Supporting Information for "Ecological emergence of thermal clines in body size"

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1. Temperature-dependent allometric scaling of net energy gain

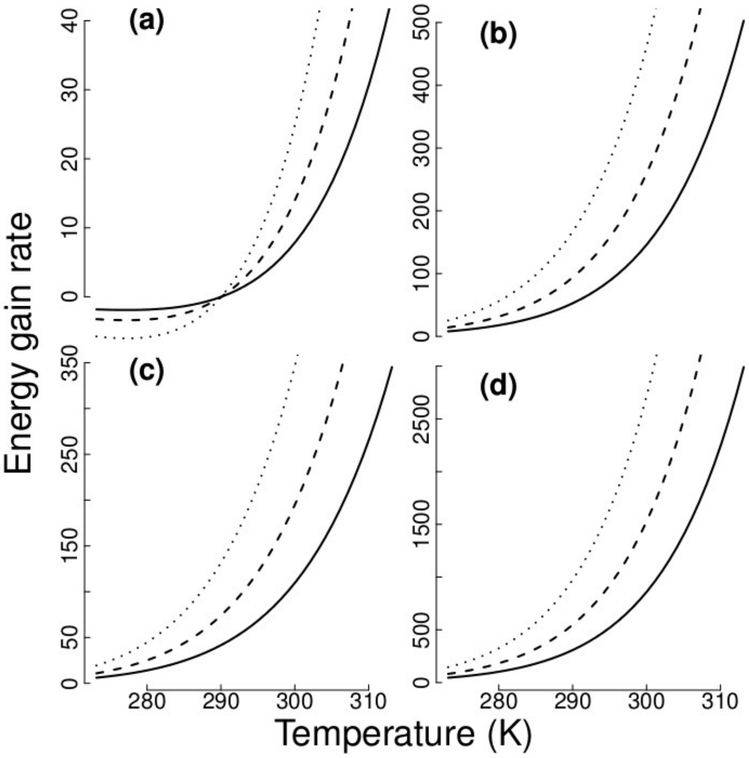

Figure S1. Mass-specific energy gain rate (defined as *I*-*M* in Eq. S1) as a function of temperature in the range 0-40ºC (273-313 K) for differently sized vertebrate ectotherms (a, c; dotted line: m_c = 1g, dashed line: m_c = 10g, solid line: m_c = 100g) and multicellular invertebrates (b, d; dotted line: m_c = 0.01g, dashed line: m_c = 0.1g, solid line: m_c = 1g) in which ingestion is either ecologically-limited (f_I=0.2, a, b) or physiologically-limited (f_I=0.9, c; d). Other parameters are as follows: vertebrate ectotherms: a_I=6.4, a_M=2.3, E_I=0.67, E_M=0.43; multicellular invertebrates: a_I=9.7, a_M=0.51, E_I=0.77, E_M=0.79.

Following Vasseur & McCann (2005) and references therein, we write the mass-specific biological rate functions including body mass and temperature scaling as:

$$\begin{cases} I = f_I a_I(T_0) m_c^{-0.25} \mathrm{e}^{E_I(T-T_0)/kTT_0} \\ M = a_M(T_0) m_c^{-0.25} \mathrm{e}^{E_M(T-T_0)/kTT_0} \end{cases} \qquad \text{Eq. S1,}$$

where *I* is energy intake rate, *M* is the rate of energy loss to metabolism, m_c is consumer body mass, $a_i(T_0)$ are empirically-derived intercepts of the allometric relationships (in kg (kg year)$^{-1}$ kg$^{0.25}$) which represent the maximum sustainable rates (physiological maxima) measured at temperature T_0, *T* is absolute temperature (in K), *k* is Boltzmann's constant (8.618×10^{-5} eV K^{-1}), E_a is activation energy (in eV) of the reaction, and f_I represents the realized fraction (in the wild) of the physiological ingestion maxima that can be attained under ideal conditions. When species are “ecologically limited” for ingestion $f_I << 1$, while $f_I \approx 1$ when species are “physiologically-limited” for ingestion (Vasseur & McCann, 2005). In Fig. S1, we posit mass-specific energy gain rate $G = I\text{-}M$ (Ohlberger *et al.*, 2011), and represent G as a function of T for differently-sized vertebrate ectotherms (Figs. S1a and c) and multicellular invertebrates (Figs. S1b and d) under either ecological (f_I=0.2, Figs. S1a and b) or physiological (f_I=0.9, Figs. S1c and d) limitation for ingestion (other parameters are as follows: vertebrate ectotherms: a_I=6.4, a_M=2.3, E_I=0.67, E_M=0.43; multicellular invertebrates: a_I=9.7, a_M=0.51, E_I=0.77, E_M=0.79). In all cases, G increases with temperature, consistent with the general finding that growth efficiency increases at higher temperatures (Angilletta & Dunham, 2003). However, the thermal sensitivity of G is higher in smaller organisms, so that warming generates a competitive asymmetry in favor of smaller organisms. Note that under “ecological limitation” and low temperatures, large vertebrates are more competitive than small vertebrates as they starve less fast (Fig. S1a). Interestingly, similar results were derived independently by Ohlberger *et al*. (2011) using more sophisticated data on perch *Perca fluvitatilis* physiological rates, which incorporated a more realistic, hump-shaped relationship between energy gain rate and temperature (i.e., temperature optimum). This suggests that, although Arrhenius kinetics do not account for the hump-shaped nature of physiological and ecological rates (Knies & Kingsolver, 2010), they still provide fairly good approximations (Dell *et al.*, 2011).

2. Log-normal distributions for size-dependent niches

Hutchinson (Hutchinson, 1957) defined the ecological niche as the range of environmental conditions that allow a population growth rate to be zero or positive. The niche can be though of as a *n* dimensional volume with its *n* axes represented by requisite resources. MacArthur & Levins (MacArthur & Levins, 1967) extend the theory by considering niche axes as "resource utilization" axes (Schoener, 2009). Instead of describing population growth variation in response to environmental variation, this resource-utilization niche describes the frequency distribution of resource use along each niche axis and directly quantifies the intensity of competition from the overlap of resource utilization niches (MacArthur & Levins, 1967; MacArthur, 1972) (Figure S2).

However, a major problem of the hypervolume approach is that its entire dimensionality generally extends beyond the technical and practical abilities of any one researcher. One way to circumvent this dimensionality problem is to collapse all resource axes onto one single, synthetic resource axis. Particularly relevant to this unidimensional approach is the use of a *consumer body size* axis (Figure S2). Indeed, body size correlates with prey size and type, ingestion rate, energy requirements, home ranges, and encounter rates (Peters, 1983; Jetz *et al.*, 2004; Brown *et al.*, 2004; Woodward *et al.*, 2005; Brose, 2010; Lang *et al.*, 2012). Hence, the strength of competition is proportional to the overlap of body size distributions between competitors (MacArthur & Levins, 1967; MacArthur, 1972). On macroevolutionary time scales, this size-dependent competition is predicted to result in character displacement and in a more or less regular spacing of potential competitors along a body size gradient; and in fact a number of examples support this prediction (Hutchinson, 1959; Pyke, 1982; Dayan *et al.*, 1989; Hermoyian *et al.*, 2002). This size-dependent, unidimensional approach to resource utilization niche can also be used to define the niche of predators for a focal species. Meta-analyses show that the average body mass of a predator is 100 times the body mass of its prey (Brose *et al.*, 2006), and the predator's niche may thus correspond to the niche of competitors, right-translated by 100 units along a body mass axis (or by 4.6 units along a body length axis since mass $\approx$ length^3). We apply this framework to compute interactions strengths experienced by individual fish in communities. We considered competition to be maximal between two individual competitors whose body size ratio is equal to 1 (MacArthur & Levins, 1967; MacArthur, 1972), and predation to be maximal when the predator/prey length ratio is equal to 4.6 (Brose *et al.*, 2006).

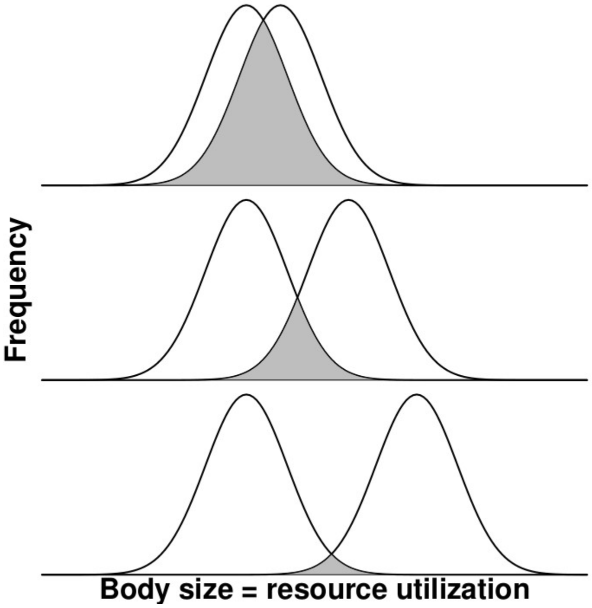

Figure S2. Multidimensional resource utilization niches projected onto a single consumer body size axis. From top to bottom, the decreasing overlap gradient between consumer size distributions determines a decreasing gradient of competition strength.

Choice of the shape of the resource utilization niche around this maximum also requires some discussions. The theory of resource utilization niches was developed assuming normal (Gaussian) utilization curves (Figure S2, (MacArthur, 1972)). However, several authors stress that normal utilization niches represent a case of limited generality (Roughgarden, 1974; Wilson, 1975; Abrams *et al.*, 2008; Pigolotti *et al.*, 2010), and there seems to be no general rule for the shape of the utilization distribution except that its variance should increase with its mean because prey-size range (niche breath) increases with predator size (Wilson, 1975; Woodward *et al.*, 2005). Here, we used a lognormal resource utilization distribution because (i) body sizes are often log-normally distributed (such as in our dataset), (ii) the variance of the log-normal distribution increases with its mean, accounting for the fact that niche breadth increases with body size, and (iii) because of its heavy right tail the lognormal distribution accounts for the fact that, within a niche, larger consumers have higher consumption rates (Brown *et al.*, 2004) and are thus likely to be stronger interactors than smaller consumers.

3. Table S1. Fish species included in our analysis. Species-specific number of observations, trophic guild, piscivory probability (based on diet data from Fishbase http://www.fishbase.org/) and mean body length in our dataset (from a log-normal distribution). Generalists: macroinvertebrates and fish; Insectivores: insects; Invertivores: insects, mollusks, and crustaceans; Omnivores: invertebrates and plants; Piscivores: fish.

Species latin name	**Species common name**	**N**	**Trophic guild**	**Piscivory probability ϕ**	**Mean body length (mm)**	code
Abramis brama	Freshwater bream	23,784	Generalist	0.5	173.8	BRE
Alburnoides bipunctatus	Schneider	75,138	Omnivore	0	73.5	SPI
Alburnus alburnus	Bleak	128,108	Insectivore	0	73.1	ABL
Ameiurus melas	Black bullhead	14,975	Generalist	1	135.3	PCH
Anguilla anguilla	Eel	180,444	Generalist	1	359.3	ANG
Aspius aspius	Asp	383	Piscivore	1	106.8	ASP
Barbus barbus	Barbel	125,293	Generalist	1	164.2	BAF
Barbus meridionalis	Mediterranean barbel	23,796	Omnivore	0	115.5	BAM
Blicca bjoerkna	White bream	33,532	Omnivore	0	110.6	BRB
Carassius sp.	Crucian carp	5,924	Omnivore	0	173.4	CAS
Chondrostoma nasus	Common nase	29,862	Omnivore	0	229.0	HOT
Chondrostoma toxostoma	French nase	17,469	Omnivore	0	134.1	TOX
Cobitis taenia	Spined loach	4,699	Omnivore	0	76.4	LOR
Cottus sp.	Sculpin	269,207	Generalist	1	64.3	CHA
Cottus petiti	Lez sculpin	1,232	Omnivore	0	33.4	CHP
Cyprinus carpio	Common carp	5,804	Generalist	0.5	286.3	CCO
Esox lucius	Pike	23,061	Piscivore	1	271.9	BRO
Gambusia holbrooki	Mosquitofish	1,603	Insectivore	0	29.6	GAM
Gasterosteus aculeatus	Threespined stickleback	18,828	Invertivore	0	41.6	EPI
Gobio sp.	Gudgeon	390,104	Omnivore	0	88.8	GOU
Gymnocephalus cernuus	Ruffe	9,267	Generalist	1	93.9	GRE
Lampetra fluviatilis	River lamprey	86	Piscivore	1	122.9	LPR
Lampetra planeri	European brook lamprey	45,423	Omnivore	0	119.8	LPP
Lepomis gibbosus	Pumpkinseed	45,725	Generalist	1	80.0	PES
Leucaspius delineatus	Sunbleak	2,181	Insectivore	0	45.7	ABH
Leuciscus burdigalensis	Rostrum dace	418	Insectivore	0	159.9	VAR
Leuciscus cephalus	Chub	419,627	Generalist	1	160.0	CHE
Leuciscus idus	Orfe	208	Generalist	0.5	98.1	IDE
Leuciscus leuciscus	Common dace	78,193	Insectivore	0	134.9	VAN
Lota lota	Burbot	4,963	Piscivore	1	244.3	LOT
Micropterus salmoides	Largemouth bass	1,459	Piscivore	1	115.7	BBG
Misgurnus fossilis	Weatherfish	1,961	Omnivore	0	140.8	LOE
Barbatula barbatula	Stone loach	281,339	Omnivore	0	69.5	LOF
Onchorhynchus mykiss	Rainbow trout	3,813	Generalist	1	217.1	TAC
Pachychilon pictus	Albanian Roach	1,815	Generalist	0.5	91.9	PAP
Perca fluviatilis	Perch	87,796	Piscivore	1	124.8	PER
Phoxinus phoxinus	Eurasian minnow	367,104	Omnivore	0	55.4	VAI
Pseudorasbora parva	Topmouth gudgeon	9,323	Generalist	0.5	58.4	PSR
Pungitius pungitius	Ninespined stickleback	16,234	Invertivore	0	37.7	EPT
Rhodeus amarus	Bitterling	39,369	Insectivore	0	46.7	BOU
Rutilus rutilus	Roach	356,333	Omnivore	0	120.9	GAR
Salaria fluviatilis	Freshwater blenny	1,217	Omnivore	0	63.3	BLE
Salmo salar	Atlantic salmon	56,089	Generalist	1	103.0	SAT
Salmo trutta	Brown trout	846,862	Generalist	1	144.2	TRF
Salvelinus fontinalis	Brook trout	412	Generalist	1	202.8	SDF
Scardinius erythrophtalmus	Rudd	16,527	Omnivore	0	108.5	ROT
Silurus glanis	Wels catfish	6,149	Generalist	1	285.3	SIL
Sander lucioperca	Pikeperch	3,640	Piscivore	1	222.3	SAN
Telestes souffia	Vairone	58,847	Omnivore	0	101.8	BLN
Thymallus thymallus	Grayling	9,419	Generalist	0.5	201.3	OBR
Tinca tinca	Tench	16,530	Invertivore	0	160.2	TAN
Zingel asper	Rhone streber	51	Omnivore	0	121.6	APR

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