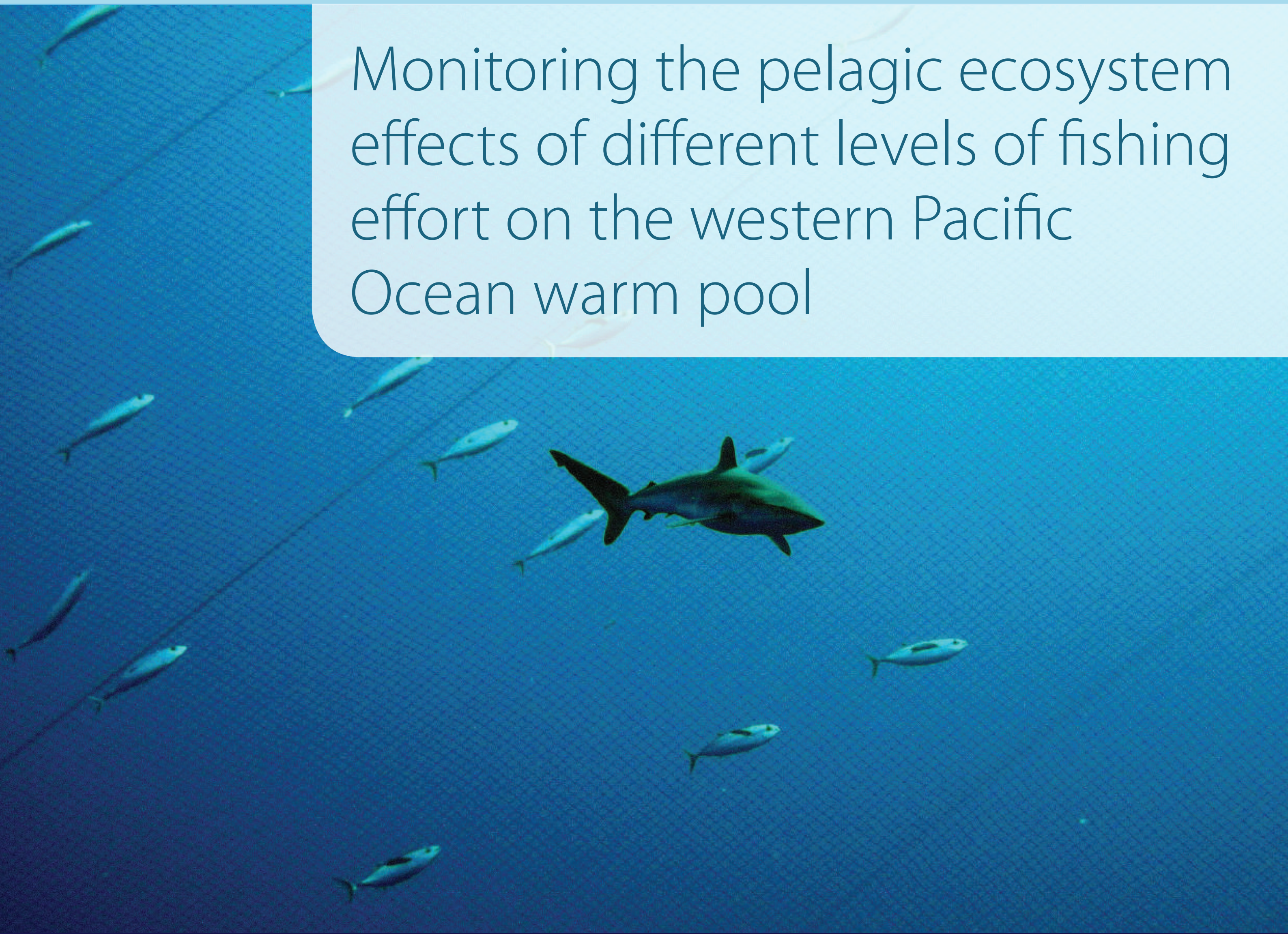
SPC
Secretariat of the Pacific Community

Monitoring the pelagic ecosystem effects of different levels of fishing effort on the western Pacific Ocean warm pool



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This report may be cited as follows:

Allain V., Griffiths S., Bell J. and Nicol S. 2015. Monitoring the pelagic ecosystem effects of different levels of fishing effort on the western Pacific Ocean warm pool. Issue-specific national report. Oceanic Fisheries Programme, Secretariat of the Pacific Community, Nouméa, New Caledonia.

This project was supported by the New Zealand Ministry of Foreign Affairs and Trade, Australian Department of Foreign Affairs and Trade (SPC–Australian Climate Change Support Programme 2011–2013), and by the 10th European Development Fund (Scientific Support to Coastal and Oceanic Fisheries Management in the Western and Central Pacific Ocean).

Design and layout: SPC Publications Section, Noumea, New Caledonia

Contents

Executive summary

1. The purpose of this report is to provide Pacific Island countries that are influenced by the warm pool (the area bounded by 10°N–15°S and 140°E–180°) with information on the potential impacts of tuna fishing on this important pelagic ecosystem, with a view to assisting these countries with developing policies that minimise the detrimental impacts of fishing through adjusting the amount and type of industrial fishing effort.

2. The specific aims of this report are to:
   1) describe the pelagic ecosystem model constructed for the warm pool;
   2) explain the key dynamics of the warm pool ecosystem; and
   3) explore the potential impacts of harvesting fish on the ecosystem.

3. The warm pool pelagic ecosystem was modelled using Ecopath with Ecosim (www.ecopath.org). Ecopath describes the static state of trophic flows (predator–prey relationships) within a food web that balance the net production of functional groups (assemblages of species with a similar ecology, or a species or a size class within a species) with all sources of mortality and migration. Ecosim is a dynamic form of Ecopath that allows the forecasting of ecosystem responses to specific perturbations (e.g. changes in water temperature or fishing effort) through time.

4. The ecosystem model constructed for the Pacific warm pool is characterised by five trophic levels (TL), a high number of trophic links between groups, and a diverse pool of prey for predators. In the model, the majority (74%) of the ecosystem's biomass is in TL 1–2 (phytoplankton, zooplankton), whereas 89% of the industrial fish catch (tuna, edible bycatch and other top predators) is in TL 3–5.

5. The model was used to explore nine different scenarios of fishing effort, ranging from measures designed to reduce and/or increase the amount of bycatch, decrease and/or increase the amount of tuna harvested by altering the

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amount of longline fishing and purse-seine fishing effort on unassociated (i.e. free) schools and on schools associated with fish aggregating devices (FADs), and by simulating the implementation of bycatch mitigation measures.

6. The outcomes of this modelling showed that the structure of the warm pool ecosystem is resistant to considerable perturbation (e.g. large changes in the harvest of the surface fish community). The intrinsic resistance of the ecosystem to perturbation appears to be related to the high diversity of predators in the food web that consume a wide range of prey.

7. The structure of the ecosystem was most sensitive to changes in the biomass of prey groups (e.g. small pelagic fish such as anchovy) because these important mid-trophic level species are both important prey for tuna, and are predators of organisms in the lower trophic levels.

8. Key indicators of the ecosystem show that: 1) the catch of bycatch species, such as sharks and billfish, in the warm pool has increased; 2) the tuna fishery has expanded in recent decades; and 3) the diversity and biomass of groups in the higher trophic levels (TL3–TL5) have diminished.

9. Some of the predicted changes in the structure of the warm pool ecosystem in response to alterations in fishing effort are expected as a direct result of fishing, whereas others are the result of indirect effects from changes in the biomass of predator or prey groups.

10. The simulations showed that the largest impacts of changes in purse-seine and longline fishing effort are likely to be on the groups comprising long-lived, bycatch species with lower productivity (e.g. silky and white-tip sharks, opah, swordfish and blue marlin). These groups are the most sensitive to changes in harvests of fish species due to their longevity, age-at-first maturity, and low rate of reproduction.

11. Increases in purse-seine fishing effort on FADs result in greater mortality of sharks, and in decreases in the biomass of some tuna species and size classes. Conversely, reductions in purse-seine fishing effort on FADs increase the numbers of sharks, although such benefits are not as pronounced when purse-seine fishing effort on FADs is transferred to purse-seine fishing on free schools of tuna. Increases in longline fishing result in greater mortality of sharks, opah and some billfish species. The negative impact on opah and billfishes is also observed when longline fishing effort is unchanged but shark mortality decreases by the implementation of shark mitigation measures.

12. The changes in the abundance of sharks predicted by the model should assist fisheries managers to evaluate the effects that different levels of purse-seine fishing effort (on both unassociated schools and schools associated with FADs) have on top-level predators, and to develop management measures that contribute to the conservation of sharks.

13. Recommendations for improving the use of ecosystem models to advise management include:
    1) identifying detailed objectives for ecosystem management;
    2) developing better ecosystem indicators;
    3) increasing the monitoring of catch and discards for bycatch species, and expanding fisheries monitoring programmes to include prey species, to provide all necessary inputs for the models; and
    4) adding a spatial component to the Ecopath with Ecosim model.

Context

The potential for fishing to have ecosystem-wide impacts has been widely recognised by Pacific Island countries. Together with the regional fisheries management agencies[1], the main Pacific Island countries under the influence of the warm pool — Federated States of Micronesia (FSM), Kiribati, Marshall Islands, Nauru, Papua New Guinea (PNG), Solomon Islands and Tuvalu — require information on the effects of the tuna fishery on the pelagic ecosystem in order to develop policies that minimise detrimental impacts. In particular, information is needed on how the warm pool ecosystem is affected by large tuna catches made in Pacific Island exclusive economic zones (EEZs) (Table 1), and by changes in fishing effort.

Assessing the impact of fishing effort and the effectiveness of conservation measures on an ecosystem is not easy; there are significant difficulties involved in modelling complex marine ecosystems, detecting changes in the relative abundance or biomass of species, and reliably attributing such changes to specific fishing activities. Quantitative ecosystem models are the only tools that can represent the complexity of the feeding (trophic) relationships between the wide range of species within a marine ecosystem, and the interactions of these relationships with major features of the environment and fishing activities.

The aims of this report are to:

1) describe the pelagic ecosystem model constructed for the warm pool;

2) assist fisheries managers with understanding the dynamics of the Pacific warm pool ecosystem; and

3) explore the potential impacts of harvesting fish on the ecosystem, both on target species and non-target species.

Table 1. Average total catch (tonnes) by all fishing methods for all tuna species caught between 2008 and 2012 from the combined exclusive economic zones (EEZs) of Pacific Island countries and territories (PICTs). The average catch (tonnes) taken from the EEZs of each of the seven countries influenced by the warm pool is also shown. Collectively, the catches of tuna from these seven counties represent 95% of the total tuna catch from all PICTs.

Year	All PICTs	PNG	Kiribati	Solomon Islands	FSM	Nauru	Tuvalu	Marshall Islands
2008	1,152,699	494,978	254,937	133,090	89,421	60,279	40,501	28,468
2009	1,224,434	455,679	331,390	122,984	118,555	59,771	63,390	16,405
2010	1,516,130	706,305	230,098	187,579	153,738	106,966	60,642	23,755
2011	1,435,523	616,664	220,858	176,684	160,347	107,810	59,642	24,652
2012	1,643,964	577,481	552,145	96,674	170,026	54,657	71,128	27,622
Average	1,394,550	570,221	317,886	143,402	138,417	77,896	59,061	24,181

PNG = Papua New Guinea; FSM = Federated States of Micronesia

1 Western and Central Pacific Fisheries Commission, the Pacific Islands Forum Fisheries Agency, and the Parties to the Nauru Agreement.

Definition of the Pacific warm pool

The Pacific warm pool is the oceanographic province in the western and central Pacific Ocean (WCPO) that is defined by the boundaries of the 28°C sea surface temperature isotherm. The surface area of the warm pool varies with the El Niño and La Niña phases of the El Niño-Southern Oscillation. However, for the purpose of developing the ecosystem model, the warm pool is defined as the area bounded by 10°N–15°S and 140°E–180° (Fig.1).

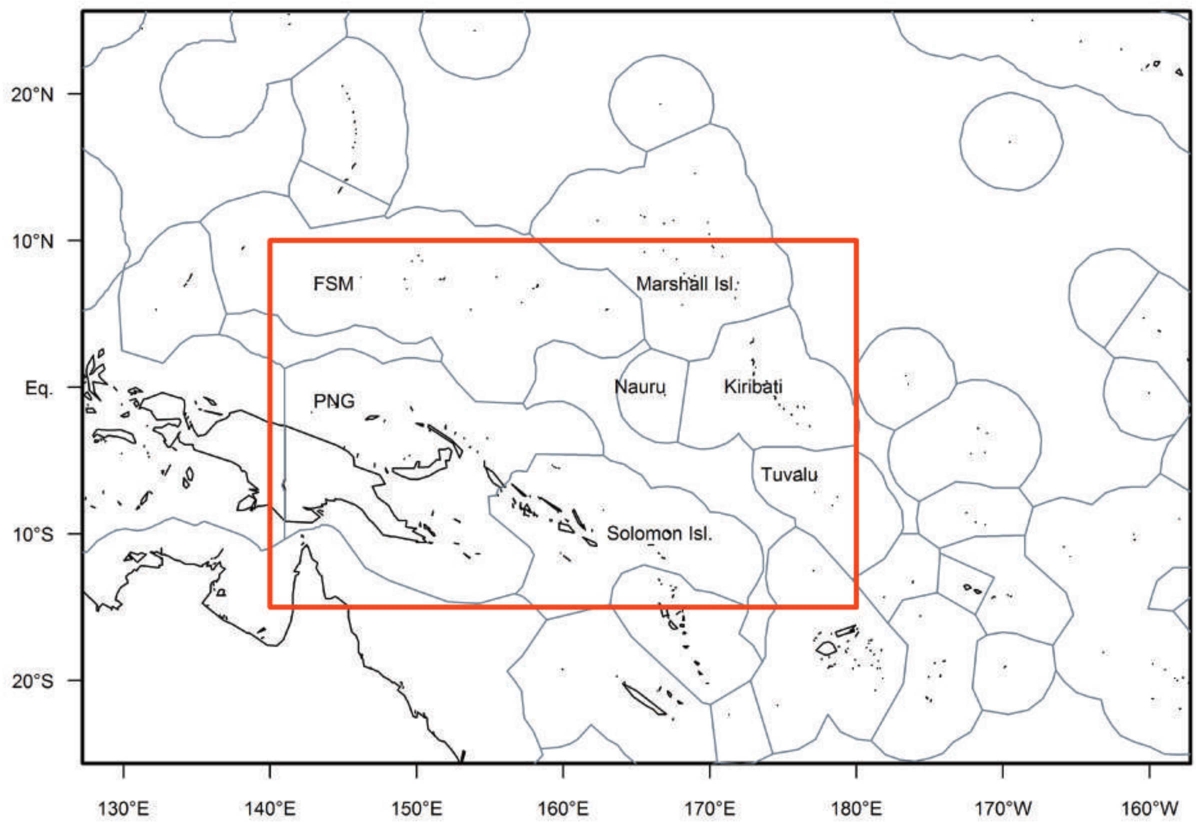


Figure 1. The boundaries of the area covered by the warm pool ecosystem model, and the exclusive economic zones of the countries included in the model. FSM = Federated States of Micronesia; PNG = Papua New Guinea.

Building the ecosystem model for the Pacific warm pool

The Pacific warm pool ecosystem was modelled using the trophic mass-balance approach within the Ecopath with Ecosim software (www.ecopath.org). Ecopath describes the static state of trophic flows within a food web (Fig. 2) that balance the net production of a functional group[2] with all sources of mortality and migration. Ecosim is a dynamic form of Ecopath that allows the forecasting of ecosystem responses to specific perturbations through time.

The model was constructed to simulate the year 2005 and comprises 44 functional groups (Table 2).

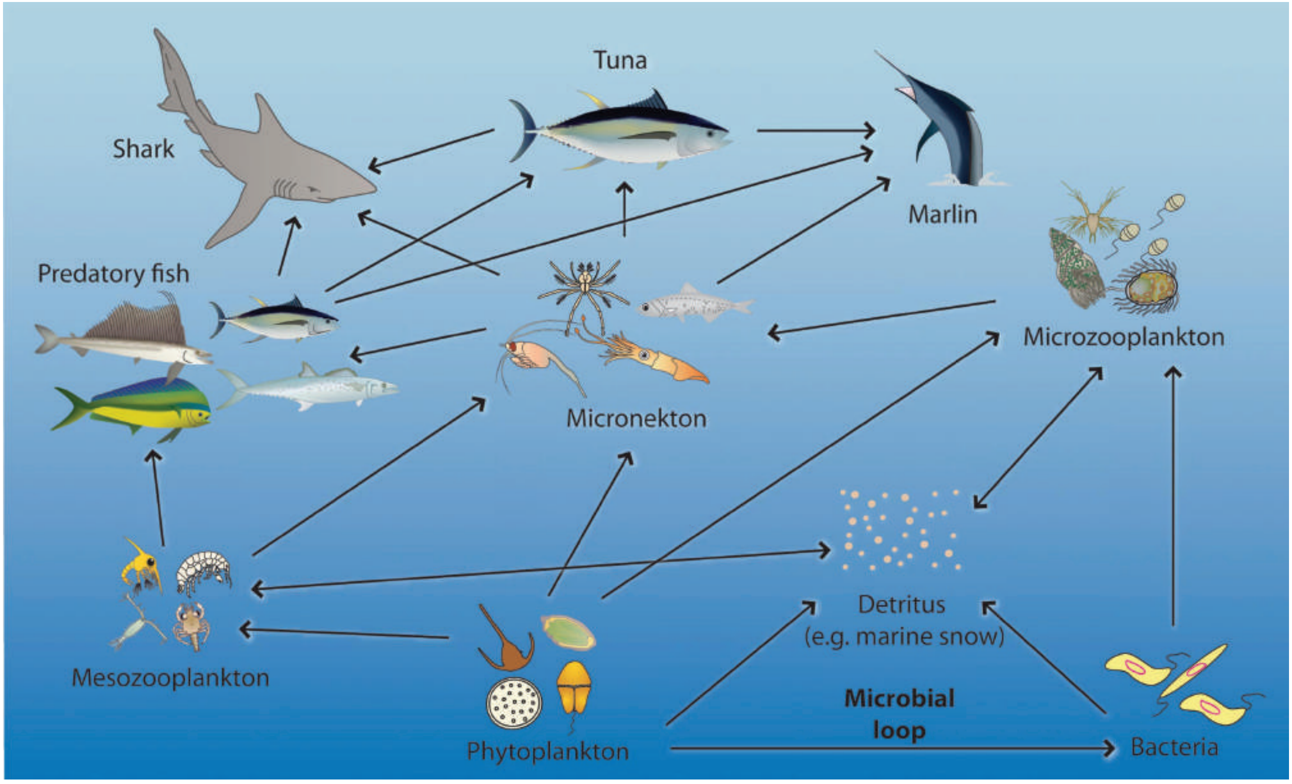


Figure 2. Simplified view of the generalised food web supporting tuna and other large pelagic fish in the warm pool. Note that at the bottom of the food web, both phytoplankton (microscopic plants) and 'marine snow' (phytoplankton and zooplankton remains decomposed by bacteria, also known as detritus) contribute trophic inputs.

Despite the large number of functional groups, the model is a simplification of the enormous complexities of ecological interactions among species within the Pacific warm pool ecosystem.

The key model parameters (biomass, production, consumption, catch, fishing mortality) for each functional group were derived from MULTIFAN-CL[3] stock assessments, the SEAPODYM[4] model, primary research data, scientific literature, and logbook data from four tuna fisheries in the model area: longline, (LL); purse-seine fishing associated with floating objects, including FADs (PSA); purse-seine fishing on unassociated schools (i.e. fishing on free schools [PSU]), and pole-and-line (PL) fishing. Data from fisheries observers on purse-seine and longline vessels were also used to construct model parameters.

Information on the feeding habits of each functional group was used to construct the diet matrix for the model. This information was based on stomach content analyses done by the Oceanic Fisheries Programme of the Secretariat of the Pacific Community, using samples from the WCPO Biological Samples Tissue Bank[5] , and supplemented by data from the Commonwealth Scientific and Industrial Research Organisation[6] .

2 A functional group can vary from several species to a single species, to a size class within a species (e.g. small yellowfin tuna, see Table 2).

3 MULTIFAN-CL, sometimes written as MFCL, is a length-based, age and spatially structured model for fisheries stock assessment (www.multifan-cl.org).

4 SEAPODYM = spatial ecosystem and populations dynamics model (www.seapodym.org).

5 See Sanchez C., Roupsard F., Allain V. and Nicol S. 2014. Tuna tissue bank for ecosystem management in the Pacific. SPC Fisheries Newsletter #144 - May–August 2014.

6 Griffiths S.P., Commonwealth Scientific and Industrial Research Organisation, Brisbane. pers. comm.

To increase the reliability of Ecosim simulations, the model was fine-tuned using 111 data time-series of biomass, and/or fishing mortality, and/or catch data for 37 functional groups (Table 2).

Overall, the model fitted the data exceptionally well for most groups.

Table 2. List of functional groups included in the Ecopath model of the Pacific warm pool. Time-series of grey-shaded groups were used to fine-tune Ecosim.

1	Turtles	16	Juvenile skipjack <24cm	31	Epipelagic mollusc
2	Small swordfish <90cm	17	Small skipjack 25-43cm	32	Migrant mesopelagic fish and other
3	Large swordfish >90cm	18	Large skipjack >43cm	33	Migrant mesopelagic mollusc
4	Blue marlin	19	Albacore	34	Mesopelagic fish and other
5	Striped marlin	20	Wahoo	35	Mesopelagic mollusc
6	Other billfish	21	Dolphinfish	36	Highly migrant bathypelagic forage
7	Mako shark	22	Small tunas	37	Migrant bathypelagic forage
8	Blue shark	23	Escolar and oilfish	38	Bathypelagic forage
9	Silky shark	24	Lancetfish	39	Mesozooplankton
10	White-tip shark	25	Opah	40	Microzooplankton
11	Other sharks	26	Pomfret	41	Large phytoplankton
12	Small bigeye <124cm	27	Rainbow runner	42	Small phytoplankton
13	Large bigeye >124cm	28	Epipelagic crustacea	43	Detritus
14	Small yellowfin <120cm	29	Epipelagic fish	44	Discards
15	Large yellowfin >120cm	30	Epipelagic small fish		

Features of the Pacific warm pool model

The completed Pacific warm pool ecosystem model is characterised by five trophic levels (TL[7]) (Fig. 3), a high number of trophic links between groups, and a diverse pool of prey for predators. The majority of the ecosystem's biomass (74%) was in TL 1–2 (phytoplankton, zooplankton) (Fig. 3), while 89% of the catch was in TL 3–5 (bycatch, tuna and other top predators).

The most important keystone group[8] in the Pacific warm pool ecosystem model is small yellowfin tuna because of this group's high production and consumption values, and diverse diet. The next most important keystone groups were the mesopelagic and epipelagic forage organisms, which have high production values as predators, but are also important prey for a range of larger fish.

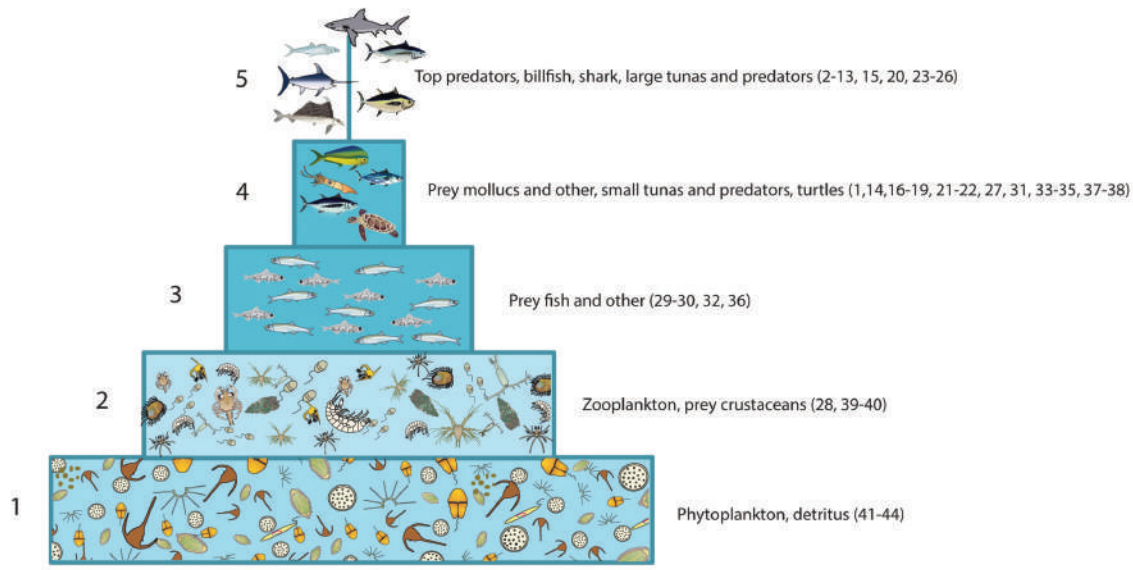


Figure 3. Repartition of the biomass (surface area of the horizontal bars) between the five trophic levels in the Pacific warm pool ecosystem model. Species composition of the trophic levels is detailed. Numbers in parentheses refer to the species groups defined in Table 2.

7 See Box 1 for explanations on the trophic level (TL).

8 An abundant and/or productive group which preys on groups with lower biomass and productivity, or a group that has an important predatory role in structuring an ecosystem even though it has a low biomass.

Responses of the ecosystem model to changes in harvest

The Ecosim component of the model was used to test the behaviour of the ecosystem model in order to better understand how the ecosystem functions and the responses of the model to changes. A first series of analyses was conducted by implementing changes in the harvest level of the surface fish community using modifications in the purse-seine fisheries (Table 3). A second series of analyses was conducted by implementing changes in the harvest level of the deep water fish community (i.e. those fish inhabiting depths of 150 m and more) through simulated changes in the longline fishery (Table 4).

The results of the analyses are expressed in two main ways:

1) positive and negative alterations in the biomasses of groups consisting of target (tuna) species, edible bycatch, other top predators, billfish, sharks, other bycatch and forage species; and

2) changes in various indicators of ecosystem function and health: the average trophic level of the catch (TLc), the fishing in balance index (FIB), and Kempton's Q index (Box 1).

The results are projections for 2026 and 2046, relative to 2016 (i.e. 10- and 30-year forecasts). These time steps were chosen to allow the simulations to reach equilibrium.

Table 3. Simulations of changes in the harvest level of surface fish communities using the Pacific warm pool ecosystem model.

Analysis	PS1	PS2	PS3	PS4	PS5
Test	Reduce bycatch of surface fish community for ecosystem sustainability	Increase harvest of surface fish community	Decrease the harvest of small bigeye and yellowfin tuna for sustainability of target species	Increase tuna harvest	Decrease the harvest of small bigeye and yellowfin tuna for sustainability of target species
Simulation description	Maintain catch of target species and reduce bycatch in PSA and PSU by 50% and by 100% in 2016, and maintain to 2026–2046	PSA effort increased linearly by 50–100% from 2016 to 2026, and maintained to 2046	PSA effort decreased abruptly by 50% and 100% in 2016, and maintained to 2026–2046	PSU effort increased abruptly by 50% and 100% in 2016, and maintained to 2026–2046	PSA effort decreased by 50% and 100% in 2016 with equivalent increases in PSU effort, maintained to 2026–2046
Expected ecosystem outcome	Increase in biomasses of bycatch species	Decreases in biomasses of small and large target species and bycatch species	Increases in biomasses of small and large targeted species and bycatch species	Decreases in biomasses of small and large targeted species and bycatch species	Increases in biomasses of targeted small tuna and decreases in biomasses of large tuna and skipjack

PS = purse-seine fishing; PSA = purse-seine fishing associated with floating objects; PSU = purse-seine fishing on free schools of tuna (unassociated)

Table 4. Simulations of changes in the harvest of deep water fish communities using the Pacific warm pool ecosystem model.

Analysis	LL1	LL2	LL3	LL4
Test	Increase harvest of deep water fish community	Decrease the harvest of large bigeye and yellowfin tuna, and reduce bycatch of deep water fish community for sustainability of target species and ecosystem	Decrease the harvest of sharks by implementing successful bycatch mitigation techniques	Decrease the harvest of turtles by implementing the no-shallow-hooks-longline[9,10] bycatch mitigation measure
Simulation description	LL effort increased linearly by 25–50% from 2016 to 2026, and maintained to 2046	LL effort decreased linearly by 25–50% from 2016 to 2026, and maintained to 2046	LL shark catches decreased by 50% and 100% from 2016 to 2026, and maintained to 2046 without changing longline effort (i.e. maintained at the 2010 level)	LL catches of turtles decreased by 100%, catches of billfishes, dolphinfish and wahoo decreased by 62% and pomfret catches increased by 75% from 2016 to 2026, and maintained to 2046 without changing longline effort (i.e. maintained at the 2010 level)
Expected ecosystem outcome	Decreases in biomasses of all species	Increases in biomasses of all species	Increases in biomasses of all shark species	Increases in biomasses of turtles and surface fish communities

LL = longline fishing

The outcomes of the analyses showed that the Pacific warm pool ecosystem structure is resistant to considerable perturbation, including, for example, large changes in the harvest of the surface fish community (Table 5, Box 1). This appears to be a reasonably common characteristic of pelagic ecosystems, possibly related to the high diversity of groups near the top of the food web that consume a wide range of prey.

The ecosystem structure was most sensitive to changes in the biomass of forage groups (e.g. mesopelagic fish). Species in these groups occupy intermediate trophic levels and are both important prey and predators.

Ecosystem indicators show that:

1) the fishery has expanded in recent decades (i.e. FIB>0);

2) fishery expansion resulted in a slight increase in the average trophic level of the catch due to increased catches of high trophic level bycatch species, such as sharks and billfish (i.e. increasing TLc); and

3) there is evidence to suggest that the diversity and biomass of the ecosystem components TL3–TL5 have diminished (decreasing Q; Box 1).

Some of the changes in the structure of the Pacific warm pool ecosystem resulting from the simulations (Table 5, Table 6) were intuitive, whereas others were a result of indirect effects from changes in the biomass of predator or prey groups (Box 2, Box 3, Box 4, Box 5). Overall, changes in the biomass of any single species were predicted to be lower than 40%. For species that have life-histories that are not resilient to harvest, declines of this magnitude may be detrimental to their long-term sustainability; such is the case with many shark species.

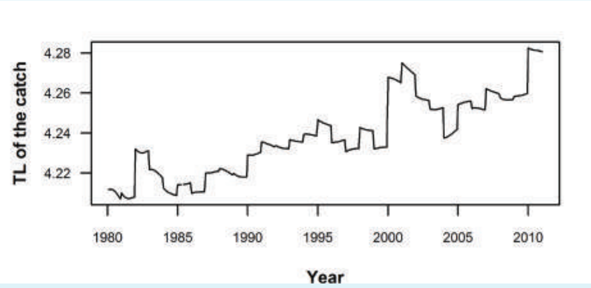
9 Beverly S., Curran D., Musyl M. and Molony B. 2009. Effects of eliminating shallow hooks from tuna longline sets on target and non-target species in the Hawaii-based pelagic tuna fishery. Fisheries Research 96:281–288. doi:10.1016/j.fishres.2008.12.010 - http://www.academia.edu/6660574/Effects_of_eliminating_shallow_hooks_from_tuna_longline_sets_on_target_and_non-target_species_in_the_Hawaii-based_pelagic_tuna_fishery.

10 http://www.spc.int/DigitalLibrary/Doc/FAME/Brochures/Set_your_LL_deep.pdf.

Box 1. Measures of ecosystem function and health

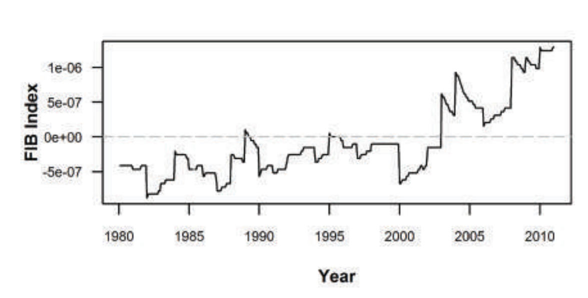
Average trophic level of the catch (TLc)

The trophic level (TL) of a functional group within an ecosystem indicates the position it occupies in the food web — as you go up the food web, TL increases. Phytoplankton, the microscopic plants at the base of the food web, are TL1; zooplankton feeding on phytoplankton are in TL2; organisms feeding on TL2 are in TL3, etc. Sharks at the top of the food web are in TL5 (Fig. 3). The average trophic level of the catch (TLc) is an indicator of the effects of fishing, and/or whether fisheries are changing their fishing or targeting practices in response to changes in the abundance or catchability of target species. For example, a decline in the abundance of large predatory fish due to overexploitation may result in fisheries shifting to smaller fish or species at lower trophic levels in order to maintain profitability; TLc would then be expected to decrease. A decrease in TLc can be considered negative for the ecosystem. Changes in TLc for the Pacific warm pool since 1980 from Ecosim are shown.



Fishing in balance (FIB)

The FIB index indicates whether fisheries are balanced in ecological terms (FIB = 0) or whether overfishing is occurring. FIB<0 occurs when catches do not increase as expected or when TLc decreases significantly given the productivity of the system, or if the effects of fishing compromise the functionality of the ecosystem. FIB>0 occurs when a fishery is expanding (e.g. there is an increase in diversity and/or biomass of bycatch). An increase or a decrease in FIB is considered negative for the ecosystem, a value of zero is considered positive and a constant value non-equal to zero is considered to be a neutral effect. Changes in the FIB index for the Pacific warm pool since 1980 from Ecosim are shown, with 2003 as a reference year (FIB = 0).



Kempton's Q index

This index indicates changes in the diversity and biomass of high trophic level species (>TL 3). A decrease in the index indicates that a reduction has occurred in the number of groups in the upper levels of the food web and in their biomasses. Lower diversity and biomass of groups with a high trophic level is considered to be negative for the ecosystem. Changes in the Q index for the Pacific warm pool since 1980 from Ecosim are shown.

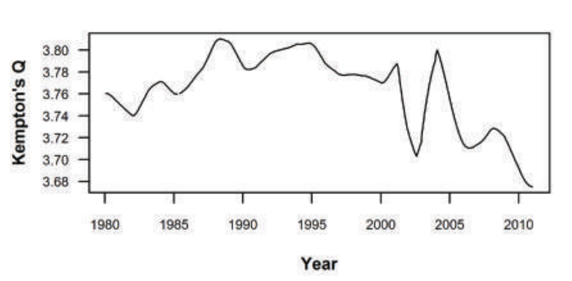


Table 5. Summary of changes in biomasses of groups of target species (tuna) and bycatch species, and ecosystem indicators, predicted for each analysis by Ecosim by altering purse-seine fishing effort. Note that only decreases or increases in biomass >5% are shown.

		Analysis				
		PS1	**PS2**	**PS3**	**PS4**	**PS5**
Test		Reduce bycatch of surface fish community for ecosystem sustainability	Increase harvest of surface fish community	Decrease the harvest of small bigeye and yellowfin tuna for sustainability of target species	Increase tuna harvest	Decrease the harvest of small bigeye and yellowfin tuna for sustainability of target species
Biomass of functional groups						
Groups of target species	**Increases**	None	Small skipjack	Large bigeye	None	Large bigeye tuna,
	Decreases	None	Large and small yellowfin tuna, large bigeye tuna, large skipjack tuna	Small bigeye	Large and small yellowfin tuna,	Large skipjack tuna, small bigeye tuna
Groups of bycatch species	**Increases**	Silky shark, white-tip shark, striped marlin, blue marlin	Escolar/ oilfish, wahoo, dolphinfish, rainbow runner, striped marlin, lancetfish, blue shark	Mako shark, silky shark, white-tip shark, other sharks, blue marlin	Striped marlin, wahoo, other billfish, escolar/ oilfish, blue shark, lancetfish, opah, dolphinfish	Mako shark, white-tip shark and other sharks
	Decreases	Opah, small and large swordfish, wahoo	Silky shark, white-tip shark, mako shark, blue marlin	Opah, wahoo,	Silky shark, blue marlin, mako shark	Blue marlin, opah
Indicators*						
TLc		0	0	+	+	+
FIB		0	-	+	0	0
Q		+	-	+	-	-

*Sign and colour indicate: a positive trend (+ = green); a negative trend (- = red); or a neutral situation (0 = white).
Indicators are: TLc = trophic level of the catch; FIB = fishing in balance index; and Q = Kempton's Q index (see Box 1 for explanations of indicators).


Photo: Marc Taquet © Ifremer

Table 6. Summary of changes in biomasses of groups of target species (tuna) and bycatch species, and ecosystem indicators, predicted for each analysis by Ecosim by altering longline fishing. Note that only decreases or increases in biomass >5% are shown.

		Analysis			
		LL1	LL2	LL3	LL4
Test		Increase harvest of deep water fish community	Decrease the harvest of large bigeye and yellowfin tuna, and reduce bycatch of deep water fish community for sustainability of target species and ecosystem	Decrease the harvest of sharks by implementing successful bycatch mitigation techniques	Decrease the harvest of turtles by implementing the no-shallow-hooks-longline bycatch mitigation measure
Biomass of functional groups					
Groups of target species	**Increases**	None	Large bigeye	None	None
	Decreases	None	None	None	None
Groups of bycatch species	**Increases**	Lancetfish	Opah, mako shark, white-tip shark other sharks, small and large swordfish, striped marlin, wahoo, silky shark	Mako shark, white-tip shark, other sharks, silky shark, blue shark	Striped marlin, wahoo, other billfish, blue marlin
	Decreases	Opah, mako shark, white-tip shark, other sharks, small and large swordfish, striped marlin, wahoo, silky shark	Lancetfish	Opah, small and large swordfish, wahoo, striped marlin, lancetfish	Opah, small and large swordfish
Indicators*					
TLc		0	0	0	0
FIB		0	0	0	0
Q		-	+	0	+

*Sign and colour indicate: a positive trend (+ = green); a negative trend (- = red); or a neutral situation (0 = white).
Indicators are: TLc = trophic level of the catch; FIB = fishing in balance index; and Q = Kempton's Q index (see Box 1 for explanations of indicators).

Implications

The simulations showed that the largest impacts of changes in the harvest of the fish community are likely to be on functional groups comprising long-lived bycatch species with lower productivity e.g. silky and white-tip sharks, opah, swordfish and blue marlin). These groups are the most sensitive to changes in the harvests of surface and deep water fish species due to their life history traits (longevity, age at first maturity and low rate of reproduction). Increases in purse-seine fishing effort levels on FADs result in greater mortality of sharks, and in decreases in biomass of some species and size classes of tuna. Conversely, reductions in purse-seine fishing effort on FADs increase the numbers of sharks, although such benefits are not as pronounced when purse-seine fishing effort on FADs is transferred to purse-seine fishing effort on free schools. Increases in longline fishing effort results in greater mortality of opah, shark species, swordfish and striped marlin, and an increase in biomass of lancetfish, while a decrease in longline fishing effort results in the opposite effects.

It is also apparent that no single indicator is able to provide a good representation of the responses of the ecosystem to changes in harvest levels, and this reflects the complexity of the ecosystem. Use of a variety of indicators is likely to be required in order to detect the full range of impacts from alterations to harvest strategies.

The predicted changes in the abundance of sharks made by the model should assist managers in evaluating the effects of fishing on top-level predators, and to develop management measures to contribute to worldwide efforts to conserve sharks.

Recommendations

Developing the model for the Pacific warm pool to simulate responses of important groups of target and bycatch species to changes in fishing effort and strategies, has led to a number of recommendations, and these are summarised below.

1. Identify detailed objectives for ecosystem management. To evaluate whether management measures designed to conserve the Pacific warm pool ecosystem are effective, managers will have to define which functional groups of species are expected to benefit, and ensure that indicators capable of detecting changes in the biomass of all groups are used.

2. Develop better ecosystem indicators. To identify changes in the structure of the Pacific warm pool ecosystem, and allow any necessary mitigation measures to be implemented before the ecosystem enters a non-desirable state, a larger set of more informative and sensitive indicators will need to be developed and tested. Use of a single or limited number of ecosystem indicators should be avoided.

3. Increase the monitoring of catch and discards for bycatch species. The development of the ecosystem model for the Pacific warm pool has demonstrated the great benefit of having reliable time series of data. Without the information on the groups of bycatch from the warm pool collected by observers, the Ecosim component of the model would not have been able to produce such good fits to data. Extending the current time series of catch data for bycatch species will be pivotal to both improving model calibrations and confidence in the simulation results.

4. Expand fisheries monitoring programmes to include forage species. The sensitivity of ecosystem structure to changes in groups of forage species means that improvements to the Pacific warm pool model (e.g. to monitor the effects of climate change) will depend on collecting better information on forage species. This can be done by arranging for fishing vessels to collect acoustic data and through the collection of stomach contents from top-level predators by fisheries observers for inclusion in the WCPO Biological Samples Tissue Bank and subsequent analysis by the Oceanic Fisheries Programme of the Secretariat of the Pacific Community.

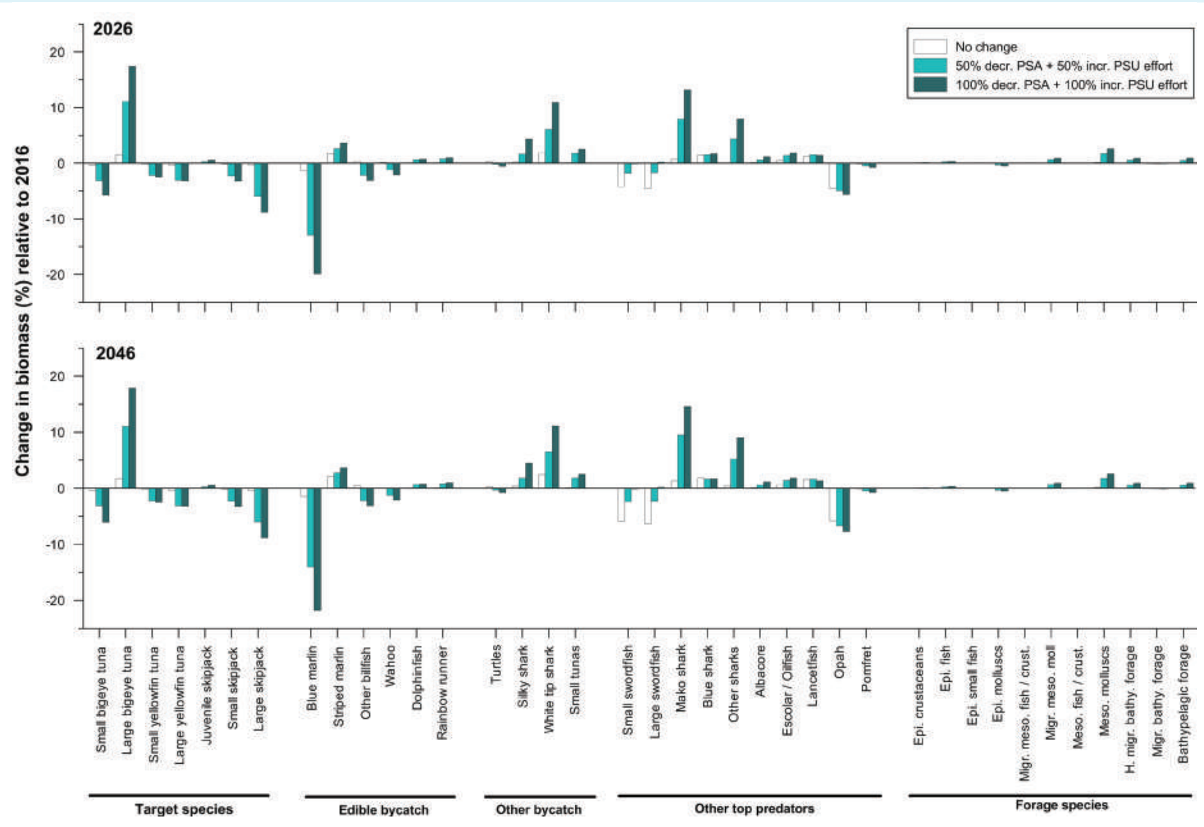
5. Add a spatial component to the Ecopath with Ecosim model. Further development of the model is needed to take into account movements of groups of organisms among areas and between the different vertical habitats in the Pacific warm pool. Spatial disaggregation of biomasses will allow for more realistic simulation of the ecosystem dynamics and such modifications should be done before further scenarios of fishing effort are evaluated.

Box 2. Results of ecosystem simulation based on purse-seine analysis PS2

ANALYSIS PS2: *Increasing the harvest of the surface fish community is considered to be desirable by fishery stakeholders. The simulation's method consists of linearly increasing effort of purse-seine fishing on FADs by 50% and 100% from 2016 to 2026, and maintaining this increased effort to 2046.*

Ecosim shows that increasing the harvest of the surface fish community through an increase in purse-seine fishing effort on FADs reduces the biomass of the following important bycatch groups due to additional fishing mortality: silky shark, white-tip shark, mako shark and blue marlin. It also reduces the following target groups: small and large yellowfin tuna, large bigeye tuna and large skipjack tuna. For the tuna groups, the greatest declines in biomass occur for the larger size classes even though small tuna are an important component of the catch of the purse-seine fishing effort on FADs. In the model, this is caused by the reduction in shark biomass (due to increased fishing effort), which has the 'knock on' effect of reducing predation on small tuna by sharks. For yellowfin tuna, the greater decreases in biomass of large fish were also due, in part, to the linking of small and large size classes (i.e. the decrease in biomass of small fish was amplified in larger fish due to the high mortality rate).

Increasing purse-seine fishing effort on FADs also resulted in a greater biomass of some bycatch groups, especially escolar/oilfish, wahoo, dolphinfish, rainbow runner, striped marlin, lancetfish and blue shark.

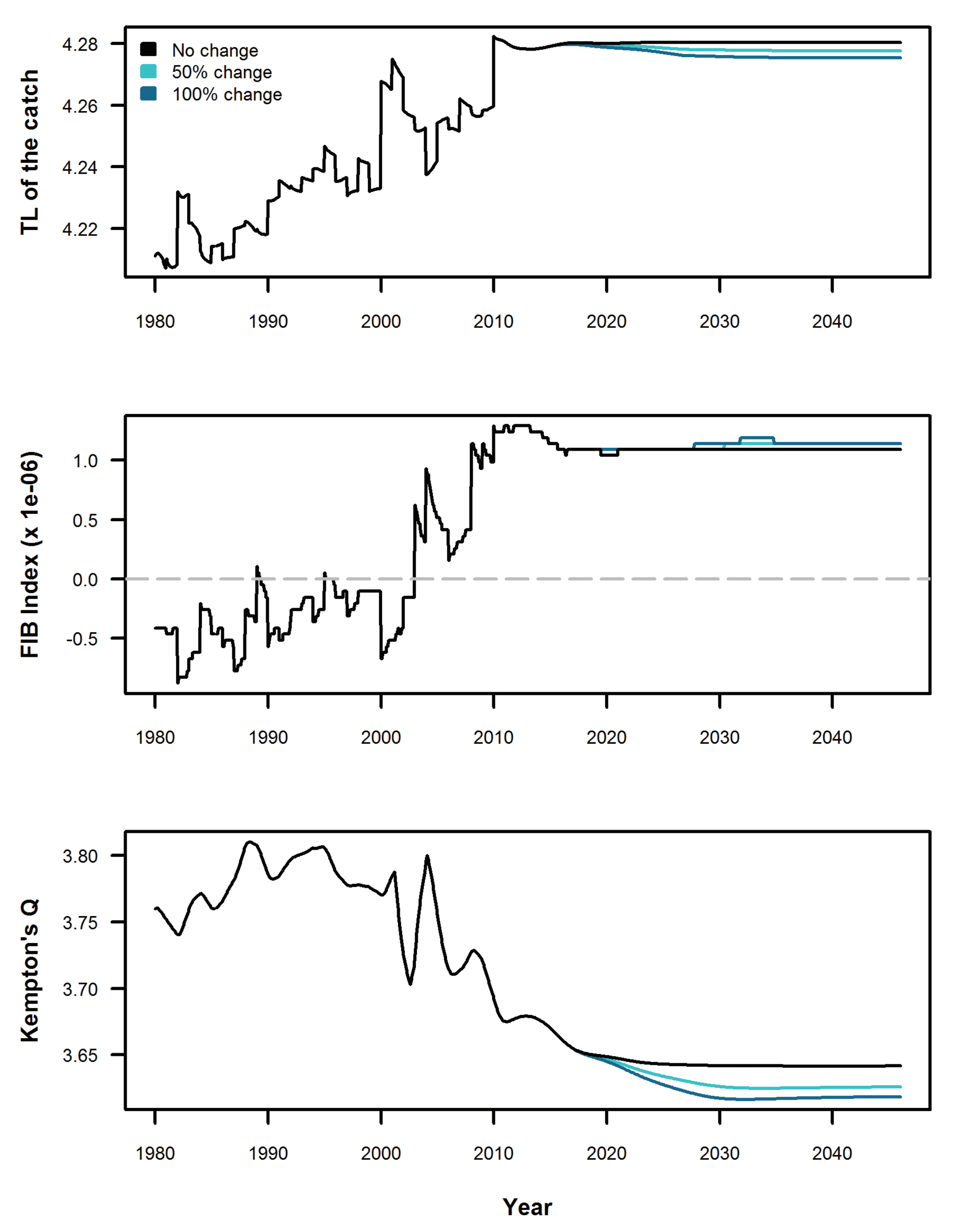


Predicted percentage changes in biomass of functional groups in 2026 and 2046 relative to 2016

Epi. = epipelagic; Meso. = mesopelagic; bathy. = bathypelagic; Migr. = migrant; H.migr . = highly migrant

Although it seems counterintuitive that the biomass of groups subject to greater fishing pressure (e.g. dolphinfish) would increase, this type of result is common in ecological systems where 'the enemy of my enemy is my friend'. In this case, the large decline in biomass of predators (marlins, sharks and tunas) allowed the biomass of some bycatch groups to increase. This result demonstrates how ecosystem models can help disentangle complex, indirect trophic interactions.

The change in TL of the catch was small. The FIB index increased, in line with the expansion of the fishery, indicating that the functionality of the ecosystem is increasingly affected over time. Kempton's Q decreased, reflecting the reduced diversity and biomass of groups at higher trophic levels (>TL 3).

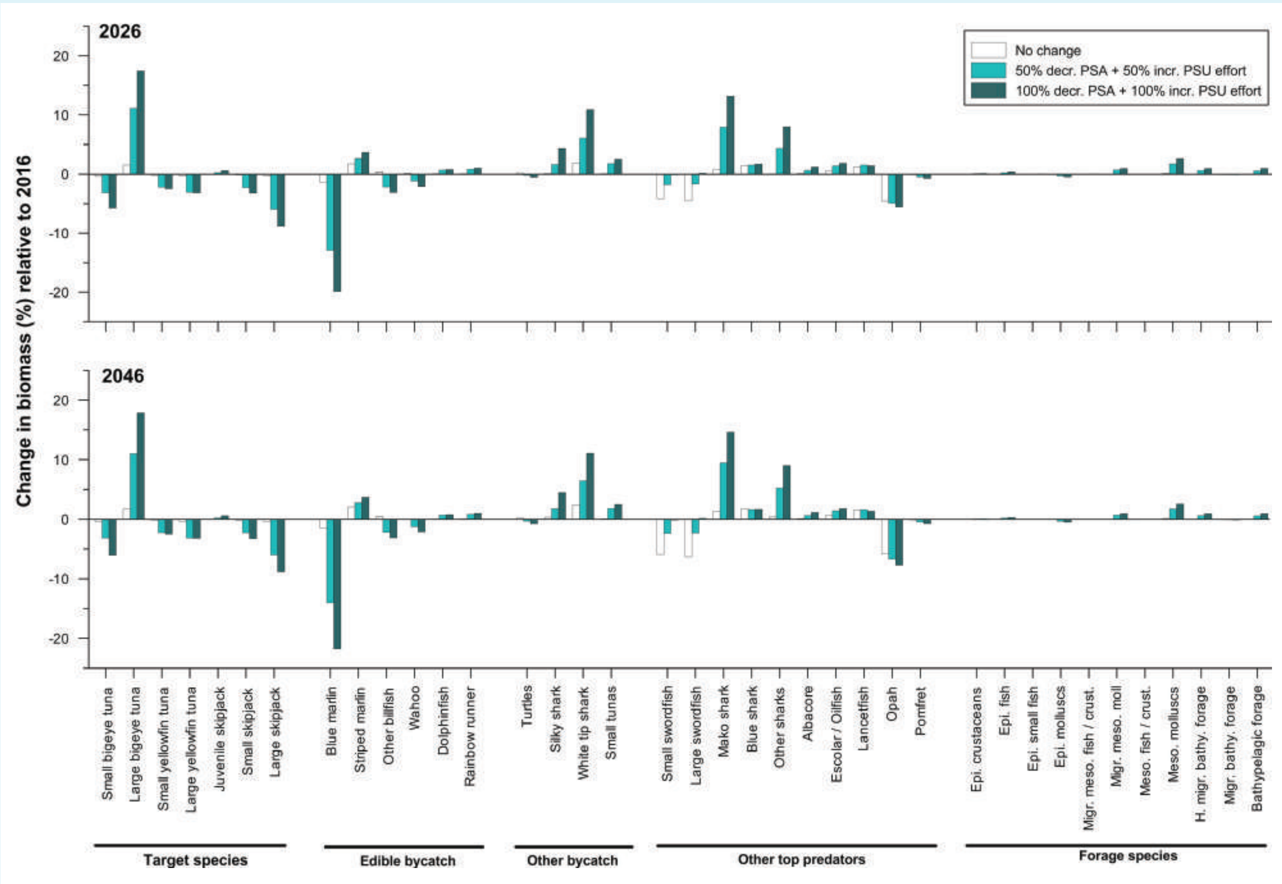


Temporal evolution of indicators of ecosystem function and health

Box 3. Results of ecosystem simulation based on purse-seine analysis PS5

ANALYSIS PS5: *To improve the sustainability of the target species, it is desirable to decrease the harvest of small surface tuna. This analysis simulated reducing purse-seine fishing effort on FADs by 50% and 100% and simultaneously transferring these levels of effort to fishing on free schools, and then maintaining the change through time to 2026 and 2046.*

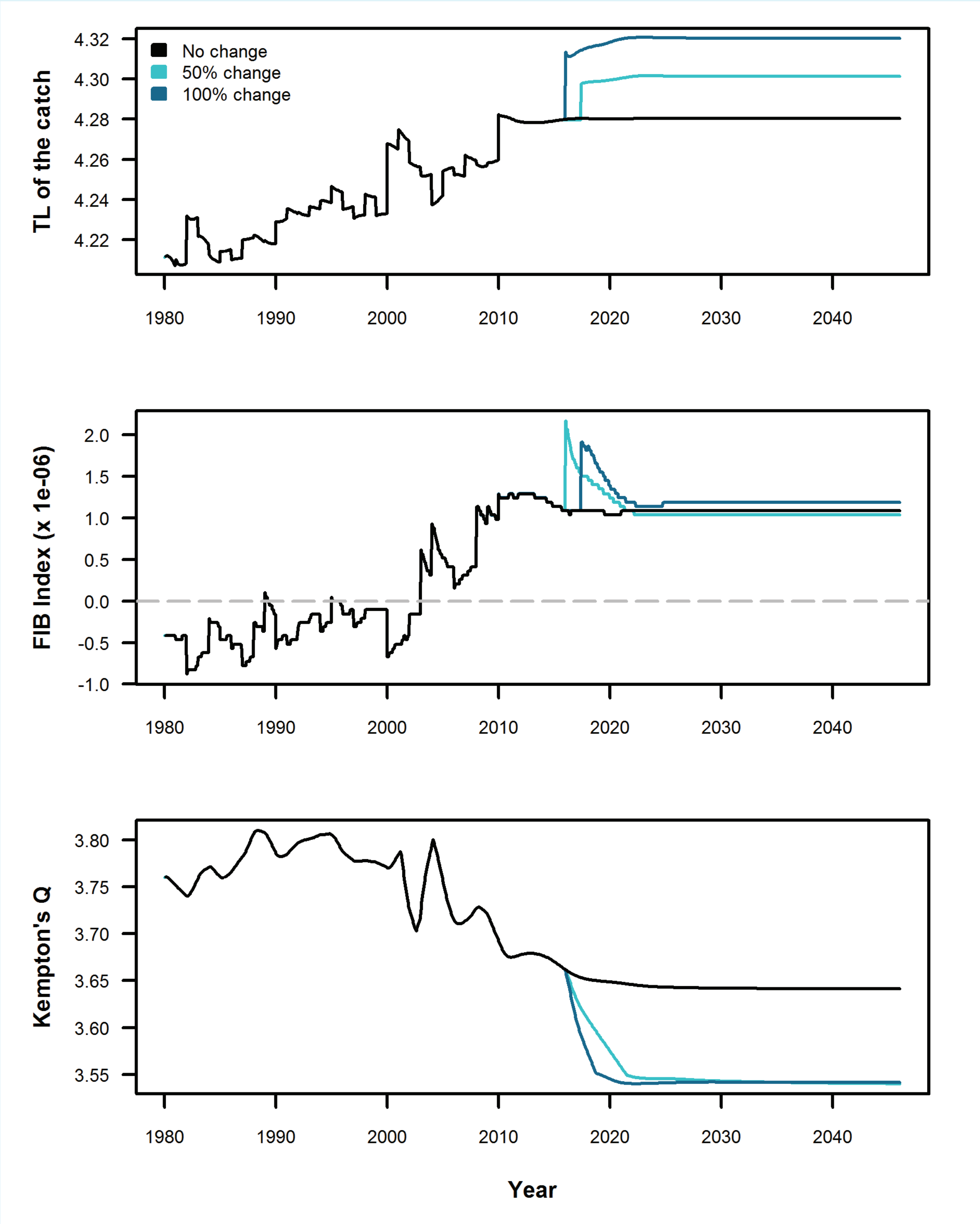
Ecosim shows that the bycatch functional groups that benefit the most from trading off purse-seine fishing effort on FADs for purse-seine fishing on free schools are mako shark, white-tip shark and other sharks; the large bigeye tuna target group also increased in biomass. Interestingly, the biomass of small bigeye tuna decreased slightly, due to the increase in biomass of sharks, which also induced large decreases in biomasses of blue marlin, large skipjack tuna and opah.



Predicted percentage changes in biomass of functional groups in 2026 and 2046 relative to 2016

Epi. = epipelagic; Meso. = mesopelagic; bathy. = bathypelagic; Migr. = migrant; H. migr. = highly migrant

TL of the catch increased slightly. The FIB index increased abruptly but then stabilised at a value similar to a 'no change' scenario. Kempton's Q decreased, indicating a reduction in the diversity and biomass of groups at higher trophic levels (>TL 3).



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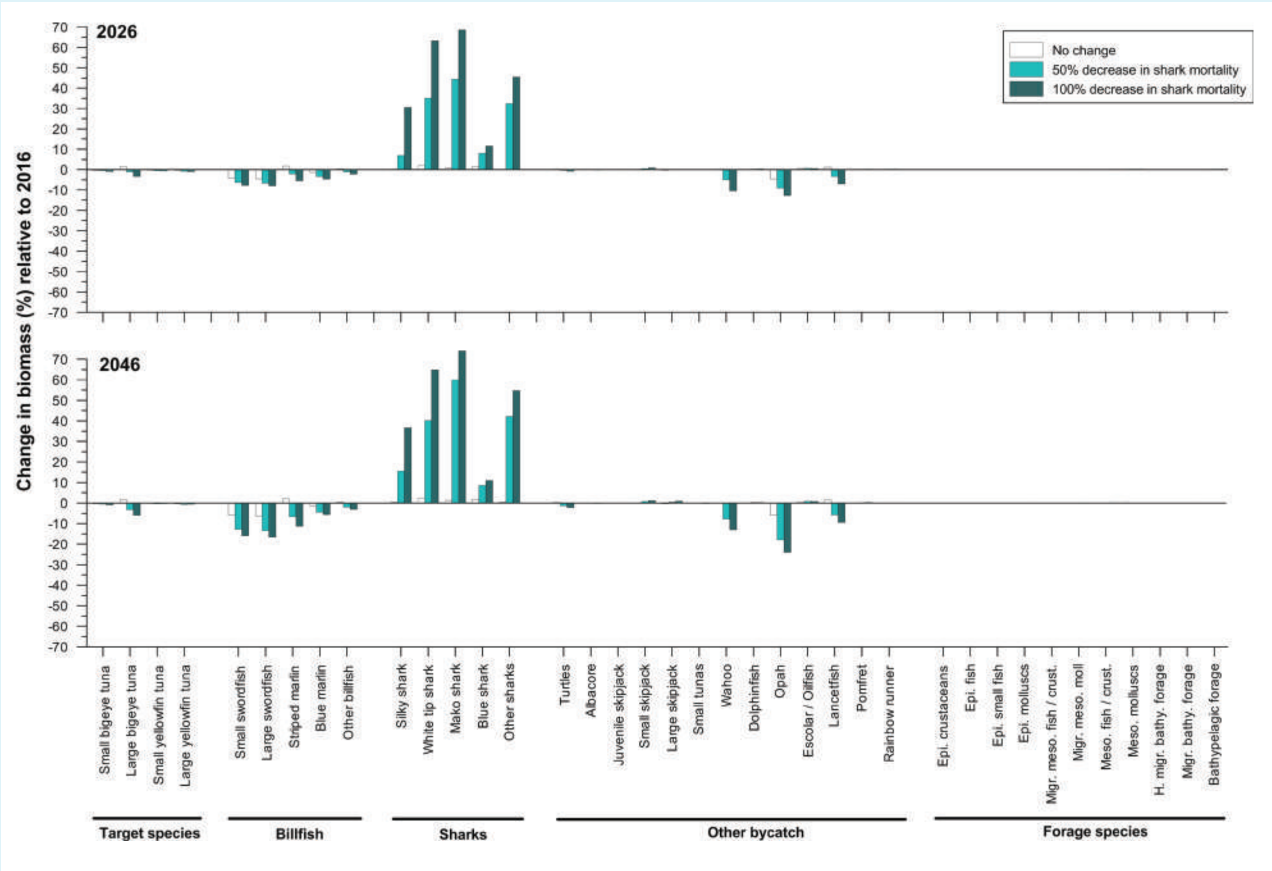
Box 4. Results of ecosystem simulation based on longline analysis LL1

ANALYSIS LL1: *Fishery managers have permitted a linear increase in the longline fishing effort by 25% and 50% of the current fishing effort for the period 2016 to 2026, and this increased effort was maintained to 2046.*

Ecosim shows that increasing harvest of the deep water fish community through an increase in effort of longline fishing reduces the biomass of the following important bycatch groups due to additional fishing mortality: opah, mako sharks, white-tip shark, other sharks, small and large swordfish, striped marlin, wahoo and silky shark. The only group experiencing a positive change in biomass was lancetfish, due to decreased predation by sharks that are, in turn, negatively impacted by the increased fishing pressure. Limited negative impact on targeted large bigeye and large yellowfin tuna was observed. It is hypothesized that the increase mortality due to increased fishing pressure is compensated by less predation by the decreasing shark groups.

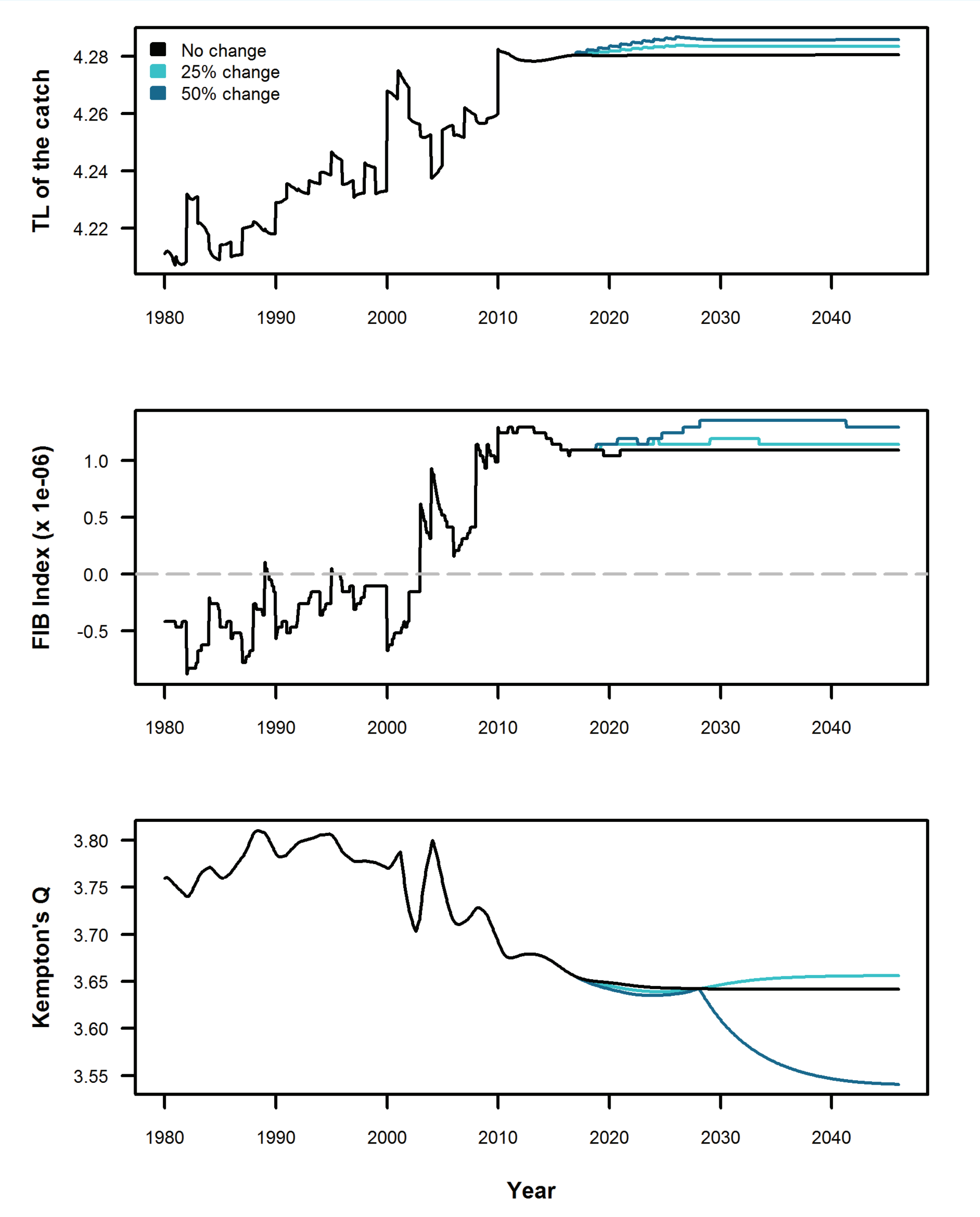


Predicted percentage changes in biomass of functional groups in 2026 and 2046 relative to 2016

Epi. = epipelagic; Meso. = mesopelagic; bathy. = bathypelagic; Migr. = migrant; H. migr. = highly migrant

The change in TL of the catch was negligible. The FIB index stabilised at values higher to a 'no change' scenario, indicating a neutral situation, neither negative nor positive. Kempton's Q decreased, reflecting the reduced diversity and biomass of groups at higher trophic levels (>TL 3).

Note that scenario LL2, where longline fishing effort was decreased by 25% and 50% of the current fishing effort, had exactly the opposite impacts on species biomass changes and ecosystem indicator trends.

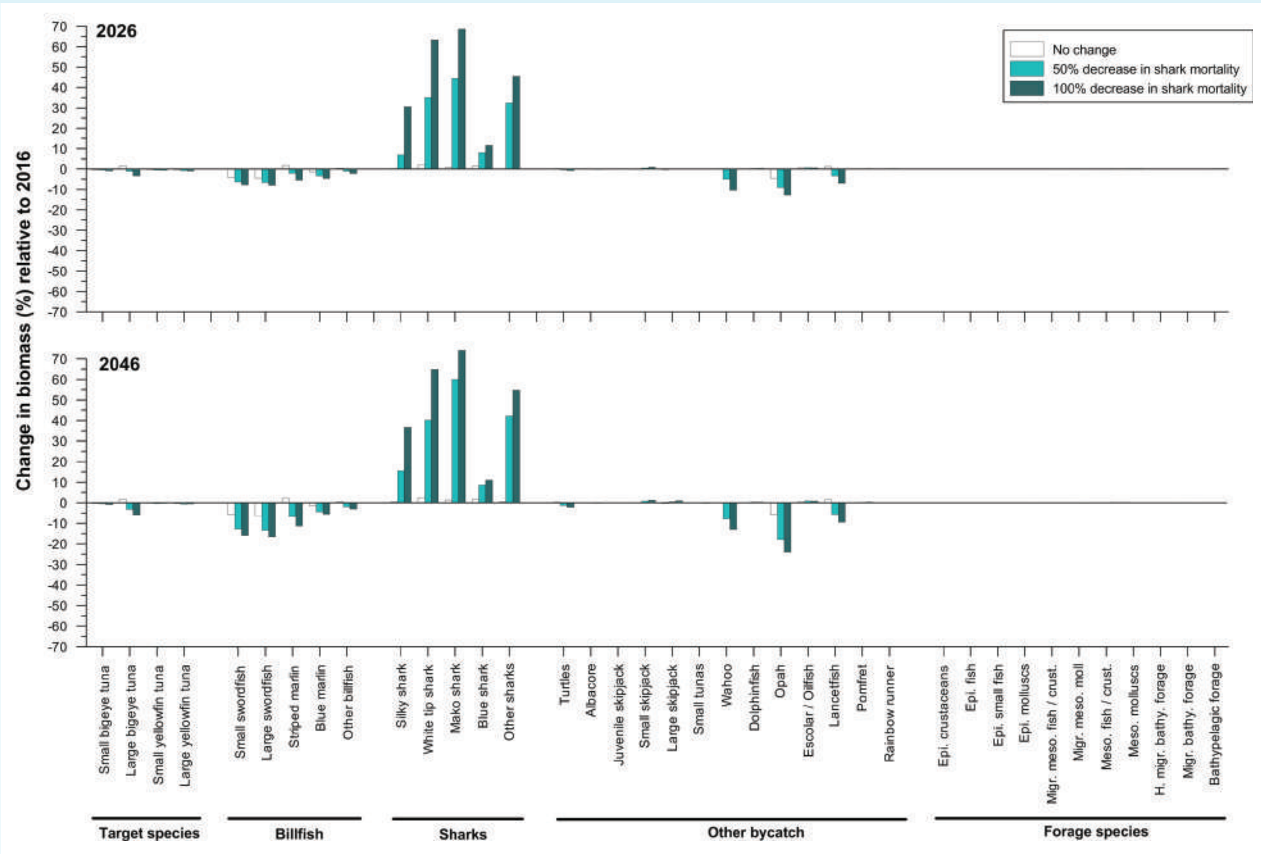


Temporal evolution of indicators of ecosystem function and health

Box 5. Results of ecosystem simulation based on longline analysis LL3

ANALYSIS LL3: *A suite of bycatch mitigation techniques have been found to be successful in reducing the catch of longline shark bycatch species by 50% or 100% without changing longline fishing effort. The longline fishing effort and associated fishing mortality was maintained at the level of 2010 for all species except sharks for which fishing mortality was decreased linearly from 2016 to 2026, and is maintained at a low level to 2046.*

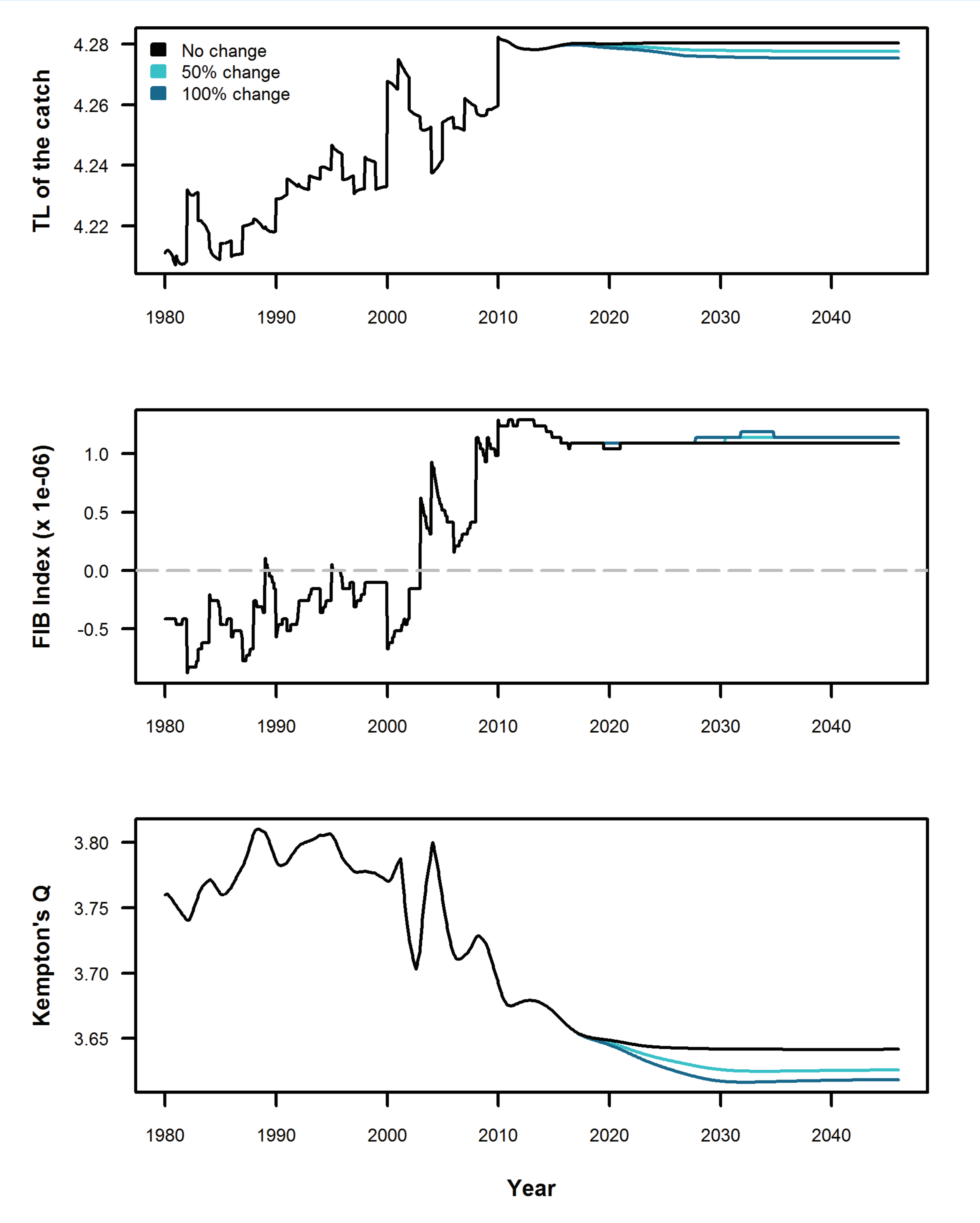
Ecosim shows that decreasing fishing mortality on longline-caught sharks increased the biomass of mako sharks, white-tip shark, other sharks, silky shark and blue shark. Higher biomasses of predatory sharks had a negative impact on the biomasses of other important bycatch groups: opah, small and large swordfish, wahoo, striped marlin and lancetfish. Limited negative impact on targeted large bigeye tuna was observed.



Predicted percentage changes in biomass of functional groups in 2026 and 2046 relative to 2016

Epi. = epipelagic; Meso. = mesopelagic; bathy. = bathypelagic; Migr. = migrant; H. migr. = highly migrant

Changes in TL of the catch and FIB were negligible. Changes in Kempton's Q were also very small, decreasing by 3%.



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