Species traits, especially feeding environment, shape their roles in marine food webs: Supplemental information

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Supplemental methods: food web details

Table S1: Basic information about the food webs used in this study. All webs were used in their original published form except for the Reef web. We removed one species (*Synodus synodus*) from this web prior to calculating species' roles as this fish had no recorded prey and was therefore incorrectly classed as a basal resource.

Web	# Species	# Links	Location	Original source
Kongsfjorden	270	1647	Kongsfjord, Norway	Jacob (unpub.)
Lough Hyne	349	5114	Lough Hyne, Ireland	Jacob (unpub.)
Reef	246	3313	American & British Virgin Islands & Puerto Rico	(Opitz, 1996)
St. Marks	143	1766	St. Marks National Wildlife Refuge, Florida, USA	(Christian & Luczkovich, 1999)
Weddell	488	15880	Weddell Sea, Antarctica	(Jacob *et al.*, 2011)
Ythan	92	417	Ythan Estuary, Scotland	(Cohen *et al.*, 2009)

Supplemental methods: trait details

In general, the traits we used are as described in the supplemental information of (Eklöf *et al.*, 2013).

Body mass

Three species in the Kongsfjorden web (*Calanus finnmarchicus*, *Diastylis rathkii*, and *Bylgides groenlandica*) did not have estimated body masses. For these species, we estimated biomasses based on related species present in the same web. *Calanus finnmarchicus* was assumed to have the same body mass as the two other *Calanus* species present in Kongsfjorden and *Diastylis rathkii* was assumed to share the same biomass as the other two *Diastylis* species present. No other *Bylgides* species were present in the Kongsfjorden web. We therefore used the mean biomass of the only two species in our dataset that were in the same family (Polynoidae) to estimate the biomass of *B. groenlandica*.

Trophic level

Each species' trophic level was defined as one plus the average of the trophic levels of its prey (i.e., prey-averaged trophic level).

Environment

The raw data we used in this study described species' feeding environments as one of: "benthic", "pelagic", "benthopelagic", "demersal", "pelagic-oceanic", "reef-associated", "land-based", and "epipelagic/ice-associated". To improve the consistency of environment types across networks, we lumped some levels of feeding environment together. Specifically, we grouped "pelagic-oceanic", and "epipelagic/ice-associated" together with "pelagic" and "reef-associated" with "benthopelagic". Note that the only "epipelagic/ice-associated" species was a single species of krill (*Thysanoessa inermis*) which forages near surface ice. "Pelagic-oceanic" was only used in the reef web, which only labelled two species (phytoplankton and zooplankton) as "pelagic". The feeding environment "reef-associated" was almost entirely found in one network (194 species in the "reef" network, six species in the Lough Hyne network; no "reef-associated" species were found in any other network). To prevent redundancy between this trait and the network-level random effect, we lumped "reef-associated" species together with "benthopelagic" species. "Land-based" species are those such as otters (*Lutra lutra*) and cormorants (*Phalacocorax aristotelis*) which forage in the water but are obliged to return to land. Such species were present in several webs; we therefore retained "land-based" as a separate feeding environment.

Metabolic category

Metabolic category could take the values of "primary producer", "invertebrate", "ectotherm vertebrate", or "endotherm vertebrate". This trait therefore incorporates some taxonomic information as well as differentiating between species with different metabolisms.

Mobility

Four categories of mobility were included in this dataset. Mobility level 1 described sessile species and those that passively float (e.g., phytoplankton). Levels 2-4 described species which crawl (level 2), are facultative swimmers (level 3), or are obligate swimmers (level 4). Note that these are very broad categories which do not take into account speed of movement, typical foraging ranges, etc.

Feeding type

Possible values for feeding type in the original data were “carnivorous”, “herbivorous”, “detrivorous”, “herbivorous/ detrivorous”, “omnivorous”, or “none”. The “none” value accounts for primary producers and other basal resources. As “herbivorous” and “detrivorous” species were rare, we labelled them as “herbivorous/detrivorous” to keep the number of possible values for feeding type low.

Feeding mode

Possible values for feeding mode in the raw data were “predator”, “scavenger”, “predator/scavenger”, “grazer”, “suspension feeder”, and “primary producer”. Similar to feeding type, ‘predator” and “scavenger” species were rare and therefore grouped with the more common “predator/scavenger”.

Table S2: Levels of each trait in our dataset. Baseline levels for each categorical trait are highlighted in bold.

Trait	Levels
log(Body mass)	continuous
Environment	**benthic**, benthopelagic, demersal, land-based, pelagic
Feeding mode	**deposit-feeder**, grazer, primary producer, predator/scavenger, suspension-feeder
Feeding type	**carnivore**, herbivore/detrivore, omnivore, primary producer
Metabolic category	**ectotherm vertebrate**, endotherm vertebrate, invertebrate
Mobility	**1: sessile/passive floater**, 2: crawler, 3: facultative swimmer, 4: obligate swimmer
Trophic level	continuous

Supplemental results: within classes

Actinopterygii

The first two PCA axes for the roles of bony fishes explained 41.1% and 20.2% of variation, respectively. As with the intermediate consumers, positions 1, 2, and 9 were most strongly associated with these axes. The best-fit model for position 1 included terms for environment, body mass, and trophic level. The frequency of position 1 increased with increasing body weight ($\beta_{BodyMass}$=2.62, p<0.001) and decreased with increasing trophic level ($\beta_{TrophicLevel}$=-0.707, p<0.001). Benthopelagic fishes had significantly lower frequencies of position 1 than benthic species ($\beta_{Environment:benthopelagic}$=-2.07, p=0.044); demersal and pelagic species did not have significantly different frequencies of position 1 than the baseline for benthic species ($\beta_{Environment:demersal}$=1.28, p=0.130; $\beta_{Environment:pelagic}$=-0.233, p=0.859). When re-running our analyses while excluding any models including trophic level, the best-fit model for the frequency of position 1 included terms for environment and body weight. The frequency of position 1 again increased with increasing body weight ($\beta_{BodyMass}$=2.10, p=0.002) and benthopelagic species again had lower frequencies of position 1 than benthic species, although not significantly ($\beta_{Environment:benthopelagic}$=-1.87, p=0.050). Demersal and pelagic species again had similar frequencies of position 1 to those of benthic species ($\beta_{Environment:demersal}$=1.10, p=0.180; $\beta_{Environment:pelagic}$=-0.296, p=0.874).

The best-fit model for position 2 included the term for trophic level. The frequency of position 2 decreased with increasing trophic level ($\beta_{TrophicLevel}$=-0.191, p=0.017). When we excluded models containing trophic level, the best-fit model for position 2 included the term for log of body mass. The frequency of position 2 decreased with increasing body mass ($\beta_{BodyMass}$=-0.877, p=0.012).

The best-fit model for position 9 included terms for environment, trophic level, and feeding type. As with the other key motifs, the frequency of position 9 decreased with increasing trophic level ($\beta_{TrophicLevel}$=-0.522, p=0.005). Although feeding environment and feeding type were both retained in the best-fit model, no level of either trait was associated with higher or lower frequencies of position 9 than the baseline. When we excluded models containing trophic level, the best-fit model for position 9 included terms for environment. Pelagic species had significantly higher frequencies of position 9 than benthic species ($\beta_{Environment:pelagic}$=2.36, p=0.037); benthopelagic and demersal species had similar frequencies of position 9 to those of benthic species ($\beta_{Environment:benthopelagic}$=0.168, p0.877 and $\beta_{Environment:demersal}$=1.76, p=0.098, respectively).

Aves

The first two PCA axes for the roles of birds explained 58.0% and 24.1% of variation, respectively. As with top predators, positions 1, 3, and 9 were most strongly associated with these axes. The best-fitting model for position 1 included only the random effect of network. This was also true when we re-ran our analyses excluding any models including trophic level.

The best-fitting model for position 3 included the term for trophic level. The frequency of position 3 increased with increasing trophic level ($\beta_{TrophicLevel}$=0.639, p=0.040). When excluding models containing trophic level, the best-fitting model for position 3 included terms for feeding type. Omnivores had significantly higher frequencies of position 3 than carnivores ($\beta_{FeedingType:omnivore}$=1.70, p=0.011) while herbivore/detrivores had similar frequencies of position 3 to those of carnivores ($\beta_{FeedingType:herbivore/detrivore}$=-15.0, p=0.997). Note that there were only two birds with the feeding type herbivore/detrivore, and neither ever appeared in position 3.

Finally, the best-fitting model for position 9 included terms for trophic level and feeding type. The frequency of position 9 decreased with increasing trophic level ($\beta_{TrophicLevel}$=-1.31, p<0.001). Although feeding type was retained in the best-fit model, no level of this trait was associated with significantly different frequencies of position 9 than that of the baseline. When excluding models containing trophic level, the best-fitting model for position 9 included terms for feeding type. Omnivorous birds had significantly lower frequencies of position 9 than carnivorous birds ($\beta_{FeedingType:omnivorous}$=-2.25, p=0.035) while herbivorous/detrivorous birds did not have significantly different frequencies of position 9 ($\beta_{FeedingType:herbivore/detrivore}$=-13.0, p=0.984).

Gastropoda

The first two PCA axes for the roles of gastropods explained 51.6% and 16.0% of variation, respectively. Positions 2, 9, and 10 were most strongly associated with these axes. The best-fit model for position 2 included terms for feeding environment, but pelagic species did not have significantly higher or lower frequencies of position 2 than the baseline (benthic species; $\beta_{Environment:pelagic}$=-12.8, p=0.955). When re-running our analyses excluding any model including trophic level, the best-fitting model for position 2 again included terms for feeding environment with identical relationships between these terms and the frequency of position 2.

The best-fit model for position 9 included terms for feeding type, environment, and trophic level. The frequency of position 9 increased with increasing trophic level ($\beta_{TrophicLevel}$=0.970, p=0.016). No levels of feeding type or environment were associated with significantly higher or lower frequencies of position 9 than the baseline. When excluding models containing trophic level, the best-fitting model included terms for feeding type and environment. No levels of feeding type or environment were associated with significantly higher or lower frequencies of position 9 than the baseline.

The best-fit model for position 10 included only the random effect of network. This was also the case when re-running our analyses excluding models containing trophic level.

Malacostraca

The first two axes for the roles of crustaceans explained 35.5% and 19.8% of variation, respectively. Positions 1, 2, and 9 were most strongly associated with these axes. The best-fitting model for position 1 included only the random effect of network. This was also the case when re-running our analyses and excluding models containing trophic level.

The best-fitting model for position 2 included terms for terms for feeding mode and body mass. The frequency of position 2 again decreased with increasing body mass

($\beta_{BodyMass}$=-2.51, p<0.001). Species with the feeding mode "predator/scavenger" had significantly lower frequencies of position 2 than detrivores ($\beta_{FeedingMode:predator/scavenger}$=-4.02, p=0.003), while species with feeding modes "grazer" and "suspension-feeder" did not have significantly different frequencies of position 2 ($\beta_{FeedingMode:grazer}$=-2.68, p=0.060 and $\beta_{FeedingMode:suspension-feeder}$=-10.6, p-0.572, respectively). When re-running our analyses excluding models containing trophic level, the best-fitting model again included terms for feeding mode and body mass, with identical relationships between these terms and the frequency of position 2.

The best-fitting model for position 9 included terms for trophic level, feeding mode, and environment. The frequency of position 9 decreased with increasing trophic level ($\beta_{TrophicLevel}$=-1.51, p<0.001). Species with the feeding modes "predator/scavenger" and "suspension-feeder" had significantly higher frequencies of position 9 than the baseline (detrivores; $\beta_{FeedingMode:predator/scavenger}$=3.11, p=0.012 and $\beta_{FeedingMode:suspension-feeder}$=3.97, p=0.025, respectively). Grazers did not have significantly different frequencies of position 9 ($\beta_{FeedingMode:grazer}$=1.93, p=0.092). Benthopelagic and pelagic species had significantly lower frequencies of position 9 than benthic species ($\beta_{Environment:benthopelagic}$=-3.61, p=0.002 and $\beta_{Environment:pelagic}$=-1.75, p=0.049, respectively). When re-running our analyses excluding models containing trophic level, the best-fitting model included terms for feeding mode and environment. Species with the feeding mode "suspension-feeder" had significantly higher frequencies of position 9 than the baseline (detrivores; $\beta_{FeedingMode:suspension-feeder}$=4.10, p=0.022) while grazers and predator-scavengers did not have significantly different frequencies of position 9 ($\beta_{FeedingMode:grazer}$=1.81, p=0.108 and $\beta_{FeedingMode:predator-scavenger}$=1.10, p=0.292, respectively). Benthopelagic species had significantly lower frequencies of position 9 than benthic species ($\beta_{Environment:benthopelagic}$=-3.27, p=0.005) while pelagic species did not have significantly different frequencies of position 9 ($\beta_{Environment:pelagic}$=-1.14, p=0.095).

Polychaeta

The first two axes for the roles of polychaetes explained 33.7% and 26.2% of variation, respectively. Positions 2 and 9 were strongly associated with the first two axes and position 10 was more weakly associated with the first axis. Position 1 was weakly associated with the second axis, to a similar extent as that of position 10 and axis 1. The best-fitting models for position 1 and position 10 included only the random effect of network. This was also the case when repeating our analyses excluding any models including trophic level.

The best-fitting models for position 2 and position 9 included trophic level. The frequency of position 2 decreased with increasing trophic level, as did the frequency of position 9 ($\beta_{TrophicLevel}$=-0.732, p=0.001 and $\beta_{TrophicLevel}$=-0.938, p=0.033, respectively). When repeating our analyses excluding models containing trophic level, the best-fitting model for position 2 included only the network effect and the best-fitting model for position 9 included terms for feeding type. Herbivore/detrivores and omnivores did not have significantly different frequencies of position 9 than carnivores ($\beta_{FeedingType:herbivore/detrivore}$=-0.442, p=0.785 and $\beta_{FeedingType:omnivore}$=-2.33, p=0.177, respectively).

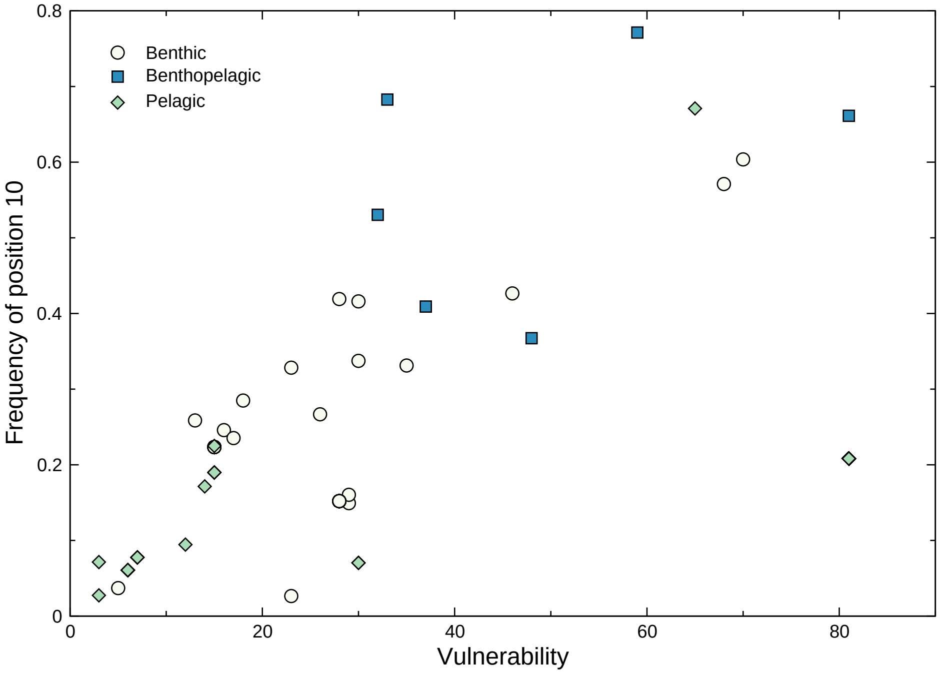
Supplemental results: basal resources

Table S3: Parameter estimates and p-values for the best-fitting models of the frequencies of positions 2, 4, and 10 in the roles of basal resources. 'NA' indicates that a particular effect was not included in the best-fitting version of a model. The best-fit models for positions 2 and 4 included only the intercept and a random effect of network (not shown). The best-fit model for position 10 included body mass, feeding environment, and the random effect. Benthic species were the baseline (intercept) feeding environment. Note that feeding mode, feeding type, metabolic category, trophic level, and mobility were nearly invariant for the trophic levels in this dataset and could not be included in our models. Coefficients relate to the logit of the frequency of each position.

	Position 2		Position 4		Position 10	
Term	β	p	β	p	β	p
Intercept	1.56	<0.001	-3.93	<0.001	-1.07	0.256
$log(BodyMass)$	NA		NA		-30.2	0.004
$Environment_{Benthopelagic}$	NA		NA		1.50	0.362
$Environment_{Pelagic}$	NA		NA		-4.71	0.004

High frequencies of position 10 (the prey position in the apparent competition motif) may reflect higher vulnerability as this motif requires two predators to share a single prey. Indeed, in our dataset the frequency of position 10 was positively and moderately strongly correlated with the vulnerability of basal resources (R^2=0.46; Fig. S1). This correlation is less than one both because we use normalised frequencies (i.e., proportions of species' roles made up by each position) rather than raw counts and because a given consumer-resource combination may form part of a three-species chain, omnivory motif, or other configuration than the direct competition motif.

Figure S1: The frequency of position 10 in the roles of basal resources increased with vulnerability.



Supplemental results: intermediate consumers

Table S4: Parameter estimates and p-values for the best-fitting model of the frequencies of positions 1, 2, and 9 in the roles of intermediate consumers. The best-fitting model for the frequency of position 1 included terms for body mass, feeding environment, and feeding type, in that order. The best-fitting model for the frequency of position 2 included terms for all traits except body mass. The best-fitting model for the frequency of position 9 included trophic level, feeding mode, feeding environment, and feeding type. Baseline levels for each trait are given in the caption of Table S2.

	Position 1		Position 2		Position 9	
Term	β	p	β	p	β	p
Intercept	-4.16	<0.001	-4.07	0.002	0.042	0.958
log(Body Mass)	9.75	<0.001	NA		NA	
$FeedingEnvironment_{Benthopelagic}$	-1.19	0.049	-0.744	0.017	-1.84	<0.001
$FeedingEnvironment_{Demersal}$	0.740	0.207	-2.99	<0.001	-0.173	0.694
$FeedingEnvironment_{Land-based}$	-16.6	0.992	-14.4	0.981	-11.5	0.983
$FeedingEnvironment_{Pelagic}$	-1.72	0.132	-1.88	<0.001	-0.353	0.226
$FeedingMode_{Grazer}$	NA		1.14	0.011	-0.983	0.020
$FeedingMode_{Primaryproducer}$	NA		NA		-15.6	0.977
$FeedingMode_{Predator-scavenger}$	NA		3.28	0.007	-0.602	0.426
$FeedingMode_{Suspension-feeder}$	NA		0.632	0.159	-0.564	0.163
$FeedingType_{Herbivore-detrivore}$	-16.5	0.992	NA		-2.07	0.005
$FeedingType_{Omnivore}$	0.493	0.332	-0.212	0.416	-1.11	0.004
$FeedingType_{Primaryproducer}$	-2.95	>0.999	24.4	0.97	NA	
$MetabolicCategory_{endothermvertebrate}$	NA		-0.510	0.677	NA	
$MetabolicCategory_{invertebrate}$	NA		-1.60	<0.001	NA	
$MetabolicCategory_{primaryproducer}$	NA		-8.50	0.986	NA	
$Mobility_{Crawling}$	NA		1.33	<0.001	NA	
$Mobility_{Facultativeswimming}$	NA		1.38	<0.001	NA	
$Mobility_{Obligateswimming}$	NA		0.877	0.099	NA	
Trophic Level	NA		-0.517	<0.001	-1.37	<0.001

Supplemental results: top predators

Table S5: Parameter estimates and p-values for the best-fitting models of the frequencies of positions 1, 3, and 9 in the roles of top predators. 'NA' indicates that a particular effect was not included in the best-fitting version of a model. The best-fitting models for the frequencies of position 1 and 3 included trophic level, while the best-fitting model for the frequency of position 9 included trophic level, body weight, and metabolic category. Ectotherm vertebrate was the baseline level of metabolic category. Coefficients refer to effects on the logit of the frequency of each motif.

	Position 1		Position 3		Position 9	
Term	β	p	β	p	β	p
Intercept	-11.1	0.161	-2.12	<0.001	2.45	0.116
log(Body Mass)	NA		NA		-11.8	0.003
$MetabolicCategory_{endothermicvertebrate}$	NA		NA		-1.76	0.255
$MetabolicCategory_{invertebrate}$	NA		NA		-5.49	0.013
Trophic Level	4.39	0.289	1.86	<0.001	-2.10	<0.001

The relationship between trophic level and the frequency of position 1 was weak and appeared to be strongly influenced by a potential outlier. This species, *Galeocerdo cuvier* – the tiger shark, was by far the most generalist top predator in our dataset and apparent competition (position 1) accounted for 81.5% of its role. With 167 different prey, it is not surprising that *G. cuvier* would consume many prey that do not directly interact and thereby create many apparent competition motifs. Indeed, the frequency of position 1 in a species' role was very strongly and positively correlated with its number of prey (R^2=0.89). In contrast, generality was weakly and negatively correlated with the frequencies of positions 3 and 9 (R^2=-0.12 and R^2=-0.37, respectively). As *G. cuvier* is a potential outlier with respect to generality, trophic level, and the frequency of position 1, we re-fit the best-fit model for position 1 excluding *G. cuvier*. In this case trophic level was not significantly related to the frequency of position 1, leading us to conclude that *G. cuvier* is indeed an outlier and was the primary driver of this model. As no other traits were included in the best-fit model, it appears that the frequency of position 1 is not strongly affected by the traits we considered here.

Supplemental results: vector loadings and mean position frequencies

Table S6: Correlations between motif positions and the two PCA axes explaining most variation in the roles of basal resources, intermediate consumers, and top predators. Position numbers correspond to those in Fig. 1 (*Main Text*). Note that positions 1 and 2 make up the apparent competition motif, positions 3, 4, and 5 form the three-species chain motif, and positions 9 and 10 comprise the direct competition motif. 'X' indicates that a position could not be occupied by a trophic group (e.g., basal resources cannot occupy consumer positions).

	Basal resources		Intermediate consumers		Top predators	
Position	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
1	X		0.261	0.469	0.071	0.790
2	-0.799	0.213	-0.820	-0.289	X	
3	X		0.105	0.226	0.661	-0.491
4	0.216	-0.77	-0.048	0.009	X	
5	X		0.041	0.104	X	
6	-0.005	-0.014	-0.013	<0.001	X	
7	X		0.004	0.019	X	
8	X		0.006	0.014	X	
9	X		0.487	-0.785	-0.746	-0.358
10	0.561	0.601	-0.073	0.105	X	
11	X		0.040	0.056	0.017	0.076
12	X		0.018	0.055	X	
13	0.028	-0.02	-0.027	0.024	X	
14	X		0.005	0.013	X	
15	<0.001	-0.009	-0.003	<0.001	X	
16	X		0.002	-0.001	<0.001	-0.002
17	X		0.002	0.001	X	
18	X		0.001	0.001	X	
19	X		0.001	-0.002	X	
20	X		0.001	-0.003	X	
21	X		0.001	-0.003	X	
22	X		0.001	-0.002	X	
23	X		0.001	-0.002	X	
24	X		0.001	-0.002	X	
25	X		0.002	-0.001	-0.002	-0.015
26	X		0.002	0.004	X	
27	X		0.001	-0.002	X	
28	X		0.001	-0.002	X	
29	X		0.001	-0.002	X	
30	X		0.001	-0.002	X	

Figure S2: Positions most strongly associated with the two major axes of variation in the roles of basal resources, intermediate consumers, and top predators. We show the proportion of variation in species' roles captured by each axes in parentheses. Position numbers are as in Fig. 1 (*main text*). We also show each position in its motif context, with the numbered position highlighted in black.

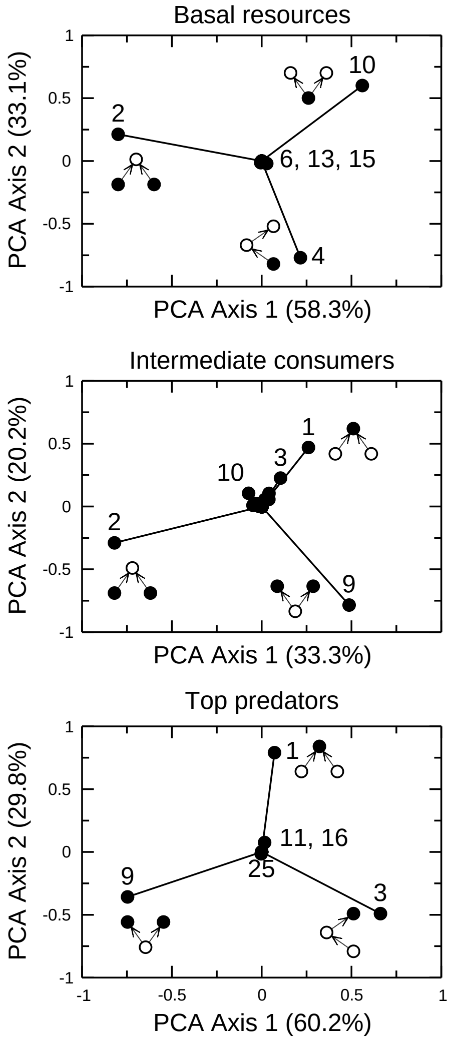


Table S7: Mean and standard deviation of each position, for each trophic group. Positions where impossible for a trophic group are indicated by 'X'.

	Basal resources		Intermediate consumers		Top predators	
Position	Mean	SD	Mean	SD	Mean	SD
1	X		0.078	0.142	0.125	0.130
2	0.550	0.188	0.392	0.261	X	
3	X		0.052	0.099	0.312	0.231
4	0.192	0.116	0.051	0.068	X	
5	X		0.044	0.048	X	
6	0.005	0.005	0.006	0.013	X	
7	X		0.003	0.014	X	
8	X		0.002	0.009	X	
9	X		0.269	0.221	0.526	0.259
10	0.215	0.152	0.047	0.076	X	
11	X		0.013	0.024	0.032	0.031
12	X		0.018	0.026	X	
13	0.037	0.026	0.016	0.020	X	
14	X		0.002	0.008	X	
15	0.001	0.002	0.002	0.004	X	
16	X		0.001	0.003	0.004	0.009
17	X		0.001	0.007	X	
18	X		0.001	0.003	X	
19	X		<0.001	0.001	X	
20	X		<0.001	0.001	X	
21	X		<0.001	<0.001	X	
22	X		<0.001	0.001	X	
23	X		<0.001	0.001	X	
24	X		<0.001	0.001	X	
25	X		0.001	0.002	0.002	0.006
26	X		0.001	0.005	X	
27	X		<0.001	0.001	X	
28	X		<0.001	0.001	X	
29	X		<0.001	0.001	X	
30	X		<0.001	0.001	X	

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