Tables

Table 1. a) The parameters, definitions, sources or remarks if relevant, and values used in the modified niche model to generate food webs.

Parameter	Definition	Value used	Sources or remarks	Values for sensitivity analysis (the number in the parentheses correspond to the number in Figure S5)
S_0	Number of species	60		
C	Connectance (proportion of realized links out of all possible)	0.15	Dunne *et al.* (2002); Bland *et al.* (2019)	
C_{error}	Error tolerance on connectance	0.025	Bland et al. (2019)	
N_{fishes}	The number of stage structured fish species	Between 2 and 6	Reasonable numbers of naturally cooccurring fish species in a community	
Th_{fish}	A node at the trophic level $> Th_{fish}$ can become a fish stage	2	The diet of fishes should include non-autotrophs (trophic level of pure herbivores is 2)	
OL_{min}	Minimum overlap of niche ranges between consecutive stages of a fish	0.2	In terms of the fraction of the union of the two feeding ranges	0.1 (#2)
$Nstage_{max}$	The maximum number of stages a fish species can have	5	Reasonable maximum numbers of fish stages	4 (#1)
$Nstage_{min}$	The minimum number of stages a fish species should have	3	Reasonable minimum numbers of fish stages	2 (#1)

Table 1. b) The parameters, definitions, values used in this study, and sources or remarks if relevant, for the allometric trophic network (ATN) model.

Parameters	Definition	Value	Sources or remarks	Values for sensitivity analysis
Z	Body mass ratio	$10^{2.6}$ for fish predators and prey $10^{1.15}$ for invertebrate predators and prey	Brose et al. (2006)	10^4 (#3) and 10^2 (#4) for fish, and $10^{0.4}$ (#5) and 10^1 (#6) for invertebrates
g_i	Autotroph intrinsic growth rate for i	Randomly drown from $0.8 < N(0.9{,}0.5) < 1$	Bland et al. (2019)	
K	Autotroph carrying capacity	540 $\mu gC/L$	Boit et al. (2012); Bland et al. (2019)	
x_i	Mass specific metabolic rate of i	0 for autotrophs $0.314M_i^{-0.15}$ for invertebrates $0.88M_i^{-0.11}$for fish	Bland et al. (2019); de Castro & Gaedke (2008); Kilen et al. (2007, 2010)	
y_{ij}	Maximum consumption rate of i eating j	4 for fish 8 for invertebrates	Brose et al. (2006); Boit et al. (2012)	
e_{ij}	Assimilation efficiency of i eating j	0.95 when j is a fish 0.75 when j is an invertebrate 0.45 when j is an autotroph	Kelso (1972); Elliott (1976), Gavoni et al. (1986); Yodzis and Innes (1992); Brose et al. (2006)	0.85 when j is a fish or an invertebrate (#7)
f_m	Fraction of assimilated carbon respired for maintenance of basic bodily functions	0.05	Modified from Bland et al. (2019); Boit et al. (2012)	0.1 (f_m and f_a were varied simultaneously) (#8)
f_a	Fraction of assimilated carbon that contributes to growth	0.5	Modified from Bland et al. (2019); Boit et al. (2012)	0.4 (f_m and f_a were varied simultaneously) (#8)

q	Hill exponent	1.8	A higher value than typically used in the ATN models (1.2-1.5) to achieve 10-20% of food webs persisting after the ATN model is run (Williams & Martinez 2004; Martinez, Williams & Dunne 2006)	1.2 (#15) and 1.5 (#16)
ω_{ij}	Prey preference (relative to toward autotrophs)	When i is a fish, 200 times toward fishes 100 times toward invertebrates When i is an invertebrate, 50 times toward fishes 100 time toward invertebrates	Fishes do not eat much autotrophs in temperate and northern regions (Gonzalez-Bergonzoni et al. 2012; Vejříková et al. 2016). Fish needs to eat fish to grow fast and large (Post 2003; Juanes et al. 2002). The values are calibrated to achieve little consumption of autotrophs by fishes with animal prey in the diets.	When i is a fish, 150 (#10) and 300 (#9) times toward fishes 100 times toward invertebrates When i is an invertebrate, 50 times toward fishes 200 time toward invertebrates (#11), or 25 times toward fishes 100 time toward invertebrates (#12)
$B_{o_{ij}}$	Half saturation density of i eating j	1.5 $\mu gC/L$ when an invertebrate i eats j 15 $\mu gC/L$ when fish i eats fish j 20 $\mu gC/L$ when fish i eats omnivore j 150 $\mu gC/L$ when fish i eats small herbivores j (more than 50 times smaller than the fish in body mass) 15 $\mu gC/L$ when fish i eats large herbivores j	(Tonin 2011; Martinez *et al.* 2012; Bland *et al.* 2019) See Figure 1 in Bland et al. (2019) Herbivores are organisms whose diets consist of autotrophs for more than 70% (Bland et al. 2019).	

		(not as much smaller than the fish in body mass)		
c_{ij}	Consumer interference competition coefficient of i eating j	• Randomly drawn from $0 \leq Exp(\lambda = 5) \leq 0.5$ when k is an invertebrate • 3×10^{-4} when fish k eats fish j • $10^{-4}$when fish k eats omnivore j • 1 when fish i eats small herbivore j • $10^{-4}$when fish k eats large herbivore j	Tonin 2011; Martinez *et al.* 2012; Bland *et al.* 2019 See Figure 1 in Bland et al. (2019) All interspecific interference competition for feeding on prey j, (c_{kj}), is set to zero (i.e., $c_{kj} = 0$ for $k \neq i$; intraspecific (within-node) interference competition only).	Full interference competition (i.e., $c_{kj} \neq 0$ when $k \neq i$, #13), or intraspecific and inter-fish stage interference competition (i.e., $c_{kj} \neq 0$ when k and i are stages of the same trophic species, #14).
p_{ij}	the fraction of resources of consumer i shared with consumer j	(the number of prey i shares with j)/the number of i's prey	Bland et al. (2019)	
I	Fraction of biomass invested to reproduction	0 for the first stage class 0.8 for the last stage class	Kuparinen et al. (2016) The increment between stages = $\frac{0.8}{(number\ of\ stages-1)}$	
P_{mature}	Probability of reaching maturation at stage $h, h = 1,2, \ldots, n$	0 for the first stage class $\left(1 + e^{-3(n-n_{50})}\right)^{-1}$ for higher stages, where $n_{50} = \frac{n}{2}$ is the stage at which 50% of the individuals become mature	Kuparinen et al. (2016)	
a_h	Fraction of biomass staying in the same stage	0.05 for $h = 1, \ldots, n-1$ 0.5 for $h = n$	Fish in the terminal stage reproduces without surplus energy and convert 50% of total biomass to offspring.	

b_h	Fraction of biomass moving to the next stage	$1 - a_h$		
L	Number of days in a growing season	90	Bland et al. (2019)	
$Th_{extinct}$	Extinction threshold	$10^{-6}\ \mu gC/L$	When biomass goes below this value, the population is considered extinct	
$Th_{explode}$	Maximum threshold	$10^{12}\ \mu gC/L$	When biomass exceeds this value, the population is no longer sustainable.	

Table 2. Equations for the model components in the ATN model.

Model component	Formulation	Sources and notes
Body mass at stage h (The von Bertalanffy isometric growth curve)	$W_h = W_\infty\left(1 - e^{-K(h-h_0)}\right)^3$, where $K = \frac{3}{v}$ $h \in \{1, \ldots, v\}$ v = terminal stage class of the fish $\left(\frac{W_v}{W_\infty}\right) = 0.9$	Pauly (1980), Froese & Binohlan (2000), Bland et al. (2019) The value of h_0 is obtained by solving the equation for h_0 with W_h= 0 and W_v from the predator-prey body mass ratio.
The fraction of mature fish at each stage	$P_{mature} = {}^{1}/_{(1 + e^{-3(h-h_{50})})}$ h_{50} = the stage at which 50% of individuals are mature	Kuparinen et al. (2016) We assume h_{50} occurs halfway through to the terminal stage.
Investment to reproduction	$I = (h - 1)(I_{max}/v)$ I_{max} = maximum investment = 0.2	Kuparinen et al. (2016)
The Leslie matrix to model growth and reproduction by the terminal stage between growing seasons	$\begin{pmatrix} B_{i,1} \\ B_{i,2} \\ B_{i,3} \\ \vdots \\ B_{i,v} \end{pmatrix}_{t+1} = \begin{pmatrix} a_1 & 0 & & 0 & 0 & b_v \\ b_1 & a_2 & & 0 & 0 & 0 \\ 0 & b_2 & a_3 & & 0 & 0 \\ 0 & 0 & \ddots & & \ddots & 0 \\ 0 & 0 & 0 & & b_{v-1} & a_v \end{pmatrix} \begin{pmatrix} B_{i,0} \\ B_{i,1} \\ B_{i,2} \\ \vdots \\ B_{i,v} \end{pmatrix}_t$ b_h = the proportion of biomass in stage h to be shifted to stage $h+1$ (or to stage 1 for $h = v$), a_h = the proportion of biomass in stage h to remain in the same stage	Modified from Bland et al. (2019)
Stage-specific harvesting sensitivity	$S_{stage} = {}^{1}/_{(1 + e^{-2(h-v/2)})}$, for $h > 1$ $S_{stage}(h = 1) = 0$	Kuparinen et al. (2016)

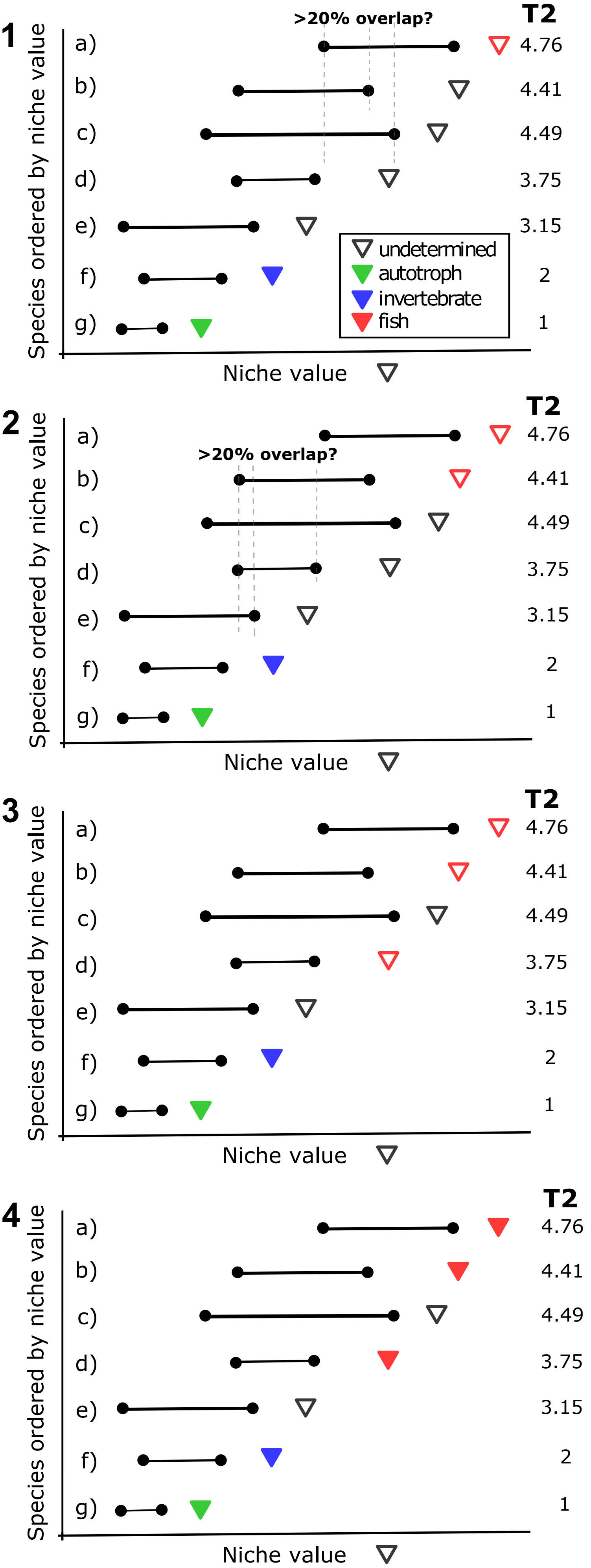
Figure captions

Figure 1. A highly simplified diagram showing how trophic species are classified and fish stages are assembled. A more detailed example is in Appendix S1. The upside-down triangles indicate niche values of the seven nodes. T2, prey-averaged trophic level, is calculated according to who eats whom in the entire community (the entire community is not shown here). 1) g is an autotroph because it has T2=1. f is an invertebrate because it has T2=2 (eats only autotrophs). a has the highest T2 and becomes the focal species (a fish candidate, indicated by an open red triangle). b and c have feeding ranges overlapping with that of a for more than 20% of the union of the two ranges and whose maxima fall in the range of a. 2) Because b's niche value is closer to a's, b is chosen as the next focal species. 3) Repeat the same procedure. d meets the conditions. 4) There are no species meeting the conditions for d in the rest of the community. Because we found 3 stages (the min number of stages is 3 in this example), we designate a, b, and d as a stage-structured fish species. 5) c has the highest T2 in the remaining nodes and becomes the next focal species. Repeat the same procedure. 6) We find e to meet the conditions but fail to find another stage because we run out of nodes. 7) c and e instead become invertebrates. In this food web, there are one species of fish with three stages, 3 species of invertebrates, and 1 autotrophic species.

Figure 2. Clarification of terminology used in this paper. The figure shows a food web (feeding relationships) with 10 nodes and 12 links. In this paper, a node, a taxon, and a trophic species mean the same, and the terms are used interchangeably. A fish species is composed of multiple stages, each of which occupies a node. The numbers in the red dots indicate stages. In this figure, there are one fish species with three stages, 3 invertebrates, and 4 autotrophs.

Figure 3. The list of the criteria used to selected food webs for further analysis.

Figure 4. a) The frequency distributions of the values of the 12 metrics measured on the 5865 linked (blue) and 9099 unlinked (orange) persisting webs. The lines of the corresponding color indicate the locations of the means. The values are average across the last 100 years of the 1000-year simulations. Total fish biomass = the sum of biomasses of all fish stages, mean CV fish biomass = mean of the CVs of individual fish stages, weighted fish body mass = body masses of fish stages weighted by relative abundance, link density = the number of links divided by the number of nodes, max TL of fish = maximum trophic level of fish stages, median PPMR fish = median predator-prey mass ratio for fish stages, fish energy gain = total energy entering fish stages, normalized fish energy gain = energy flow through individual links into fish stages divided by the total energy gained by the recipient fish stages (see the explanation in the text), skew(fish energy gain) = skewness of energy flow through individual links into fish stages.
b) The frequency distributions of the bootstrap differences in means between the linked and unlinked food webs (linked – unlinked) in terms of the 12 metrics. The black dotted lines indicate the locations of the means.



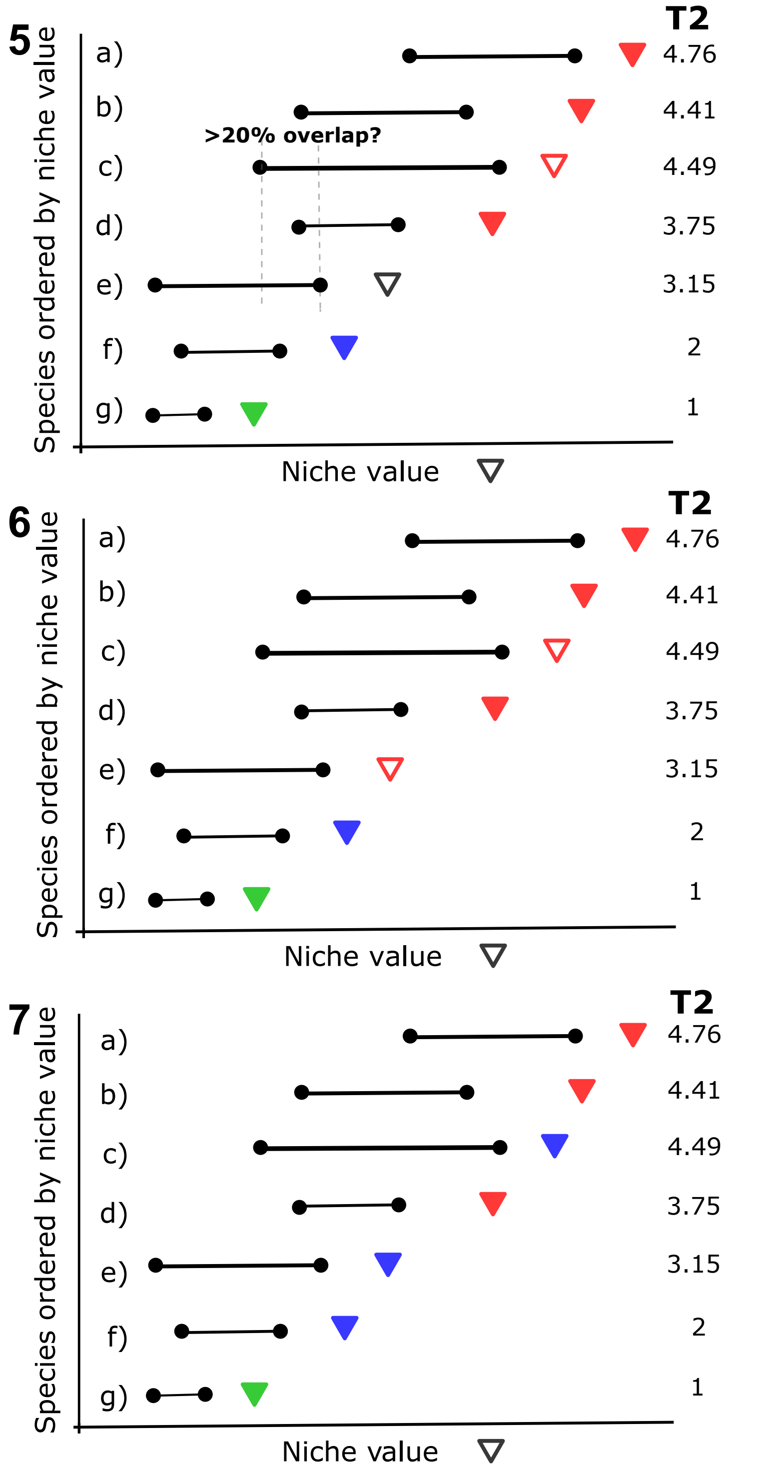
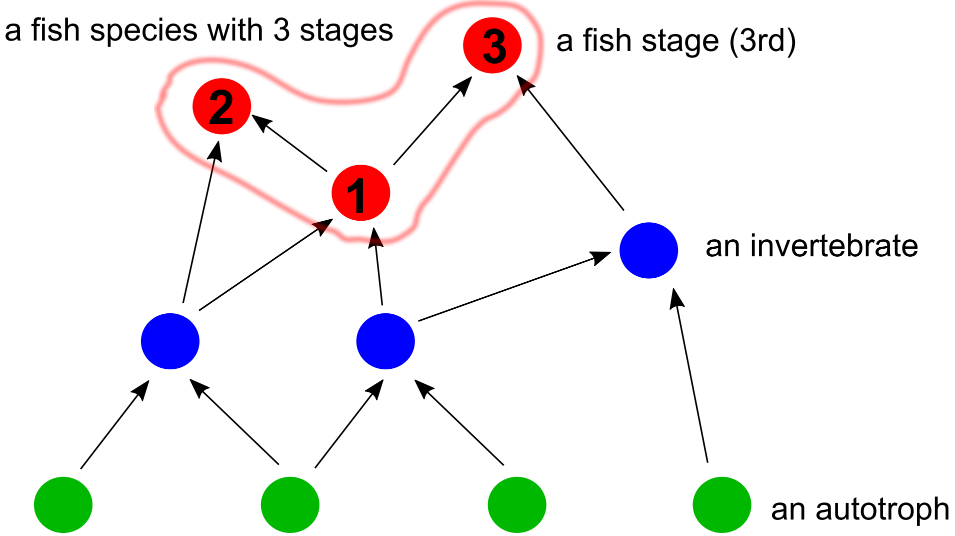


Figure 1. A highly simplified diagram showing how trophic species are classified and fish stages are assembled. A more detailed example is in Appendix S1. The upside-down triangles indicate niche values of the seven nodes. T2, prey-averaged trophic level, is calculated according to who eats whom in the entire community (the entire community is not shown here). 1) g is an autotroph because it has T2=1. f is an invertebrate because it has T2=2 (eats only autotrophs). a has the highest T2 and becomes the focal species (a fish candidate, indicated by an open red triangle). b and c have feeding ranges overlapping with that of a for more than 20% of the union of the two ranges and whose maxima fall in the range of a. 2) Because b's niche value is closer to a's, b is chosen as the next focal species. 3) Repeat the same procedure. d meets the conditions. 4) There are no species meeting the conditions for d in the rest of the community. Because we found 3 stages (the min number of stages is 3 in this example), we designate a, b, and d as a stage-structured fish species. 5) c has the highest T2 in the remaining nodes and becomes the next focal species. Repeat the same procedure. 6) We find e to meet the conditions but fail to find another stage because we rn out of nodes. 7) c and e instead become invertebrates. In this food web, there are one species of fish with three stages, 3 species of invertebrates, and 1 autotrophic species.

Figure 1

Figure 2



a node = a taxon = a trophic species

Figure 3

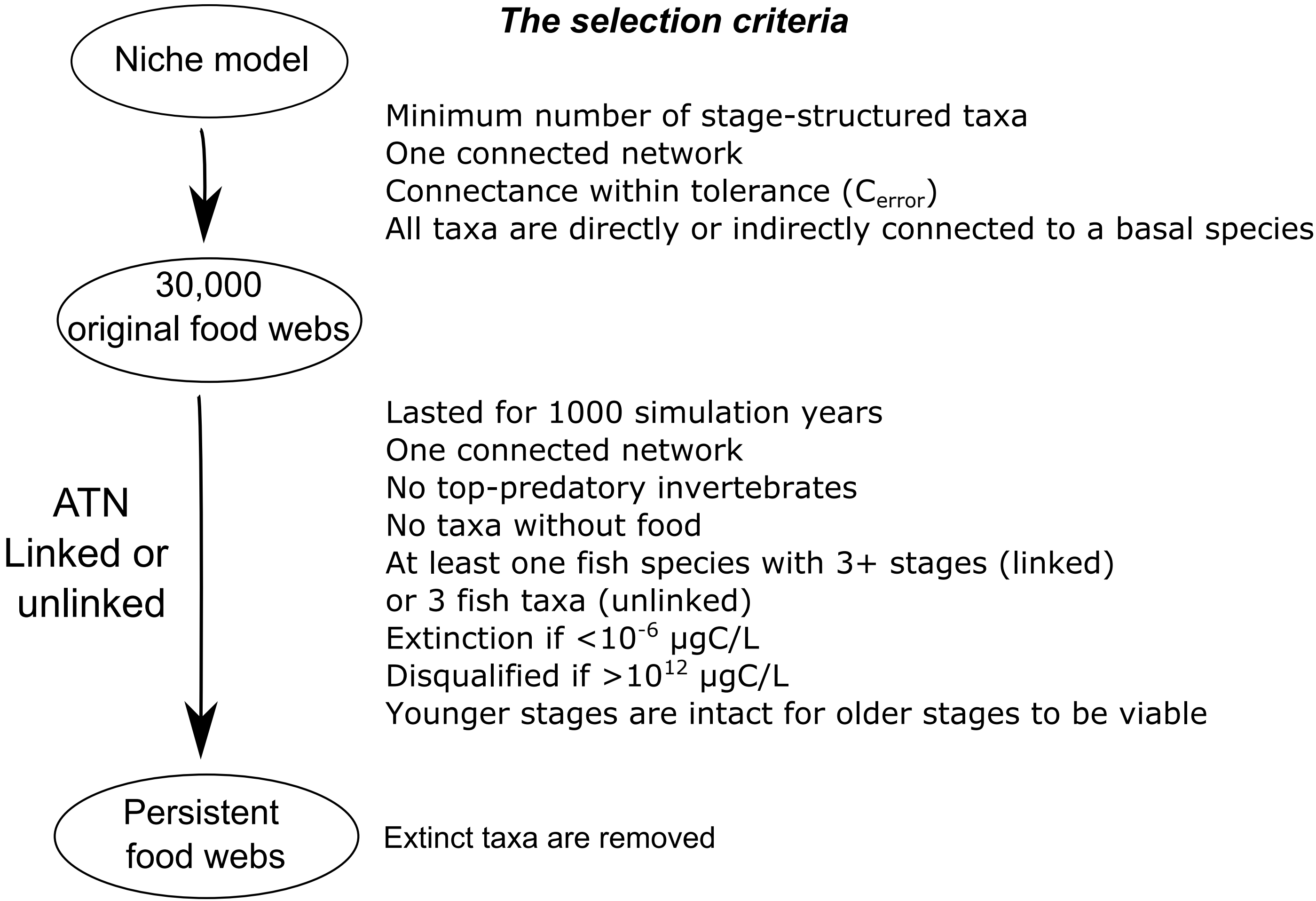
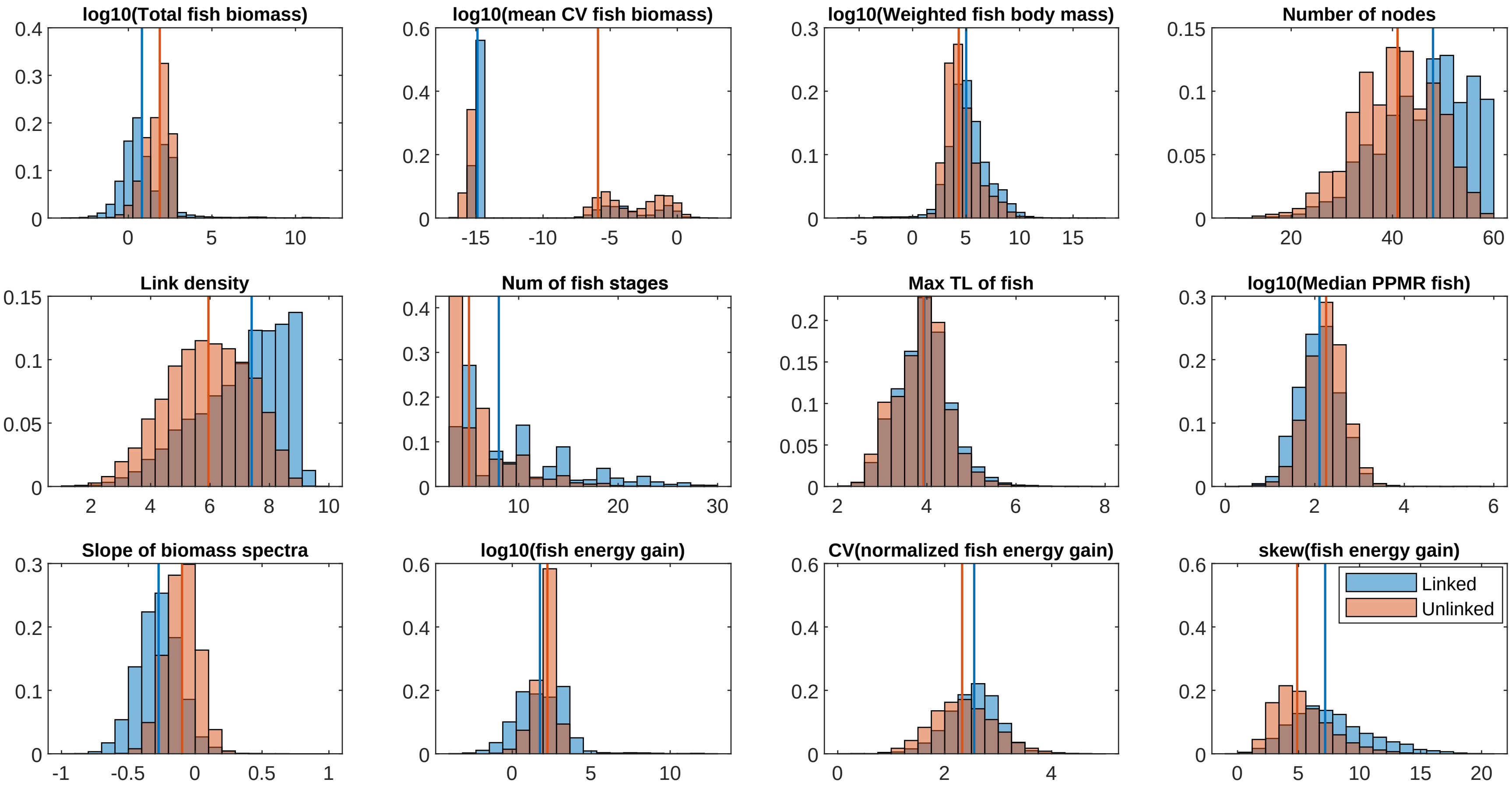
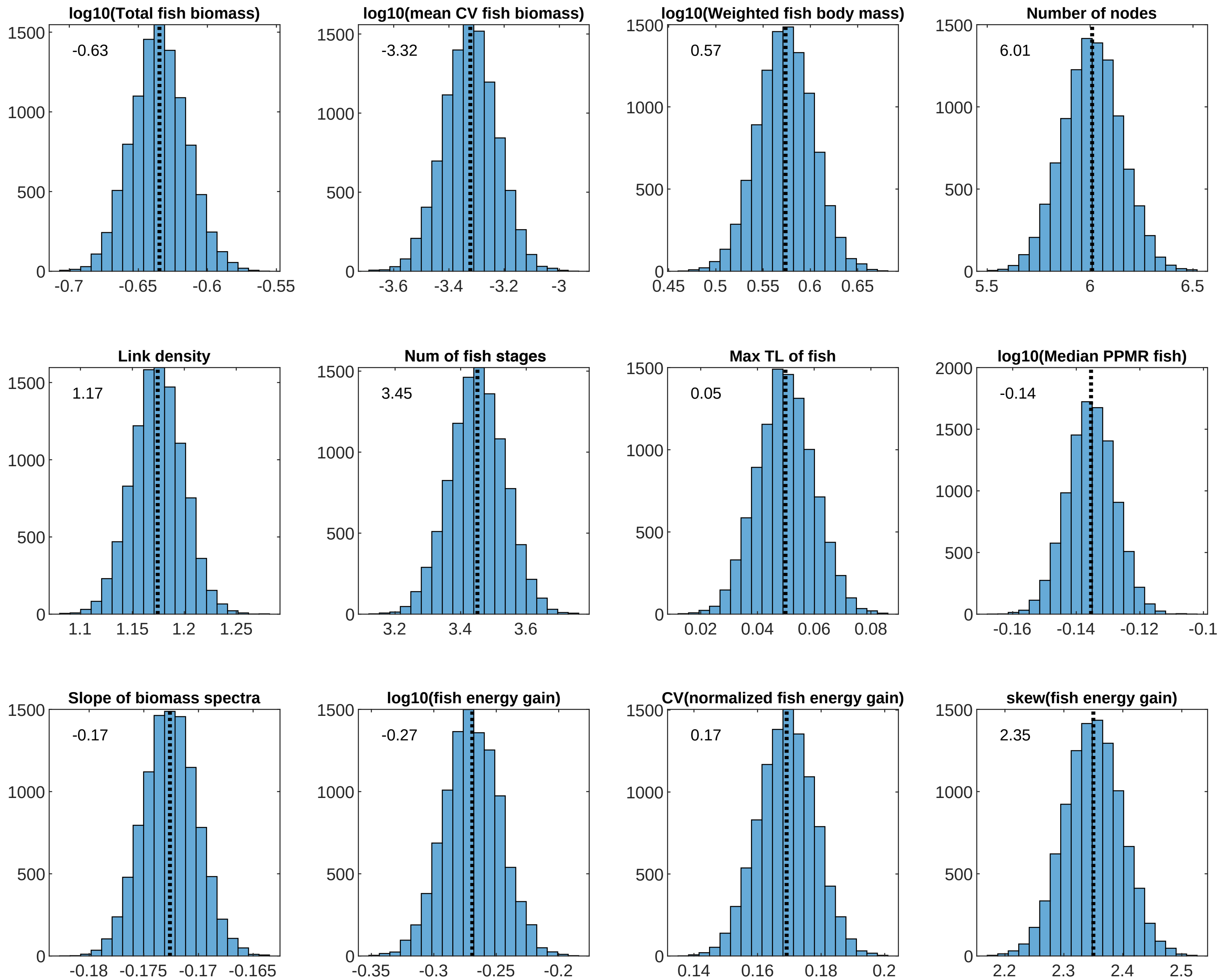

The selection criteria
Niche model
Minimum number of stage-structured taxa
One connected network
Connectance within tolerance (C_{error})
All taxa are directly or indirectly connected to a basal species
30,000 original food webs
ATN Linked or unlinked
Lasted for 1000 simulation years
One connected network
No top-predatory invertebrates
No taxa without food
At least one fish species with 3+ stages (linked)
or 3 fish taxa (unlinked)
Extinction if $<10^{-6}$ μgC/L
Disqualified if $>10^{12}$ μgC/L
Younger stages are intact for older stages to be viable
Persistent food webs
Extinct taxa are removed

Figure 4a



log10(Total fish biomass)
log10(mean CV fish biomass)
log10(Weighted fish body mass)
Number of nodes
Link density
Num of fish stages
Max TL of fish
log10(Median PPMR fish)
Slope of biomass spectra
log10(fish energy gain)
CV(normalized fish energy gain)
skew(fish energy gain)
Linked
Unlinked

Figure 4b


log10(Total fish biomass)
-0.63
log10(mean CV fish biomass)
-3.32
log10(Weighted fish body mass)
0.57
Number of nodes
6.01
Link density
1.17
Num of fish stages
3.45
Max TL of fish
0.05
log10(Median PPMR fish)
-0.14
Slope of biomass spectra
-0.17
log10(fish energy gain)
-0.27
CV(normalized fish energy gain)
0.17
skew(fish energy gain)
2.35