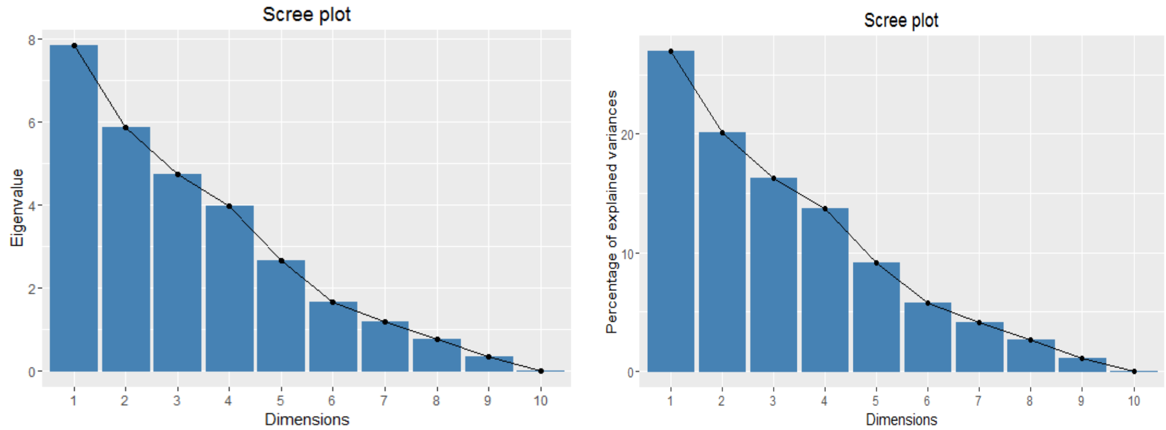

Fig. S5.1. Scree plot of (*left*) eigenvalue and (*right*) percentage of explained variance of the principal component analyses of the diet matrix of the Ecopath models.

Assessing which functional groups contribute most to each of the four PCs (Fig S5.2), we see that tiger sharks, reef sharks and jacks, sea birds and subphotic piscivores had the greatest impact. These predator groups were selected to assess their influence on the system structure and dynamics in general and their influence on monk seal biomass in particular.

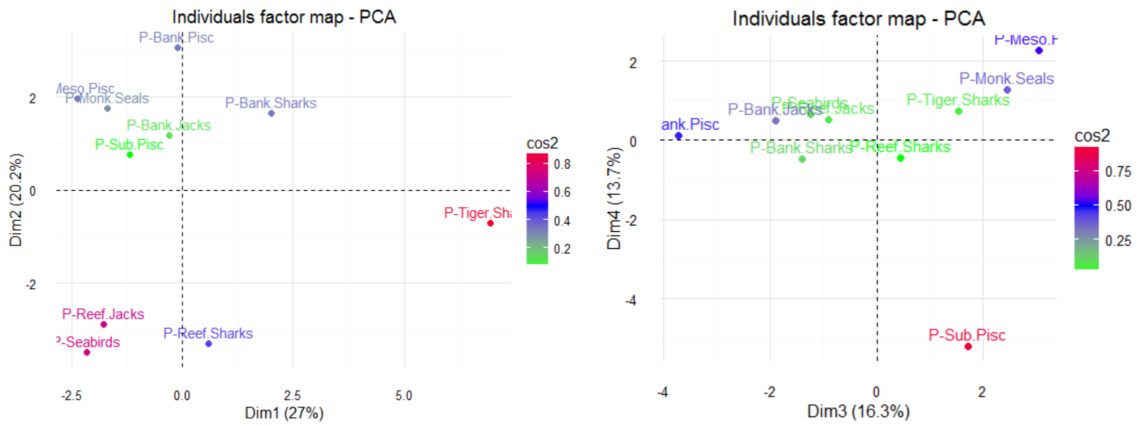

Fig. S5.2. Individual factor map of functional groups for (*left*) the first two PCs and (*right*) PCs 3 and 4. Groups are color coded according to their contribution based on Cos2, with red indicating a high contribution and green low.

From the biplots (Fig S5.3), we can also see that monk seals are highly clustered with the functional groups mesophotic planktivores, meso. piscivores, meso. benthic carnivores (BC), meso. forage fish, and to a lesser extent, with benthic bottomfish. These functional prey groups were selected for prey perturbation scenarios to understand the influence of these prey groups on the system in terms of influencing monk seal biomass.

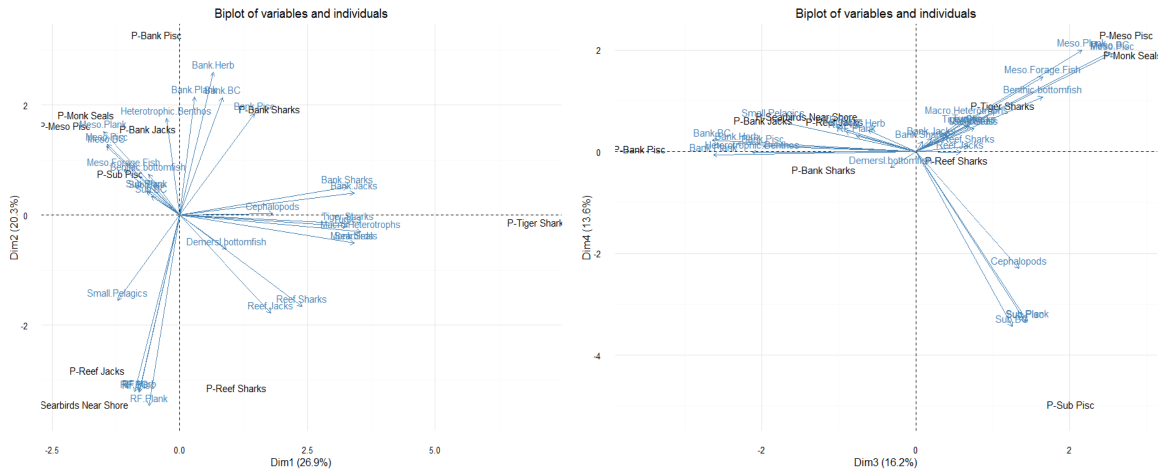

Fig. S5.3. Biplot of diet components and predators for the (*left*) first 2 PCs and (*right*) PCs 3 and 4.

Supplement 6. Pre-balance check of input parameters

Several rules of thumb have been established to ensure that any potential problems are captured before network model outputs are used (Link 2010, Heymans et al. 2016). These criteria include:

1. Range of biomass should span 5-7 orders of magnitude across trophic levels, with a decline in slope (y-axis on log scale) of 5-10% across all taxa (Fig S6.1)
2. Biomass ratios show higher biomass of prey compared to predators and higher biomass compared to next trophic level (Table S6.1).
3. Vital rates decline across taxa with increasing trophic levels except for homeotherms, which have values above the trend line (Fig S6.2).
4. Like the biomass ratios, the vital rate ratios of predators should be higher than those of prey (Table S6.2), all P/B ratios should be lower than that of the primary producers, and P/C (gross efficiency) should be less than one. In general, the P/C ratio should be between 0.1 and 0.3 (Darwall et al. 2010).

These guidelines are to inform the modeler about potential ‘misbehavior’ of groups which could indicate mis-parameterization triggering reassessment of those input parameters. Figure S6.1 shows that the Laysan model indeed has a biomass range that spans 5 orders of magnitude with declining biomass toward higher trophic levels. Reef fish groups are generally a little above the trendline but since these are from field survey data, we believe they are correct. Cephalopods, macro heterotrophs, and benthic algae also had high biomass. These values were calculated by the model itself based on the vital rates and predation on this group. We increased the predation by increasing the EE for those groups by 15%. Table S6.1 shows that, in general, we comply with the biomass ratio guidelines, although the small pelagics to zooplankton ratio is very close to 1, indicating too much predation pressure on the zooplankton group. For both groups, Ecopath calculated the biomass, and because there is a lot of predation pressure on the small pelagics especially by sea birds and jacks, the biomass estimate was quite high according to the diagnostic checks (Fig S6.1). However, biomass estimates of the main predator groups were model derived, and we are confident that they are within the CVs provided in the uncertainty analysis.

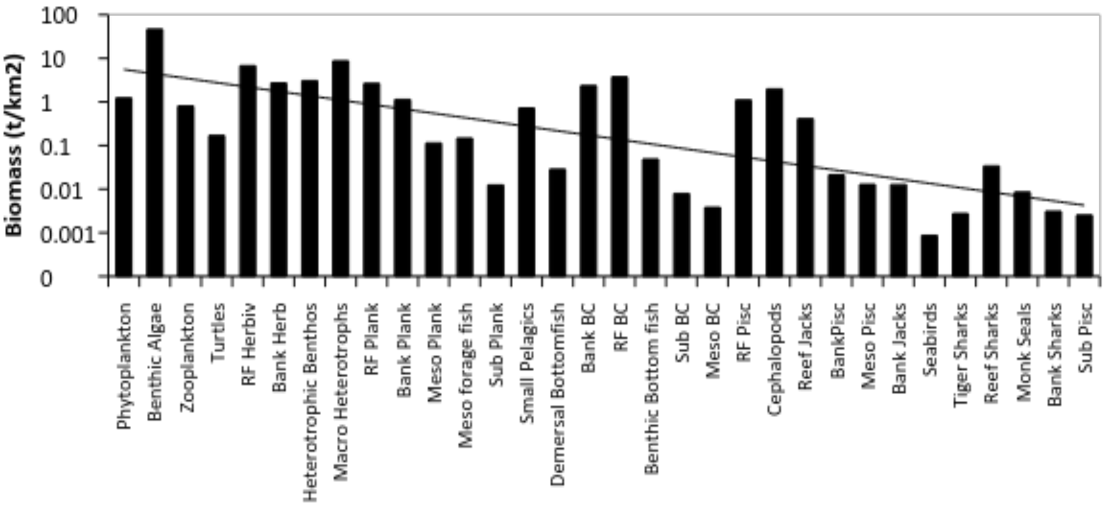

Fig. S6.1. Biomass decomposition across trophic levels.

Table S6.1. Biomass ratio checks

Groups	ratio	Trophic level	Biomass
Small pelagics: zooplankton	0.90	V+	0.47
Zooplankton: phytoplankton	0.65	IV	2.50
Small pelagics: phytoplankton	0.58	III	17.45
Demersal: benthic Invertebrates	0.67	II	16.26
Marine mammals and birds: small pelagics	0.06	I	47.34
Zooplankton: all benthos	0.26		
% small pelagics of all fish	0.06		
% macrobenthis of all invertebrates	0.63		

In general, the vital rates decline with an increase in trophic level with, as expected, the exception in C/B for seabirds and monk seals. These are homeostatic groups and need to increase metabolic rate, and hence consumption, to adjust their body temperature (Fig S6.2).

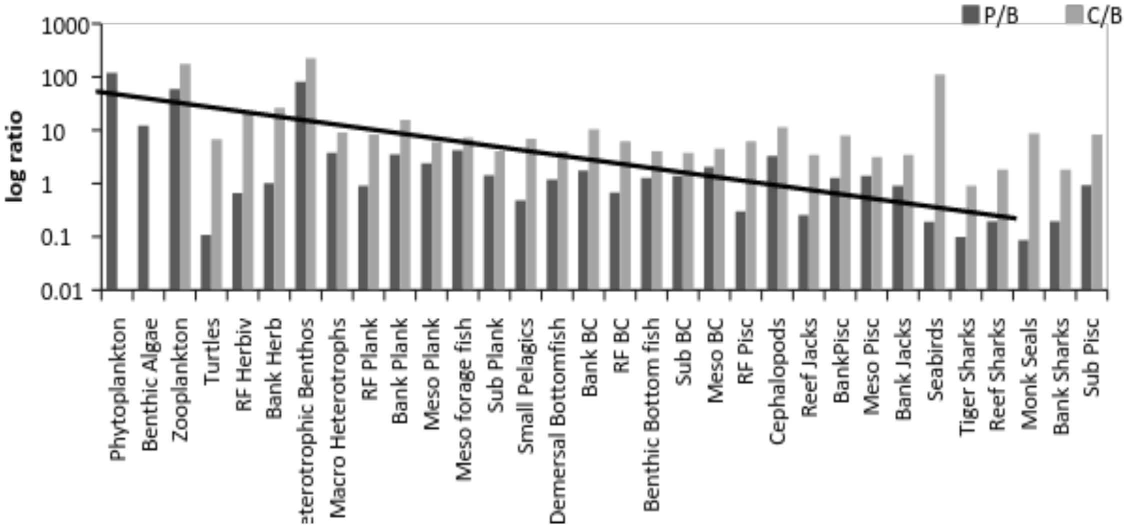

Fig. S6.2. Vital rates decreasing with increasing trophic level (from left to right on x-axis) except for consumption of homeotherms (seabirds and monk seals). P: production, C: consumption, B: biomass.

The P/B ratio of zooplankton to phytoplankton was 0.88, indicating potential imbalance in the ecosystem structure likely caused by mis-parameterization. Based on this rate, we increased the P/B of phytoplankton to 120 per year, a value which has been reported for phytoplankton groups in Hawaii (Howell et al. 2013). This correction led to a zooplankton:phytoplankton P/B ratio of 0.49. The gross efficiency (P/C) values were between 0.1 and 0.3, with the exception of turtles, herbivorous fish groups, seabirds, and monk seals. For the homeostatic groups, seabirds and monk seals, high metabolic rates needed to adjust body temperature signify a high consumption rate, resulting in a low gross efficiency. The turtles' population consists predominantly (60%-70%) of juveniles that consume more to account for growth (Todd T. Jones, PIFSC, pers comm, Dec 2015). The P/B and C/B for the herbivorous fish groups are based on the relationship from Pauly (1980, 1986) or Palomares and Pauly (1998), with biomass data from field surveys (PIFSC CREP) to obtain a weighted average for both groups and we therefore did not change these values.

Supplement 7. Diet information monk seals

The diet matrix is the foundation of food web models. Much research has been conducted on the diet of monk seals using fatty acid (Iverson et al. 2011) and fecal analyses (Goodman-Lowe 1998, Longenecker et al. 2006, Cahoon et al. 2013). These methods differ substantially in their strengths and limitations (Jobling 1987, Iverson et al. 2004, Bowen & Iverson 2013). While the presence of a particular species remnants found in scat is a sure sign it was ingested, fecal hard part analysis suffers from biases due to differential rates of digestion of soft tissues, and the likelihood of only the most recent meals analyzed (those closest to the haul out site where feces are available for collection). Fatty acid analysis, on the other hand, purportedly represents a more complete picture of diet items incorporated into animal tissue; however, models of fatty acid composition are only as good as the prey library and prey groups can be falsely assigned if not all diet items are sampled. Widely different compositions of monk seal diets were suggested by each method. For example, fatty acid analysis (Iverson et al. 2011) indicated bottomfish comprised 49.5% of the monk seal diet, but according to fecal analyses by Goodman-Lowe (1998), bottomfish only comprised 1.5%. Given the importance of the diet matrix in balancing the ecopath models, we also constructed the FFS and LAY models with diet data based on fecal analyses and evaluated the fit to observed data.

Table S7.1. Diet composition of monk seals based on two different methods of analyses.

Prey groups of monk seals	**Fecal analyses**	**Fatty acid analyses**
Benthic Bottom fish	0.01463	0.495
Demersal Bottomfish	0	0.005
Reef Piscivores	0.10147	0
Reef Planktivores	0.02738	0
Reef Herbivores	0.08415	0.025
Reef Benthic Carnivores	0.20743	0
Bank Piscivores	0.0655	0
Bank Planktivores	0.01162	0
Bank Herbivores	0.05784	0.048
Bank Bentic Carnivore	0.13443	0
Meso Piscivores	0.10177	0.06
Meso Planktivores	0	0.137
Meso Bentic Carnivore	0.01158	0.036
Meso forage fish	0	0.004
Sub Piscivores	0	0.005
Sub Benthic Carnivores	0.00548	0.002
Sub Planktivores	0	0.04
Macro Heterotrophs	0	0.04
Cephalopods	0.17672	0.1
Heterotrophic Benthos	0	0.003

Results of the model fitting showed that the fit between predicted and observed monk seal data was not as good when using diet based on fecal analyses compared to fatty acid analyses (Table S7.1). For example, using the fecal diet for monk seals in FFS gave similar results as using the fatty acid diet but only after setting the vulnerability of benthic bottomfish to 1, i.e., defacto 'decoupling' the predator-prey dependency (Table S7.2).

Table S7.2. Model fits for monk seals (MS) and benthic bottomfish (BF) under simulation of different external drivers and using either diet based on fecal analyses (FC) or fatty acid analyses (FA).

System	External driver(s)	SS MS Diet:FC	SS BF Diet:FC	SS MS Diet:FA	SS BF Diet:FA
LAY	Fishery	1.56	0.13	0.06	1.06
FFS	Fishery	4.94	0.11	5.10	0.15
LAY	Fishery + PDO	0.36	5.84	0.26	6.70
FFS	Fishery + PDO	0.50	6.77	0.09	16.4

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