

# **The importance of habitat and life-history to extinction risk in sharks, skates, rays and chimaeras**

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**ELECTRONIC SUPPLEMENTARY MATERIAL**

## PHYLOGENETIC RELATIONSHIPS

Since a phylogenetic tree of chondrichthyans that includes all the species considered in our analysis is not available, a tree was built from topologies taken from different studies (Garland *et al.* 2005) (figure S1). The phylogenetic relationships among major groups of Chondrichthyes were taken from Naylor *et al.* (2005). Major relationships within Batoidea were according to McEachran *et al.* (1996) and McEachran & Aschliman (2004). Within Batoidea, the relationships among species of Myliobatiformes follow Dunn *et al.* (2003), with relationships within Dasyatidae according to Rosenberger (2001). Relationships among species of Rajiformes follow McEachran & Dunn (1998), with the clade of *Raja montagui*, *R. asterias* and *R. clavata* according to Tinti *et al.* (2003). Major relationships within Selachii are according to Naylor *et al.* (2005). The relationships within Squaliformes follow Shirai (1996) and Shirai & Nakaya (1990), and within Lamniformes follow Naylor *et al.* (1997). The relationships among the different families within Carcharhiniformes are according to Iglésias *et al.* (2005), and relationships within Carcharhinidae and Sphyrnidae follow Naylor (1992).

Relative branch lengths were determined from the calibrated phylogenetic tree of Shirai (1996) due to the absence of branch length data in most studies of chondrichthyan phylogeny. Branch lengths of a given taxon were set according to the appearance of its first fossil representative. The middle point between the ages of two adjacent nodes was used when the age of a node was unknown.

## R CODES FOR THE ANALYSES

```
#Code for phylogenetic tree
```

```
cat("((((((((((((((((Carcharhinus_galapagensis:0.0084,Carcharhinu  
s_obscurus:0.0084,Carcharhinus_longimanus:0.0084,Prionace_glauca  
:0.0084):0.0084,Carcharhinus_falciformis:0.017):0.0084,Carcharhi  
nus_plumbeus:0.0254):0.0084,Carcharhinus_signatus:0.0338,(Carcha  
rhinus_brachyurus:0.0169,Carcharhinus_brevipinna:0.0169):0.0169,  
Carcharhinus_sorraha:0.0338,Carcharhinus_amblyrhynchos:0.0338,Car
```

```
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_limbatus:0.0338,Carcharhinus_tilstoni:0.0338,Carcharhinus_leuca
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_brevirostris:0.059,Galeocerdo_cuvier:0.059):0.059,Furgaleus_mac
ki:0.118,(Mustelus_antarcticus:0.059,Mustelus_californicus:0.059
,Mustelus_canis:0.059,Mustelus_henlei:0.059,Mustelus_lenticulatu
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cyliorhinus_canicula:0.33):0.157,(((Isurus_oxyrinchus:0.1143,Car
charodon_carcharias:0.1143):0.1143,(Lamna_nasus:0.1143,Lamna_dit
ropis:0.1143):0.1143):0.1143,(Alopias_pelagicus:0.1715,Alopias_s
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terus_spinax:0.093):0.093,(Centroselachus_crepidater:0.1,Dalattia
s_licha:0.1):0.086):0.3597,((Centrophorus_acus:0.113575,Centroph
orus_granulosus:0.113575,Centrophorus_squamosus:0.113575):0.205,
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lainvillei:0.265,Squalus_megalops:0.265,Squalus_mitsukurii:0.265
):0.265,(Squatina_californica:0.265,Squatina_guggenheim:0.265,Sq
uatina_occulata:0.265):0.265):0.0157):0.1313,Notorynchus_cepedian
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ja_brachyura:0.076):0.076,Raja_binoculata:0.152,(Dipturus_chilen
sis:0.076,Dipturus_trachydermus:0.076):0.076):0.076,(Amblyraja_r
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ucoraja_erinacea:0.076):0.076):0.076):0.0958,(Rhinobatos_horkeli
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:0.0271):0.04,((Dasyatis_pastinaca:0.01355,Dasyatis_americana:0.
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hus_paucimaculatus:0.03605,Urolophus_lobatus:0.03605):0.03605):0
.1):0.1721):0.0198):0.1785):0.1785):0.279,(Chimaera_monstrosa:0.
609,(Callorhynchus_milli:0.592,Callorhynchus_capensis:0.592):0.0
17):0.391);",file="chondros",sep="\n")
```

```
treechon<-read.tree("chondros")
```

```
#Code to compute correlograms for
```

```
#Age at maturity (age)
```

```

correlogram.formula(age~subclass/cohort/order/family/genus)

#Growth completion rate (k)

correlogram.formula(k~subclass/cohort/order/family/genus)

#Longevity

correlogram.formula(longevity~subclass/cohort/order/family/genus
)

#Extinction risk (Fext)

correlogram.formula(Fext~subclass/cohort/order/family/genus)

#Code for phylogenetic models for

#Growth completion rate (k)

compar.gee(k~habitat+maturity.size,phy=treechon,family="Gamma"(l
ink="log"))

#Age at maturity (age)

compar.gee(age~habitat+maturity.size,phy=treechon,family="Gamma"
(link="log"))

#Longevity

compar.gee(longevity~habitat+maturity.size,phy=treechon,family="
Gamma"(link="log"))

#Extinction risk (Fext)

compar.gee(Fext~habitat+reproductive.mode+maturity.size,phy=tree
chon,family="Gamma"(link="log"))

#Code for taxonomy models for

#Growth completion rate (k)

summary(lme(log(k)~habitat+maturity.size,random=~1|subclass/coho
rt/order/family/genus/species))

#Age at maturity (age)

```

```
summary(lme(log(age)~habitat+maturity.size,random=~1|subclass/cohort/order/family/genus/species))
```

```
#Longevity
```

```
summary(lme(log(longevity)~habitat+maturity.size,random=~1|subclass/cohort/order/family/genus/species))
```

```
#Extinction risk (Fext)
```

```
summary(lme(log(Fext)~habitat+reproductive.mode,random=~1|subclass/cohort/order/family/genus/species))
```

```
#Code to model extinction risk (Fext) by taxonomic order
```

```
compar.gee(Fext~order,phy=arbchon,family="Gamma"(link="log"))
```

## FIGURES

Figure S1. Phylogenetic tree of Chondrichthyes (sharks, rays and chimaeras) used in the generalized estimating equation model to control for phylogenetic correlation. The tree is a composite from published partial trees (see References for phylogenetic relationships).

Figure S2. Correlogram of normalized Moran's  $I$  autocorrelation index of age at maturity, growth completion rate (von Bertalanffy's  $k$ ), longevity and extinction risk ( $F_{\text{extinct}}$ ) for taxonomic groups of the class Chondrichthyes (sharks, rays and chimaeras). Filled and empty circles represent significant ( $p < 0.05$ ) and non significant correlations, respectively. G = genus, F = family, O = order, C = cohort and S = subclass.

Figure S3. Relationship between age at maturity, growth completion rate and longevity (estimated as maximum observed age) with maximum body size in chondrichthyans from continental shelves (open circles), open ocean (grey circles) and deep sea (black circles). The axis for maximum size has a log scale to improve visualization.

Figure S1

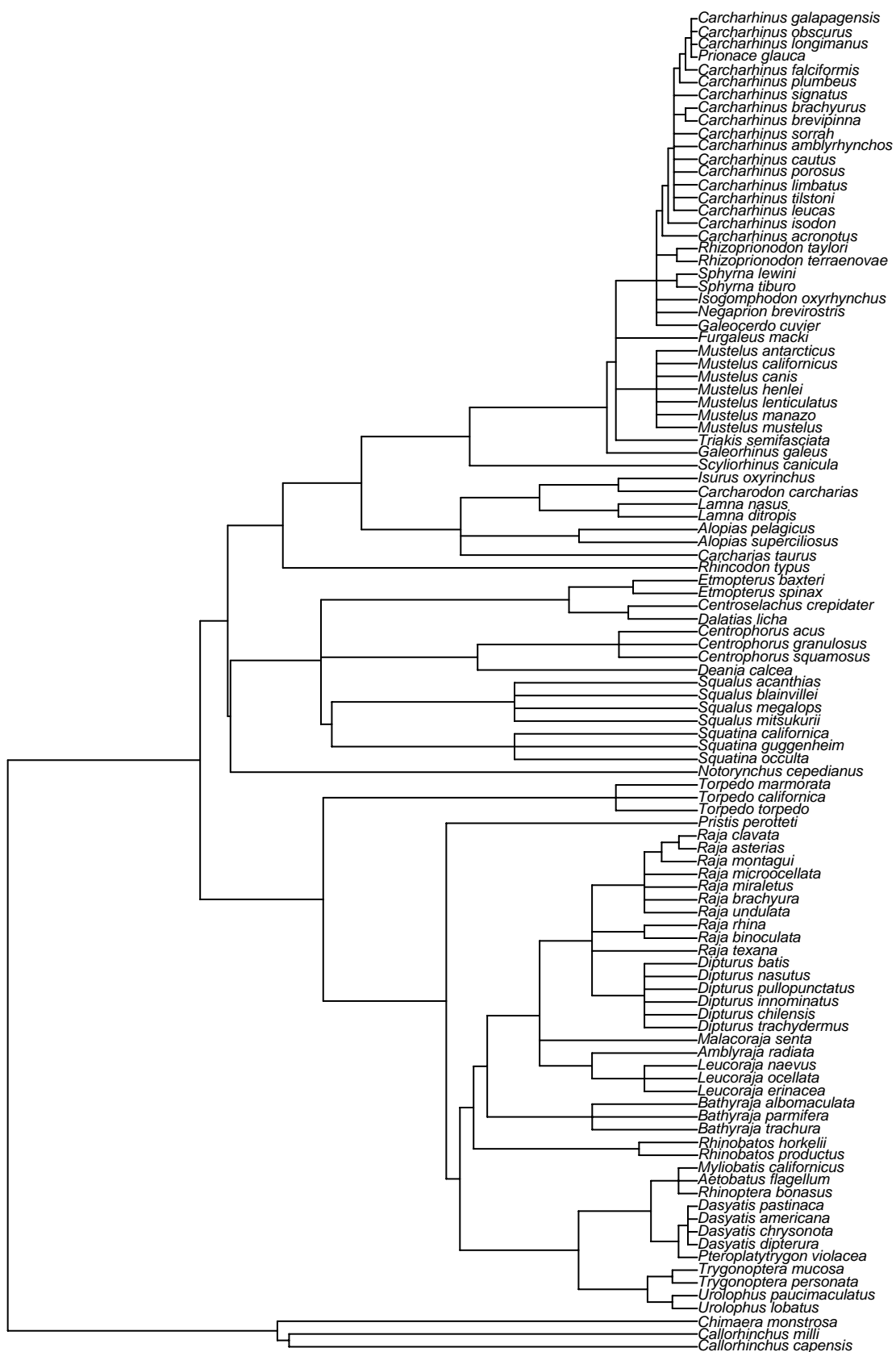


Figure S2

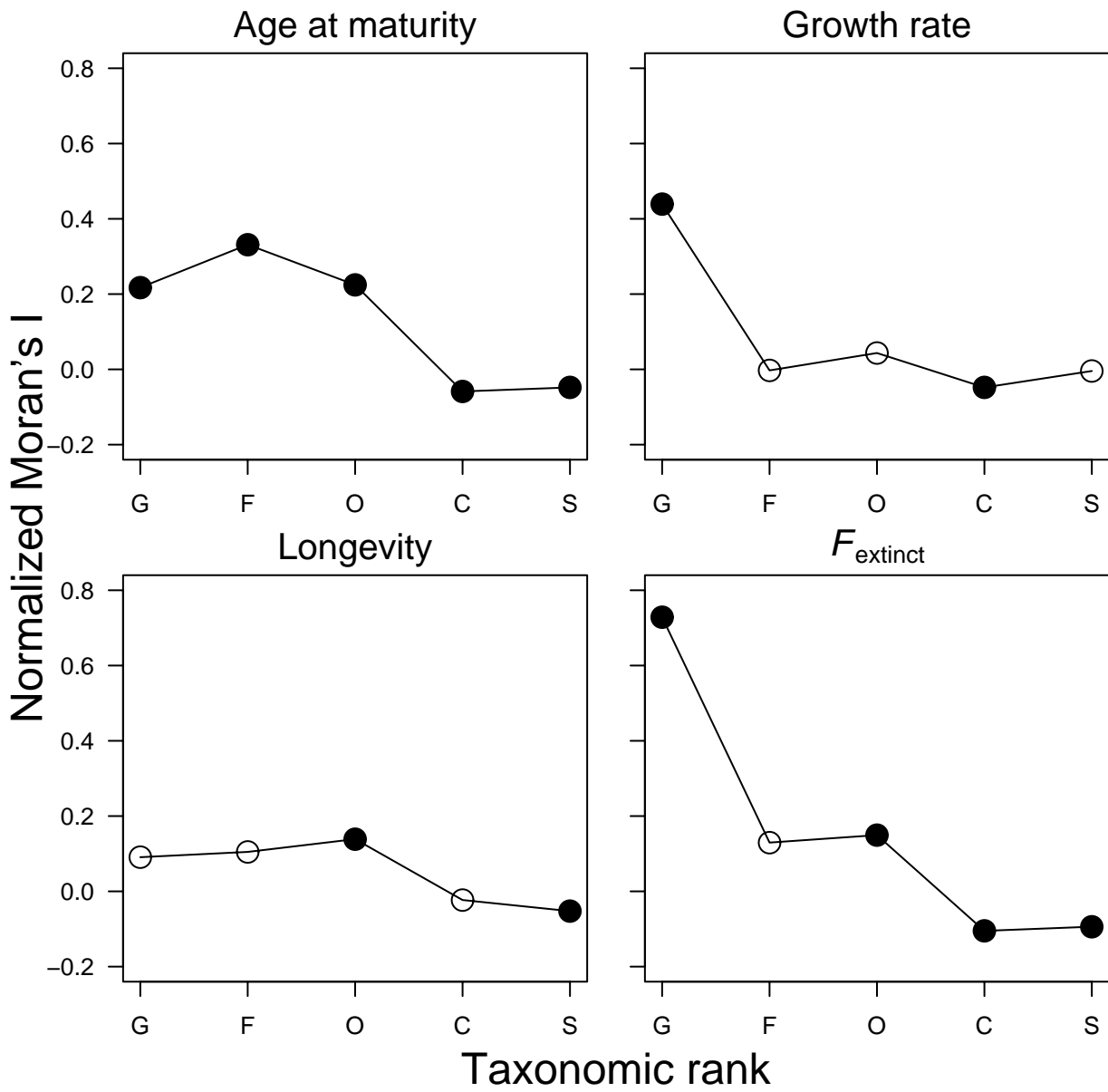


Figure S3

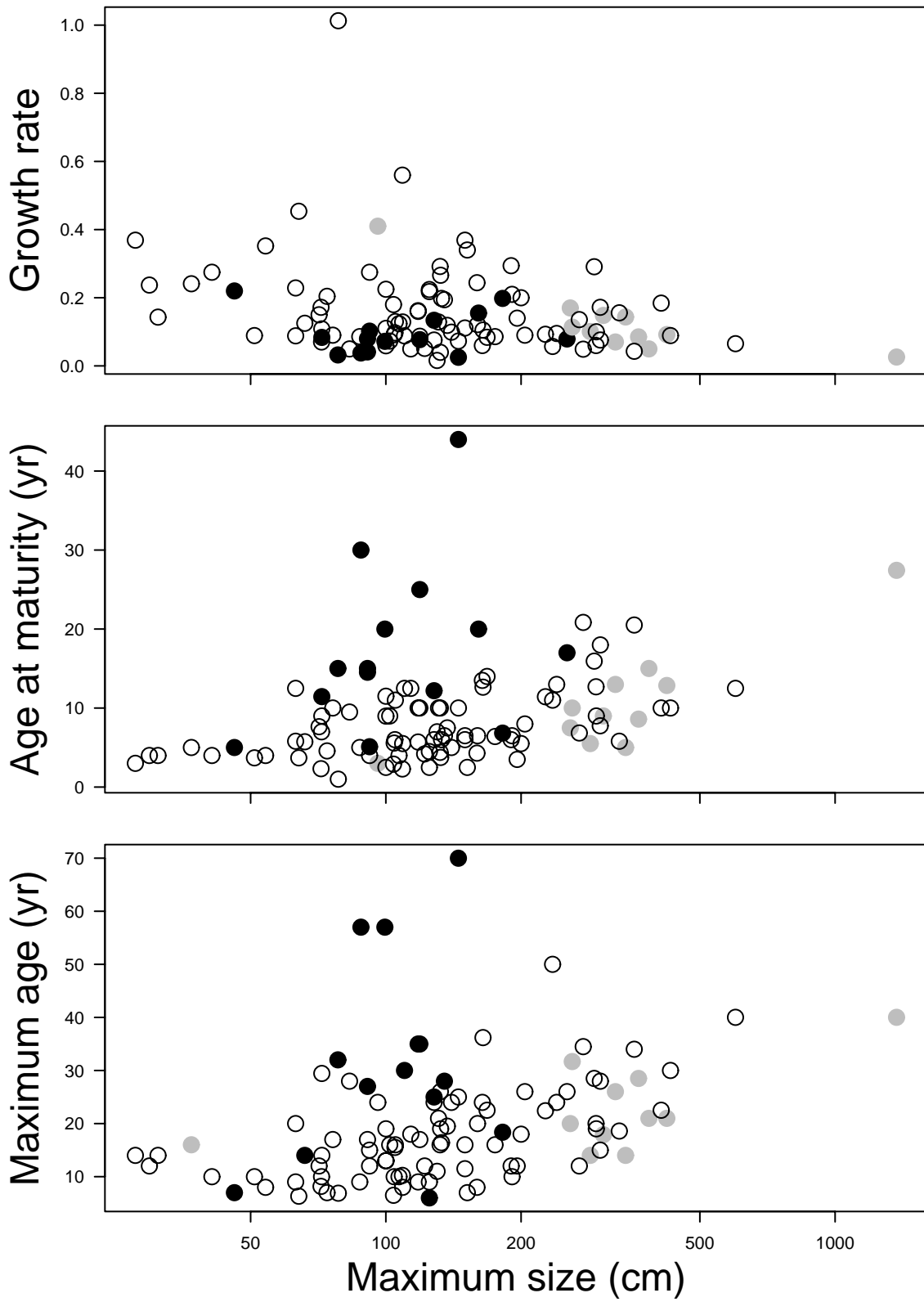


Table S1. Life history and environmental data for 105 chondrichthyan species.  $m_{\text{rep}}$  = reproductive mode (O = oviparous;  $V_a$ ,  $V_p$ ,  $V_l$ ,  $V_o$ , and  $V_h$  indicate adelphophagic, placental, lecithotrophic, oophagic, and histotrophic viviparity, respectively);  $s_{\text{max}}$  = maximum size;  $s_{\text{mat}}$  = size at maturity;  $k$  = growth completion rate from the von Bertalanffy growth model;  $a_{\text{max}}$  = maximum observed age;  $a_{\text{mat}}$  = age at maturity;  $l$  = litter size;  $i$  = interbirth interval; and  $F_{\text{extinct}}$  = fishery mortality to drive a species to extinction. Sizes are given in total length except for those of the orders Myliobatiformes and Chimaeriformes, which correspond to disc width and fork length, respectively.

Order Family	Species	Common name	Habitat	$m_{\text{rep}}$	$s_{\text{max}}$ (cm)	$s_{\text{mat}}$ (cm)	$k$	$a_{\text{max}}$ (yr)	$a_{\text{mat}}$ (yr)	$l$	$i$ (yr)	$F_{\text{extinct}}$	Source
SUBCLASS: ELASMOBRANCHII													
Cohort: Selachii													
Carchariniiformes													
Carcharhinidae	<i>Carcharhinus acronotus</i>	blacknose shark	shelf	$V_p$	132.4	102.4	0.266	19	3.8	3.9	2	0.197	1-4
	<i>Carcharhinus amblyrhynchos</i>	gray reef shark	shelf	$V_p$	190	125	0.294	12	6	4.1	2	0.174	5, 6
	<i>Carcharhinus brachyurus</i>	copper shark	shelf	$V_p$	275	206.1	0.049	34.5	20.9	16.6	2	0.145	7-11
	<i>Carcharhinus brevipinna</i>	spinner shark	shelf	$V_p$	294.1	217	0.1	19	9	8.5	2	0.209	4, 12-15
	<i>Carcharhinus cautus</i>	nervous shark	shelf	$V_p$	133	100.7	0.198	16.4	6	4.2	2	0.177	16
	<i>Carcharhinus falciformis</i>	silky shark	oceanic	$V_p$	305	225	0.148	17.9	9	6.5	2	0.209	17-19
	<i>Carcharhinus galapagensis</i>	Galapagos shark	shelf	$V_p$	300	227.5	0.172	15	7.8	8.7	2	0.232	5, 20
	<i>Carcharhinus isodon</i>	finetooth shark	shelf	$V_p$	159.6	123	0.244	8	4.3	4	2	0.192	21, 22
	<i>Carcharhinus leucas</i>	bull shark	shelf	$V_p$	300.2	225	0.076	28	18	9.9	2	0.126	4, 23-26
	<i>Carcharhinus limbatus</i>	blacktip shark	shelf	$V_p$	191	160	0.21	10	6.5	4.6	2	0.182	4, 27-30
	<i>Carcharhinus longimanus</i>	oceanic whitetip shark	oceanic	$V_p$	285	183.3	0.101	14	5.5	6.1	2	0.240	31-33
	<i>Carcharhinus obscurus</i>	dusky shark	shelf	$V_p$	357.2	279.3	0.043	34	20.5	10	3	0.110	34-38
	<i>Carcharhinus plumbeus</i>	sandbar shark	shelf	$V_p$	226.5	176	0.093	22.4	11.4	7.9	2	0.181	39-42
	<i>Carcharhinus porosus</i>	smalltail shark	shelf	$V_p$	128	70	0.076	24	6	4.5	1	0.278	43, 44
	<i>Carcharhinus signatus</i>	night shark	oceanic	$V_p$	260	202.5	0.114	31.7	10	11.1	2	0.217	45, 46
	<i>Carcharhinus sorrah</i>	spottail shark	shelf	$V_p$	151.8	95	0.34	7	2.5	3.1	1	0.355	47, 48
	<i>Carcharhinus tilstoni</i>	Australian blacktip shark	shelf	$V_p$	196	115	0.14	12	3.5	3	1	0.295	47, 48
	<i>Galeocerdo cuvier</i>	tiger shark	shelf	$V_l$	410	333.5	0.184	22.5	10	31.5	2	0.317	4, 35, 49-52
	<i>Isogomphodon oxyrhynchus</i>	daggernose shark	shelf	$V_p$	160	115	0.121	20	6.5	5	2	0.192	53, 54
	<i>Negaprion brevirostris</i>	lemon shark	shelf	$V_p$	293.6	239	0.06	20	12.7	7.4	2	0.158	55-57
	<i>Prionace glauca</i>	blue shark	oceanic	$V_p$	341.8	206.5	0.146	14	5	30	1	0.637	58-61
	<i>Rhizoprionodon taylori</i>	Australian sharpnose shark	shelf	$V_p$	78.4	57.5	1.013	7	1	4.5	1	0.893	62-64
	<i>Rhizoprionodon terraenovae</i>	Atlantic sharpnose shark	shelf	$V_p$	108.9	78.5	0.56	10.2	2.3	4.4	1	0.540	65, 66
Scyliorhinidae	<i>Scyliorhinus canicula</i>	lesser-spotted catshark	shelf	O	71	57	0.15	12	7.6	45.5	1	0.497	67-71



Myliobatiformes													
Dasyatidae	<i>Dasyatis americana</i>	southern stingray	shelf	V <sub>h</sub>	200	77.5	0.2 <sup>a</sup>	18	5.5	4.2	1	0.283	145, 146
	<i>Dasyatis chrysonota</i>	blue stingray	shelf	V <sub>h</sub>	71.9	50	0.07	10	7	6.2	1	0.289	147, 148
	<i>Dasyatis dipterura</i>	diamond stingray	shelf	V <sub>h</sub>	83	57.3	0.05	28	9.5	2	1	0.138	149
	<i>Dasyatis pastinaca</i>	common stingray	shelf	V <sub>h</sub>	51	24	0.089	10	3.7	6.2	1	0.448	150, 151
	<i>Pteroplatytrygon violacea</i>	pelagic stingray	oceanic	V <sub>h</sub>	96	45	0.41	24	3	4.5	1	0.428	152, 153
Myliobatidae	<i>Aetobatus flagellum</i>	longheaded eagle ray	shelf	V <sub>h</sub>	150	90	0.111	16	6	3.5	1	0.215	154, 155
	<i>Myliobatis californicus</i>	bat ray	shelf	V <sub>h</sub>	140	88.1	0.099	24	5	3.8	1	0.282	156, 157
Rhinopteridae	<i>Rhinoptera bonasus</i>	cownose ray	shelf	V <sub>h</sub>	104.8	77.7	0.097	15.5	6	1	1	0.085	158-160
Urolophidae	<i>Trygonoptera mucosa</i>	western shovelnose stingaree	shelf	V <sub>h</sub>	36.9	25.3	0.241	16	5	1.1	1	0.093	161
	<i>Trygonoptera personata</i>	masked stingaree	shelf	V <sub>h</sub>	31.1	22.8	0.143	14	4	1.2	1	0.101	161
	<i>Urolophus lobatus</i>	lobed stingaree	shelf	V <sub>h</sub>	27.7	20.1	0.369	14	3	1.3	1	0.102	162
	<i>Urolophus paucimaculatus</i>	sparsely-spotted stingaree	shelf	V <sub>h</sub>	29.8	20.4	0.237	12	4	2.5	1	0.241	163, 164
	Pristiiformes												
Pristidae	<i>Pristis perotteti</i>	large-tooth sawfish	shelf	V <sub>1</sub>	430	300	0.089	30	10	7.3	2	0.183	165-167
Rajiformes													
Rajidae	<i>Amblyraja radiata</i>	thorny skate	shelf	O	105	91.7	0.13	16	11	31	1	0.336	168-170
	<i>Bathyraja albomaculata</i>	white-dotted skate	shelf	O	76.2	59.4	0.09	17	10	--	1	--	171, 172
	<i>Bathyraja parmifera</i>	Alaska skate	shelf	O	119	93	0.087	17	10	--	1	--	173
	<i>Bathyraja trachura</i>	rougthead skate	deep	O	91	74	0.08	17	14.5	--	1	--	174
	<i>Dipturus batis</i>	common skate	shelf	O	235	130.8	0.057	50	11	--	1	--	175
	<i>Dipturus chilensis</i>	beaked skate	shelf	O	168	106	0.084	22.5	14	48.2	1	0.304	176, 177
	<i>Dipturus innominatus</i>	New Zealand smooth skate	shelf	O	240	112.2	0.095	24	13	--	1	--	178
	<i>Dipturus nasutus</i>	New Zealand rough skate	shelf	O	118	59.1	0.16	9	5.7	--	1	--	178
	<i>Dipturus pullopunctatus</i>	slime skate	shelf	O	113.7	99.1	0.05	18	12.5	--	1	--	179
	<i>Dipturus trachydermus</i>	roughskin skate	deep	O	253	215	0.079	26	17	48.7	1	0.259	180
	<i>Leucoraja erinacea</i>	little skate	shelf	O	54	40	0.352	8	4	30	1	0.769	181, 182
	<i>Leucoraja naevus</i>	cuckoo ray	shelf	O	72	59	0.108	14	9	90	1	0.501	175, 183
	<i>Leucoraja ocellata</i>	winter skate	shelf	O	100	76	0.059	29	11.5	35	1	0.333	182, 184-186
	<i>Malacoraja senta</i>	smooth skate	shelf	O	66	40.5	0.125	14	5.7	--	1	--	187, 188
	<i>Raja asterias</i>	starry ray	shelf	O	64	56.1	0.454	6.3	3.7	73	1	1.043	189, 190
	<i>Raja binoculata</i>	big skate	shelf	O	203.9	90	0.09	26	8	1260	1	0.858	191, 192
	<i>Raja brachyura</i>	blonde ray	shelf	O	109	83.6	0.129	8	5.5	90	1	0.768	193, 194
	<i>Raja clavata</i>	thornback ray	shelf	O	104.4	66.2	0.091	10	5.6	142	1	0.843	194, 195, 196
<i>Raja microocellata</i>	small-eyed ray	shelf	O	87.5	58	0.086	9	5	57.5	1	0.754	195	
<i>Raja miraletus</i>	brown ray	shelf	O	71.7	35	0.172	8.2	2.3	61	1	1.522	197, 198	
<i>Raja montagui</i>	spotted ray	shelf	O	74	56.8	0.204	7	4.6	60	1	0.831	192-195	
<i>Raja rhina</i>	longnose skate	shelf	O	132.2	83	0.04	26	10	--	1	--	191	
<i>Raja texana</i>	roundel skate	shelf	O	63	53.7	0.229	9	5.8	--	1	--	199	
<i>Raja undulata</i>	undulate ray	shelf	O	100	76.2	0.11	13	9	--	1	--	200,201	

Rhinobatiformes													
Rhinobatidae	<i>Rhinobatos horkelii</i>	Brazilian guitarfish	shelf	V <sub>1</sub>	135	100.5	0.194	28	6.5	6	1	0.291	202, 203
	<i>Rhinobatos productus</i>	shovelnose guitarfish	shelf	V <sub>1</sub>	130	99	0.016	11	7	9	1	0.334	204, 205
Torpediniformes													
Torpedinidae	<i>Torpedo californica</i>	Pacific electric ray	shelf	V <sub>1</sub>	102	73.1	0.073	16	9	17	1	0.338	206
	<i>Torpedo marmorata</i>	spotted torpedo	shelf	V <sub>1</sub>	63	44	0.088 <sup>a</sup>	20	12.5	11	3	0.159	207, 208
	<i>Torpedo torpedo</i>	common torpedo	shelf	V <sub>1</sub>	41	22	0.275 <sup>a</sup>	10	4	3.4	1	0.300	209
<hr/> SUBCLASS: HOLOCEPHALI <hr/>													
Chimaeriformes													
Callorhynchidae	<i>Callorhynchus capensis</i>	Cape elephantfish	shelf	O	60	49.6	0.051	12	4.2	22	1	0.672	210-212
	<i>Callorhynchus milii</i>	elephant fish	shelf	O	97	71	0.224	15	4.5	13	1	0.532	213-215
Chimaeridae	<i>Chimaera monstrosa</i>	rabbit fish	deep	O	74	45.9	0.084	29.4	11.5	22 <sup>b</sup>	1	0.299	211, 216, 217

<sup>a</sup> taken from the fecundity of *Callorhynchus capensis*. <sup>b</sup> calculated from equations 7 and 8 of source 218.

Table S2. Coefficients (standard error within brackets) of linear models relating the fishing mortality required to drive a population to extinction ( $F_{\text{extinct}}$ ) with habitat and life history traits.  $F_{\text{extinct}}$  was calculated with  $a_{\text{sel}} = 0$ . Habitat and reproductive mode coefficients are relative to deep-sea species and adelphophagic species, respectively. \* $p \leq 0.05$ , \*\* $p \leq 0.01$ , \*\*\* $p \leq 0.001$ .

Variables	Taxonomy	Phylogeny
Intercept	-3.153 (0.485)***	-2.643 (0.486)***
Habitat (oceanic)	0.803 (0.216)***	0.972 (0.139)***
(shelf)	0.593 (0.163)***	0.439 (0.134)**
Size at maturity	—	-0.002 (<0.001)***
Reproductive mode (histotrophic)	0.714 (0.489)	0.435 (0.502)
(lecitotrophic)	1.045 (0.472)*	1.135 (0.415)**
(oophagic)	0.440 (0.529)	0.375 (0.353)
(placental)	1.211 (0.484)*	1.035 (0.420)
(oviparous)	1.855 (0.491)***	1.611 (0.440)**

Table S3. Coefficients (standard error within brackets) of linear models relating the fishing mortality required to drive a population to extinction ( $F_{\text{extinct}}$ ) with habitat and life history traits.  $F_{\text{extinct}}$  was calculated with  $a_{\text{sel}}$  = age at maturity. Habitat and reproductive mode coefficients are relative to deep-sea species and adelphophagic species, respectively. \* $p \leq 0.05$ , \*\* $p \leq 0.01$ , \*\*\* $p \leq 0.001$ .

Variables	Taxonomy	Phylogeny
Intercept	-1.892 (0.599)**	-2.184 (0.477)**
Habitat (oceanic)	0.879 (0.258)**	0.751 (0.136)***
(shelf)	0.512 (0.202)*	0.352 (0.132)*
Size at maturity	—	-0.002 (<0.001)***
Reproductive mode (histotrophic)	0.749 (0.613)	1.136 (0.493)
(lecitotrophic)	1.731 (0.585)***	1.881 (0.408)***
(oophagic)	0.862 (0.671)	0.765 (0.347)
(placental)	1.469 (0.600)	1.622 (0.412)
(oviparous)	2.548 (0.619)***	2.856 (0.431)***

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