

Forage species

Who is key?

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Data availability statement

All datasets and R code necessary to replicate the analyses and findings reported here are publicly available in a Github repository at https://github.com/MontereyBayAquarium/SFW_foragefish. The repository also includes a step-by-step methods manual for identifying key forage species using the indices discussed in this report.



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Executive summary

Forage species are important not only due to their high economic value to fisheries but also because they represent important food sources to sustain higher trophic level species in an ecosystem. Some forage species are of particular importance to the continued functioning of an ecosystem or the survival of other species and are therefore considered key species. Depletion of their stocks is likely to have cascading effects throughout the ecosystem. Identifying “key” forage species is thus vital for establishing accurate and effective management and for the re-evaluation of existing harvest strategies. It remains unclear which forage species that are important to the United States and global seafood markets are “key” in their ecosystems and may warrant a more cautionary approach to harvest strategies. To identify their potential key role, this study computed three indices that consider trophic connections between species within an ecosystem food web using data from existing static ecosystem models. The connectance index and the Supportive Role to Fishery ecosystems (SURF) index were calculated from mass-balanced models. Additionally, the SURF index was calculated from energy-balanced models. Of the 105 forage species in the 30 ecosystems considered in this study, 101 (96.2%) were identified as key forage species by the connectance index, 35 (33.3%) by the mass-balanced SURF index, and 44 (41.9%) by the energy-balanced SURF index. The high number of key forage species identified by the connectance index can be attributed to its reliance on the presence of trophic connections rather than their presence and importance. The SURF indices identified key species based on the presence of connections as well as the strength of those connections. There was a large overlap between the results of the mass-balanced and energy-balanced SURF indices. Discrepancies between outcomes of the two SURF indices were noted only for species with above-average energy content. Their higher energy content led to higher energy SURF index values compared to their mass SURF index values, causing them to exceed the threshold and be classified as key based on energy. Results of the energy SURF index should in most cases override results for the other two indices because it incorporates information on the importance of trophic connections (rather than just presence) and considers increased importance of forage species with higher-than-average energy content values. Caveats and uncertainties related to the methods used to identify key forage species and their results are discussed near the end of the report. Despite data limitations, the SURF energy index provides an empirical, ecosystem-based approach to identifying key forage species, offering valuable insights into their role in ecosystem structure and function. This, in turn, supports informed decision-making and the re-evaluation of harvest strategies to mitigate potential ecological impacts from fishing.



Introduction and rationale

Forage species are small schooling fish or invertebrate species that serve as the primary prey for mammals, birds and other predators and, as such, channel a large amount of energy from the lowest trophic levels (plankton) to the upper trophic levels (predators) within an ecosystem (Cury et al., 2000; Smith et al., 2011; Pikitch et al., 2012a; Pikitch et al., 2012b; Engelhard et al., 2013). Forage species, therefore, play an important role in marine food webs. Furthermore, their predators include larger fish or invertebrates that are often important for commercial, recreational and cultural fisheries worldwide (Alder et al., 2008; Pikitch et al., 2012b) and that provide widespread social and cultural benefits (Thornton et al., 2010; Levin et al., 2016). As such, forage species are not only ecologically but also economically highly valuable. Species that generally qualify as forage species include anchovies, sardines, herring, squid, and krill (Siple et al., 2019).

Given their ecological and economic importance, appropriate stock management and reference points for forage species are crucial. However, the management of forage species is challenging. Forage fish exhibit r-selected life history traits, including high fecundity, short lifespan, early maturation and high natural mortality (Pikitch et al., 2012a). These traits, combined with high levels of predation by upper trophic level predators and their response to environmental conditions, cause large temporal oscillations in their biomass (Walters et al., 2016; McClatchie et al., 2017; Jacobsen and Essington, 2018). This makes their stock assessments difficult, resulting in high uncertainty regarding their reference points and concurrent harvest strategies. Additionally, large biomass fluctuations that are common for forage species make them particularly prone to stock collapses (McClatchie et al., 2017; Trochta et al., 2020), especially when harvest strategies are inappropriate due to overestimated biomass (Essington et al., 2015; Pinsky and Byler, 2015). To minimize the probability and severity of the collapse of forage species stocks, their management and reference points require tailoring based on a species' specific ecological role in the ecosystem, variable productivity and life history traits (Siple et al., 2019).

Forage species have been the focus of an increased effort to integrate an ecosystem approach into fisheries assessment and management (Garcia et al., 2003; Pikitch et al., 2004; Garcia and Cochrane, 2005; Smith et al., 2011; Pikitch et al., 2012a; Pikitch et al., 2012b; Kaplan et al., 2017). In contrast to traditional fisheries management, which considers species separately, ecosystem-based fisheries management considers the food web dynamics of the complete ecosystem and all its component species. For example, predation on a forage species by land-based predators can be spatially and temporarily localized yet can represent significant depletion of a forage species and thus must also be considered (Pikitch et al., 2012a; Plagányi and Butterworth, 2012; Watters et al., 2013). Some forage species play an even more vital role than others and are defined as "key" within an ecosystem. Typical levels of harvest of key species may be disruptive and result in significant ecosystem effects (Smith et al., 2011; Pikitch et al., 2012a; Pikitch et al., 2012b). These key species may warrant more conservative harvest levels than those usually applied to other fishery species. However, this is being debated in scientific circles with some authors finding that



the abundance of forage fish species has only minimal impact on predator productivity (Free et al., 2021). Nevertheless, the identification of key forage species is important to inform ecosystem-based management and concurrent decision-making regarding harvest strategies to prevent stock collapse and the cascading effects of harvest strategies and reference points for species that play a key role in marine ecosystems.

Several methods have been proposed to identify whether a forage species plays a key role in an ecosystem according to its trophic connections. Smith et al. (2011) suggested the relative connectance of a forage species in a food web, hereafter referred to as the connectance index. The connectance index represents the relative connectance of a species in a food web scaled to the complexity of the food web, i.e., the total number of linkages between species in the complete food web (Smith et al., 2011). This metric treats all trophic links the same, ignoring the importance of the trophic link between predators and prey. It was found to be sensitive to the aggregation level of species in a food web model (Plagányi and Essington, 2014). As an alternative metric to determine key forage species, Plagányi and Essington (2014) developed the Supportive Role to Fishery ecosystems (SURF) mass-scaled index, hereafter referred to as the mass SURF index. In addition to the number of predator species dependent on a forage species, the mass SURF index considers the level of dependency of a predator species on a forage species (Plagányi and Essington, 2014). Relying on empirical diet data, a high diet fraction by mass indicates a high or extreme dependence by a predator on a forage species (Plagányi and Essington, 2014). Furthermore, the weight of dependence increases non-linearly to distinguish between predators that are highly dependent on a forage species (diet fraction close to 1) and predators that rely minimally on a forage species (small diet fraction). In contrast to the connectance index, the mass SURF index is robust to predator species' aggregation. Finally, the SURF index was applied to determine key forage species in a food web using models based on energy rather than mass (e.g., Surma et al., 2022), hereafter referred to as the energy SURF index. This method considers that the importance of a forage species in an ecosystem can be inflated by their potentially elevated energy contents compared to other prey species in an ecosystem (Anthony et al., 2000; Spitz et al., 2010; Spitz and Jouma'a, 2013).

For many forage species, including those crucial to commercial fisheries, it remains uncertain whether they play a key role in their ecosystems, which could necessitate special attention in harvest strategies and reference points. Under the "Seafood Watch Wild Capture Fisheries Standard" (Monterey Bay Aquarium Seafood Watch, 2020), fisheries targeting key forage species are given special consideration to ensure that their harvest does not disrupt the ecosystem's structure, function or health. However, identifying which forage species warrant this extra consideration is challenging. This study employed the connectance and two SURF indices to assess whether forage species, including those that are important to U.S. and global seafood markets, should be classified as key, thereby requiring special management status and unique consideration under the Seafood Watch Fisheries Standard.



Methods

Data

This study considered ecosystems and their forage species that are of interest to Seafood Watch and for which data were available. The initial determination that a species is a forage species was based on the literature (see, for example, supplementary Table E-2 in Pikitch et al., 2012a; Hilborn et al., 2017; Siple et al., 2019). To calculate the three indices and determine whether a forage species was “key”, diet composition data, biomass data (either as existing estimations or as resolved by the model), and consumption per biomass data of food webs were used from existing static, mass-balanced ecosystem models built in Ecopath with Ecosim (EwE; Christensen and Walters, 2004). EwE is used to model the dynamics (e.g., spatial and temporal) of marine and aquatic ecosystems (Walters et al., 1997; Christensen et al., 2014) and support ecosystem-based-management (Coll et al., 2015; Heymans et al., 2016). The diet composition data used for EwE models are presented as a matrix including the proportion of each predator’s diet for each of its prey species by means of mass balance.

To ensure appropriate quality and resolution of data for this study, the models from which data were used met multiple criteria regarding their organization of functional species groups. First, to accurately represent a complete ecosystem’s food web, species from all trophic levels – whether as individual species or aggregated groups – needed to be included. Often, models disregard the upper trophic level of a food web, including piscivorous seabirds and marine mammals which regularly heavily rely on forage species as primary prey. Also, forage species needed to be included as separate species rather than as aggregated groups to allow calculation of indices for individual species and because aggregation is known to affect SURF indices (Plagányi and Essington, 2014) and likely also the connectance index. For all ecosystems, data were used from the most recent EwE model that fulfilled these requirements. The sources of the data used for each ecosystem considered by this study are shown in Table 1.



Table 1. Information on the ecosystem models used for this study, including their source, the functional group name and scientific name of the forage species of interest, and the total number (#) of functional groups in the original and aggregated ecosystem model.

Ecosystem model	Source	Functional group name	Scientific name	Comments	# functional groups original model	# functional groups aggregated model
Bay of Biscay	Corrales et al. (2022)	European sardine	<i>Sardina pilchardus</i>		53	34
		European anchovy	<i>Engraulis encrasicolus</i>			
		Mackerel	<i>Scomber colias, S. scombrus</i>	<i>Scomber</i> spp. combined		
California Current	Koehn et al. (2016)	Euphausiids	<i>Euphausiacea</i>		94	33
		Pacific sardine	<i>Sardinops sagax</i>			
		Northern anchovy	<i>Engraulis mordax</i>			
		Herring	<i>Clupea pallasii</i>			
		Pacific mackerel	<i>Scomber japonicus</i>			
		Market squid	<i>Doryteuthis opalescens</i>			
Chesapeake Bay – Gulf Stream	Dias et al. (2019)	U.S. menhaden	<i>Brevoortia tyrannus</i>		59	33
		Atlantic herring	<i>Clupea harengus</i>			
		Anadromous alosines	-			
		Anchovies	-			
		Mackerel	<i>Scomber scombrus</i>			
Chile – Central	Neira and Arancibia (2004)	Peruvian anchoveta	<i>Engraulis ringens</i>		23	22
		Common sardine	<i>Strangomera bentincki</i>			
		Pacific jack mackerel	<i>Trachurus symmetricus</i>			
Chile – North	Barros et al. (2014)	Peruvian anchoveta	<i>Engraulis ringens</i>		22	-
		Sardine	<i>Sardinops sagax</i>			
		Pacific jack mackerel	<i>Trachurus symmetricus</i>			
Ecuador	Neira et al. (2022)	Pacific anchoveta	<i>Cetengraulis mysticetus</i>		24	-
		Chub mackerel	<i>Scomber japonicus</i>			
		Red-eye round herring	<i>Etrumeus acuminatus</i>			

Ecosystem model	Source	Functional group name	Scientific name	Comments	# functional groups original model	# functional groups aggregated model
Gulf of Cadiz	Torres et al. (2013)	European sardine	<i>Sardina pilchardus</i>	Scomber spp. combined	44	27
		European anchovy	<i>Engraulis encrasicolus</i>			
		Mackerels	<i>Scomber colias</i> , <i>S. scombrus</i>			
Gulf of Maine	Dias et al. (2022)	Herring	<i>Clupea harengus</i>		46	30
		Alosines	<i>Alosa spp.</i>			
		Atlantic mackerel	<i>Scomber scombrus</i>			
		Butterfish	<i>Prepilus triacanthus</i>			
		Small pelagics	-			
Gulf of St Lawrence (northwest Atlantic, California)	Morissette et al. (2003)	Capelin	<i>Mallotus villosus</i>		32	23
		Sand lance	<i>Ammodytes americanus</i>			
India – west coast	Mohamed et al. (2008)	Cephalopods	-	Includes Indian squid <i>Uroteuthis duvaucelii</i>	25	24
		Mackerel	<i>Rastrelliger kanagurta</i>			
		Clupeids	-			
		Anchovies	-			
Irish Sea	Bentley et al. (2019)	Sandeels	-		41	26
		Atlantic herring	<i>Clupea harengus</i>			
		European sprat	<i>Sprattus sprattus</i>			
Japan – east coast	Watari et al. (2019)	Japanese sardine	<i>Sardinops melanostictus</i>		41	23
		Japanese anchovy	<i>Engraulis japonicus</i>			
		Chub mackerel	<i>Scomber japonicus</i>			
		Spotted (blue) mackerel	<i>Scomber australasicus</i>			
		Round herring	<i>Etrumeus teres</i>			
		Krill	<i>Euphausiidae</i>			

Ecosystem model	Source	Functional group name	Scientific name	Comments	# functional groups original model	# functional groups aggregated model
Lake Superior	Cox and Kitchell (2004)	Smelt Lake herring	<i>Osmerus mordax</i> <i>Coregonus artedii</i>		25	18
Mauritania	Guénette et al. (2014)	Mackerel Sardine Sardinelles	<i>Scomber japonicus</i> <i>Sardina pilchardus</i> -	Includes round sardinella (<i>Sardinella aurita</i>), Madeiran sardinella (<i>Sardinella maderensis</i>) and European anchovy (<i>Engraulis encrasicolus</i>)	52	29
Mediterranean Sea – Adriatic Sea	Coll et al. (2009)	European pilchard European anchovy Mackerel	<i>Sardina pilchardus</i> <i>Engraulis encrasicolus</i> <i>Scomber scombrus</i>		41	27
Mediterranean Sea – Aegean Sea	Keramidas et al. (2022)	European pilchard European anchovy Mackerel	<i>Sardina pilchardus</i> <i>Engraulis encrasicolus</i> <i>Scomber spp.</i>	<i>Scomber colias</i> , <i>Scomber scombrus</i>	45	36
Mediterranean Sea – Gulf of Alicante (closest to Alboran Sea)	García-Rodríguez et al. (2021)	European pilchard European anchovy Mackerels	<i>Sardina pilchardus</i> <i>Engraulis encrasicolus</i> <i>Scomber spp.</i>		46	34
Mediterranean Sea – Gulf of Lion	Seyer et al. (2023)	European pilchard European anchovy Sprat Mackerel	<i>Sardina pilchardus</i> <i>Engraulis encrasicolus</i> <i>Sprattus sprattus</i> <i>Scomber scombrus</i>		69	37
Mediterranean Sea – Gulf of Lion and Spain	Corrales et al. (2015)	European pilchard European anchovy Round sardinella Sprat Mackerel	<i>Sardina pilchardus</i> <i>Engraulis encrasicolus</i> <i>Sardinella aurita</i> <i>Sprattus sprattus</i> <i>Scomber scombrus</i>		55	36

Ecosystem model	Source	Functional group name	Scientific name	Comments	# functional groups original model	# functional groups aggregated model
Mediterranean Sea – Ionian Sea	Moutopoulos et al. (2013)	European pilchard	<i>Sardina pilchardus</i>		40	29
		European anchovy	<i>Engraulis encrasicolus</i>			
		Mackerel	<i>Scomber scombrus</i>			
Mediterranean Sea – Strait of Sicily	Agnetta et al. (2019)	European sardine	<i>Sardina pilchardus</i>		73	32
		European anchovy	<i>Engraulis encrasicolus</i>			
		Euphausiids	<i>Euphausiacea</i>			
Morocco – Atlantic coast	Stanford et al. (2001)	Sardines	-	Includes European sprat (<i>Sprattus sprattus</i>), European pilchard (<i>Sardina pilchardus</i>), round sardinella (<i>Sardinella aurita</i>), Madeiran sardinella (<i>Sardinella maderensis</i>) and European anchovy (<i>Engraulis encrasicolus</i>)	39	34
		Commercial medium pelagic fish	-	Includes various mackerel species, including <i>Scomber scombrus</i>		
Northern Humboldt Current	Chiaverano et al. (2018)	Sardine	<i>Sardinops sagax</i>		40	31
		Peruvian anchoveta	<i>Engraulis ringens</i>			
		Chilean jack mackerel	<i>Trachurus murphyi</i>			
		Chub mackerel	<i>Scomber japonicus</i>			
Northwest Atlantic – Canada	Tam and Bundy (2019)	Herring	<i>Clupea harengus</i>		49	25
		Sand lance	<i>Ammodytes dubius</i>			
		Capelin	<i>Mallotus villosus</i>			
		Other planktivorous fish incl. mackerel	-	Includes Atlantic mackerel (<i>Scomber scombrus</i>)		
Portugal	Veiga-Malta et al. (2019)	European sardine	<i>Sardina pilchardus</i>		34	24
		European anchovy	<i>Engraulis encrasicolus</i>			

Ecosystem model	Source	Functional group name	Scientific name	Comments	# functional groups original model	# functional groups aggregated model
		Mackerel	<i>Scomber scombrus</i>			
		Chub mackerel	<i>Scomber colias</i>			
Southeast Gulf of Alaska – 1900	Surma et al. (2019)	Forage fish	-		81	29
		Pacific saury	<i>Cololabis saira</i>			
		Eulachon	<i>Thaleichthys pacificus</i>			
		Pacific herring	<i>Clupea pallasii</i>			
Southeast Gulf of Alaska – 1950	Surma et al. (2019)	Forage fish	-		81	29
		Pacific saury	<i>Cololabis saira</i>			
		Eulachon	<i>Thaleichthys pacificus</i>			
		Pacific herring	<i>Clupea pallasii</i>			
SE Gulf of Alaska – current	Surma et al. (2019)	Forage fish	-		81	29
		Pacific saury	<i>Cololabis saira</i>			
		Eulachon	<i>Thaleichthys pacificus</i>			
		Pacific herring	<i>Clupea pallasii</i>			
South Korea	Kim et al. (2022)	Japanese anchovy	<i>Engraulis japonicus</i>		18	18
		Chub mackerel	<i>Scomber japonicus</i>			



Species group aggregation

All ecosystem models used in this study had unique ways of organizing functional species groups. To standardize and make the models comparable, this study aggregated species/groups from lower trophic levels (e.g., microzooplankton, mesozooplankton, macrozooplankton) and higher trophic levels (e.g., seabirds, cetaceans, pinnipeds, apex predatory fish). Forage species were not aggregated, as this could impact the SURF indices (Plagányi and Essington, 2014) and potentially the connectance index as well. To further ensure comparability, this study also excluded different age/size classes within species (Plagányi and Essington, 2014).

The proportion of each prey type in the diets of aggregated predator groups was calculated following Plagányi and Essington (2014). First, consumption in metric tonnes per year for each original functional group was determined by multiplying the consumption per biomass per year (Q/B) by biomass (in metric tonnes per km²). This total consumption by each predator was then used to calculate the consumption of each prey species. These values were summed across the aggregated predator species/groups and divided by the total consumption of the aggregated predator groups to determine diet proportions. Finally, the diet proportions were summed for the aggregated prey species/groups.

Calculating indices

The recalculated diet composition matrix including the aggregated species/groups was then used to calculate the connectance index, mass SURF index and energy SURF index. The functional groups “discards” and “import”, regularly included in the food webs of EwE models, were not included to calculate the total number of trophic linkages within the ecosystem as these came from outside the ecosystem.

THE CONNECTANCE INDEX

The connectance index represented the connectance of a species/group in a food web relative to the complexity of the food web and was calculated as the number of links involving a species/group as both prey and predator divided by the total number of links in a food web (Smith et al., 2011). Smith et al. (2011) suggested that a connectance above 0.04 identifies key species/groups.

THE MASS SUPPORTIVE ROLE TO FISHERY ECOSYSTEMS INDEX

The mass Supportive Role to Fishery ecosystems (SURF) index for prey species/group i with S predators, developed by Plagányi and Essington (2014), was calculated as:

$$SURF_i = \frac{\sum_{j=1}^S p_{ij}^2}{L}$$

Where i is the prey species/group, j is the predator of the prey species, S is the total number of predators that a prey species/group is predated by, p_{ij} is the diet fraction for which predator j relies on prey species/group i and L is the total number of linkages (with $p_{ij} > 0$) in the ecosystem food web.

The mass SURF index is a similar calculation to the connectance index, except that the connectance calculation constrains p_{ij} to be either 0 (the prey species is not consumed by a predator) or 1 (the



prey species is consumed by a predator), while the SURF index incorporates the importance of a forage species to a predator by including a proportion of the predator's diet by mass represented by a forage species as a value between 0 and 1. Plagányi and Essington (2014) determined that prey species with a SURF above 0.001 are key in the ecosystem.

THE ENERGY SURF INDEX

The calculation of the energy SURF index was similar to that of the mass SURF index, except that it considered predators' diets according to energy rather than mass. The actual consumption of each predator species/group j on a prey species/group i was multiplied by the energy contents of prey species/group i . The same threshold to define key species for the mass SURF index (0.001) was used for the energy SURF index, as suggested by Surma et al. (2022). As such, a species with energy contents higher than the average energy contents of species in the ecosystem will have an energy SURF index higher than its mass SURF index.

Ideally, a published energy content value (kJ per gram of wet weight) of a species in the relevant ecosystems was applied. However, if such information was not available, an energy content value for the same species in a different ecosystem was used. If those data were not available, the energy content value of a comparable species, family or order was used. For prey groups that included multiple species, an average energy content value of the species (or comparable species, family or order) was applied. The constant energy content values of adult specimens of a species were used.

If a forage species of interest in the disaggregated model was sub-classed by age it was defined as key if one of the age classes was determined key by the index.



Results

Of the 105 forage species in the 30 ecosystems considered in this study, 101 (96.2%) were identified as key forage species by the connectance index, 35 (33.3%) by the mass-balanced SURF index and 44 (41.9%) by the energy-balanced SURF index (Table 2). The differences in results among the indices indicate that the identification of key species depends on 1) whether the level of predator dependence on prey is considered (connectance index vs. mass/energy SURF index) and 2) whether this dependence is quantified by mass (mass SURF index) or energy (energy SURF index; Table 2).

The relatively high percentage of species identified as key by the connectance index compared to the SURF indices (Table 2) can be attributed to the connectance index's reliance on the number of trophic connections rather than their importance. Additionally, unlike the SURF indices, the connectance index values might be higher due to the aggregation of predator species, as demonstrated by Plagányi and Essington (2014). This aggregation could cause the connectance index value for forage species to surpass the threshold, leading to their identification as key species.

There is a significant overlap between the results of the two SURF indices (Table 2). However, some forage species were identified as key by the energy SURF index but not by the mass SURF index (Table 2). This discrepancy occurred for species with above-average energy content that had mass SURF index values slightly below the threshold and were thus not classified as key based on mass. Their higher energy content led to higher energy SURF index values compared to their mass SURF index values, causing them to exceed the threshold and be classified as key using the energy SURF index.

For results based on the original food web models (without group aggregations), see Table A1 in the Appendix.

Table 2. The three indices calculated for the forage species of interest based on the aggregated models. Values highlighted in color indicate species identified as key, with the color gradient showing the relative importance of key species within ecosystems per index (yellow indicating the least important and dark orange most importance key species).

Ecosystem model	Model group name	Scientific name	Index		
			Connectance	Mass SURF	Energy SURF
Bay of Biscay	European sardine	<i>Sardina pilchardus</i>	0.0488	0.0006	0.0013
	European anchovy	<i>Engraulis encrasicolus</i>	0.0488	0.0001	0.0001
	Mackerel	<i>Scomber colias</i> , <i>S. scombrus</i>	0.0705	0.0001	0.0002
California Current	Euphausiids	<i>Euphausiacea</i>	0.0806	0.0110	0.0152
	Pacific sardine	<i>Sardinops sagax</i>	0.0448	0.0000	0.0001
	Northern anchovy	<i>Engraulis mordax</i>	0.0567	0.0002	0.0005
	Herring	<i>Clupea pallasii</i>	0.0478	0.0001	0.0001
	Pacific mackerel	<i>Scomber japonicus</i>	0.0567	0.0000	0.0000
	Market squid	<i>Doryteuthis opalescens</i>	0.0537	0.0001	0.0001
Chesapeake Bay – Gulf Stream	U.S. menhaden	<i>Brevoortia tyrannus</i>	0.0391	0.0003	0.0002
	Atlantic herring	<i>Clupea harengus</i>	0.0615	0.0006	0.0022
	Anadromous alosines	-	0.0642	0.0000	0.0000
	Anchovies	-	0.0503	0.0014	0.0012
	Mackerel	<i>Scomber scombrus</i>	0.0447	0.0000	0.0000
Chile – central	Peruvian anchoveta	<i>Engraulis ringens</i>	0.1231	0.0022	0.0020
	Common sardine	<i>Strangomera bentincki</i>	0.1231	0.0032	0.0061
	Pacific jack mackerel	<i>Trachurus symmetricus</i>	0.1077	0.0042	0.0062
Chile – north	Peruvian anchoveta	<i>Engraulis ringens</i>	0.1705	0.0081	0.0066
	Sardine	<i>Sardinops sagax</i>	0.1250	0.0014	0.0028
	Pacific jack mackerel	<i>Trachurus symmetricus</i>	0.1250	0.0005	0.0005
Ecuador	Pacific anchoveta	<i>Cetengraulis mysticetus</i>	0.0538	0.0000	0.0000
	Chub mackerel	<i>Scomber japonicus</i>	0.1290	0.0011	0.0026
	Red-eye round herring	<i>Etrumeus acuminatus</i>	0.0968	0.0004	0.0006
Gulf of Cadiz	European sardine	<i>Sardina pilchardus</i>	0.0432	0.0008	0.0011
	European anchovy	<i>Engraulis encrasicolus</i>	0.0486	0.0005	0.0006
	Mackerels	<i>Scomber colias</i> , <i>S. scombrus</i>	0.0649	0.0003	0.0006
Gulf of Maine	Herring	<i>Clupea harengus</i>	0.0734	0.0014	0.0026
	Alosines	<i>Alosa spp.</i>	0.0455	0.0000	0.0000
	Atlantic mackerel	<i>Scomber scombrus</i>	0.0699	0.0000	0.0000
	Butterfish	<i>Prepilus triacanthus</i>	0.0490	0.0000	0.0000
	Small pelagics	-	0.0699	0.0021	0.0021
Gulf of St Lawrence (northwest Atlantic, California)	Capelin	<i>Mallotus villosus</i>	0.0932	0.0038	0.0081
	Sand lance	<i>Ammodytes americanus</i>	0.0745	0.0017	0.0010

Ecosystem model	Model group name	Scientific name	Index		
			Connectance	Mass SURF	Energy SURF
India – west coast	Cephalopods	(incl. Indian squid <i>Uroteuthis duvaucelii</i>)	0.0930	0.0002	0.0001
	Mackerel	<i>Rastrelliger kanagurta</i>	0.0291	0.0001	0.0001
	Clupeids	-	0.0872	0.0004	0.0007
	Anchovies	-	0.0988	0.0016	0.0020
Irish Sea	Sandeels	-	0.0691	0.0022	0.0019
	Atlantic herring	<i>Clupea harengus</i>	0.0904	0.0003	0.0010
	European sprat	<i>Sprattus sprattus</i>	0.0691	0.0005	0.0008
Japan – east coast	Japanese sardine	<i>Sardinops melanostictus</i>	0.0863	0.0001	0.0003
	Japanese anchovy	<i>Engraulis japonicus</i>	0.0791	0.0012	0.0034
	Chub mackerel	<i>Scomber japonicus</i>	0.0791	0.0001	0.0003
	Spotted (blue) mackerel	<i>Scomber australasicus</i>	0.0791	0.0001	0.0002
	Round herring	<i>Etrumeus teres</i>	0.0432	0.0000	0.0000
	Krill	<i>Euphausiidae</i>	0.1367	0.0068	0.0116
Lake Superior	Smelt	<i>Osmerus mordax</i>	0.1667	0.0023	0.0018
	Lake herring	<i>Coregonus artedi</i>	0.1667	0.0030	0.0030
Mauritania	Mackerel	<i>Scomber japonicus</i>	0.0744	0.0000	0.0000
	European sardine	<i>Sardina pilchardus</i>	0.0496	0.0002	0.0003
	Sardinellas	-	0.0579	0.0014	0.0019
Mediterranean Sea – Adriatic Sea	European pilchard	<i>Sardina pilchardus</i>	0.1154	0.0041	0.0048
	European anchovy	<i>Engraulis encrasicolus</i>	0.0865	0.0017	0.0018
	Mackerel	<i>Scomber scombrus</i>	0.0962	0.0007	0.0009
Mediterranean Sea – Aegean Sea	European pilchard	<i>Sardina pilchardus</i>	0.0591	0.0014	0.0027
	European anchovy	<i>Engraulis encrasicolus</i>	0.0549	0.0012	0.0017
	Mackerel	<i>Scomber spp.</i>	0.0422	0.0000	0.0000
Mediterranean Sea – Gulf of Alicante (closest to Alboran Sea)	European pilchard	<i>Sardina pilchardus</i>	0.0535	0.0019	0.0036
	European anchovy	<i>Engraulis encrasicolus</i>	0.0502	0.0001	0.0001
	Mackerels	<i>Scomber spp.</i>	0.0502	0.0001	0.0002
Mediterranean Sea – Gulf of Lion	European pilchard	<i>Sardina pilchardus</i>	0.0560	0.0008	0.0011
	European anchovy	<i>Engraulis encrasicolus</i>	0.0560	0.0007	0.0007
	Sprat	<i>Sprattus sprattus</i>	0.0448	0.0009	0.0015
	Mackerel	<i>Scomber scombrus</i>	0.0336	0.0000	0.0000
Mediterranean Sea – Gulf of Lion & Spain	European pilchard	<i>Sardina pilchardus</i>	0.0695	0.0012	0.0029
	European anchovy	<i>Engraulis encrasicolus</i>	0.0588	0.0004	0.0007
	Round sardinella	<i>Sardinella aurita</i>	0.0428	0.0000	0.0000
	Sprat	<i>Sprattus sprattus</i>	0.0107	0.0000	0.0000
	Mackerel	<i>Scomber scombrus</i>	0.0535	0.0001	0.0001

Ecosystem model	Model group name	Scientific name	Index		
			Connectance	Mass SURF	Energy SURF
Mediterranean Sea – Ionian Sea	European pilchard	<i>Sardina pilchardus</i>	0.0708	0.0006	0.0010
	European anchovy	<i>Engraulis encrasicolus</i>	0.0708	0.0019	0.0026
	Mackerel	<i>Scomber scombrus</i>	0.0583	0.0000	0.0000
Mediterranean Sea – Strait of Sicily	European sardine	<i>Sardina pilchardus</i>	0.0517	0.0001	0.0002
	European anchovy	<i>Engraulis encrasicolus</i>	0.0627	0.0004	0.0006
	Euphausiids	<i>Euphausiacea</i>	0.0627	0.0002	0.0003
Morocco – Atlantic coast	Sardines	-	0.0693	0.0007	0.0012
	Commercial medium pelagic fish	-	0.0730	0.0005	0.0008
Northern Humboldt Current	Sardine	<i>Sardinops sagax</i>	0.0714	0.0004	0.0007
	Peruvian anchoveta	<i>Engraulis ringens</i>	0.1104	0.0095	0.0091
	Chilean jack mackerel	<i>Trachurus murphyi</i>	0.0974	0.0003	0.0003
	Chub mackerel	<i>Scomber japonicus</i>	0.0909	0.0003	0.0008
Northwest Atlantic – Canada	Herring	<i>Clupea harengus</i>	0.0552	0.0001	0.0003
	Sand lance	<i>Ammodytes dubius</i>	0.0859	0.0005	0.0004
	Capelin	<i>Mallotus villosus</i>	0.0798	0.0032	0.0066
	Other planktivorous fish incl. mackerel	-	0.0982	0.0015	0.0023
Portugal	European sardine	<i>Sardina pilchardus</i>	0.0859	0.0025	0.0044
	European anchovy	<i>Engraulis encrasicolus</i>	0.0675	0.0000	0.0000
	Mackerel	<i>Scomber scombrus</i>	0.0613	0.0004	0.0005
	Chub mackerel	<i>Scomber colias</i>	0.1043	0.0004	0.0006
Southeast Gulf of Alaska – 1900	Forage fish	-	0.0909	0.0017	0.0022
	Pacific saury	<i>Cololabis saira</i>	0.0670	0.0002	0.0005
	Eulachon	<i>Thaleichthys pacificus</i>	0.0718	0.0001	0.0002
	Pacific herring	<i>Clupea pallasii</i>	0.0526	0.0001	0.0001
Southeast Gulf of Alaska – 1950	Forage fish	-	0.0909	0.0020	0.0022
	Pacific saury	<i>Cololabis saira</i>	0.0670	0.0000	0.0000
	Eulachon	<i>Thaleichthys pacificus</i>	0.0718	0.0000	0.0001
	Pacific herring	<i>Clupea pallasii</i>	0.0526	0.0006	0.0013
Southeast Gulf of Alaska – current	Forage fish	-	0.0909	0.0023	0.0025
	Pacific saury	<i>Cololabis saira</i>	0.0670	0.0000	0.0000
	Eulachon	<i>Thaleichthys pacificus</i>	0.0718	0.0000	0.0001
	Pacific herring	<i>Clupea pallasii</i>	0.0526	0.0003	0.0008
South Korea	Japanese anchovy	<i>Engraulis japonicus</i>	0.1066	0.0013	0.0029
	Chub mackerel	<i>Scomber japonicus</i>	0.0820	0.0030	0.0061



Discussion

Parameter uncertainties

The results of the indices, and consequently the identification of key forage species, are inevitably subject to uncertainty due to variability in the parameter values used for their calculation. Several key aspects contribute to this uncertainty. First, the diet composition data (diet proportions) from the food web models used to calculate the two SURF indices generally include large confidence intervals due to logistical restraints in data collection, observation errors and inconsistencies across different sources. Variations in spatial and temporal scales of data collection further complicate the creation of a representative diet matrix, which is essential for calculating the indices. Similarly, biomass data, used to calculate the diet matrix adjusted for group aggregation, also include large confidence intervals. Additionally, uncertainty in energy density data, also stemming from logistical constraints in data collection, directly impacts the SURF energy index. Finally, forage species were identified as key based on thresholds previously established for each index, yet which remain indeterminate, introducing further uncertainty into the identification process. Some species may score just below the threshold and therefore not be classified as key. Given the variability in diet data and the uncertainties associated with the indices, this should be considered when interpreting the results.

Other study limitations

Other study limitations that could influence this study's outcomes include:

- **Model structural complexity:** The food web models used in the study, while valuable for understanding marine ecosystems, simplify the complex dynamics between species within these environments in regards of number of functional groups, temporal scale and spatial dynamics. Although aggregating forage species significantly increases the SURF index (Plagányi and Essington, 2014), this approach might still be relevant depending on the objectives for determining the keyness of forage species (e.g., Koehn et al., 2016). Aggregation may be appropriate if two forage species within an ecosystem co-occur in predator diets, predators switch between these species when one is scarce, the species are of similar size, have overlapping spatial distributions, and are simultaneously targeted by the same fisheries (Koehn et al., 2016). In other words, when several forage species are considered "functionally equivalent" (Koehn et al., 2016), it may be useful to evaluate them as a group to determine their key status, even if individually they would not be classified as key. Also, the aggregation of other groups may influence the index of the species of interest. Further research is required to create a better understanding of the effect of aggregation and the aggregation of species (other than forage species) in relation to



different trophic levels on the calculated indices of species. This remains particularly unclear for species with trophic levels lower than forage species.

- **Variability in ecosystem conditions:** In addition to fishing pressures, the abundance and availability of forage species within an ecosystem can vary spatially and temporally (annually, seasonally and decadal) due to natural and ecological fluctuations, affecting predator diet composition. However, diet studies are often conducted over just one year or season (usually summer) in accessible waters. When forage species are scarce during such studies, their contribution to the ecosystem is likely underestimated, leading to an underestimation of their indices and failing to identify them as key species. Conversely, long-lived predators may track this variability and rely on the periodic abundance of certain forage species for survival and reproduction. To avoid false negatives in identifying key species, index calculations should ideally be based on data collected during periods of typical environmental conditions and high forage species abundance (Plagányi and Essington, 2014). Future research should focus on improving data collection and analytical tools to identify key species that may become crucial when abundant but are not recognized as key by current indices.
- **Time window of data collection:** The indices in this study are based on data (diet composition, biomass and consumption per biomass) from existing ecosystem food web models, which may cover varying time periods. Some of these models used data that were collected over a long period. For example, the California Current Ecosystem model by Koehn et al. (2016) used whale diet data from the 1920s due to a lack of more recent data. Such models aim to represent the general functioning of the ecosystem. In contrast, other models, like those by Torres et al. (2013), provide a snapshot of the ecosystem using data collected over shorter periods.
- **Definition of a “key” forage species:** The designation of a forage species as “key” by the three indices is based solely on its trophic interactions as represented in the selected food web model. However, a species may be considered key for reasons not captured by these indices, and vice versa. For instance, predator-prey preferences could make forage species that are actively selected by predators more important than the current indices suggest.



Concluding remarks

Results from the energy SURF index should generally take precedence over those from the other two indices. This is because the connectance index accounts only for the presence of connections within a food web, without considering their importance. In other words, it treats all trophic connections equally and does not differentiate between minor and major contributions of prey to predators' diets, which undermines the goal of identifying key forage species. On the other hand, while forage species are defined by their role in transferring energy from lower trophic level species to higher trophic level species, the mass SURF index is based on mass rather than energy. This means the mass SURF index might miss forage species that are key due to their high energy content, which is essential for channeling energy through the food web. However, if energy content data for species are unavailable or include high levels of uncertainty, the mass SURF index may be preferred for more reliable calculations, despite being based on mass rather than energy.

To conclude, this study demonstrates a straightforward and empirical method for identifying key forage species for an ecosystem-based approach to fisheries management. The energy SURF index offers valuable insights into which forage species are crucial as prey for predators and, therefore, vital for maintaining ecosystem structure and function. This study identified which forage species, important to the U.S. and global seafood markets, are key to the functioning of their ecosystems and that require a special management status. These key forage species may necessitate more conservative harvest strategies and reference points to avoid stock collapse and prevent cascading effects on ecosystems. The identification of these key forage species enables more informed decision-making regarding harvest levels and management approaches. It also facilitates the re-evaluation of existing harvest strategies to mitigate significant ecological impacts of fishing. Ultimately, this approach can be used to enhance the sustainability of fisheries and conservation strategies, and to ensure the protection of essential ecological functions and the overall health of ecosystems.




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Appendix

Appendix 1. Results for disaggregated ecosystem models

Table A1. The three indices calculated for forage species of interest based on the original disaggregated ecosystem models. Index values are color-coded on a gradient from yellow (indicating values just above the threshold) to dark orange (indicating values significantly above the threshold). For forage species that were categorized in different classes (e.g., age or stock) in the disaggregated models, the highest index value is displayed.

Ecosystem model	Model group name	Scientific name	Index		
			Connectance	Mass SURF	Energy SURF
Bay of Biscay	European sardine	<i>Sardina pilchardus</i>	0.0392	0.0005	0.0011
	European anchovy	<i>Engraulis encrasicolus</i>	0.0378	0.0001	0.0000
	Mackerel	<i>Scomber colias, S. scombrus</i>	0.0459	0.0002	0.0003
California Current	Euphausiids	<i>Euphausiacea</i>	0.0501	0.0085	0.0106
	Pacific sardine	<i>Sardinops sagax</i>	0.0246	0.0001	0.0003
	Northern anchovy	<i>Engraulis mordax</i>	0.0399	0.0006	0.0012
	Herring	<i>Clupea pallasii</i>	0.0374	0.0002	0.0004
	Pacific mackerel	<i>Scomber japonicus</i>	0.0204	0.0000	0.0000
	Market squid	<i>Doryteuthis opalescens</i>	0.0340	0.0003	0.0008
Chesapeake Bay – Gulf Stream	U.S. menhaden	<i>Brevoortia tyrannus</i>	0.0289	0.0001	0.0001
	Atlantic herring	<i>Clupea harengus</i>	0.0418	0.0007	0.0021
	Anadromous alosines	-	0.0407	0.0000	0.0000
	Anchovies	-	0.0386	0.0018	0.0016
	Mackerel	<i>Scomber scombrus</i>	0.0311	0.0000	0.0000
Chile – central	Peruvian anchoveta	<i>Engraulis ringens</i>	0.1200	0.0026	0.0025
	Common sardine	<i>Strangomera bentincki</i>	0.1200	0.0034	0.0068
	Pacific jack mackerel	<i>Trachurus symmetricus</i>	0.0933	0.0037	0.0054
Chile – north	Peruvian anchoveta	<i>Engraulis ringens</i>	0.1705	0.0081	0.0066
	Sardine	<i>Sardinops sagax</i>	0.1250	0.0014	0.0028
	Pacific jack mackerel	<i>Trachurus symmetricus</i>	0.1250	0.0005	0.0005
Ecuador	Pacific anchoveta	<i>Cetengraulis mysticetus</i>	0.0538	0.0000	0.0000
	Chub mackerel	<i>Scomber japonicus</i>	0.1290	0.0011	0.0026
	Red-eye round herring	<i>Etrumeus acuminatus</i>	0.0968	0.0004	0.0006
Gulf of Cadiz	European sardine	<i>Sardina pilchardus</i>	0.0270	0.0006	0.0008
	European anchovy	<i>Engraulis encrasicolus</i>	0.0393	0.0007	0.0009
	Mackerels	<i>Scomber colias, S. scombrus</i>	0.0393	0.0003	0.0006

Ecosystem model	Model group name	Scientific name	Index		
			Connectance	Mass SURF	Energy SURF
Gulf of Maine	Herring	<i>Clupea harengus</i>	0.0587	0.0017	0.0038
	Alosines	<i>Alosa spp.</i>	0.0419	0.0000	0.0000
	Atlantic mackerel	<i>Scomber scombrus</i>	0.0487	0.0001	0.0002
	Butterfish	<i>Prepilus triacanthus</i>	0.0386	0.0000	0.0000
	Small pelagics	-	0.0554	0.0018	0.0023
Gulf of St Lawrence (northwest Atlantic, California)	Capelin	<i>Mallotus villosus</i>	0.0839	0.0053	0.0091
	Sand lance	<i>Ammodytes americanus</i>	0.0594	0.0011	0.0007
India – west coast	Cephalopods	(incl. Indian squid <i>Uroteuthis duvaucelii</i>)	0.0930	0.0002	0.0001
	Mackerel	<i>Rastrelliger kanagurta</i>	0.0291	0.0001	0.0001
	Clupeids	-	0.0872	0.0004	0.0007
	Anchovies	-	0.0988	0.0016	0.0020
Irish Sea	Sandeels	-	0.0535	0.0012	0.0011
	Atlantic herring	<i>Clupea harengus</i>	0.0558	0.0003	0.0009
	European sprat	<i>Sprattus sprattus</i>	0.0581	0.0008	0.0012
Japan – east coast	Japanese sardine	<i>Sardinops melanostictus</i>	0.0766	0.0001	0.0004
	Japanese anchovy	<i>Engraulis japonicus</i>	0.0657	0.0007	0.0019
	Chub mackerel	<i>Scomber japonicus</i>	0.0620	0.0001	0.0003
	Spotted (blue) mackerel	<i>Scomber australasicus</i>	0.0620	0.0001	0.0002
	Round herring	<i>Etrumeus teres</i>	0.0328	0.0000	0.0000
	Krill	<i>Euphausiidae</i>	0.0766	0.0024	0.0044
Lake Superior	Smelt	<i>Osmerus mordax</i>	0.1130	0.0012	0.0009
	Lake herring	<i>Coregonus artedii</i>	0.1304	0.0032	0.0033
Mauritania	Mackerel	<i>Scomber japonicus</i>	0.0412	0.0000	0.0000
	European Sardine	<i>Sardina pilchardus</i>	0.0240	0.0001	0.0001
	Sardinelles	-	0.0412	0.0007	0.0009
Mediterranean Sea – Adriatic Sea	European pilchard	<i>Sardina pilchardus</i>	0.0821	0.0031	0.0035
	European anchovy	<i>Engraulis encrasicolus</i>	0.0580	0.0031	0.0030
	Mackerel	<i>Scomber scombrus</i>	0.0580	0.0004	0.0005
Mediterranean Sea – Aegean Sea	European pilchard	<i>Sardina pilchardus</i>	0.0523	0.0012	0.0023
	European anchovy	<i>Engraulis encrasicolus</i>	0.0458	0.0009	0.0013
	Mackerel	<i>Scomber spp.</i>	0.0327	0.0000	0.0000
Mediterranean Sea – Gulf of Alicante (closest to Alboran Sea)	European pilchard	<i>Sardina pilchardus</i>	0.0434	0.0016	0.0027
	European anchovy	<i>Engraulis encrasicolus</i>	0.0414	0.0001	0.0001
	Mackerels	<i>Scomber spp.</i>	0.0335	0.0001	0.0001

Ecosystem model	Model group name	Scientific name	Index		
			Connectance	Mass SURF	Energy SURF
Mediterranean Sea – Gulf of Lion	European pilchard	<i>Sardina pilchardus</i>	0.0307	0.0005	0.0006
	European anchovy	<i>Engraulis encrasicolus</i>	0.0293	0.0013	0.0014
	Sprat	<i>Sprattus sprattus</i>	0.0264	0.0005	0.0008
	Mackerel	<i>Scomber scombrus</i>	0.0190	0.0003	0.0004
Mediterranean Sea – Gulf of Lion & Spain	European pilchard	<i>Sardina pilchardus</i>	0.0453	0.0005	0.0010
	European anchovy	<i>Engraulis encrasicolus</i>	0.0378	0.0002	0.0004
	Round sardinella	<i>Sardinella aurita</i>	0.0227	0.0000	0.0000
	Sprat	<i>Sprattus sprattus</i>	0.0050	0.0000	0.0000
	Mackerel	<i>Scomber scombrus</i>	0.0277	0.0000	0.0001
Mediterranean Sea – Ionian Sea	European pilchard	<i>Sardina pilchardus</i>	0.0728	0.0015	0.0020
	European anchovy	<i>Engraulis encrasicolus</i>	0.0700	0.0027	0.0032
	Mackerel	<i>Scomber scombrus</i>	0.0448	0.0000	0.0000
Mediterranean Sea – Strait of Sicily	European sardine	<i>Sardina pilchardus</i>	0.0234	0.0001	0.0001
	European anchovy	<i>Engraulis encrasicolus</i>	0.0246	0.0003	0.0003
	Euphausiids	<i>Euphausiacea</i>	0.0386	0.0009	0.0014
Morocco – Atlantic coast	Sardines	-	0.0630	0.0006	0.0011
	Commercial medium pelagic fish	-	0.0630	0.0004	0.0007
Northern Humboldt Current	Sardine	<i>Sardinops sagax</i>	0.0556	0.0003	0.0005
	Peruvian anchoveta	<i>Engraulis ringens</i>	0.1065	0.0087	0.0087
	Chilean jack mackerel	<i>Trachurus murphyi</i>	0.0694	0.0002	0.0002
	Chub mackerel	<i>Scomber japonicus</i>	0.0648	0.0002	0.0005
Northwest Atlantic – Canada	Herring	<i>Clupea harengus</i>	0.0270	0.0001	0.0003
	Sand lance	<i>Ammodytes dubius</i>	0.0711	0.0011	0.0010
	Capelin	<i>Mallotus villosus</i>	0.0760	0.0033	0.0065
	Other planktivorous fish including mackerel	-	0.0539	0.0009	0.0011
Portugal	European sardine	<i>Sardina pilchardus</i>	0.0766	0.0028	0.0046
	European anchovy	<i>Engraulis encrasicolus</i>	0.0511	0.0000	0.0000
	Mackerel	<i>Scomber scombrus</i>	0.0511	0.0002	0.0003
	Chub mackerel	<i>Scomber colias</i>	0.0839	0.0005	0.0007
Southeastern Gulf of Alaska – 1900	Forage fish	-	0.0508	0.0017	0.0021
	Pacific saury	<i>Cololabis saira</i>	0.0254	0.0001	0.0002
	Eulachon	<i>Thaleichthys pacificus</i>	0.0335	0.0000	0.0001
	Pacific herring	<i>Clupea pallasii</i>	0.0264	0.0000	0.0000

Ecosystem model	Model group name	Scientific name	Index		
			Connectance	Mass SURF	Energy SURF
Southeastern Gulf of Alaska – 1950	Forage fish	-	0.0508	0.0012	0.0014
	Pacific saury	<i>Cololabis saira</i>	0.0254	0.0000	0.0000
	Eulachon	<i>Thaleichthys pacificus</i>	0.0335	0.0000	0.0001
	Pacific herring	<i>Clupea pallasii</i>	0.0264	0.0000	0.0001
Southeastern Gulf of Alaska – current	Forage fish	-	0.0508	0.0014	0.0017
	Pacific saury	<i>Cololabis saira</i>	0.0254	0.0000	0.0000
	Eulachon	<i>Thaleichthys pacificus</i>	0.0335	0.0000	0.0001
	Pacific herring	<i>Clupea pallasii</i>	0.0264	0.0000	0.0000
South Korea	Japanese anchovy	<i>Engraulis japonicus</i>	0.1066	0.0013	0.0029
	Chub mackerel	<i>Scomber japonicus</i>	0.0820	0.0030	0.0061

Appendix 2: Background information for all ecosystems included in the study

BAY OF BISCAY

The model area as considered in the food web model for the Bay of Biscay, developed by Corrales et al. (2022), was in the northeast Atlantic and ranged from Brest (Brittany, France) in the north to Cabo de Finisterre (Galicia, Spain) in the south (Figure A1). The area included the continental shelf and upper slope, between 0 and 1000 m isobaths (Figure A1) and had a total area size of 120,433 km². Its latitudinal limits are well-defined due to its geomorphological, oceanographic and biological characteristics (Valdés and Lavín, 2002; Borja et al., 2019). The modeled area included coastal waters which are important feeding and nursing habitats for many species. The model represented the mean ecosystem functioning from 2000 to 2003, for which more reliable and available data existed. Figure A1. The waters and bathymetry of the Gulf of Biscay for which Corrales et al. (2022) produced a food web model. For the original map with information on the study area see Corrales et al. (2022).

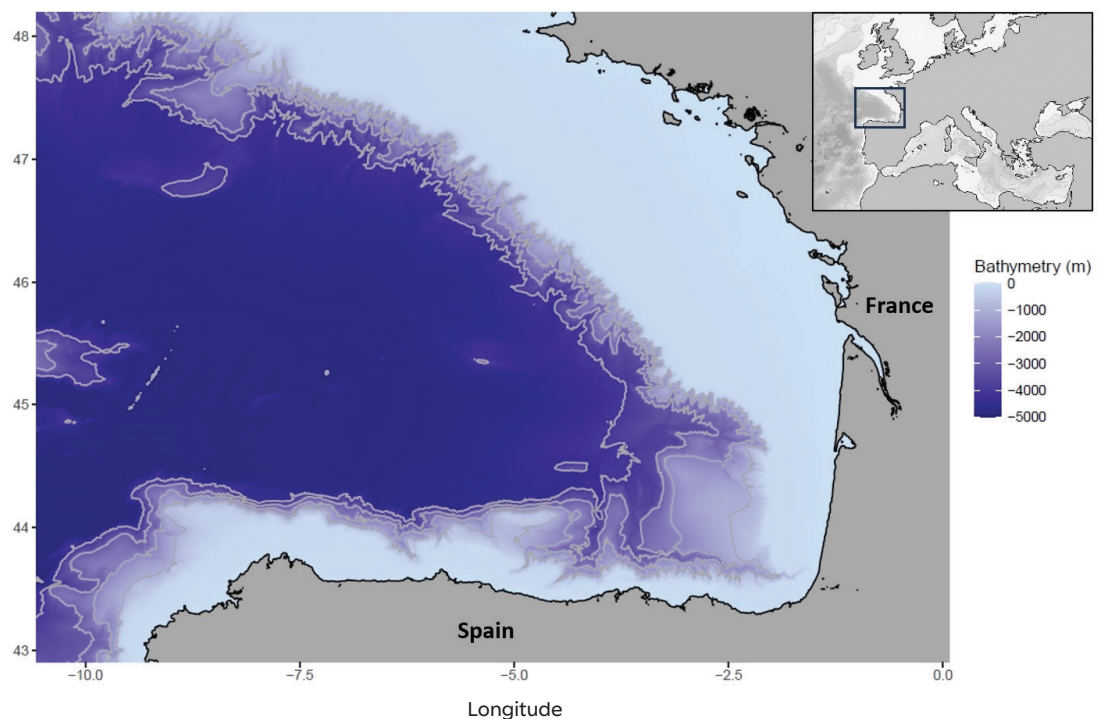


Figure A1. The waters and bathymetry of the Gulf of Biscay for which Corrales et al. (2022) produced a food web model. For the original map with information on the study area see Corrales et al. (2022).

CALIFORNIA CURRENT

The model area as considered in the food web model for the complete California Current system developed by Koehn et al. (2016) included both the northern and southern upwelling system, ranging from the northern tip of Vancouver Island (British Columbia, Canada) to Punta Eugenia (Baja California, Mexico) and the 2000-m isobath offshore (Figure A2). The total model area size was 302,000 km². The area included most of the habitats of commercially important forage fish that overlapped with predators' habitats, e.g., sardine occurs offshore in the southern part of the system (Zwolinski et al., 2012), anchovy and herring mainly occur inshore and/or in the northern part (Koehn et al., 2016). Additionally, the model area included both important seabird breeding colonies in the north (near the northern part of Vancouver Island) and pinniped breeding colonies in the south (on the Baja Peninsula). For more details, see Koehn et al. (2016). Koehn et al. (2016) developed the model to assess the general functioning of the entire California Current as one ecosystem for an unspecified period.

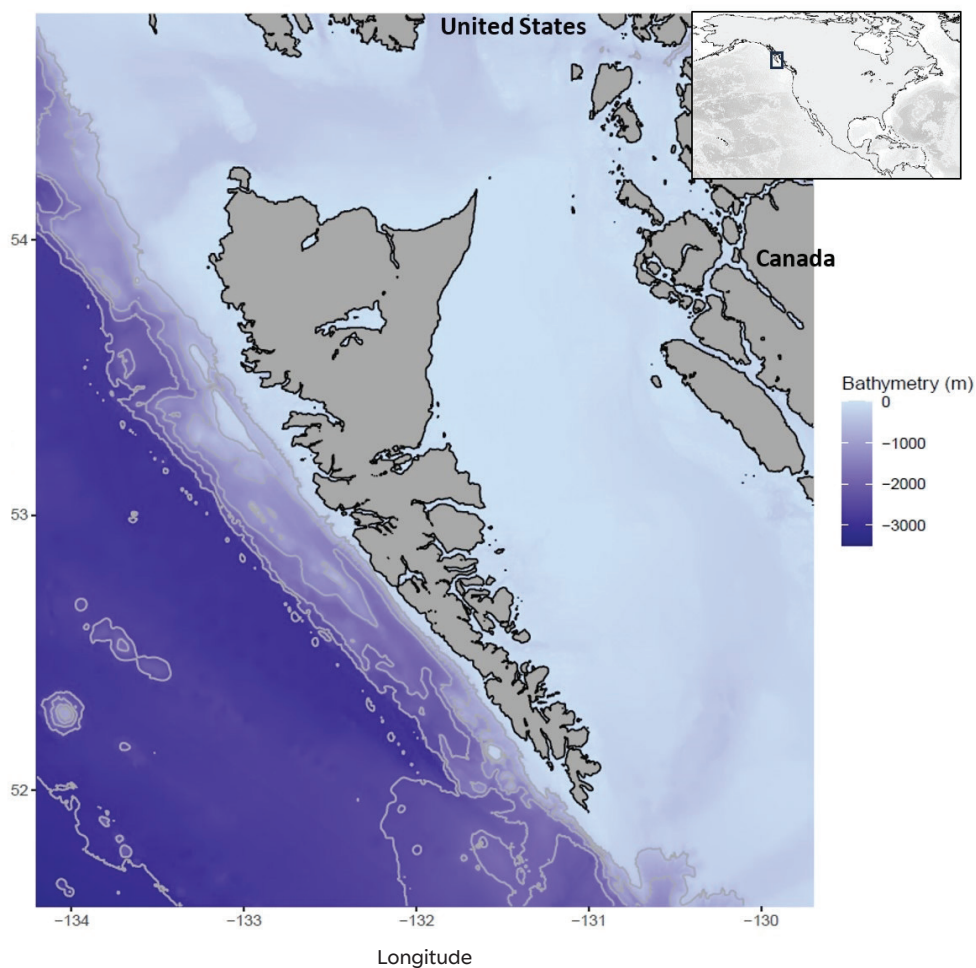


Figure A2. The waters and bathymetry of the complete California Current for which Koehn et al. (2016) produced a food web model. For the original map with information on the study area see Koehn et al. (2016).

CHESAPEAKE BAY – GULF STREAM

The model area as considered for the Chesapeake Bay – Gulf Stream model by Dias et al. (2019) is located in the northwest Atlantic, close to the Canadian border and includes the Gulf of Maine, Georges Bank, southern New England and Middle Atlantic Bight (Figure A3). The area extended out to the U.S. Exclusive Economic Zone (EEZ) and had a total size of 246,662 km². This area is important for anadromous forage fish populations and predators as this marine ecosystem is largely influenced by three northern New England watersheds, including the Androscoggin, Kennebec and Penobscot river systems which have a total size of 1,280 km². As such, there is a strong connection between marine and freshwater ecosystems. The authors used the model to assess the existing (closed) ecosystem conditions in 2000 due to the availability of data between 1996 and 2000.

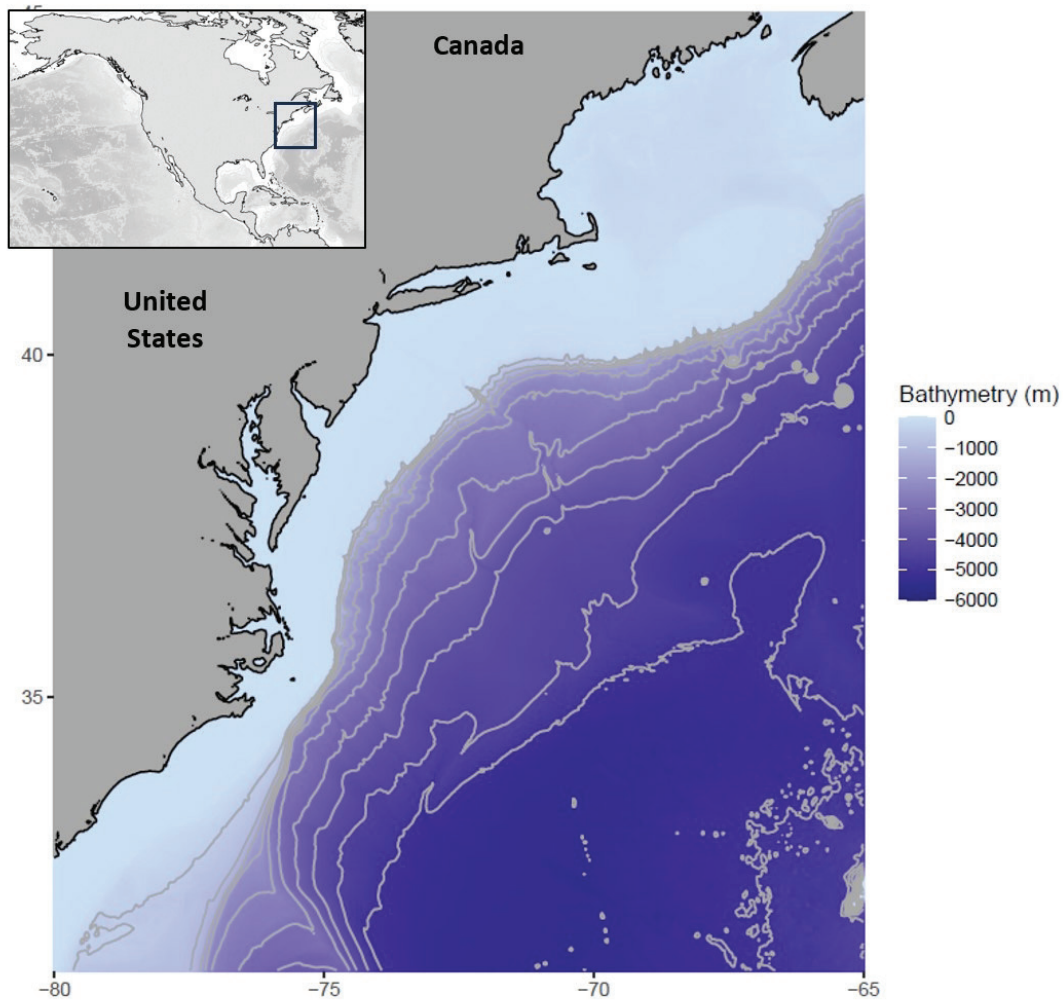


Figure A3. The waters and bathymetry of the northwest Atlantic, including the Chesapeake Bay and other ecoregions, for which Dias et al. (2019) produced a food web model. For the original map with information on the study area see Dias et al. (2019).

CHILE – CENTRAL

Neira and Arancibia (2004) developed a food web model for the upwelling ecosystem off central Chile (Figure A4). The model area ranged from approximately 33°S to 39°S and 72°W to 74°W (Figure A4) (up to 30 nautical miles offshore), including a total area size of 50,042 km². These waters represent the main fishing grounds of commercial purse seine and trawling fleets (Neira and Arancibia, 2004). The study area is part of the southern Humboldt Current upwelling system, and its remarkably high primary productivity is influenced by the occurrence of moderate seasonal (September to March) wind-driven coastal upwelling events (Strub et al., 1998; Daneri et al., 2000). Its high fish biomass sustains important fisheries (Food and Agriculture Organization, 1995). The study area is further characterized by a relatively narrow continental shelf of less than 30 nautical miles (Neira and Arancibia, 2004). Neira and Arancibia (2004) developed the food web model to analyze the trophic interactions and community structure in the central Chile upwelling system for the year 1992, during which fish stocks were considered healthy (i.e., not heavily exploited) and no significant environmental changes occurred. Diet data were collected from existing literature.

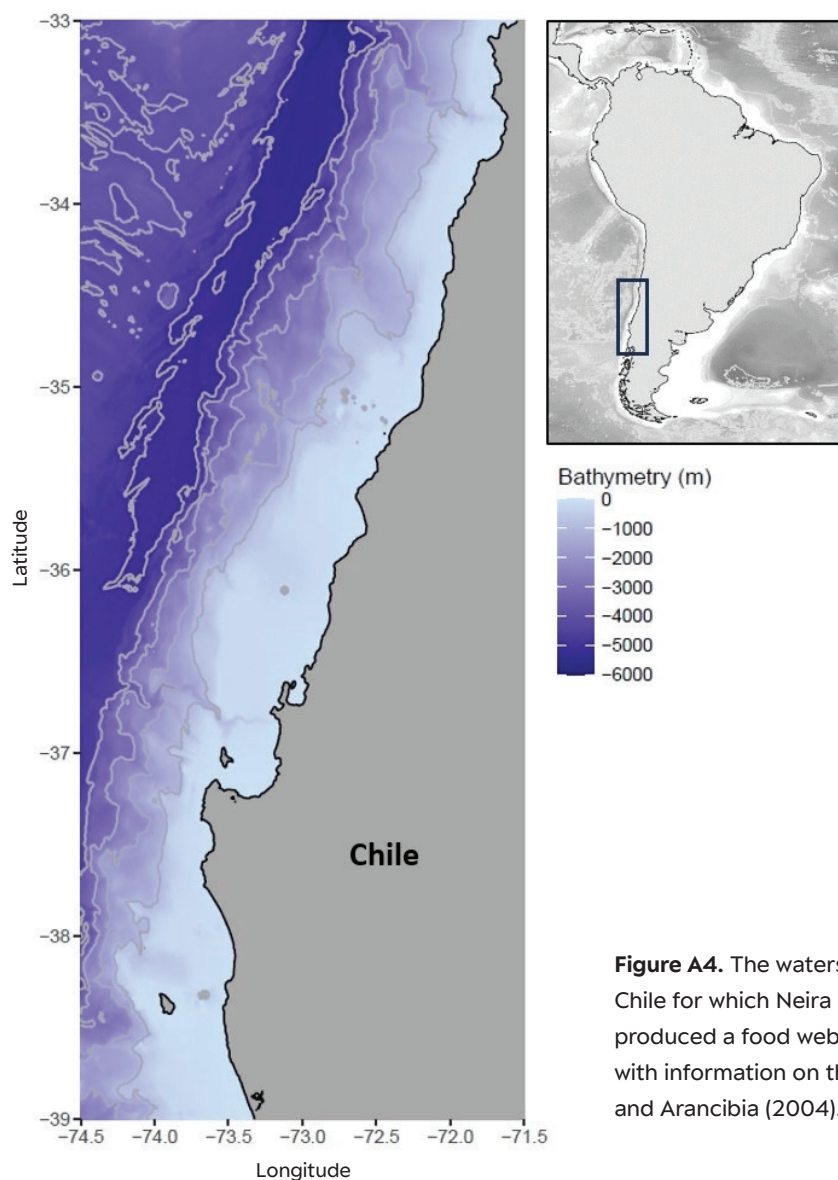


Figure A4. The waters and bathymetry off central Chile for which Neira and Arancibia (2004) produced a food web model. For the original map with information on the study area see Neira and Arancibia (2004).

CHILE – NORTH

Barros et al. (2014) developed a food web model for the upwelling ecosystem off northern Chile (Figure A5). The model area ranged from approximately 18.3°S to 24.0°S and 71.8°W to 70.1°W (Figure A5) (up to 60 nautical miles offshore), including a total area size of 65,000 km². These waters represent the main fishing grounds for the commercial and artisanal purse seine fisheries targeting pelagic fish (Serra, 1986), including anchovy, mackerel, jack mackerel and sardine (Castillo et al., 1997, 1999; Braun et al., 1999). The area is influenced by permanent coastal upwelling (Fuenzalida, 1990; Shaffer et al., 1999; Blanco et al., 2001) due to the Humboldt Current System and is therefore characterized by high productivity (Thiel et al., 2007; Carr, 2002). Other oceanographic features of the area include low turbulence, almost-permanent increased sea surface temperature with cold coastal water (Bernal, 1990; Cubillos et al., 1998) and interannual effects by El Niño–Southern Oscillation (ENSO) events (Fuenzalida, 1992). Barros et al. (2014) developed the food web model for 1997 to assess predator-prey interactions, community structure and trophic flows in the upwelling ecosystem in relation to the strong ENSO conditions during that year. Diet data were collected from published information.

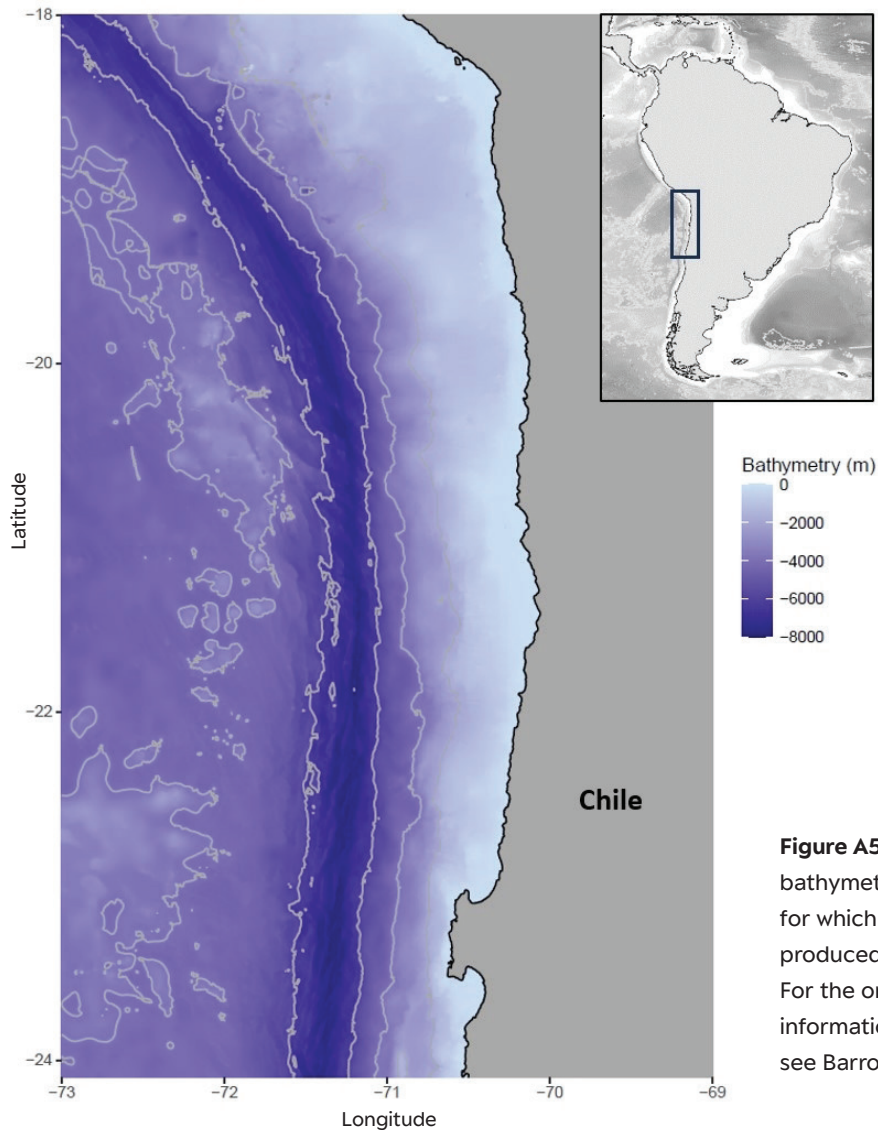
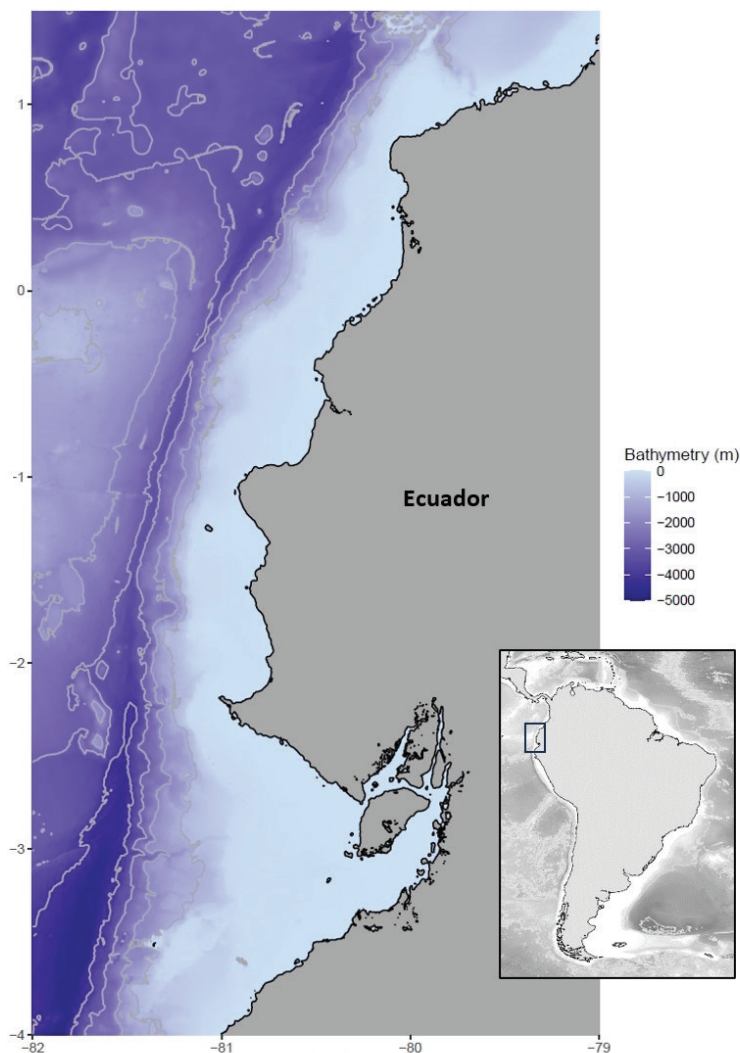


Figure A5. The waters and bathymetry off northern Chile for which Barros et al. (2014) produced a food web model. For the original map with information on the study area see Barros et al. (2014).



ECUADOR

Neira et al. (2022) developed a food web model to represent the marine ecosystem that supports the small pelagic fisheries in Ecuador. The model area is in the central east Pacific Ocean, ranging from approximately 1°N to 4°S and 82°W to 79°W (Figure A6) and includes the entire coastline of Ecuador. It comprises a total area of approximately 44,566 km² and contains six Marine Protected Areas with a total surface of 1,478 km². The model area inhabits all the species that make up the small pelagic fishery off the coast of Ecuador (Figure A6). The area is affected by the Humboldt Current in the south and exhibits a high species richness – the highest species richness occurs in the southern part of the model area, the Gulf of Guayaquil (Cruz et al., 2003). Habitat types within the area are diverse and include sandy beaches, estuaries with mangroves, lagoons, rocky shores, mixed substrates and coral reefs. Neira et al. (2022) developed the food web model to assess the trophic marine food web off the coast of Ecuador, focusing on small pelagic fish species and their role in the ecosystem and the potential impacts of different fishing scenarios. The year 1995 was selected as the model's baseline year as most biomass estimates of the small pelagic stocks and environmental variables were assessed for the first time in that year. Diet data were taken from published literature.



5. The waters and
try off the coast of Ecuador
| Neira et al. (2022) produced
eb model. For the original
| information on the study
Neira et al. (2022)

GULF OF CADIZ

The model area as considered in the food web model for the Gulf of Cadiz developed by Torres et al. (2013) was located at the southwestern corner of the Iberian Peninsula, covering an extensive marine area of Portugal, Spain (Europe) and Morocco (Africa), and bordering the Spanish coast along 300 km (Figure A7). This ecosystem is the southernmost European Atlantic shelf sea connecting the Atlantic Ocean with the western Mediterranean Sea. The total size of the modeled area was 7,224 km² and included depths between 15 and 800 m (Figure A7). Important characteristics of the gulf include its bathymetry, warm-temperate climate, oceanographic processes, river outflows and wind systems (Jiménez et al., 1998; Millán, 1999; Vila et al., 2004; Ramos et al., 2012). Together, these characteristics make this ecosystem a vital habitat for the reproduction of some commercially important forage fish, including anchovy and sardine (Baldó and Drake, 2002; Sobrino et al., 2005; García-Isarch et al., 2006). Torres et al. (2013) excluded the coastal area from their model given its purpose and the available data. Their food web model represented an annual average situation of the ecosystem in 2009, for which the best data were available and during which most of the diet composition data were collected (Torres, 2013).

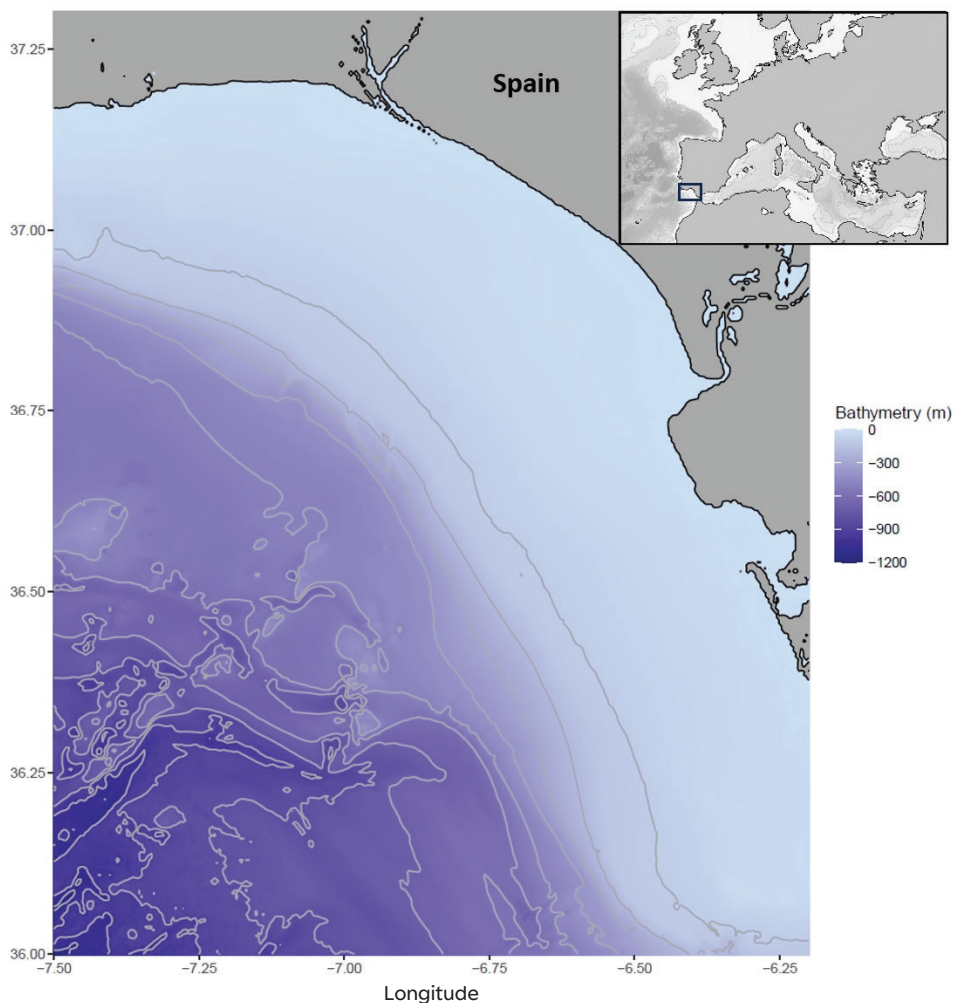


Figure A7. The waters and bathymetry of the Gulf of Cadiz for which Torres et al. (2013) produced a food web model. For the original map with information on the study area see Torres et al. (2013).

GULF OF MAINE

Dias et al. (2022) developed a food web model for the Gulf of Maine which is in the northwest Atlantic at the U.S.-Canada border, ranging from approximately 44°N to 41°N and 71°W to 65°W (Figure A8). The Gulf of Maine ecoregion comprises a total area of 79,128 km² that is enclosed to the west and north by the North American mainland and linked to the ocean to the southeast through one major channel (Figure A8). Important rivers include the Penobscot, Kennebec and Androscoggin. The Gulf's waters are largely isolated from the ocean to the south by shoals and banks restricting flows into and out of the Gulf. The three major basins contained within the Gulf are isolated from each other beneath the 650-foot (200 m) isobath. The Gulf's cold waters, extreme tidal mixing, diverse bottom and coastal kelp forests enable its biodiversity and high productivity. Both anadromous and oceanodromous forage fish species are of great importance to the ecosystem's food webs and fisheries' productivity (Dias et al., 2019). River herring (*Alewife Alosa pseudoharengus* and blueback herring *A. aestivalis*) and American shad (*A. sapidissima*) dominate the anadromous forage fish pool. Dias et al. (2022) developed this food web model to assess how increasing river-to-ocean connectivity that resembled 19th century conditions would potentially impact the ecosystem with data collection from 2000.

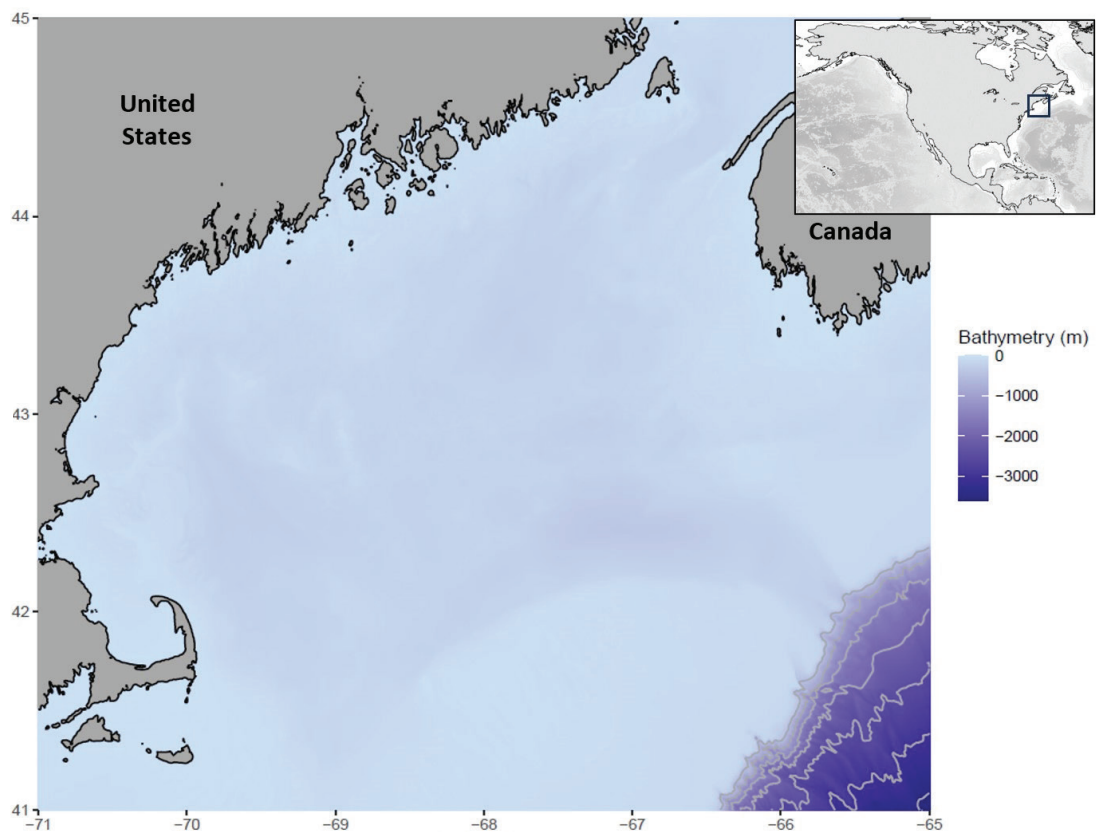


Figure A8. The waters and bathymetry of the Gulf of Maine for which Dias et al. (2022) produced a food web model. For the original map with information on the study area see Dias et al. (2022).

GULF OF ST. LAWRENCE (NORTHWEST ATLANTIC, CALIFORNIA)

Morisette et al. (2003) developed a food web model for the northern Gulf of St. Lawrence. This gulf is in the northwest Atlantic and semi-enclosed by the Canadian mainland in the north, west and south, and by Newfoundland in the east (Figure A9). The total area of this gulf is about 200,000 km², ranging from approximately 51.4°N to 47.4°N and 67.3°W to 56.9°W, with almost half of this area exhibiting deep channels (Figure A9). Its waters are connected to the Atlantic Ocean by Cabot Strait in the south and the Strait of Belle-Isle in the north (Figure A9), through which it is supplied with relatively warm and cold water, respectively. Additionally, a vast amount of freshwater enters through several large rivers, including the St. Lawrence River. The modeled area covered a total area of 103,812 km², excluding the shallow water zone. The northern Gulf of St. Lawrence's ecosystem is characterized by phytoplankton, a low diversity of large zooplankton species, a relatively low abundance of fish (mainly cod, herring and redfish), and a high abundance of juvenile fish (primarily capelin, *Mallotus villosus*) (de Lafontaine et al., 1991). Morisette et al. (2003) developed this model to assess the trophic flows of this ecosystem during the mid-1980s before the groundfish stock collapsed. Diet data from this period relevant to the region was used for functional groups in the model where possible.

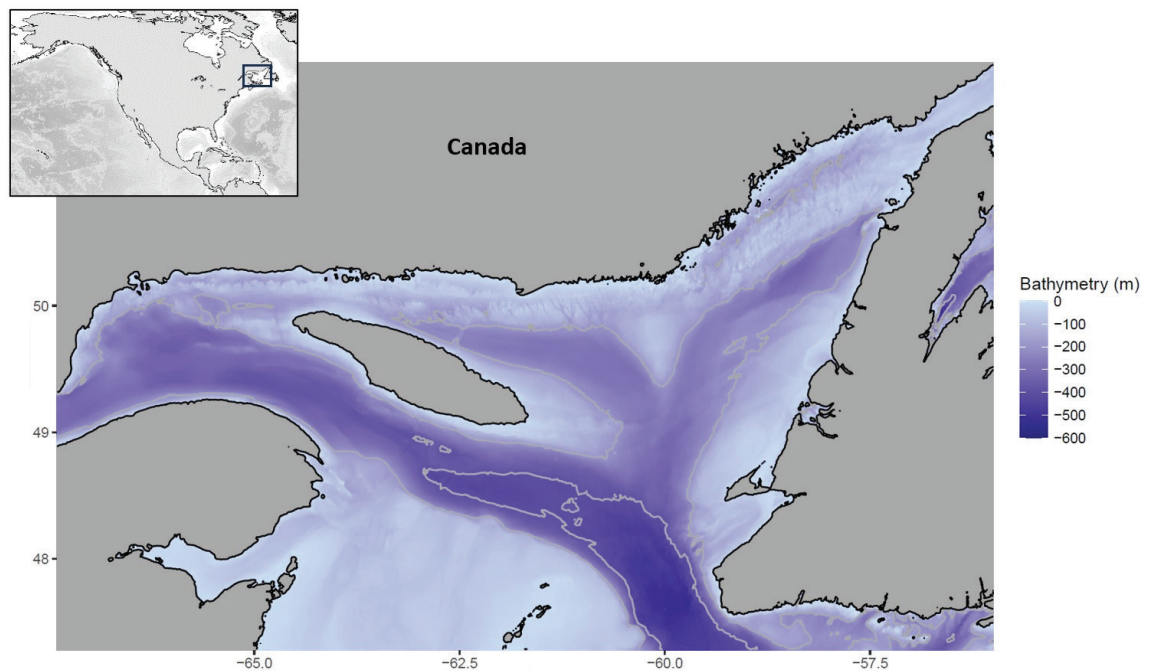


Figure A9. The waters and bathymetry of the Gulf of St. Lawrence for which Morisette et al. (2003) produced a food web model. For the original map with information on the study area see Morisette et al. (2003).

INDIA – WEST COAST, ARABIAN SEA

The food web model developed by Mohamed et al. (2008) concerned the marine ecosystem in the Arabian Sea off the coast of Karnataka State, west India. It included the marine ecosystem along the 300 km long coast of Karnataka State in west India as part of the Arabian Sea. The model area reached along the 300 km long coast and extended from 12°N to 15°N and 73°E to 76°E (Figure A10), representing an area of 27,000 km². The area reflects a tropical upwelling zone from June to September and includes several estuaries that are of ecological and biological importance (Mohamed et al., 2008). Fishing fleets within the model area target pelagic species, including mackerel and sardines, and demersal finfishes, prawns and cephalopods. Mohamed et al. (2008) constructed the mass balance ecosystem model using fish landing data collected from 1999 to 2001 as a preliminary exercise to create a general understanding of the ecosystem and the impacts by fisheries.

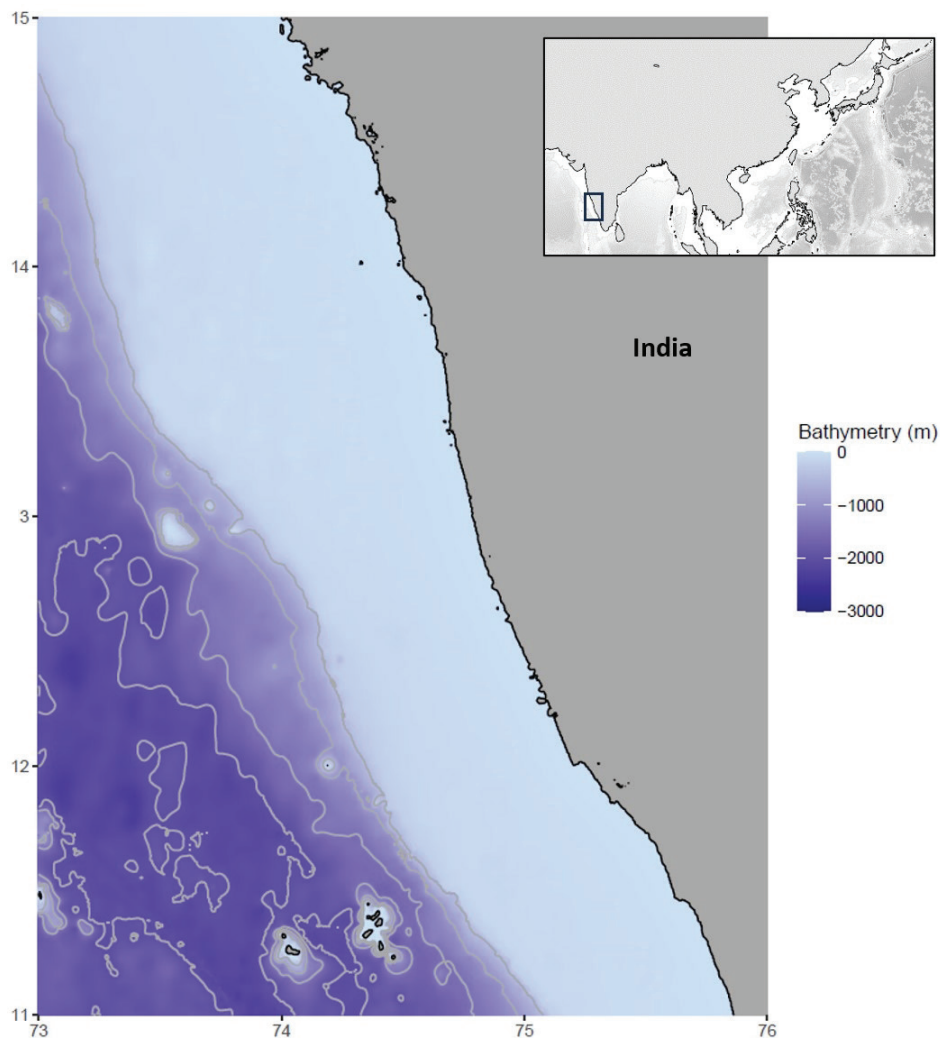


Figure A10. The waters and bathymetry of the Arabian Sea off the west Indian coast for which Mohamed et al. (2008) produced a food web model. For the original map with information on the study area see Mohamed et al. (2008).

IRISH SEA

The model area considered for the Irish Sea model by Bentley et al. (2019) is located between the islands of Great Britain on the east and Ireland on the west and comprises approximately 58,000 km² (Figure A11). In the north, the Irish Sea is connected to the Firth of Clyde and the Atlantic via the North Channel and links in the south to the Celtic Sea via the St. George's Channel (Figure A11). Its maximum depth reaches 275 m in the North Channel (Figure A11) and water generally flows from south to north. The model was created to evaluate the general functioning of the ecosystem.

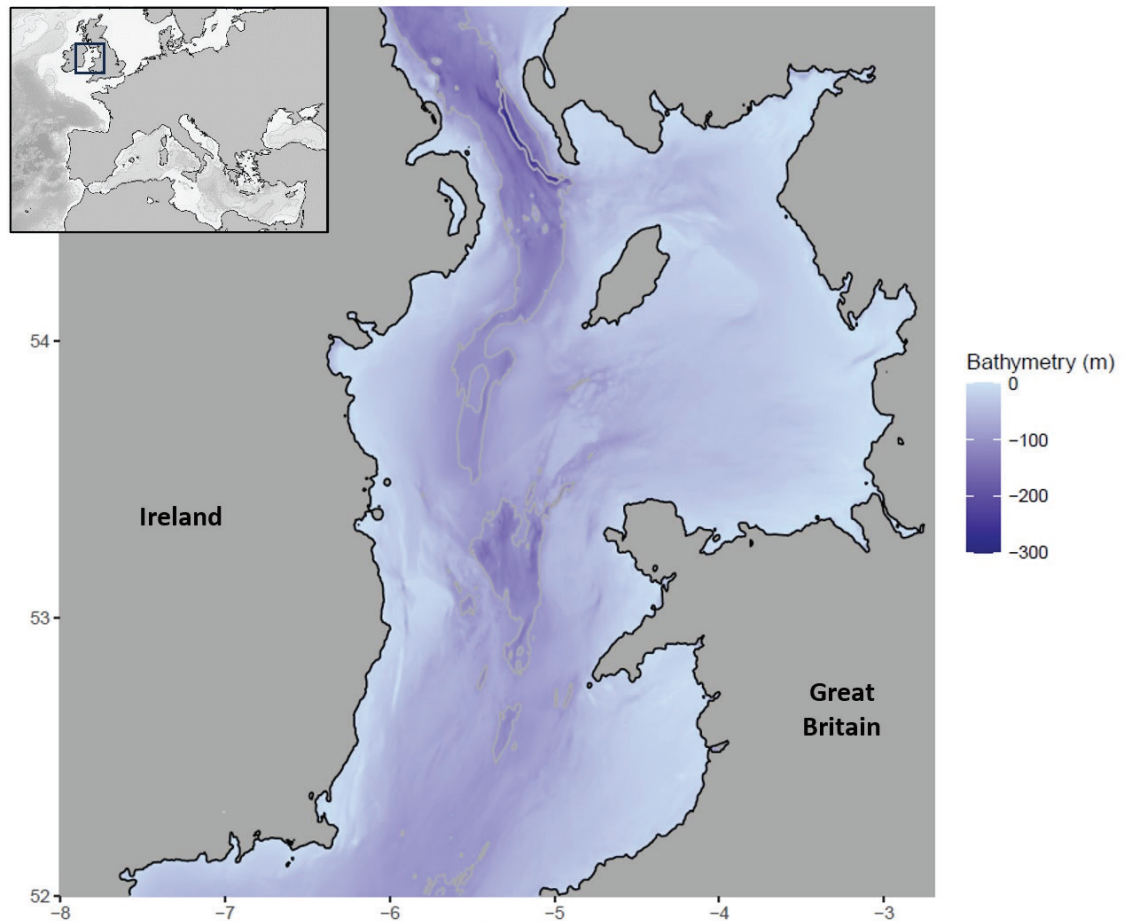


Figure A11. The waters and bathymetry of the Irish Sea for which Bentley et al. (2019) produced a food web model. For the original map with information on the study area see Bentley et al. (2019).

JAPAN – EAST COAST

In the northern part of the western North Pacific, two currents influence the waters off eastern Japan. The Oyashio Current from the north is a cold, low-salinity, subarctic current. The Kuroshio Current in the south is a warm, high-salinity subtropical current, that influences the local Japanese sardine and anchovy spawning area and transitions into the Kuroshio extension, transporting eggs, larvae and juveniles of these fishes (Watari et al., 2019). For their food web model, Watari et al. (2019) considered three different regions off the east coast of Japan (Figure A12), including the coastal Oyashio region (186,128 km²), the coastal Kuroshio region (186,220 km²) and the offshore region (540,754 km²). For more details, see Watari et al. (2019). For this study, these three regions were considered together as one ecosystem and thus an overall area size of 913,102 km². Watari et al. (2019) used their model to assess the role of forage fish species in the ecosystem for 2013 for which most data were collected compared to other years.

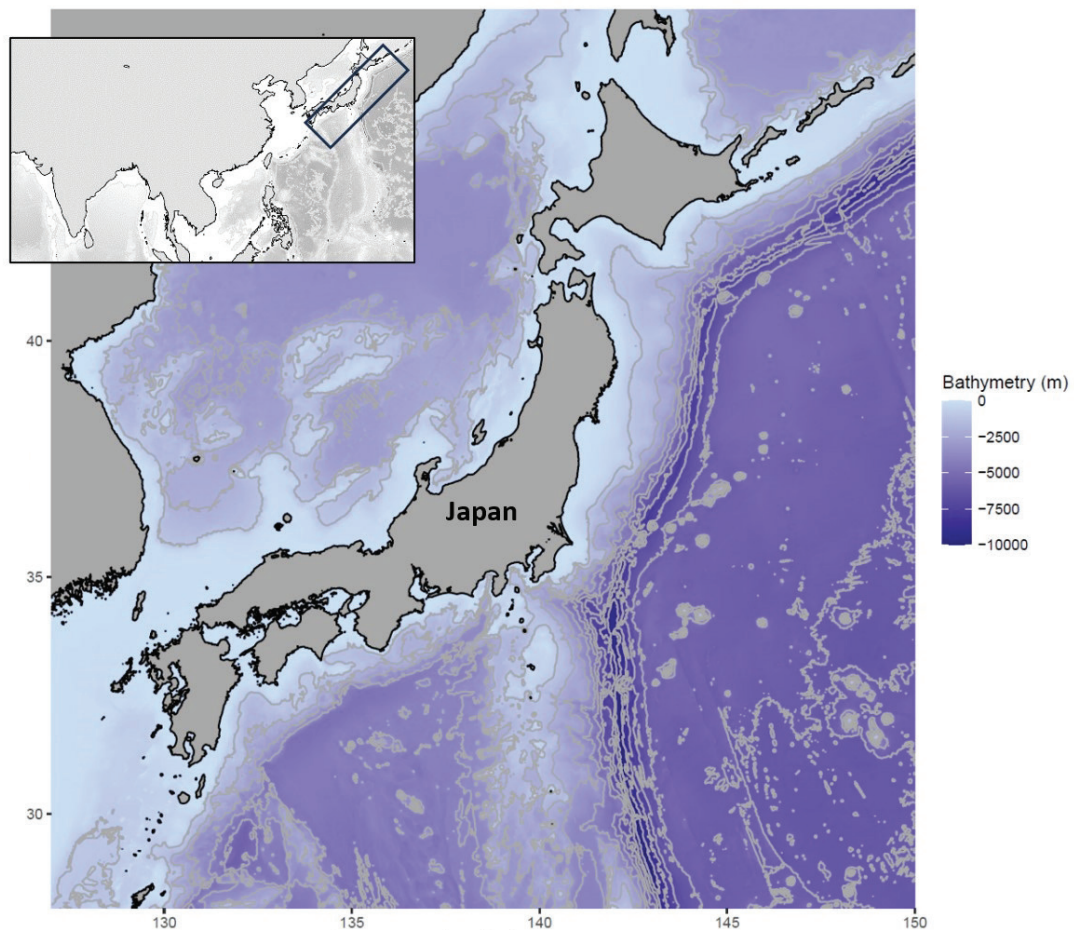


Figure A12. The waters and bathymetry off the Japanese east coast for which Watari et al. (2019) produced food web models. For the original map with information on the study area see Watari et al. (2019).

LAKE SUPERIOR

The food web model developed by Cox and Kitchell (2004) concerned Lake Superior (part of the Greater Lakes system) which is in North America on the Canada–U.S. border and extends from 49°N to 46°N and 92°W to 84°W (Figure A13). It is the largest freshwater lake in the world with a surface area of 82,100 km² and an average depth of 483 ft. (147 m). Via St. Mary's River, it drains into Lake Huron and then through the lower Great Lakes to the St. Lawrence River and, ultimately, the Atlantic Ocean. Overfishing and invasion by the exotic sea lamprey caused a lake-wide collapse of the dominant piscivore (lake trout) and zooplanktivore (whitefish and lake herring) species, affecting the lake's food web structure. Although lake trout recovered to historical levels, lake herring has not. Cox and Kitchell (2004) developed the food web model of the Lake Superior fish community for the year 1929, reflecting the ecosystem before the introduction of sea lamprey, to assess the recruitment failure of lake herring.

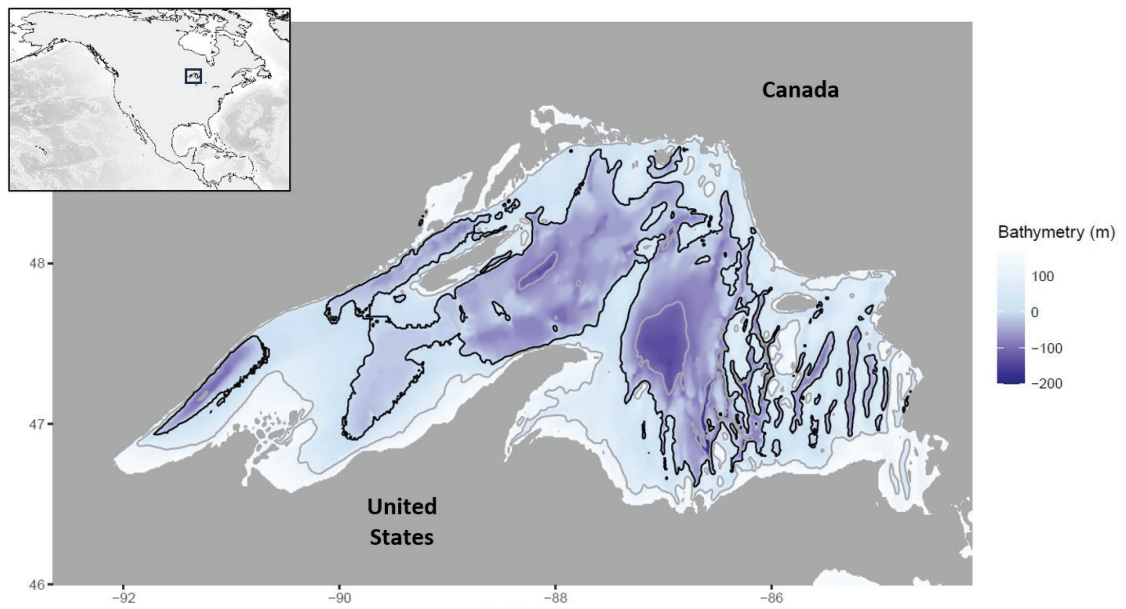


Figure A13. The waters and bathymetry of Lake Superior for which Cox and Kitchell (2004) produced a food web model. The black line represents the sea level isobath. For the original map with information on the study area see Cox and Kitchell (2004).

MAURITANIA

The model area in the northeast Atlantic that was considered by Gu nette et al. (2014) for the ecosystem of Mauritania stretched from 20 46'N in the north to 16 04'N in the south (Figure A14) and up to the 200 m isobath. This area included the Banc d'Arguin National Park and had a total size of 33,224 km². The Banc d'Arguin is the largest marine protected area in Africa (6,450 km²) and includes key habitats for migratory birds, such as large beaches, tidal flats and seagrass beds. A permanent upwelling system exists on the northern end of the model area (Cap Blanc), while further south within the model area (Nouakchott) upwelling occurs nine months per year. Gu nette et al. (2014) developed their model to evaluate the ecosystem between 1991 and 2006.

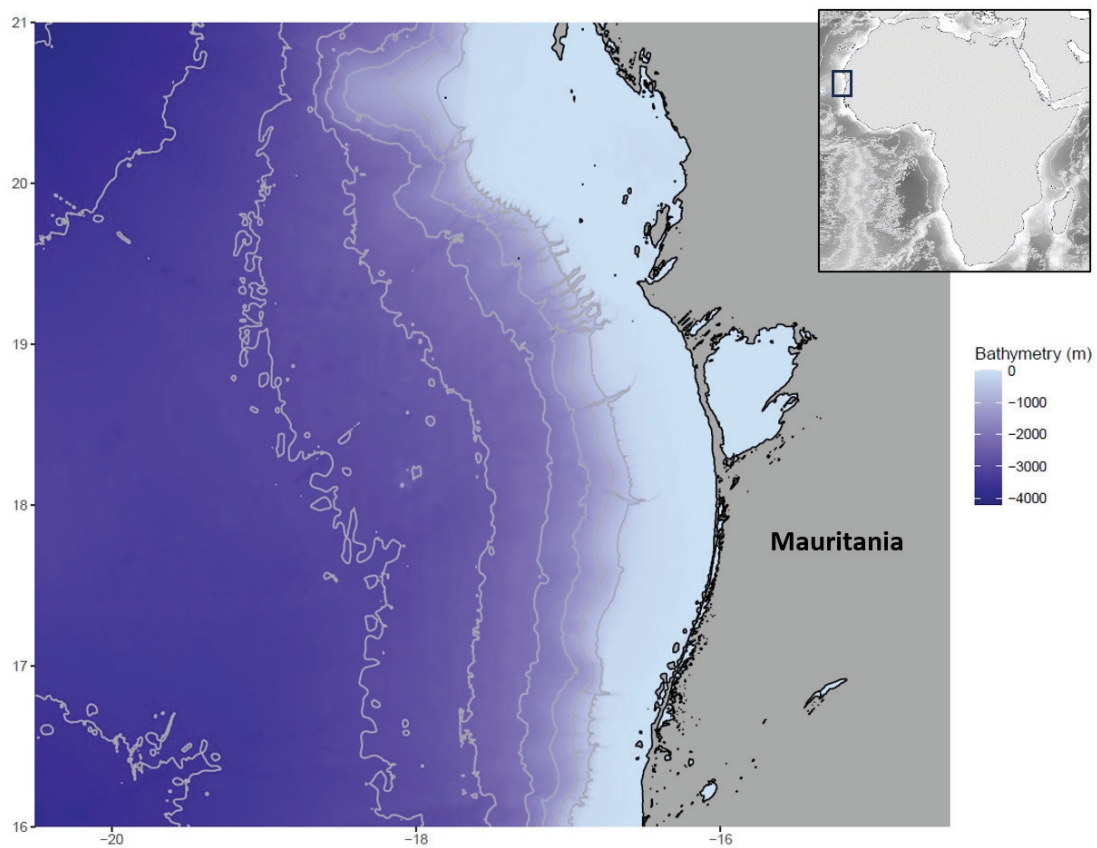


Figure A14. The waters and bathymetry off the Mauritanian coast for which Gu nette et al. (2014) produced a food web model. For the original map with information on the study area see Gu nette et al. (2014).

MEDITERRANEAN SEA – ADRIATIC SEA

Coll et al. (2009) developed a food web model for the north-central Adriatic Sea. The Adriatic Sea is the most northern arm of the Mediterranean Sea and is largely enclosed by land on the west, north and east. It has only a relatively small connectivity to the Ionian Sea, represented by the Strait of Otranto. The north-central Adriatic Sea, as modeled by Coll et al. (2009) ranged from 46°N to 42°N and 12°E to 17°E and covered a total area of approximately 55,500 km² that included a depth range between 10 and 200 m (Figure A15). This area concerns relatively shallow waters compared to the southern area which has a maximum depth of approximately 1,200 m. Furthermore, the model area exhibits the widest continental shelf in the Mediterranean Sea and is of great importance for Italian and European fisheries, including those targeting sardine and anchovy. The area's high biodiversity is due to several favorable environmental conditions. It has a lower salinity than the rest of the Mediterranean and a high primary production influenced by nutrient-rich freshwater being discharged by numerous rivers. The bottom is either muddy or sandy. Coll et al. (2009) developed this model to examine changes and their drivers in marine resources in this ecosystem from 1975 to 2002. Initial diet data were taken from a 1990s model, based on scientific literature (Coll et al., 2007) and adjusted to represent the ecosystem's food web in 1975, before the collapse of the anchovy stock and the decrease of other small pelagic fish species.

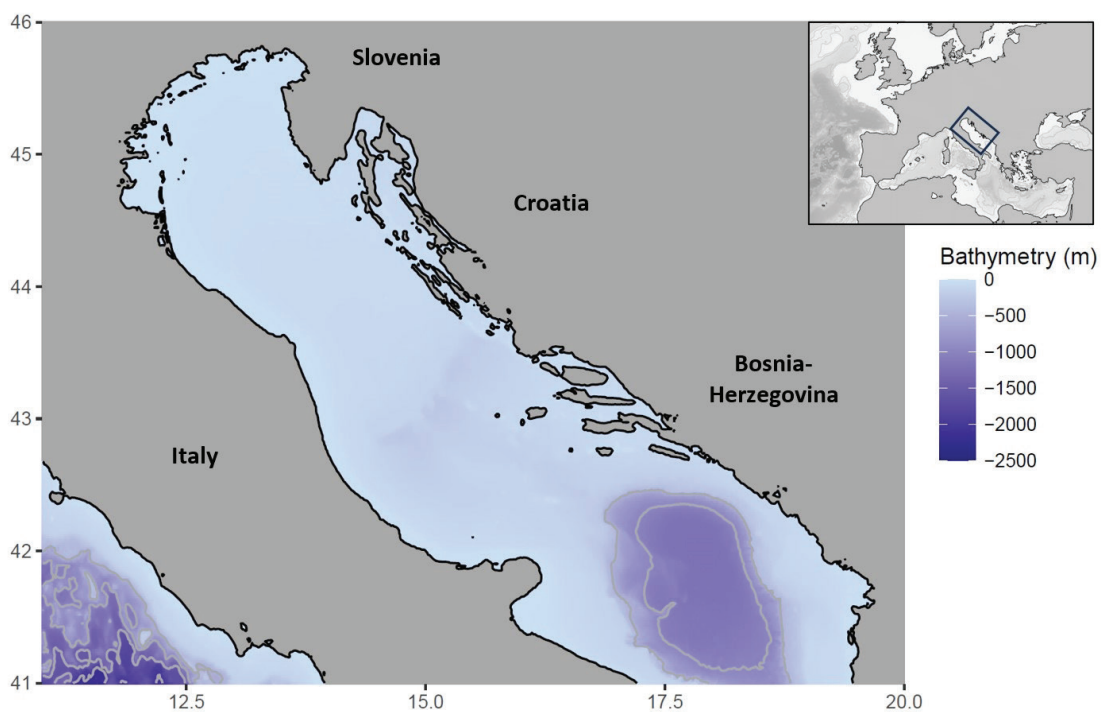


Figure A15. The waters and bathymetry of the north-central Adriatic Sea for which Coll et al. (2009) produced a food web model. For the original map with information on the study area see Coll et al. (2009).

MEDITERRANEAN SEA – AEGEAN SEA

The model area as considered by Keramidas et al. (2022) to study the ecosystem of the Aegean Sea concerned a relatively closed area in the eastern Mediterranean Sea (Figure A16). It was surrounded by Greece in the west and north and Türkiye in the east and includes many islands and islets. It counted approximately 201,535 km² and had a maximum depth of 2250 m. This area is deemed one of the most productive areas of the eastern Mediterranean Sea, particularly the north due to its inflow of nutrient-rich and lower-salinity waters from the Black Sea and large rivers. The authors used the model to study the function of the ecosystem in this sea between 2003 and 2006.

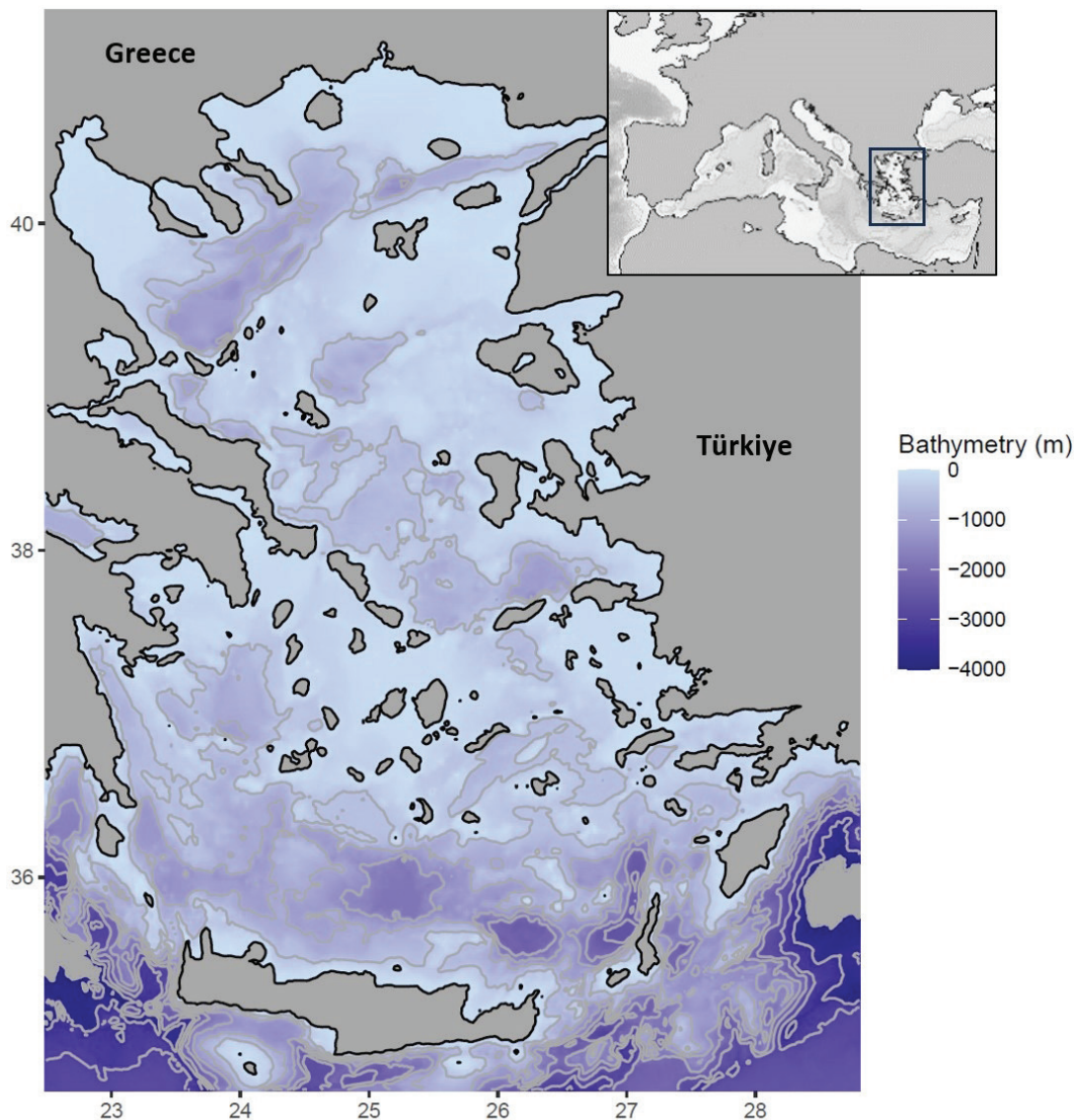


Figure A16. The waters and bathymetry of the Aegean Sea for which Keramidas et al. (2022) produced a food web model. For the original map with information on the study area see Keramidas et al. (2022).

MEDITERRANEAN SEA – GULF OF ALICANTE (CLOSEST TO ALBORAN SEA)

García-Rodríguez et al. (2021) developed a food web model for the Gulf of Alicante in the western Mediterranean Sea off the Spanish east coast, including the continental shelf and upper slope (Figure A17). The model area ranged from approximately 38.7°N to 37.5°N and 0.7°W to 0.6°E and concerned a total area size of 7,085 km² with a depth ranging between 50 and 800 m (Figure A17). The Alicante continental shelf's average width is 32 km, dominated by sandy and muddy bottoms. The slope has a uniform relief with a width between 30 and 52 km. The area included two major canyons: one is gently sloping and the other is narrower and rugged with a head connecting at the foot of the continental slope at a depth of 650 m. The ecosystem differs from the rest of the Mediterranean due to the influence of the Atlantic current coming through the Alboran Sea and an anticyclone circulation between the southern and northern cape of the area. There are two anticyclonic eddies, one outside and another inside the continental shelf. García-Rodríguez et al. (2021) developed a food web model in the early 2010s to examine the ecosystem of the Gulf of Alicante and investigate its singularities. Diet data were collected from published information on the area or, where needed, from the same species in similar ecosystems.

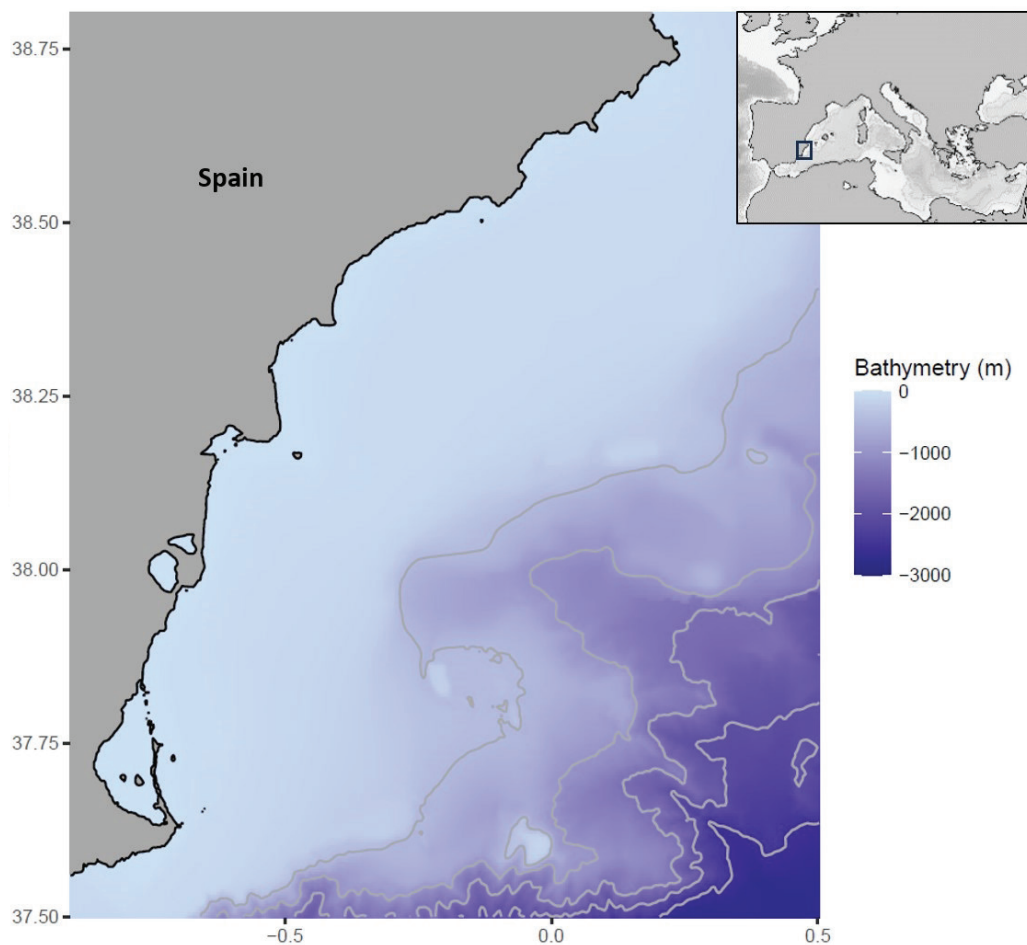


Figure A17. The waters and bathymetry of the Gulf of Alicante for which García-Rodríguez et al. (2021) produced a food web model. For the original map with information on the study area see García-Rodríguez et al. (2021).

MEDITERRANEAN SEA – GULF OF LION

Seyer et al. (2023) developed a food web model for the Gulf of Lion, located in the northwestern Mediterranean Sea (Figure A18). The model area ranged from approximately 43.5°N to 42.4°N and 3°E to 5.5°E and concerned a total area of 12,172 km² with depths ranging between 0 and 200 m (Figure A18). The 200 m isobath separates the continental shelf and the canyons of the continental slope (Figure A18). Important environmental characteristics of the area include strong continental northwestern and northern winds producing coastal upwellings; a mesoscale circulation of the western Mediterranean; and the freshwater discharge by the Rhone River. These characteristics lead to both high primary and secondary production. The bottom includes sandy and muddy substrates and some seagrass meadows. Seyer et al. (2023) developed this model to examine the general trophic functioning of the Gulf of Lion between 2010 and 2014, after changes observed from 2008. Diet data were obtained from the available literature.

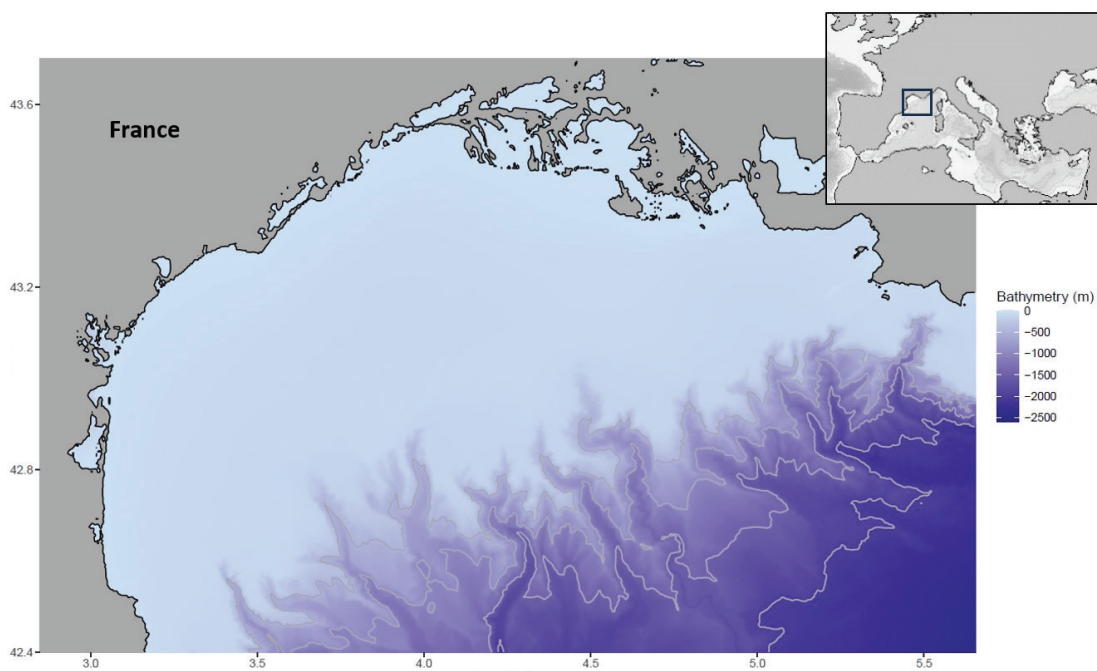


Figure A18. The waters and bathymetry of the Gulf of Lion for which Seyer et al. (2023) produced a food web model. For the original map with information on the study area see Seyer et al. (2023).

MEDITERRANEAN SEA – GULF OF LION AND EAST COAST SPAIN

Corrales et al. (2015) developed a food web model for the northwestern Mediterranean Sea including part of the Balearic Sea (Spain) and the Gulf of Lion (France) (Figure A19). The model area ranged from approximately 44°N to 38°N and 0° to 6°E and concerned a total area of 45,547 km² with a depth ranging between 0 and 1000 m (Figure A19). This area represents shared fish stocks (e.g., hake and anchovy) and fishing fleets. Depths of 0–50 m contain important feeding areas for most species or functional groups in the model, while the 1000 m limit is the boundary at which bottom trawling is allowed. The connectivity between the Gulf of Lion and the Balearic Sea is characterized by the general southward flow and related anchovy larvae transport (Sabatés et al., 2001; Ospina-Alvarez et al., 2012). Corrales et al. (2015) developed this model to characterize the structure and functioning of the area's marine continental shelf and slope area in the early 2000s. Diet data were collected from published information from the region or ecological similar areas.

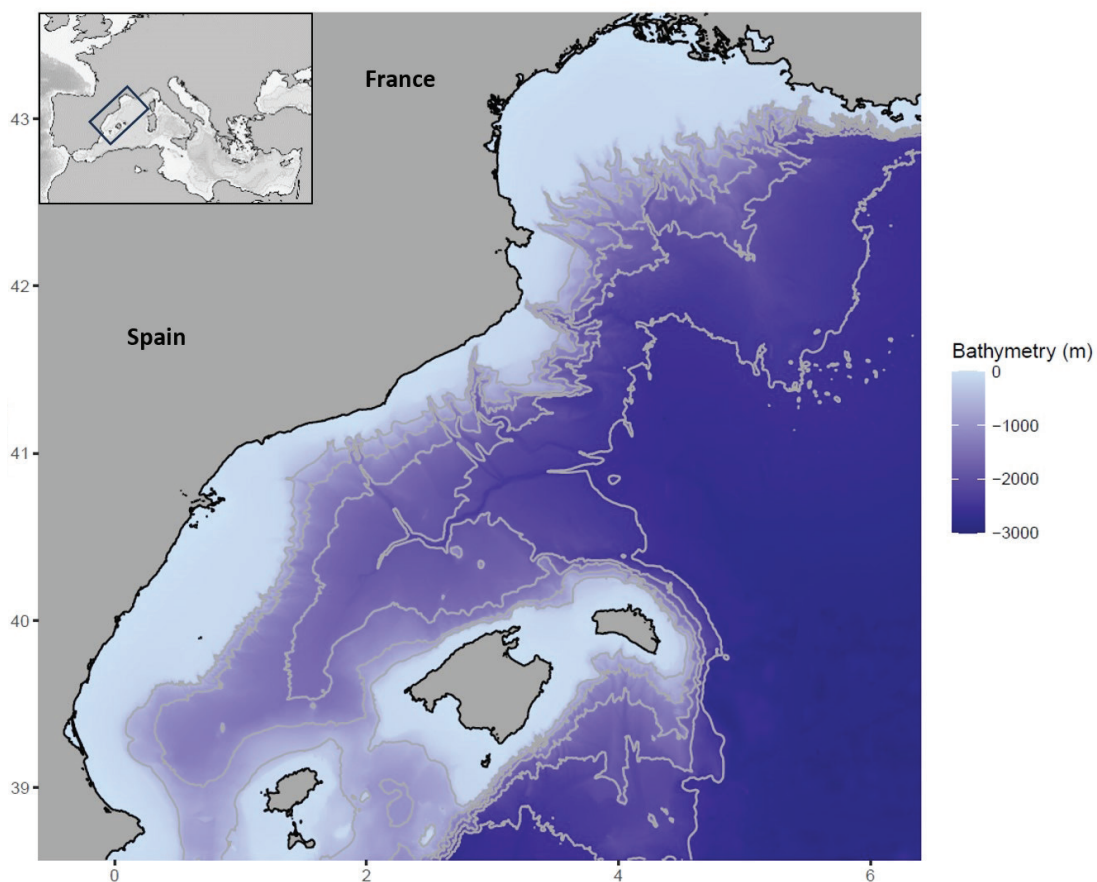


Figure A19. The waters and bathymetry of the Gulf of Lion (France) and part of the Balearic Sea (Spain) for which Corrales et al. (2015) produced a food web model. For the original map with information on the study area see Corrales et al. (2015).

MEDITERRANEAN SEA – IONIAN SEA

Moutopoulos et al. (2013) developed a food web model for the Ionian Sea located in the Mediterranean Sea off the Greek west coast, including a narrow continental shelf and a large marine area (Figure A20). The model area ranged from approximately 40°N to 36°N and 19°E to 22°E and concerned a total area size of 49,149 km² with a depth ranging between 50 and 1100 m (Figure A20). The Ionian Sea is a pelagic ecosystem with low nutrients, chlorophyll-a levels and zooplankton biomass. Furthermore, it is among the most oligotrophic ecosystems in the Mediterranean Sea characterized by a complex food web structure. Moutopoulos et al. (2013) developed this food web model for the 1990s to examine yearly biomass flows in the Ionian Sea food web for the period 1998–2006, the ecological role of different species and impacts by fisheries. Diet data were obtained from published information.

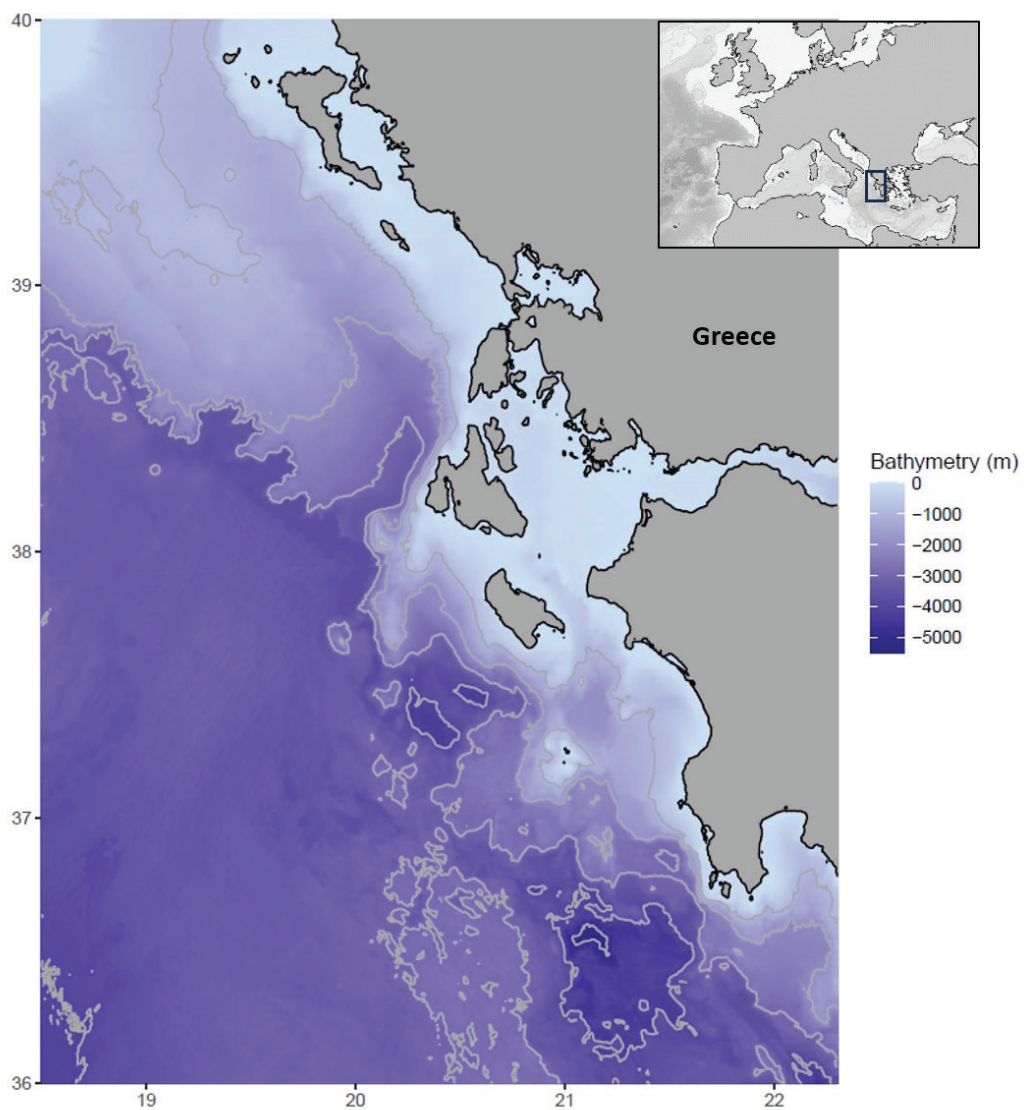


Figure A20. The waters and bathymetry of the Ionian Sea for which Moutopoulos et al. (2013) produced a food web model. For the original map with information on the study area see Moutopoulos et al. (2013).

MEDITERRANEAN SEA – STRAIT OF SICILY

Agnetta et al. (2019) developed a food web model for the northern part of the Strait of Sicily, which is located centrally in the Mediterranean Sea off the south coast of Sicily (Figure A21). The model area ranged from approximately 38°N to 35°N and 11°E to 16°E and concerned a total area size of about 61,000 km² with a depth ranging between 10 and 800 m (Figure A21). The central waters of the area are represented by a narrow continental shelf separating two banks (Figure A21). The area's bottom structure is complex due to sedimentary and volcanic seamounts influencing the region's hydrology and its slope is irregular due to trenches and steep areas. Permanent cyclonic currents around the two banks produce upwelling, whereas frequent wind-induced upwelling enhances coastal primary production. Stable environmental conditions around the two banks help sustain spawning and nursery areas of commercially important species and biodiversity hot spots. Agnetta et al. (2019) developed this model for 2004–2005 to examine the relationship between the benthic–pelagic coupling and mixed fisheries. Diet data were collected from published and unpublished information.

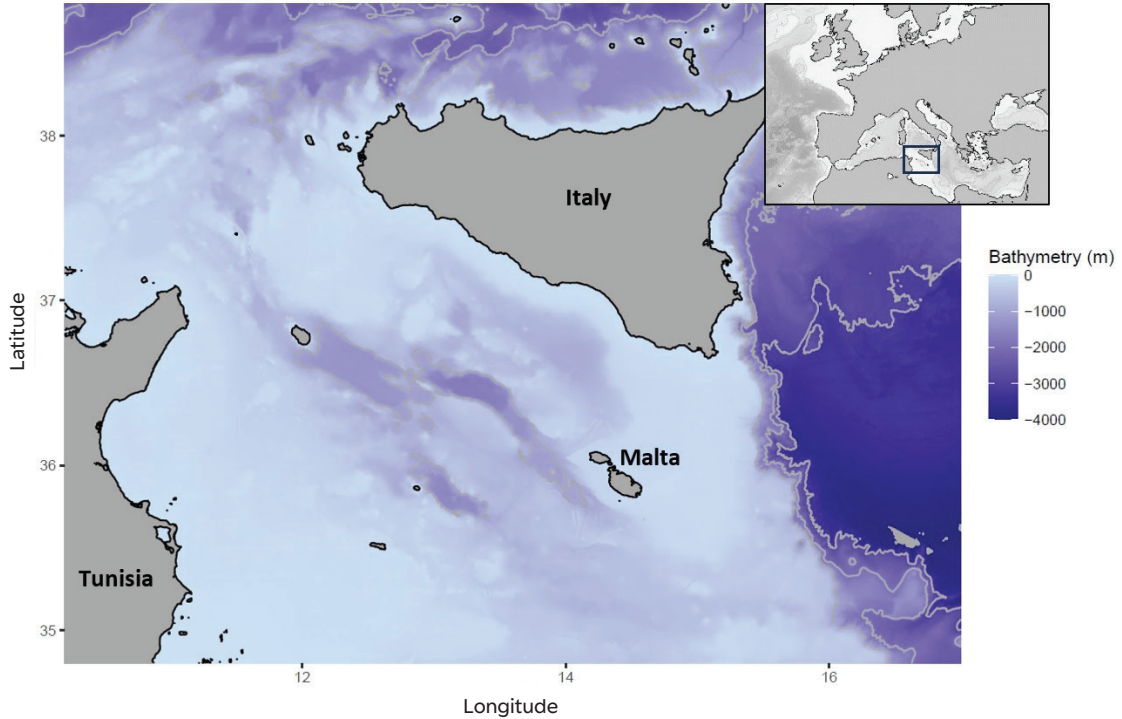


Figure A21. The waters and bathymetry of the northern Strait of Sicily for which Agnetta et al. (2019) produced a food web model. For the original map with information on the study area see Agnetta et al. (2019).

MOROCCO – ATLANTIC COAST

The model area as considered in the food web model for the Moroccan (Atlantic) coast developed by Stanford et al. (2001) ranged from Tangier (36°N) in the north to Cape Blanc (20°N) in the south (Figure A22) and was as wide as the EEZ (extending over more than 200 nm), representing a total area size of 586,900 km². The upwelling system within the area is driven by the combination of trade winds and the Canary Current (Stanford et al., 2001), which transports cold water along the northwest African coast from the northeast to the southwest. Upwelling intensity varies with coastal topography and season (due to varying trade winds throughout the year). As such, the upwelling system includes three subsystems, with upwelling north of 25°N occurring primarily during the summer, south of 20°N during the winter and spring, and between 20°N and 25°N year-round (Stanford et al., 2001). Since Stanford et al. (2001) had no access to biomass estimates for the 1990s, their model represents the mid-1980s.

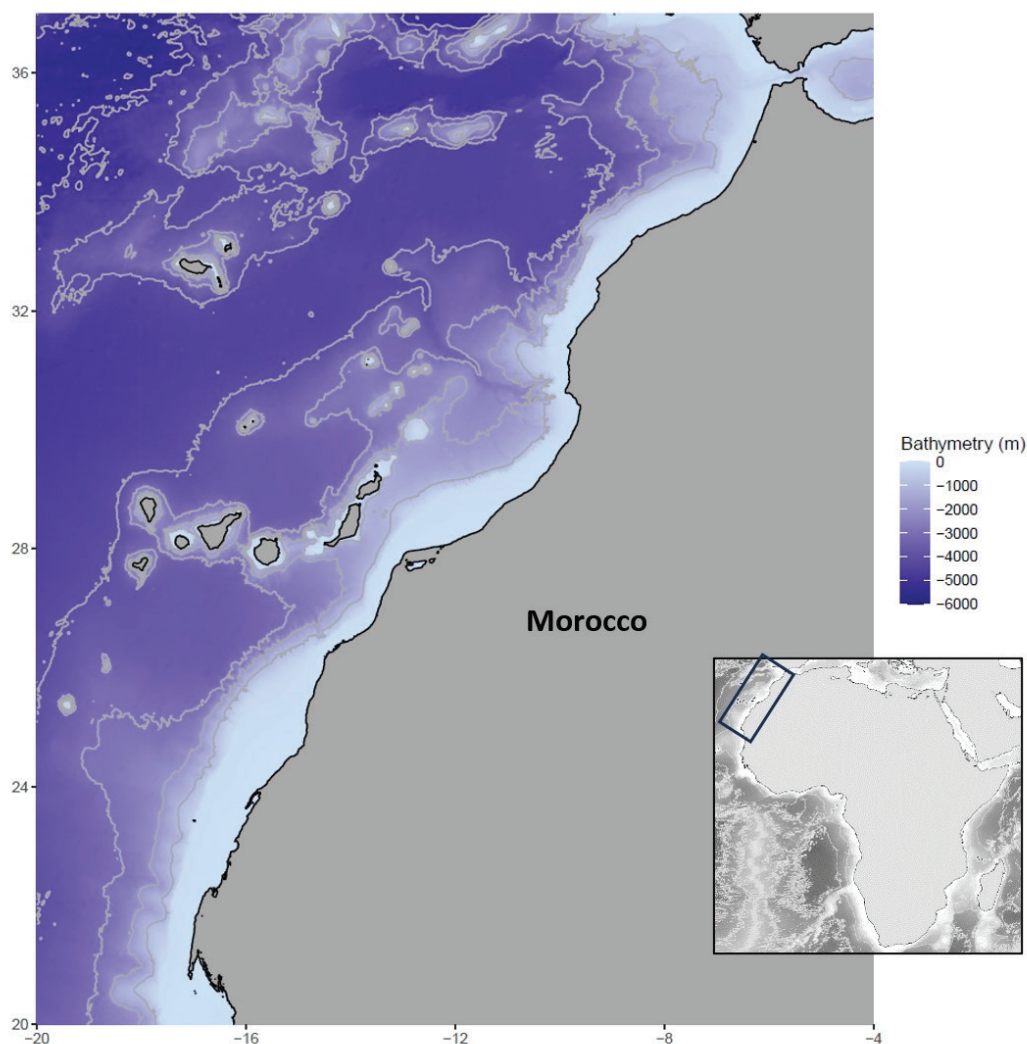


Figure A22. The waters and bathymetry off the Atlantic Moroccan coast for which Stanford et al. (2001) produced a food web model. For the original map with information on the study area see Stanford et al. (2001).

NORTHERN HUMBOLDT CURRENT

The model area considered in the food web model for the Northern Humboldt Current ecosystem as developed by Chiaverano et al. (2018) extended from 4°S to 16°S (Figure A23) and 111 km (60 nm) off the Peruvian coast, representing an area size of 165,000 km². This area concerns a year-round upwelling system (Carr, 2001) and included vital habitats of commercially important forage fish, including sardines (Chavez et al., 2008; Cardenas-Quintana et al., 2015) and anchovy, with the latter representing world's largest fishery by weight (Pennington et al., 2006; Chavez et al., 2008). Chiaverano et al. (2018) used the model to assess the role of large jellyfish and forage fish in the Northern Humboldt Current in general.

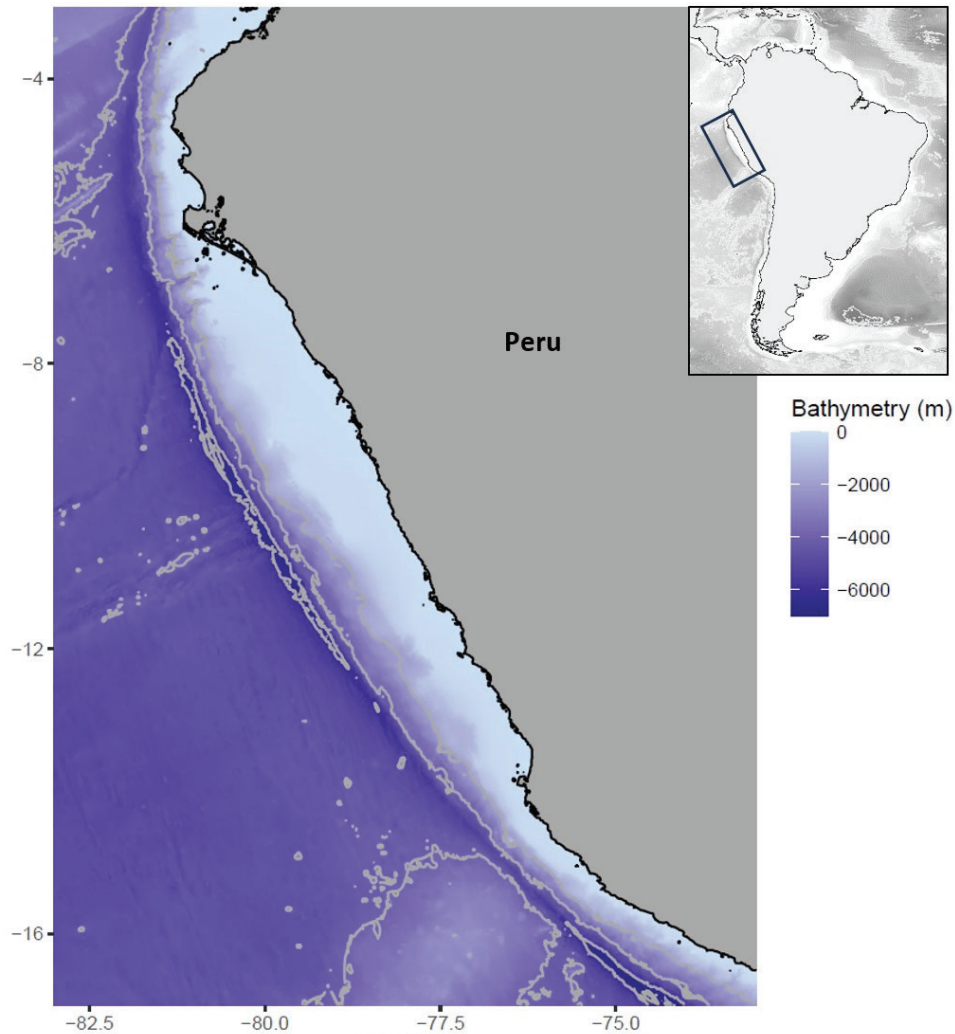


Figure A23. The waters and bathymetry of the Northern Humboldt Current ecosystem off the Peruvian coast for which Chiaverano et al. (2018) produced a food web model. For the original map with information on the study area see Chiaverano et al. (2018)

NORTHWEST ATLANTIC – CANADA

The model area as considered for the northwest Atlantic Canadian model by Tam and Bundy (2019) consists of the southern part of the Labrador Shelf, the northeast Newfoundland Shelf and the Grand Bank and stretches up to the 1000 m isobaths offshore (Figure A24). The area has a size of approximately 495,000 km² and includes most major commercial species. The authors developed this model to assess the general functioning of the ecosystem between 2013 and 2015 when the biomasses of major commercial species were relatively constant.

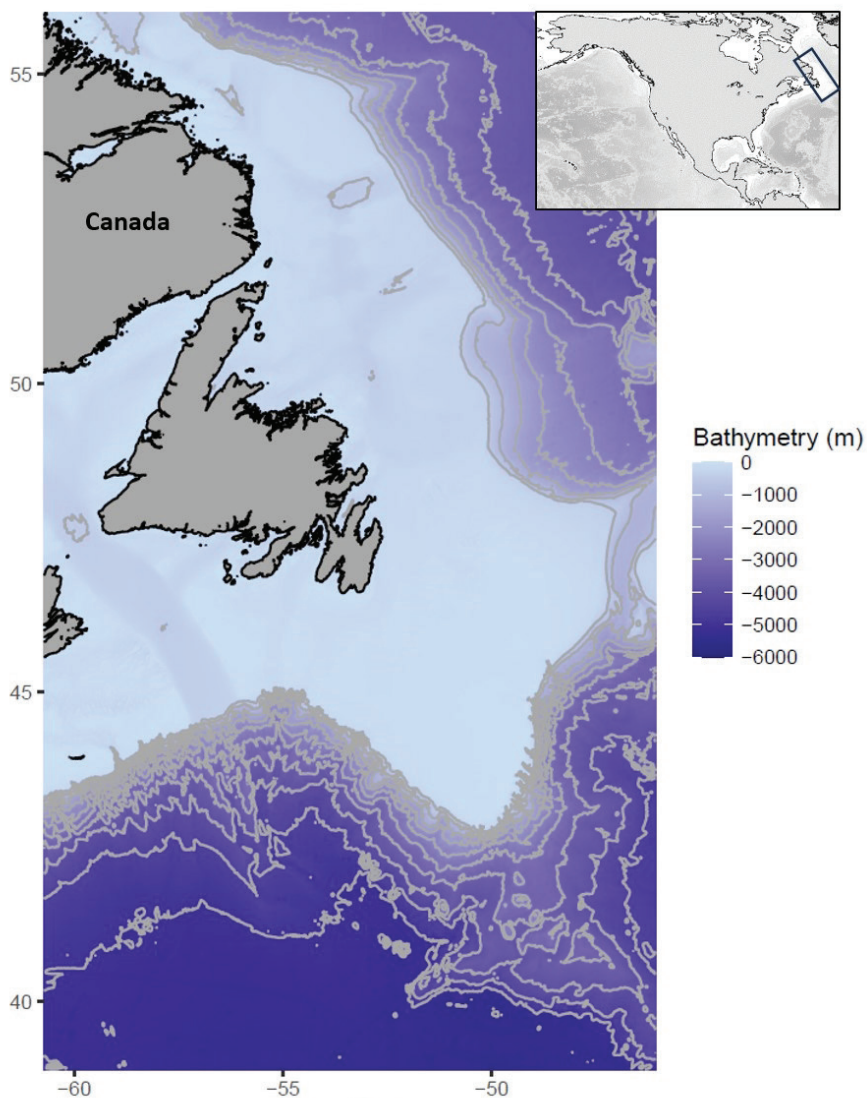


Figure A24. The waters and bathymetry of the northwest Atlantic (Canada) for which Tam and Bundy (2019) produced a food web model. For the original map with information on the study area see Tam and Bundy (2019).

PORTUGAL

The northeast Atlantic food web model developed by Veiga-Malta et al. (2019) included the Portuguese continental shelf ecosystem with a surface area of approximately 22,000 km² between 36.5° and 42° N and between 10.5° and 7.5° W and depths between 30 and 200 m (Figure A25). The width of the continental shelf varies between approximately 5 and 70 km with an average of 45 km (Figure A25). The model was used to study the continental shelf ecosystem between 2006 and 2009.

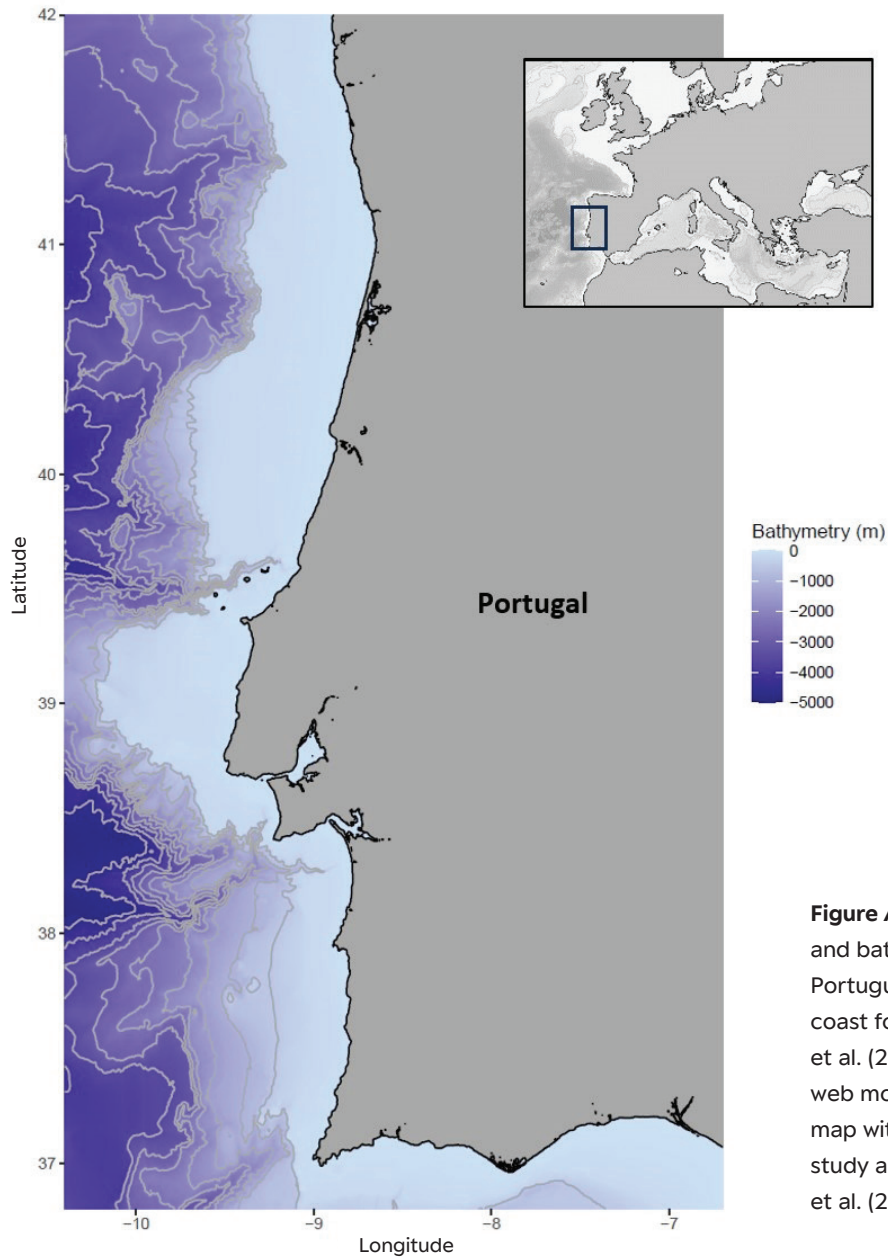


Figure A25. The waters and bathymetry off the Portuguese continental coast for which Veiga-Malta et al. (2019) produced a food web model. For the original map with information on the study area see Veiga-Malta et al. (2019).

SOUTH KOREA

The model area as considered by the food web model for the waters surrounding South Korea, developed by Kim et al. (2022), included the waters within the Korean EEZ in the Sea of Japan (East Sea), Yellow Sea and East China Sea (Figure A26). As such, it overlapped partly with the Tsushima Warm Current between South Korea and Japan, which channels warm water from the East China Sea into the East Sea (or Sea of Japan) in a northeast direction. Korea divided its surrounding waters into 1,331 sea zones (grids with an average area of 2,580 km²). The model area included 167 of these zones and had a total area size of 393,862 km². Kim et al. (2022) used the model to make predictions for the ecosystem for 2024 and 2069, five years and 50 years from 2019, the year their assessment was conducted.

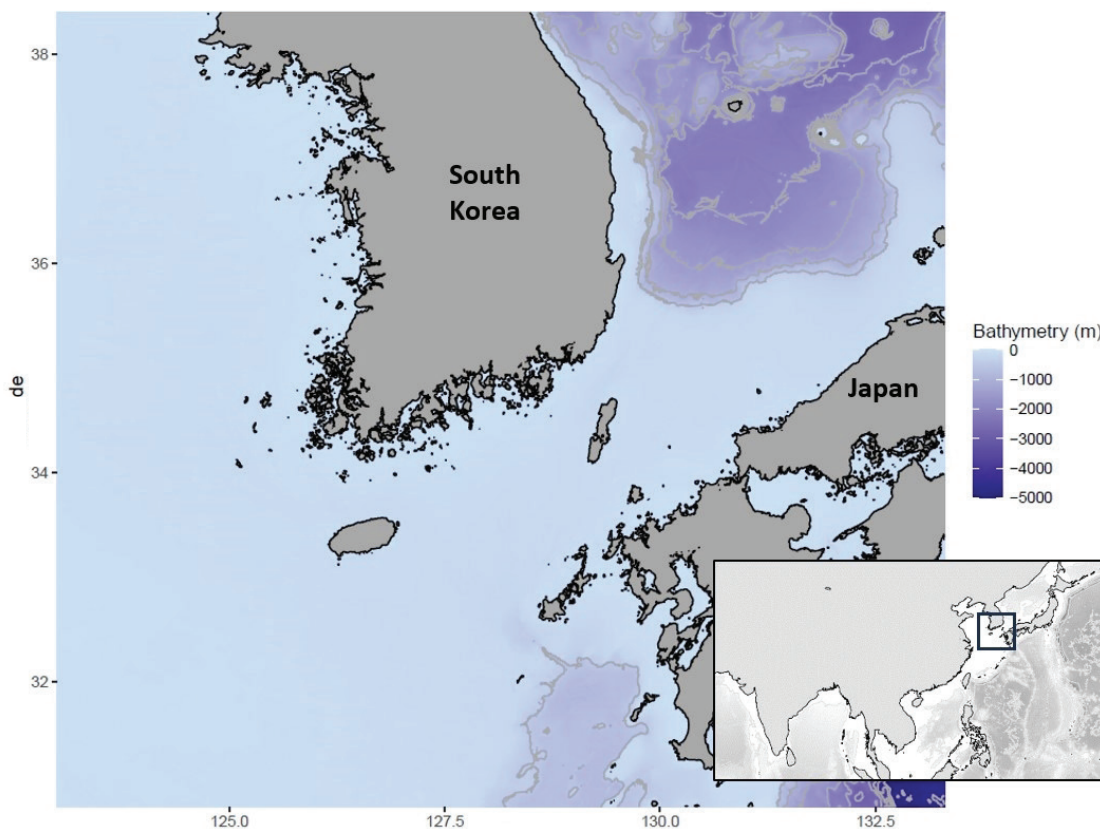


Figure A26. The waters and bathymetry off South Korea for which Kim et al. (2022) produced a food web model. For the original map with information on the study area see Kim et al. (2022).

SOUTHEASTERN GULF OF ALASKA – BRITISH COLUMBIA

Surma et al. (2019) developed a food web model for the ecosystem of the southeastern Gulf of Alaska off British Columbia (Figure A27). The model area ranged from approximately 54.8°N to 51.6°N and 134°W to 130°W (Figure A27), surrounding the archipelago of Haida Gwaii, with a total area size of approximately 81,000 km². The study area includes feeding grounds for four herring stocks targeted by commercial and Indigenous fisheries (Fisheries and Oceans Canada, 2016). The ecosystem is influenced by the southerly Alaska Current, originating from the westerly North Pacific Current (generally) just south of Haida Gwaii (Batten and Welch 2004). As a result, this ecosystem exhibits more frequent incursions and a higher biomass of Pacific hake (Berger et al., 2017), and lower biomass of walleye pollock (Guénette, 2005) than southeast Alaska and has a high biodiversity and productivity. It features diverse habitats, including estuaries, fjords, rocky reefs, sandy banks, kelp forests, eelgrass beds and rare glass sponge reefs, with a steep continental shelf break off the west coast of Haida Gwaii (PNCIMAI, 2011, Figure A27). Other oceanographic features of this coast include anticyclonic mesoscale eddies during winter which draw nutrients into the open northeast Pacific and boost primary and potentially secondary productivity (Whitney and Robert, 2002). Surma et al. (2019) developed the food web model for different periods (1900, 1950 and present) to analyze the structure and dynamics of the ecosystem, with particular emphasis on the role of Pacific herring (*Clupea pallasii*). Diet data were collected from existing literature and expert opinion.

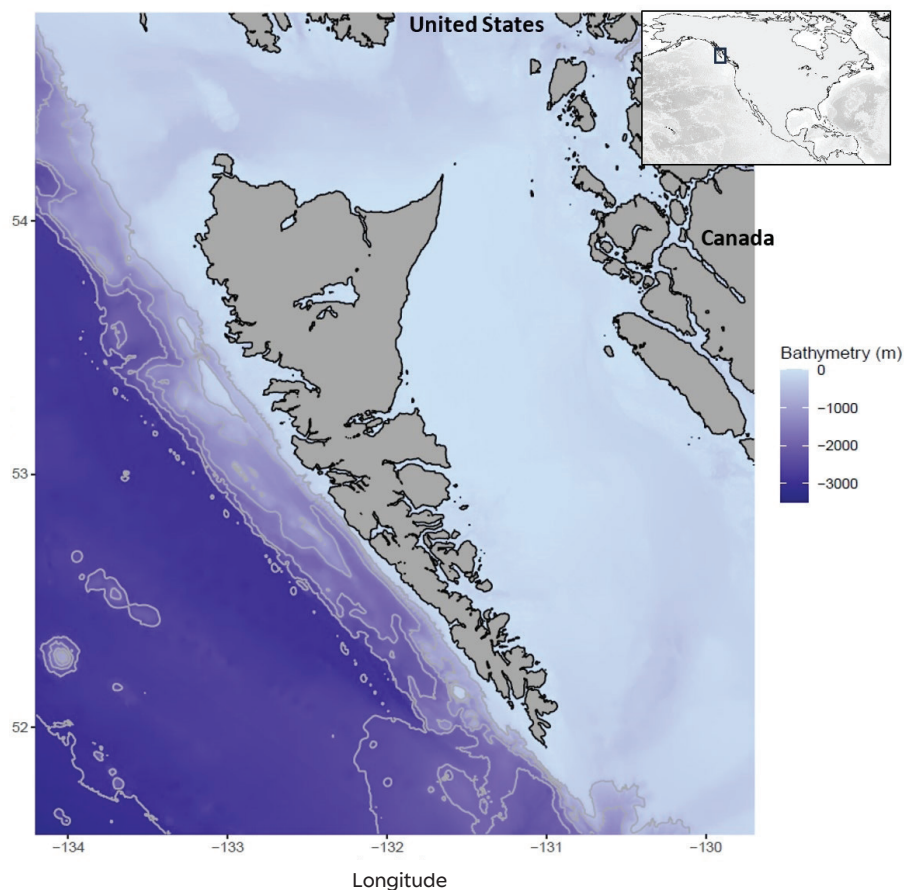


Figure A27. The waters and bathymetry of the southeastern Gulf of Alaska for which Surma et al. (2019) produced a food web model. For the original map with information on the study area see Surma et al. (2019).