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Supporting Online Material for

Impacts of Fishing Low–Trophic Level Species on Marine Ecosystems

Anthony D.M. Smith, Christopher J. Brown, Catherine M. Bulman, Elizabeth A. Fulton, Penny Johnson, Isaac C. Kaplan, Hector Lozano-Montes, Steven Mackinson, Martin Marzloff, Lynne J. Shannon, Yunne-Jai Shin, Jorge Tam

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We used existing validated ecosystem models to explore how various levels of exploitation of LTL species in five ecosystems affected other food web components. The trophic level of the adult stage of the LTL species selected ranged from 2.1 (krill) to 3.9 (mackerel). Details of the groups included in each model are in Table S1.

The southern Benguela ecosystem comprises an eastern boundary current upwelling system off southwest Africa that supports several large and commercially important demersal and pelagic fisheries. Two ecosystem models were examined for this case study, an EwE model comprising 31 groups (*1*) and an OSMOSE model comprising 10 groups (*2, 3*). The OSMOSE model focuses on a subset of key forage and demersal species which represent 94% of the total catch in the 1990s, but does not include higher trophic level predators such as seabirds and marine mammals.

The northern Humboldt ecosystem comprises an eastern boundary current upwelling system off Peru that supports the world's largest single species fishery (for Peruvian anchovy). The ecosystem is characterised by very high levels of productivity and is strongly influenced by environmental forcing, particularly ENSO cycles that can dramatically alter the structure of the system. Two ecosystem models were examined for this case study, an EwE model comprising 31 groups (*4, 5*) and an OSMOSE model comprising 8 groups (*6*). The OSMOSE model focuses on a subset of key forage and demersal species but does not include higher trophic level predators such as seabirds and marine mammals.

The south east Australian ecosystem comprises a shelf and upper slope system along the eastern and southern coasts of Australia. In the main it is not strongly influenced by upwelling and does not support large fisheries. Two ecosystem models were examined for this case study, an EwE model comprising 57 groups (*7*) and an Atlantis model comprising 55 groups (*8*). The Atlantis model has detailed spatial representation and covers most of the region. It includes age structure in most vertebrate groups and some invertebrate groups, allowing representation of ontogenetic shifts in diet. The EwE model covers a smaller part of the spatial domain of the Atlantis model, does not include spatial structure, and most groups are represented as single biomass pools.

The California Current ecosystem comprises an eastern boundary current upwelling system off the west coast of the US that supports several large and commercially important demersal and pelagic fisheries. There is a considerable degree of inter-annual environmental forcing of the system including by the Pacific Decadal Oscillation and El Niño-Southern Oscillation. Two ecosystem models were examined for this case study, an EwE model comprising 60 groups (*9*) and an Atlantis model comprising 52 groups (*10, 11*). Both models cover a similar spatial area though the domain for the Atlantis model extends further south. Atlantis includes age structure in most vertebrate groups and some invertebrate groups, allowing representation of ontogenetic shifts in diet. The EwE model does not include spatial structure, and all groups are represented as single biomass pools.

The North Sea ecosystem comprises a partially enclosed shelf system that supports several large and commercially important demersal and pelagic fisheries and is regarded as heavily fished. One ecosystem model was examined for this case study, an EwE model comprising 65 groups (*12*, *13*).

The same analyses were undertaken for all case studies and models. Models were run to near present time using historical environmental forcing and fishing effort levels. The models were then run forward for 50 years with a range of harvest rates applied to selected LTL species, while all other fished groups were fished at status quo harvest rates corresponding to the end of the historical period. Future inter-annual environmental forcing was included for the Atlantis models, but was not included for the EwE and OSMOSE models.

The models were used to explore the impact of fishing LTL species on all other groups in each ecosystem. The analysis looks at the relative impact on other groups (expressed as the percent change in final biomass of that group relative to its final biomass in the scenario where the LTL species is unfished) of depleting the focal LTL species to 75%, 40%, 20% and 0% of its unfished biomass level (referred to in the main text as depletion levels of 25%, 60%, 80% and 100%). These depletion levels correspond respectively to the target for krill in the Southern Ocean, a common default proxy for MSY target biomass, a common biomass limit reference point, and extirpation. Where the group declines when the focal LTL species is fished, the relative impact will be negative down to a minimum value of -100% (the group is extirpated). If there is no change in abundance of the group from fishing the LTL group, the relative impact is zero. If the group increases due to fishing the LTL species then the relative impact will be some positive value (which can exceed 100%). Figure S1 shows the distribution of impact size for two levels of depletion of LTL species across all modelled ecosystems. Figure S2 shows the distribution of absolute impact size broken down by individual models.

For each case study and model, results were explored for several focal LTL species. These included species with existing target fisheries (such as anchovy, sardines and mackerel) as well as some groups that are not currently the focus of target fishing in those ecosystems (such as mesopelagic fish and krill). Due to the very large volume of results from all combinations of case study, model and focal LTL species plus the very large number of ecological groups in each model, we also looked for ways to summarise results. We initially explored several system level indicators (including mean trophic level of the catch, piscivore to planktivore ratio, and pelagic to benthic ratio) but these proved not to be informative. The two most useful indicators we found were a “frequency of impact score” that measured the percentage of ecological groups with relative changes in biomass greater than 40%, and a “rank impact score” where rank 1 meant that no group in the ecosystem had a change in relative biomass of more than 20%, rank 2 meant that no group had a change in relative biomass of more than 60%, and rank 3 meant that at least one group had a change in relative biomass of more than 60%. For both indicators, both positive and negative changes in biomass of impacted groups were considered important. The frequency of impact score is an indicator that summarises impact across all groups, while the rank impact score measures worst case outcomes. In some cases results were summarised across all groups, while in others the impacts on other commercial species, or on marine mammals and seabirds, were examined separately.

Empirical support for model results

All the models used in this study have been calibrated against time series data for the ecosystems in which they have been applied. However the future harvest scenarios and resulting abundance levels for LTL species used in the analysis take the model outside previously observed ranges in some instances. It is therefore worth considering whether the predictions about impacts of depleting LTL species on other groups have any additional empirical support in these ecosystems. In general, this will rely on observed responses of some predators, particularly birds and mammals, to environmentally driven fluctuations in some of the LTL species of interest. We consider this issue for each of the five ecosystems in this study.

California current

In the California Current, inter-annual variability in forage species abundance, driven by oceanographic patterns of El Niño-La Niña, provides evidence of the importance of these groups for supporting upper trophic levels. The bulk of this evidence is for birds and mammals, which demonstrate changes in growth, reproduction, and behavior due to depletion in forage species. For instance, the abundance, growth, and fledging mass (a correlate of fitness) of birds such as Cassin's auklet (*Ptychoramphus aleuticus*) and the rhinoceros auklet *(Cerorhinca monocerata)* are affected by local abundance of euphausiids, particularly *Thysanoessa spinifera, (14, 15)* or anchovies *(16)*. Local abundance of baleen whales in Monterey Bay declined early in the 1997-1998 El Niño event, apparently due to coast wide declines in euphausiids, but then increased within Monterey Bay later during the El Niño as whales concentrated in this area due to its relatively high productivity *(17)*. Similarly marked changes were found in the distribution of marine mammals such as California sea lions *Zalophus californianus*, and humpback whales *Megaptera novaeangliae* during El Niño (*18*), which were attributed to decreases in forage species availability in southern areas.

The California current EwE and Atlantis models predict some but not all of these effects (Table S1C). For example, the California current EwE model predicts a substantial decline in several bird species when forage fish decline, and moderate effects for decline in euphausiids. The Atlantis model also predicts that depletion of euphausiids will lead to moderate, 15 to 25% declines in some birds and mammals. Overall, empirical data for mammals and birds supports simulated numerical and/or growth responses; however the models are not intended to capture behavioral or movement responses of predators.

SE Australia

Pilchards (sardines) suffered two mass mortality events in southern Australia during the 1990s and several studies examined the impacts on sea birds. The breeding success of the Australasian gannet declined after the 1998 event with the composition of pilchards in the diet reducing from 60% to 5% (*19*). The breeding success of Little penguins was low for two years following the 1995 mortality event and there was low survival in the winter of 1995 (*20, 21*). Little terns were not affected by the 1995 event, but declined following the 1998 event (*22*).

The EwE model predicts a substantial decline in penguins from fishing small pelagics, which include pilchards (Table S1D). Other seabirds showed a lower but still substantial decline. The base case formulation of the Atlantis model does not predict substantial declines in sea birds (penguins are not differentiated) but plausible alternative parameterisations (see Table S1D) do show such declines.

North Sea

In the North Sea, where the Wee Bankie sand eel (*Ammodytes marinus*) fishing grounds have been closed since 2000 because of concerns about impacts on seabirds, evidence indicates a positive link between the abundance of adult and juvenile sand eels and the consumption and breeding success of black-legged kittiwakes (*Risssa tridactyla*) (*23, 24*). Six other seabird species known to forage in the same area were not linked with changes in sand eel abundance suggesting that, although fishery closures may have beneficial effects for seabirds that are highly dependent upon species targeted by fisheries, the role of environmental conditions is also likely to be important.

As well as being important for seabirds, sand eels form part of the staple diet of many North Sea fish predators (*25*) and marine mammals, particularly the harbour porpoise (*Phocoena phocoena)* and the common seal (*Phoca vitulina*). Harbour porpoises are found throughout the North Sea and are known to be the most abundant cetacean species in the region (*26*). Demonstrating that more porpoises starved to death in low sand eel years (2002 and 2003) compared to other periods, McLeod *et al*. (*27*) raised concern about the possible implications for porpoise populations, given declines in the availability of sand eels since 2002. Evans (*28*) similarly suggested that changes in harbour porpoise abundance during the 1980s might be related to annual variation in sand eel populations since spawning stock biomass of sand eels declined markedly from 1984–92, when porpoise populations also apparently declined. Common seals are thought to forage over large distances, regularly visiting offshore sites including the sand eel-rich Dogger Bank. Although common seals preferentially consume demersal fish such as whiting and plaice (*29*), they are thought to be more reliant on sand eels as a key prey in comparison with the larger, and more abundant grey seal (*Halichoerus grypus*) (*30*).

Studies on consumption of sand eels by predatory fish on the Dogger Bank North Sea (*29*) show that the diet flexibility and ability to substitute diet shortfalls with other prey items suggests that predatory fishes are perhaps less crucially dependent on local sand eel abundance than for example the seabird colonies of Scotland (*24*). This is supported by other research showing that predatory fish tend to be generalist feeders and hence less reliant on a particular prey resource. Aggregative responses of predatory fish to high densities of sand eels on the Dogger Bank (*31*) and evidence that the predators' condition index is higher when their consumption of sand eels is high (*32*) provide some evidence that locally intensive sand eel fisheries may indirectly impact on predatory fish.

The EwE model for the North Sea predicts that many groups are substantially affected by declines in sand eel abundance (Table S1E). In broad agreement with the empirical data, groups that decline by more than 40% when sand eel is depleted by 60% include whiting, rays, sea birds, seals and minke whales (*Balaenoptera acutorostrata)*. Declines of toothed whales (principally harbor porpoise) are approximately 20%.

Southern Benguela

There are several examples in the Benguela ecosystem where prey depletion has been shown to strongly affect seabirds (*33*). In the northern Benguela ecosystem off Namibia, large declines in African penguin, Cape gannet and Cape cormorant have been significantly related to biomass of sardine and anchovy. In the southern Benguela off South Africa, the relationships have been more complex. Cape gannets and Cape cormorants remained stable after the collapse of sardine in the late 1950s, whereas African penguins declined. Sardine recovered in the 1980s and 1990s, but by the early 2000s the stock has shifted in distribution by 400km to the south and east (*34*), severely reducing available prey for breeding seabirds along South Africa's west coast, and at least partly influencing the observed large declines in African penguin and Cape gannet off the west coast of South Africa.

The EwE model for the southern Benguela predicts substantial declines in several groups, including sea birds, seals and cetaceans, when sardines are reduced in abundance due to fishing (Table S1B). The OSMOSE model does not represent sea birds or marine mammals but does predict a decline in predatory fish (the top predators in this representation of the ecosystem) in response to fishing sardines.

Northern Humboldt

Fluctuations in dominant forage species such as Peruvian anchoveta, which is seven times more abundant than any other fish species in the region and four times more abundant than macrozooplankton *(4*), may have large impacts on predators such as Humboldt penguins *Spheniscus humboldti* (*35*). The availability of anchovy and sardine has been linked to the dynamics of other sea bird populations in the region, including guanay cormorants (*Phalacrocorax bougainvillii*) (*36, 37*) as well as fur seal (*Arctocephalus australis*) and sea lion (*Otaria byronia*) (*38*).

The EwE model for the Northern Humboldt predicts large decreases in abundance in a range of groups with depletion of anchovy, including seabirds and marine mammals (Table S1A). The OSMOSE model does not represent these groups.

Sensitivity to model assumptions

Model sensitivity to parameterization is always an issue and especially when considering the dynamics of complex ecosystem models. Consequently we paid particular attention to this when evaluating the results of the depletion experiments – using fitted, well established models and multiple parameterisations for the systems (where available, e.g. Atlantis-SE). Predator-prey connections and structural sensitivity are one of the key uncertainties in ecosystem models. As the different modelling platforms treat trophic interactions in different ways, the robustness of the results across the models strengthens confidence in the generality of the results. Of the modelling approaches, OSMOSE is the least susceptible to sensitivity around trophic connections as they are emergent features from the size-based feeding used in this individual-based model (i.e. no functional feeding term is defined for the model). Atlantis does use a matrix of potential trophic connections to define potential links and then filters these through gape limitation, habitat mediation and co-occurrence of predator and prey to determine actual connections. Depending on the dominance of different processes across different species, Atlantis models can be sensitive to the maximum magnitude defined for the potential links. To check against this sensitivity, multiple versions of the connection matrix were run (from extremes where predation was the dominant process in the system to others where links were not universally strong) with qualitatively similar outcomes (i.e. similar numbers of groups affected by the depletion of small pelagics, though as expected the details of which species were impacted did vary between the different parameterisations). Finally, EwE is known to be potentially very sensitive to the setting of the vulnerability parameters defining predator-prey interactions. All EwE models have been fit to time series data so the models have vulnerabilities tuned to each specific system. Moreover in each case, across the different interactions, the vulnerability settings represent a mix of top-down and bottom-up connections. As a result it is very unlikely that, across the ecosystems examined, the results are unduly or inappropriately influenced by the vulnerabilities – further verified by the fact that the results are broadly consistent with those from other models that do not use vulnerability terms.

Reference points for LTL species

Reference points for LTL species vary widely as does their current exploitation status. A recent review for small pelagic species including anchovy and sardines (*39*) found outcomes ranging from complete protection of forage species (e.g. in Alaska) to severe overfishing (e.g. Namibian sardine). Current status relative to maximum biomass levels for anchovy stocks ranged from 10 to 96%, with half the stocks less than B_{40} (40% of maximum levels) and 80% of stocks less than B_{75}. For sardine stocks, the corresponding range was 1 to 71%, with 70% of stocks less than B_{40}.

Harvest strategies, including target and limit reference points, vary widely (*39*). A number of stocks, including some that are heavily depleted, have essentially “status quo” strategies, designed only to prevent further depletion of the stock. Many stocks have target exploitation rates close to MSY levels or proxies for MSY. Default biomass targets for Australian stocks are 20% above B_{MSY}, with a limit reference point at half B_{MSY}. Anchovy and sardine are managed in the southern Benguela using operational management procedures (*40*) that correspond to target biomass levels relative to unfished levels of 68% for sardine and 61% for anchovy. Peruvian anchovy are managed so as to maintain the stock above a minimum biomass currently set at 5 million tonnes (about 25% of the maximum biomass in 1970 but a higher fraction of recent average biomass). The most recent stock assessment for California sardines (one of three main forage fish, along with anchovies and herring) does not explicitly estimate F_{MSY} or MSY (*41*). However, the current stock-wide harvest guideline is equal to 15% of the biomass above 150,000 tonnes. This harvest rate varies with environmental conditions.

Connectance

We considered a range of alternative forms for connectance, including correcting for average system connectance, weighting connectance by the relative biomass of the LTL species, a diet-weighted mean biomass flow through each LTL species, and a measure that extends the measure to connectance of the predator and prey groups. As none of these measures shed further light on the attributes of the LTL species that result in larger impacts on other parts of the ecosystem, and each is more complex to calculate and communicate, we retained the simple measure reported in the main text.

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Table S1. This table shows the groups represented in each model, as well as the groups that are impacted by the depletion of each LTL group. The numbers in bold represent the groups that show a reduction in biomass when the LTL group is reduced to B40 (40% of unfished level, i.e. 60% depletion level). The non-bold numbers represent groups that show an increase in biomass when the LTL group is reduced.

Table S1A: Northern Humboldt ecosystem

#	EwE	groups impacted by > 40% @ B40	#	OSMOSE	groups impacted by > 40% @ B40
1	Diatoms		1	Munida (red squat lobster)	2, **5**
2	Dinoflagellates		2	Sardine	
3	Microzooplankton		3	Anchovy	1, 4, 8
4	Mesozooplankton		4	Mesopelagics	-
5	Macrozooplankton	**10, 12, 14, 15,** 20, **31**	5	Jumbo squid	
6	Gelatinous zoop		6	Jack mackerel	2, 7
7	Macrobenthos		7	Mackerel	
8	Sardine	**28**	8	Hake	
9	Anchovy	6, 8, **16, 17, 18, 19,** 20, **23, 28, 29, 30, 31**			
10	Mesopelagics	2, **3,** 5, 6, 8, 12, 14, 15, 16, 17, 18, 19, 21, 22, 23, 24, 27, 28, 30, 31			
11	Jumbo squid				
12	Other Cephalopods				
13	Other small pelagic fish				
14	Jack Mackerel	12, 16, 23, 28, 30, **31**			
15	Other mackerel				
16	Other large pelagic fish				
17	Small hake				
18	Large hake				
19	Flatfishes				
20	Small demersal fish				
21	Benthic elasmobranchs				
22	Butter fishes				
23	Conger				
24	Medium demersal fish				
25	Medium sciaenids				
26	Sea robin				
27	Catfishes				
28	Chondrichthyans				
29	Seabirds				
30	Pinnipeds				
31	Cetaceans				

Table S1B: Southern Benguela ecosystem

#	EwE	groups impacted by > 40% @ B40	#	OSMOSE	groups impacted by > 40% @ B40
1	Phytoplankton		1	Macrozooplank (Euphausiids)	
2	Benthic producers		2	Anchovy	9, **10**
3	Microzooplankton		3	Sardine	**9, 10**
4	Mesozooplankton		4	Redeye	**10**
5	Macrozooplankton		5	Mesopelagics	
6	Gelatinous zooplankton		6	*Merluccius capensis*	
7	Anchovy	10	7	*Merluccius paradoxus*	
8	Sardine	10, **16, 27, 28, 29**	8	Horse Mackerel	
9	Redeye	10	9	Snoek	
10	Other small pelagic fish	-	10	Silver kob	
11	Chub mackerel				
12	Juvenile horse mackerel				
13	Adult horse mackerel				
14	Mesopelagics	**10,** 11, 22			
15	Snoek				
16	Other large pelagic fish				
17	Cephalopods				
18	Small *Merluccius capensis*				
19	Large *Merluccius capensis*				
20	Small *Merluccius paradoxus*				
21	Large *Merluccius paradoxus*				
22	Pelagic-feeding demersal fish				
23	Benthic-feeding demersal fish				
24	Pelagic-feeding chondrichthyans				
25	Benthic-feeding chondrichthyans				
26	Apex predator chondrichthyans				
27	Seals				
28	Cetaceans				
29	Seabirds				
30	Meiobenthos				
31	Macrobenthos				

Table S1C: California Current ecosystem

#	EwE	groups impacted by > 40% @ B40	#	Atlantis	groups impacted by > 40% @ B40
1	phytoplankton		1	Diatoms	
2	infauna		2	Picophytoplankton	
3	amphipods		3	Kelp	
4	epibenthic		4	Seagrass	
5	micro zooplankton		5	Microzooplankton	
6	copepods		6	Mesozooplankton	
7	euphausiids	**10, 21, 23, 28, 29, 34,** 38	7	Large zooplankton	-
8	carnivorous zooplankton		8	Gelatinous zooplankton	
9	small jellies		9	Pelagic bacteria	
10	large jellies		10	Squid	
11	Pandalid shrimp		11	Shrimp	
12	Benthic shrimp		12	Benthic bacteria	
13	Dungeness crab		13	Meiobenthos	
14	Tanner Crab		14	Deposit feeders	
15	cephalopods		15	Polychaetes	
16	forage fish	8, 20, 27, 28, 29, **32,** 37, **46, 47, 49, 50, 51, 52**	16	Megazoobenthos	
17	mesopelagics	-	17	Shallow macrozoobenthos	
18	benthic fish		18	Deep macrozoobenthos	
19	macrourids		19	Herbivorous grazers	
20	sardine	-	20	Anemones and deep corals	
21	mackerel	-	21	Sponges and corals	
22	salmon		22	Bivalves	
23	hake		23	Myctophids	1, 5, **6,** 7, **8, 35,** 37
24	skates		24	*Sebastes jordani*	
25	dogfish		25	Shallow small rockfish	
26	sablefish		26	Deep small rockfish	
27	Juvenile rockfish		27	Grenadiers	
28	Pacific ocean perch		28	Nearshore demersals	
29	Canary rockfish		29	Small flatfish (soles)	
30	Widow rockfish		30	Deep large rockfish	
31	Yellowtail rockfish		31	Shallow large rockfish	
32	Black rockfish		32	Midwater rockfish	
33	Shelf rockfish		33	*Merluccius productus*	
34	Slope rockfish		34	*Anopoploma fimbria*	
35	Shortspine thornyhead		35	Mackerel	**43**
36	Longspine thornyhead		36	Small pelagics	**43**
37	Juvenile thornhead		37	Salmon	
38	Juvenile roundfish		38	Large flatfish	
39	lingcod		39	Ophiodon elongates	
40	Juvenile flatfish		40	Thunnus alalunga	
41	English sole		41	Small demersal sharks	
42	Petrale sole		42	Large demersal sharks	
43	Small flatfish		43	Pelagic sharks	
44	Rex sole		44	Skates and rays	
45	Dover sole		45	Puffinus griseus	
46	Arrowtooth flounder		46	Diving seabirds	
47	Pacific Halibut		47	Surface seabirds	
48	albacore		48	Sea otter	
49	coastal sharks		49	Pinnipeds	
50	shearwaters		50	Toothed whales	
51	murres		51	Baleen whales	
52	gulls		52	Orcinus orca	
53	orcas				
54	toothed whales				
55	sperm whales				
56	harbor seals				
57	sea lions				
58	fur seals				
59	grey whales				
60	baleen whales				

Table S1D: SE Australia ecosystem. Additional groups impacted under alternative parameterisations in the Atlantis model are shown in red.

#	EwE	groups impacted by > 40% @ B40	#	Atlantis	groups impacted by > 40% @ B40
1	Macrophytes		1	Pelagic bacteria	
2	Phytoplankton		2	Benthic bacteria	
3	Small zooplankton		3	Picophytoplankton	
4	Large zooplankton		4	Diatoms	
5	Krill	3, 6, 8, 13, 17, 25, 26, 28, 34, 38, **40,** 41, 53	5	Kelp	
6	Gelatinous nekton		6	Seagrass	
7	Polychaeta		7	Heterotrophic flagellates	
8	Megabenthos		8	Copepods	
9	Macrobenthos		9	Krill	3, 8, **10, 23, 25** **1**, **4**, **5**, **6**, 11, **19**, 22, 26, 27, **28**, **33**, **35**, 36, 38, **41**, **46**, **48**, **52**, **54**
10	Pelagic prawns		10	Arrow squid	
11	Squid		11	Scallops	
12	Mesopelagic fishes	5, **15,** 16, **20, 22, 25, 27, 28, 29, 35,** 37, **38, 40, 46, 54**	12	Shallow demersal filter feeders	
13	Large pelagic piscivores		13	Deep demersal filter feeders	
14	Large pelagic fishes		14	Benthic grazers	
15	Medium pelagic piscivores		15	Other crustaceans	
16	Medium pelagic fishes		16	Rock lobster	
17	Small pelagic fishes	**13,** 43, **53**	17	Megazoobenthos	
18	Large slope piscivores		18	Prawns	
19	Large slope fishes		19	Meiobenthos	
20	Medium slope piscivores		20	Benthic deposit feeders	
21	Medium slope fishes		21	Benthic carnivores	
22	Small slope piscivores		22	Small pelgic fish	- **24**, **48**, 50, **55**
23	Small slope fishes		23	Mesopelagic fish	- **1**, **4**, **5**, **8**, 9, **10**, **19**, 22, 24, 25, 26, **27**, **28**, **29**, 31, **32**, **33**, **35**, 36, **41**, **44**, 45
24	Oreos		24	Mackerel	48
25	Ribaldo		25	Red bait	
26	Slope ocean perch		26	Morwong	
27	Blue grenadier		27	Cardinalfish	
28	Blue-eye trevalla		28	Gemfish	
29	Large shelf piscivores		29	Shallow piscivores	
30	Large shelf fishes		30	Spotted warehou	
31	Medium shelf piscivores		31	Tunas	
32	Medium shelf fishes		32	School whiting	
33	Small shelf piscivores		33	Deep demersal fish	
34	Small shelf fishes		34	Blue grenadier	
35	Cardinal fish		35	Shallow demersal fish	
36	Eastern school whiting		36	Redfish	
37	Cucumberfish		37	Ribaldo	
38	Chinaman leatherjacket		38	Flathead	
39	Shelf ocean perch		39	Ling	
40	Gemfish		40	Orange Roughy	
41	Flathead		41	Blue-eye trevalla	
42	Jackass morwong		42	Gummy shark	
43	Jack mackerel	-	43	Demersal sharks	
44	Dories		44	Deepwater dogfish	
45	Ling		45	Pelagic sharks	
46	Redfish		46	School shark	
47	Redbait	-	47	Skates and rays	
48	Warehou		48	Seabirds	
49	Rays		49	Blue warehou	
50	Demersal sharks		50	Seals	
51	Pelagic sharks		51	Gulper sharks	
52	Tunas & billfish		52	Baleen whales	

53	Penguins	53	Dolphins
54	Seabirds	54	Orcas
55	Seals	55	Sealions
56	Baleen whales		
57	Toothed whales		

Table S1E: North Sea ecosystem

#	EwE	groups impacted by > 40% @ B40
1	Phytoplankton	
2	Planktonic microflora	
3	Benthic microflora	
4	Meiofauna	
5	Sessile epifauna	
6	Small infauna	
7	Small mobile epifauna	
8	Shrimp	
9	Infaunal macrobenthos	
10	Epifaunal macrobenthos	
11	Nephrops	
12	Large crabs	
13	Gelatinous zooplankton	
14	Copepods	
15	Carnivorous zooplankton	**20,** 36, **38, 44, 45, 46, 47, 51, 62**
16	Fish larvae	
17	Squid & cuttlefish	
18	Filter-feeding pelagic fish	
19	Small demersal fish	
20	Large demersal fish	
21	Catfish (Wolf-fish)	
22	Dragonets	
23	Halibut	
24	Megrim	
25	Turbot and brill	
26	Witch	
27	Lemon sole	
28	Sole	
29	Flounder	
30	Long-rough dab	
31	Dab	
32	Plaice	
33	Sandeels	**23,** 24, 36, 38, 42, **50, 51, 56, 57, 62, 63, 65**
34	Horse mackerel	
35	Mackerel	36, **45**
36	Sprat	38, 51
37	Adult Herring	24, 44, 45
38	Juvenile Herring	
39	Gurnards	
40	Monkfish	
41	Other gadoids (small)	
42	Other gadoids (large)	
43	Norway pout	
44	Blue whiting	
45	Hake	
46	Adult Saithe	
47	Juvenile Saithe	
48	Adult Haddock	
49	Juvenile Haddock	
50	Adult Whiting	
51	Juvenile Whiting	
52	Adult Cod	
53	Juvenile Cod	
54	Skate + cuckoo ray	
55	Thornback & Spotted ray	
56	Starry ray & others	
57	Juvenile rays	
58	Small sharks	
59	Large sharks	
60	Spurdog	

61	Juvenile sharks
62	Seabirds
63	Seals
64	Toothed whales
65	Baleen whales

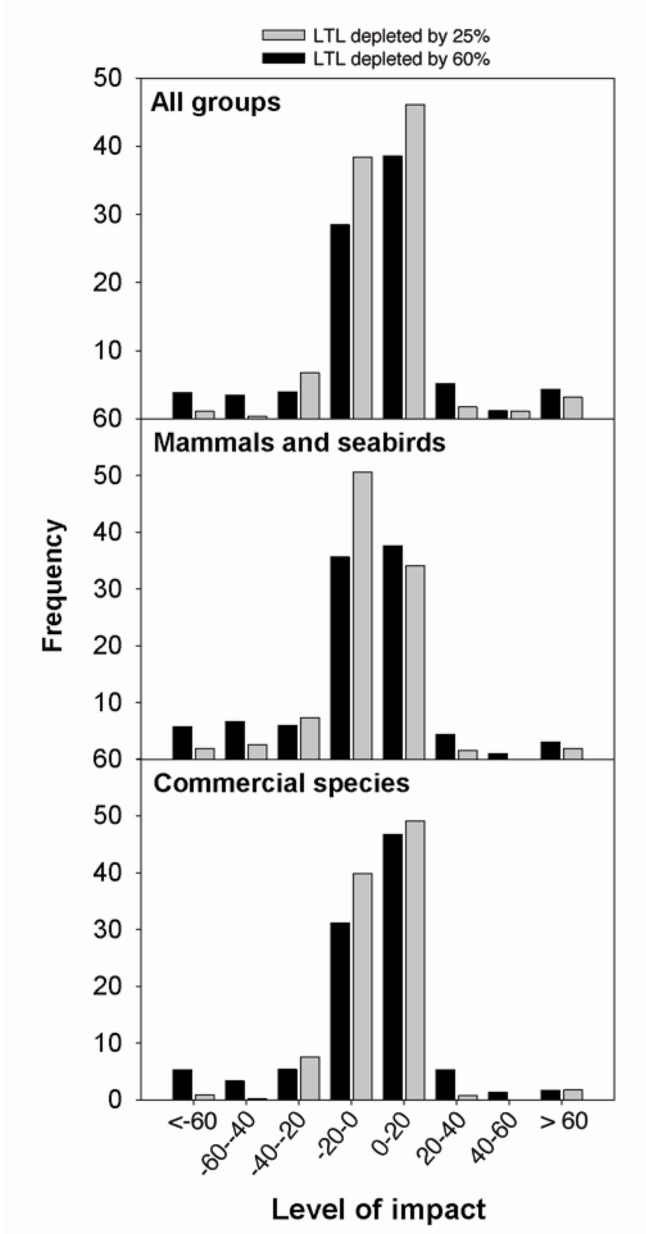

Figure S1. Distribution of impact on other trophic groups of depleting LTL species by 25% (grey) and 60% (black). Impact is measured as the % change in biomass of each group relative to its biomass when the LTL species is not fished. Results are shown for all ecosystems, models and LTL species; other trophic groups can increase or decrease as a result of depleting the LTL species.

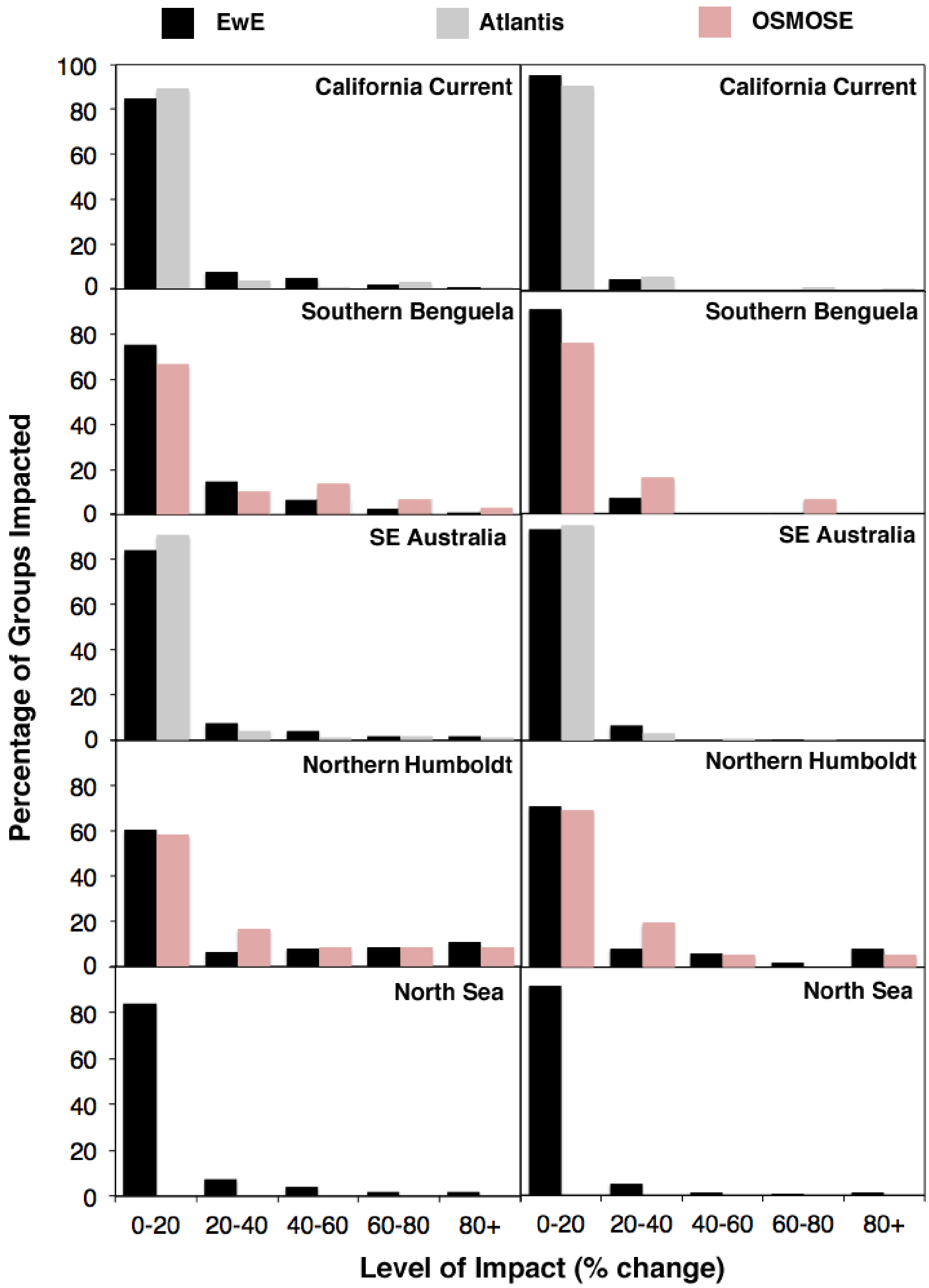

Figure S2. Effect of model structure on pattern of impact – EwE (black), OSMOSE (red), Atlantis (blue). Figures on left are for 60% depletion of LTL species, figures on right are for 25% depletion of LTL species.

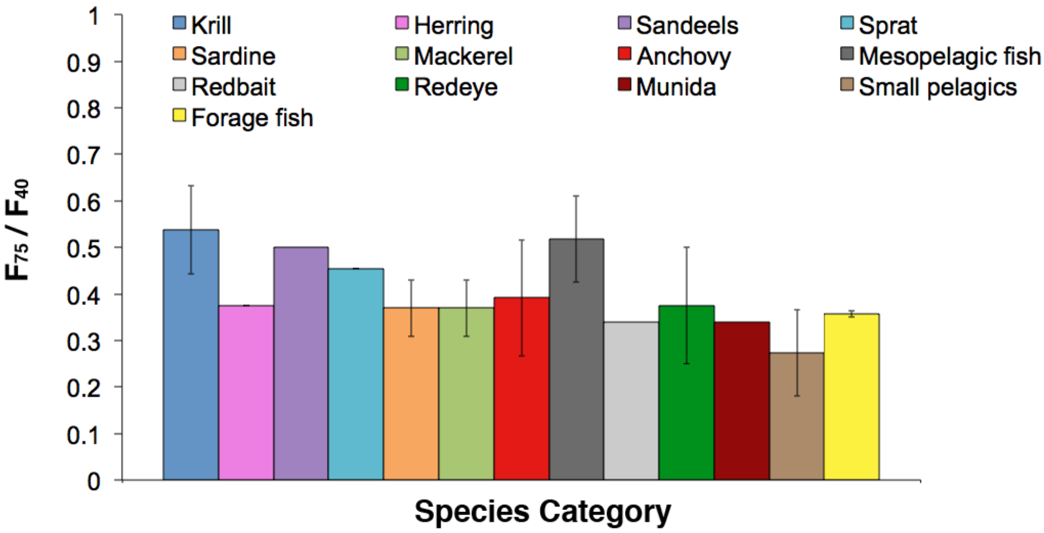

Figure S3. Ratio of fishing mortality rate F at 25% depletion (75% unfished F_{75}) to F at 60% depletion (40% unfished F_{40}) for selected LTL species. The error bars show the standard error across all the models and ecosystems for each LTL species category.