Appendix A. Ecosystems and models

Table A1. High-trophic-level (HTL) and low-trophic-level (LTL) Species/taxa included and ecosystem models applied in each ecosystem.

Ecosystem	Modelled HLT group species/taxa	Modelled LTL group species/taxa	Ecosystem model
Black Sea	Atlantic bonito, Bluefish, Atlantic mackerel, Whiting, Turbot, Red mullet, Spiny dogfish	Horse mackerel, Shad, Sprat, Anchovy	Ecopath with Ecosim
North Sea	Dab, Whiting, Sole, Gurnard, Plaice, Haddock, Cod, Saithe	Sprat, Sandeel, Norway Pout, Herring	Size Spectrum
South Catalan Sea	Benthopelagic cephalopods, Conger eel, Anglerfish, Demersal fishes (3), Adult hake, Demersal sharks, Atlantic bonito, Swordfish and Tuna, Loggerhead turtles, Audouin's gull, Other sea birds, Dolphins	Shrimps, Crabs, Norway lobster, Benthic invertebrates, Benthic cephalopods, Mullets, Flatfishes, Poor cod, Juvenile hake, Blue whiting, Demersal fishes (1), Demersal fishes (2), Benthopelagic fishes, European anchovy, Sardine adults, Other small pelagic fishes, Horse mackerel, Mackerel	Ecopath with Ecosim
Southeastern Australian	Shallow Demersals, Flathead, Pink Ling, Trevalla, Gummy Shark, Small Pelagic Tuna, Demersal Shark, Dogfish, Grenadier, Pelagic Shark, Gulper Shark, Shallow Piscivores	Mackerel, Myctophids, Red Bait, Squid, Krill	Atlantis
Southern Benguela	Chub mackerel, Adult Horse mackerel, Snoek, Other large pelagics, Merluccius capensis, Merluccius paradoxus, Pelagicdemersals, Benthicdemersals, Pelagic Chondrichthyes, Benthic Chondrichthyes, Apex Chondrichthyes	Anchovy, Sardine, Redeye, Other small pelagics, Juvenile Horse mackerel, Mesopelagics, Cephalopods,	Ecopath with Ecosim
West coast Canada	Walleye pollock, Pacific cod, Lingcod, Spiny dogfish, Spotted ratfish, Harbour seal	Euphausiids, Shrimp, Pacific herring,	OSMOSE
Western Scotland	Cod mature, Haddock mature, Whiting mature, Pollock, Gurnards, Monkfish, Rays,Sharks, Large demersals,	Flatfish, Other small fish, Mackerel, Horse mackerel, Blue whiting, Herring, Norway pout, Sandeel, Sprat, Nephrops, Lobster, Edible crab, Crustaceans, Cephalopod, Scallops	Ecopath with Ecosim
West Florida Shelf	King mackerel, Amberjacks, Red grouper, Gag grouper, Red snapper,	Sardine Herring Scad Complex, Anchovies and Silversides, Coastal omnivores, Reef carnivores, Reef omnivores, Shrimps, Large crabs	OSMOSE
Western Scotian Shelf	Sharks, Cod, Silver Hake, Halibut, Pollock, Demerdal piscivores, Large benthivores, Skates, Dogfish, Redfish, American plaice, Flounders, Haddock adult	Haddock young, Longhorn sculpin, Herring, Other pelagic, Mackerel, Mesopelagic, Small-medium benthivores, Squids, Lobster, Crabs, Shrimps, Scallop	Ecopath with Ecosim

Table A2. Descriptions of ecosystem models applied in the study.

	Atlantis	Ecopath with Ecosim	OSMOSE	Size Spectrum
Summary description	Whole ecosystem model from hydrodynamic conditions to foodweb and human users	Mass-balance model of marine foodwebs that accounts for the flow of biomass between trophic groups.	Size-structured Individual-based model of fish community dynamics with coupling with hydrodynamic and biogeochemical models (end-to-end model).	Multispecies model describing the flux of biomass along size classes
Key features	Includes age structure and major ecological processes such as full life history closure, gap-limited predation, habitats, movement, biogeochemical nutrient cycling and a range of effort allocation options.	Ecosim is a dynamic model describing the predator-prey interactions from primary producers to top predators. Can include multiple stanzas representing different age classes.	The whole life cycle of the species is modelled (migration, food-dependent growth, reproduction and mortality) in space and time.	Trophic interactions are size-based and the dynamics of multiple focus fish species is modelled.
Currency	Nitrogen	Biomass	Individual biomass and numbers	Biomass
Spatial structure	2D, polygons	None	2D, regular grid. Vertical distribution of fish is handled through a matrix of accessibility.	None
Parameter-ization	Depends on configuration, but usually extensive parameterisation is required. Also needs physical drivers and initial system state.	Needs time series of abundance/biomass and/or fishing effort/mortality and ideally environmental drivers in Ecosim to fit the model to data.	Life history traits, predator to prey size ratios, fish spatial distribution data. Data needs for model calibration: biomass indices and commercial catch data	Life history traits, predator to prey size ratios
Age structure	Vertebrates: 10 age classes	"Multistanza" age classes for some species/functional groups	Fish age is tracked; discretization depends on time step.	No age structure, but each species/functional group is fully size structured
Functional response	Holling Type I,II,III, others	Function repsonse is an emergent property of Ecosim, based on the "Foraging Arena".	Functional response is not imposed. Predation emerges from individual interactions and maximum ingestion rate.	Holling Type II
Reproduction	Ricker, Beverton, fixed number per adult, others	Intrinsic population growth rate for non-stanza groups; recruitment emerges from fecundity and feeding behaviour for multi-stanza groups.	Based on fecundity and spawning stock biomass, recruitment emerges	Beverton-Holt stock-recruitment
Movement/ migration	Foraging and seasonal migration	No movement in the case studies here	Foraging and seasonal migration	No movement
Fishing	Spatial: Fleets' catch, effort, or fishing mortality rates	Fleets' catch, effort, or fishing mortality rates	Fishing mortality rates	Fishing effort, size selectivity

Appendix B. Frequencies of three ecologically-risky combined effects over variable spaces of fishing mortality and phytoplankton biomass

In order to better understand triggers causing the risky combined effects (i.e., negative synergism, positively dampened effects and negative antagonism), we further explored the occurrences of these risky combined effects over the multiplier spaces of fishing mortality and phytoplankton biomass under different fishing strategies. Across all ecosystems, the occurrences of ecologically risky effects over the variable spaces of fishing mortality and phytoplankton biomass are dependent on specific fishing strategies (i.e., an "all-trophic-level" (F_all) strategy representing broad-scale exploitation where the focus taxa are all taxa retained in commercial or subsistence fisheries; a "high-trophic-level" (F_htl) strategy focusing on predatory taxa that include large demersal and large pelagic taxa; and a "low-trophic-level" (F_ltl) strategy focusing on all forage taxa retained in commercial or subsistence fisheries). Under fishing strategies F_all and F_ltl, negative synergism and positively dampened effects mostly occur at low phytoplankton biomass and high fishing mortality for all three groups, i.e., ALL, HTL, and LTL (Figs. B1, B3). Under fishing strategy F_htl, the HTL group displays similar pattern as above. However, the ALL and LTL groups are more likely subject to negative synergism and positively dampened effects at low fishing mortality and low phytoplankton biomass (Fig. B2). This is likely due to the fact that lower fishing mortality on the HTL group results in higher HTL biomass and thus higher predation mortality on the LTL group. The occurrence of negative antagonism is rare under all three fishing strategies and for all trophic groups; no general pattern can be derived over the fishing mortality and phytoplankton biomass space.

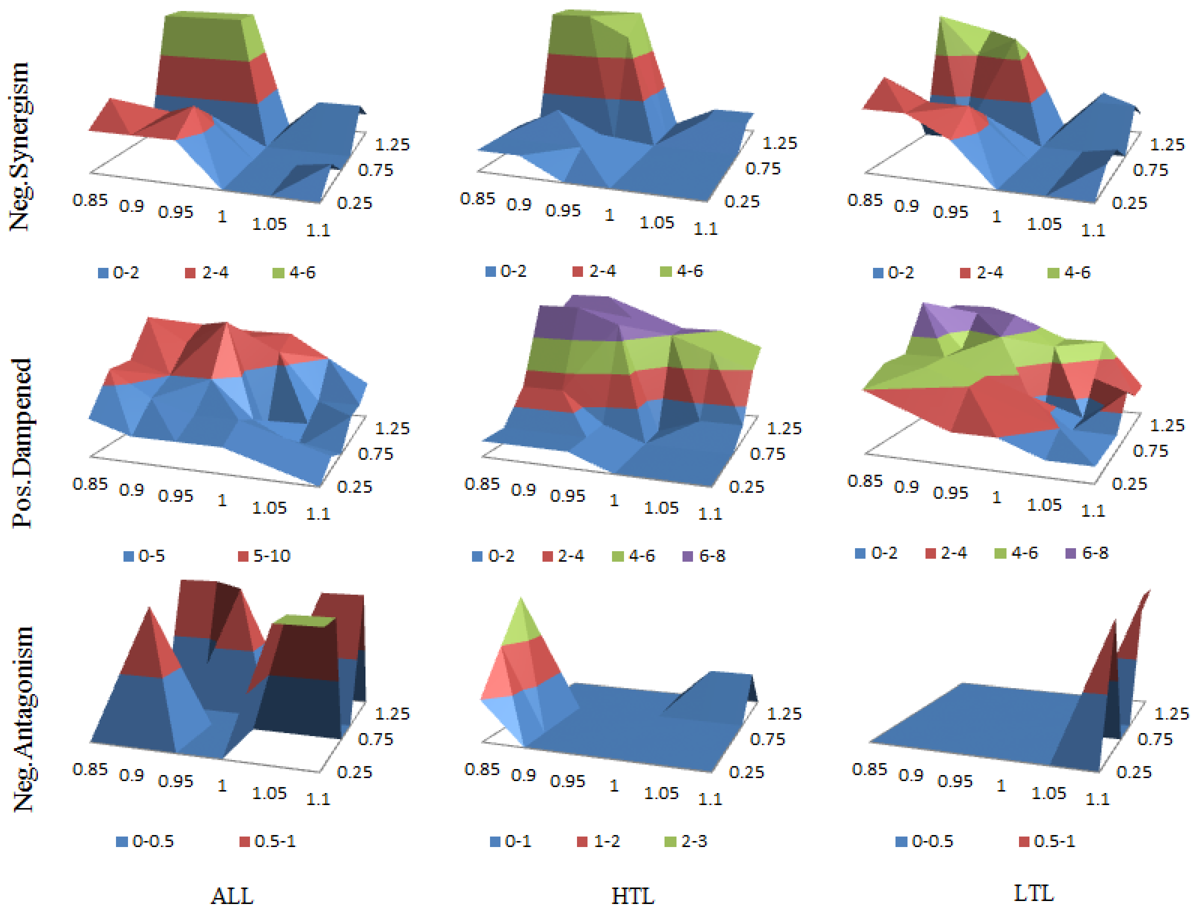

Figure B1. Frequencies of three ecologically-risky combined effects (negative antagonism, positive dampened, and negative synergism) over variable spaces of fishing and phytoplankton biomass change for all- (ALL), high- (HTL), and low-trophic-level (LTL) groups recorded over fishing strategy of F_all (focusing on all trophic levels) with x- and y-axes being the multipliers of phytoplankton biomass and fishing mortality.

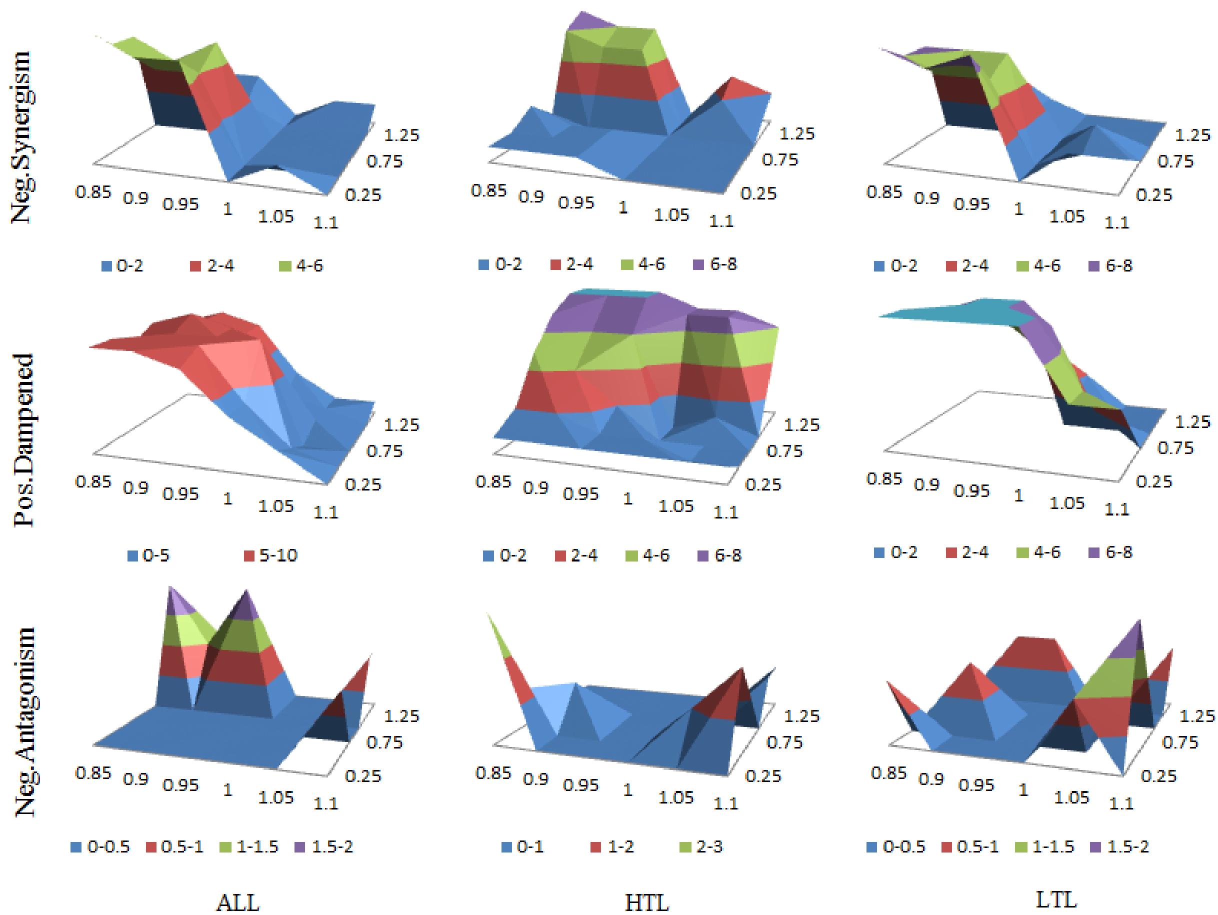

Figure B2. Frequencies of three ecologically-risky combined effects (negative antagonism, positive dampened, and negative synergism) over variable spaces of fishing and phytoplankton biomass change for all- (ALL), high- (HTL), and low-trophic-level (LTL) groups recorded over fishing strategy of F_htl (focusing on high trophic level) with x- and y-axes being the multipliers of phytoplankton biomass and fishing mortality.

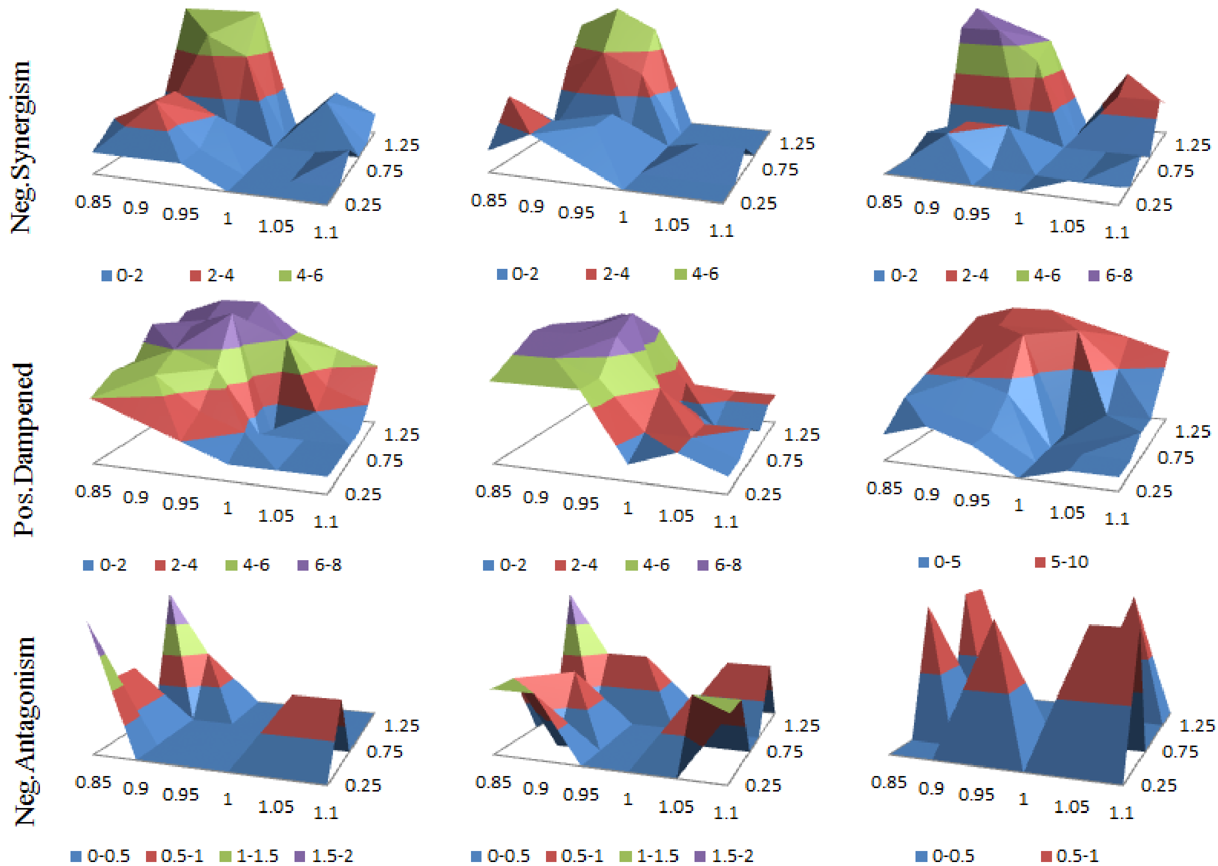

Figure B3. Frequencies of three ecologically-risky combined effects (negative antagonism, positive dampened, and negative synergism) over variable spaces of fishing and phytoplankton biomass change for all- (ALL), high- (HTL), and low-trophic-level (LTL) groups recorded over fishing strategy of F_ltl (focusing on low trophic level) with x- and y-axes being the multipliers of phytoplankton biomass and fishing mortality.

Appendix C. Linking obtained simulated patterns to features of ecosystem structure

Aside from the general patterns across the ecosystems related to the combined effects especially those that are ecologically risky, understanding how the characteristics of the different ecosystems play a role in the resultant combined effects is also beneficial. How the combined effects manifest depend not only on the ecosystem structure, but also on exploitation history, as well as model structure. We attempted to functionally link the obtained simulated patterns to features of ecosystem structure.

One ecological indicator that indicates ecosystem structure and has been explored in the IndiSeas project (Fu *et al.*, 2015) is the proportion of predatory fish (%Pred). This indicator reflects the relative abundance of predatory and non-predatory species and is relevant to fishing strategies (especially F_htl and F_ltl) and trophic groups (HTL and LTL). As fishing on HTL increases, we can expect that %Pred decreases. However, how %Pred changes with phytoplankton biomass is less intuitive and more ecosystem-specific. We specifically investigated how %Pred changed with the increasing phytoplankton biomass (multiplier γ increasing from 0.85 to 1.1) using linear regression under six scenarios of fishing strategies (F_htl with fishing multiplier $\lambda = 0.25$, 1, and 1.5; F_ltl with $\lambda = 0.25$, 1, and 1.5). A significantly positive or negative slope (confidence interval does not contain zero) indicates a significant increase or decrease of HTL with increasing phytoplankton biomass. The Southeastern Australian ecosystem is omitted because all species surveyed are predatory fish, thus the proportion of predatory fish remains at 1.

Table C1 provides the %Pred values for the six fishing strategies with phytoplankton biomass multiplier $\gamma = 1$. Comparisons of these %Pred values could infer the general levels of current fishing mortality on HTL and LTL. If %Pred at F_ltl with $\lambda = 1.5$ is greater than that at F_htl with $\lambda = 0.25$, current fishing mortality F_curr on LTL is low in the ecosystem which applies to the Black Sea, the North Sea, West Coast Canada, and Western Scotland; F_curr on LTL is high for the Southern Catalan Sea, the Southern Benguela, the West Florida Shelf, and the Western Scotian Shelf. If %Pred at F_htl with $\lambda = 1.5$ is greater than that at F_ltl with $\lambda = 0.25$, F_curr on HTL is high in the ecosystem which applies to the the North Sea, the Southern Catalan Sea, the Southern Benguela, the West Florida Shelf; F_curr on HTL is low in the Black Sea, West Coast Canada, and Western Scotland, and the Western Scotian Shelf.

In the Southern Benguela, where F_curr for both HTL and LTL is high, significant negative slopes of %Pred under all scenarios indicates that LTL increases with increasing phytoplankton biomass, and it is an LTL-dominant ecosystem with LTL being subjected to negative synergism and HLT to positive dampened effect under fish strategies F_all and F_htl. In contrast, the Southern Catalan Sea (F_curr for both HTL and LTL are also high) has significant positive slopes of %Pred except for F_hlt with $\lambda = 0.25$, indicating that increasing phytoplankton biomass cannot compensate the LTL group for the increasing predation mortality, and it is a HTL-dominant ecosystem with LTL prone to negative synergism under F_all. West Coast Canada ecosystem has low F_curr for both HTL and LTL groups. Under all F_htl scenarios, significant negative slope indicates that LTL group increases with increasing phytoplankton biomass, and the system is dominated by LTL species. Under the low F_curr on LTL, the system manifestes negative synergism for the LTL group and positively dampened effects for the HTL group under F_all and F_htl strategies. The Western Scotian Shelf ecosystem has significant positive slope of %Pred under all fishing strategy scenarios, indicating food has been a limiting factor for HTL group. For the LTL group, increasing phytoplankton biomass can not compensate the increasing of predation mortality. Under the high F_curr for the LTL group, HTL species dominate in the system resulting in negative synergism for the LTL group and positively dampened effects for the HTL group under fishing strategies F_htl and F_ltl.

Reference

Fu, C., Large, S., Knight, B., Richardson, A., Bundy, A., Reygondeau, G., Boldt, J et al. 2015. Relationships among fisheries exploitation, environmental conditions, and ecological indicators across a series of marine ecosystems. Journal of Marine Systems, 148: 101-111.

Shin, Y.-J., Bundy, A., Shannon, L.J., Blanchard, J.L., Chuenpagdee, R., Coll, M., Knight, B., Lynam, C., Piet, G., Richardson, A.J., and the IndiSeas Working Group, 2012. Global in scope and regionally rich: an IndiSeas workshop helps shape the future of marine ecosystem indicators. Rev. Fish Biol. Fish. 22: 835–845.

Table C1. Proportion of predatory fish (%Pred) in eight ecosystems obtained at phytoplankton biomass multiplier $\gamma = 1$ and under six scenarios of fishing strategies (F_htl with fishing multiplier $\lambda = 0.25$, 1, and 1.5; F_ltl with $\lambda = 0.25$, 1, and 1.5). Under these six fishing strategies, slope of %Pred was obtained through linear regression over all the γ values. The p values (p-val) and confidence intervals (lower bound CI.lb and upper bound CI.ub) provide with the statistical significance levels.

		Fishing Stategy F_htl						Fishing Stategy F_ltl				
	Ecosystem_Model	%Pred	Slope	p-val	CI.lb	CI.ub		%Pred	Slope	p-val	CI.lb	CI.ub
a.	Black Sea_EwE	0.158	-0.561	0.129	-1.376	0.255		0.170	-0.172	0.058	-0.354	0.009
λ = 0.25	North Sea_SizeS	0.597	0.108	0.721	-0.672	0.888		0.286	0.790	0.000	0.636	0.944
	Catalan Sea.S_EwE	0.276	0.173	0.114	-0.066	0.412		0.167	0.297	0.005	0.152	0.441
	Benguela.S_EwE	0.609	-0.226	0.000	-0.272	-0.181		0.185	-0.339	0.000	-0.405	-0.273
	Canada.W_OSMOSE	0.404	-0.065	0.007	-0.101	-0.030		0.550	-0.016	0.283	-0.051	0.020
	Scotland.W_EwE	0.469	0.042	0.000	0.041	0.042		0.485	0.012	0.000	0.010	0.013
	Florida Shelf.W_OSMOSE	0.269	-0.017	0.188	-0.047	0.013		0.030	0.000	0.998	-0.007	0.007
	Scotian Shelf.W_EwE	0.237	0.228	0.000	0.203	0.253		0.165	0.281	0.000	0.236	0.327
b.	Black Sea_EwE	0.170	-1.053	0.025	-1.889	-0.217		0.171	-0.063	0.170	-0.167	0.042
λ = 1	North Sea_SizeS	0.471	0.451	0.005	0.222	0.680		0.409	2.092	0.022	0.486	3.698
	Catalan Sea.S_EwE	0.205	0.637	0.001	0.435	0.838		0.176	0.289	0.000	0.217	0.362
	Benguela.S_EwE	0.321	-0.168	0.000	-0.183	-0.154		0.230	-0.513	0.000	-0.593	-0.433
	Canada.W_OSMOSE	0.252	-0.060	0.014	-0.100	-0.020		0.753	0.037	0.016	0.011	0.063
	Scotland.W_EwE	0.427	0.039	0.000	0.031	0.048		0.549	-0.143	0.000	-0.155	-0.130
	Florida Shelf.W_OSMOSE	0.150	0.018	0.244	-0.019	0.056		0.018	0.002	0.426	-0.004	0.008
	Scotian Shelf.W_EwE	0.164	0.227	0.000	0.193	0.261		0.142	0.169	0.001	0.114	0.224
c.	Black Sea_EwE	0.166	-0.214	0.409	-0.860	0.431		0.169	-0.106	0.028	-0.193	-0.018
λ = 1.5	North Sea_SizeS	0.368	0.364	0.000	0.321	0.407		0.853	0.214	0.001	0.151	0.276
	Catalan Sea.S_EwE	0.215	1.123	0.000	0.911	1.335		0.215	0.329	0.000	0.284	0.374
	Benguela.S_EwE	0.242	-0.340	0.000	-0.375	-0.304		0.289	-0.674	0.000	-0.768	-0.581
	Canada.W_OSMOSE	0.180	-0.420	0.018	-0.721	-0.119		0.833	0.030	0.001	0.020	0.040
	Scotland.W_EwE	0.396	0.055	0.000	0.040	0.070		0.612	-0.347	0.000	-0.387	-0.306
	Florida Shelf.W_OSMOSE	0.098	-0.001	0.906	-0.016	0.015		0.015	-0.002	0.242	-0.007	0.002
	Scotian Shelf.W_EwE	0.123	0.291	0.000	0.276	0.306		0.174	0.088	0.000	0.074	0.102