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**WCPO ECOSYSTEM INDICATOR TRENDS AND RESULTS FROM ECOPATH
SIMULATIONS.**

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Executive Summary

Introduction

This Information Paper contributes to Project 46 “Development/review of models, such as full development of an ECOSIM model, for evaluation of fishery and environmental impacts on ecosystem, including development of reference points” and provides complimentary analyses for Project 43 “Ecological Risk Analysis, including PSA” and Project 62 “SEAPODYM simulation modeling”.

The responsibilities for RFMOs has expanded over the last decade with monitoring and reporting upon the ecosystem impacts of fishing now an important aspect of evaluating the sustainability of fisheries. A critical step to developing appropriate monitoring and reporting protocols is an understanding of the processes by which marine ecosystems are structured. Fishing is not the only anthropogenic factor that may have negative impacts on marine ecosystems and decoupling fishing from these other impacts (e.g. climate change) will aid in the identification of appropriate ecosystem indicators of fishing impacts and appropriate reference points for implementation of management actions. Ecosystem modeling in combination with analyses of fisheries catch and observer data is one of the tools that can assist this process. In addition to assisting with the identification of ecosystem indicators ecosystem models can also be used to assess whether management is robust to the combined impacts on oceans.

To progress the identification of appropriate ecosystem indicators for the WCPO this paper reports on:

- (1) recent comparative analyses of logsheet and observer data in Hawaii and New Caledonia to examine trends in bycatch catch rates and ecosystem indicators (mean trophic level of the catch, annual proportion of apex predators and annual proportion of predator with high turn-over);
- (2) recent progress on modeling the warm pool ecosystem, with simulations of the impact of fishing and climate change undertaken.

The Scientific Committee is invited to both note the report, but also provide guidance on the utility of this report as an regular product to complement information provided in the Ecosystem and Bycatch Theme and the general working papers that summarizes the WCPO fisheries.

Results

Logsheet and Observer Data

Statistically significant linear trends were detected for 9 species in Hawaii: declining trends for albacore, bigeye, blue shark, shortbill spearfish and striped marlin, and increasing trends for dolphinfish, sickle pomfret, escolar and snake mackerel and no significant trends for skipjack, yellowfin, wahoo and lancetfish. Changes were between 3% and 9% annually for species with decreasing trends, and were from 6% to 18% annually for species with increasing trends. The species with declining trends had trophic level of 4.0 or larger and the species with increasing trends had trophic levels of 3.9 or less.

Significant trends were observed for 6 species in New Caledonia (excluding albacore, yellowfin, bigeye and striped marlin for confidentiality issues): decreasing trends for mako shark, opah, swordfish and sailfish and increasing trends for shortbill spearfish and dolphinfish. Changes were between 5% and 10% annually for species with decreasing and increasing trends. The trend for dolphinfish was as high as 29% according to observer data. Annual changes above 10% were non-significant for a number of species such as lancetfish, skipjack, escolar and black marlin due to the high variability of the annual CPUE. No major difference was noticed in the trophic level of species with increasing or decreasing trend.

In Hawaii, the mean annual trophic level of the top 13 species in the catch has declined over the time series by about 0.19 (or 5%) from about 3.85 to 3.66. The percentage of the catch of the top 13 species composed of apex predators ($TL \geq 4.0$) has declined from about 70% to 40%. The percentage of the catch of the top 13 species with relatively high P/B (≥ 1.0) has approximately doubled from about 20% to 40%.

In New Caledonia the mean annual trophic level of the 18 species in the catch varied during the period studied and showed a decrease of about 0.06 (or 1.5%) from about 3.96 to 3.90. The percentage of the catch of the 18 species composed of apex predators ($TL \geq 4.0$) has declined from about 80% to 75%. The percentage of the catch of the 18 species with relatively high P/B (≥ 1.0) has showed a slight decline from about 30% to 25%.

The stronger impact on the ecosystem observed in Hawaii could be related to the important increase in fishing effort in Hawaii while in New Caledonia the effort has been stable during the studied period.

Ecosystem Modelling

Predicted IPCC climate change scenarios were introduced into the Warm Pool Ecoapth model using a trend of declining phytoplankton biomass, resulting in declines in the biomass of all trophic levels by up to 22% to 2100.

A combination of increased fishing and climate change produced complex trophic cascades, causing unpredictable increases and decreases in the biomass of groups representing all trophic levels, similar to unpredictable wasp-waist ecosystems in productive temperate ecosystems.

Conclusions

We demonstrated that ecosystems respond to both top-down and bottom-up processes and apply some ecosystem indicators that maybe suitable for regular reporting on ecosystem changes in the WCPO.

Ecosystem models provide a powerful tool for posing ‘what if’ scenarios to understand the effects of specific, or a combination of, perturbations on complex ecological systems.

Ecosystem indicators and modeling will benefit from better quality data particularly bycatch data from the fisheries, a higher observer coverage rate and better biological information for bycatch species. The observer coverage in New Caledonia has approached 8 % in recent years which is in the upper level of longline coverage for the WCPO. Our analyses suggest that this rate may not be sufficient to detect a number of ecosystem and species trends (at least in the short term). With improved co-ordination among fishery agencies and RMFOs long-term ecological datasets can be cost-effectively collected which should improve the statistical power of the models used to detect trends and describe and tune ecosystem structure.

Introduction

The importance of an ecosystem-based fisheries management (EBFM) is widely accepted and frameworks and approaches were developed to practically implement such management (Levin et al 2009, Tallis et al 2010, Sainsbury et al 2000, Link 2002, Smith et al 2007). For example, Tallis et al (2010) describe a seven steps strategy framework. The first step, which is largely political, is 1) identifying the ecosystem objectives such as protection of a particular species (e.g. sea turtles, sharks). Following steps are:

2. defining appropriate indicators to monitor the status of the ecosystem and trends relative to objective,
3. setting target values or important trends for each ecosystem indicator that represent a desired state for the system,
4. analysing the risk (i.e. the behaviour of the indicators when ecosystem faces a threat such as increased fishing pressure),
5. assessing management options (i.e. evaluate how management actions are likely to affect indicators)
6. implementing programmes to monitor how indicators evolve
7. evaluating the chosen management strategies (i.e. based on monitoring, management performance is assessed relative to objectives, using indicators)

Despite considerable progress in the recent decade, it remains difficult to put these principles into practices and few examples of EBFM exist (Tallis et al. 2010, Ruckelshaus et al 2008). There are numerous reasons why implementation is difficult. Some reasons are: the lack of clear goal for ecosystem management, objectives are too broad (ex: “the goal is to maintain ecosystem health and sustainability”), conflicting objectives (ex: optimize yield of one species and protect another species), the difficulty of the inter-disciplinary context with multiple stakeholders, the complexity of the ecosystem and the lack of knowledge of its functioning, the lack of a recognised methodology and analytical tools (equivalent to the broadly used single-species stock assessment), the absence of recognised indicators and thresholds that managers could directly used to take decisions (equivalent to reference points such as BMSY for single-species management) ...

A critical step for implementing EBFM is an understanding of the processes by which marine ecosystems are structured (Roemmich and McGowan, 1995; Pauly et al., 1998; Timmermann et al., 1999; Sibert et al., 2006; Poloczanska et al., 2007; Molinero et al., 2008). Ecosystem modelling is one of the tools identified to help implementing EBFM (Walters et al 2005, Ruckelshaus et al 2008, Levin et al 2009, Pitcher and Cochrane 2002). Another critical step is the monitoring of the ecosystem to observe and understand the changes occurring, to improve the modelling and predictions.

The structure of marine ecosystems has generally been viewed to be controlled by one of two mechanisms: ‘bottom-up’ control (resource-driven) where the dynamics of primary productivity controls the production and biomass higher trophic levels, or ‘top-down’ control (consumer-driven) where predation by high trophic level predators controls the abundance and composition of prey in lower trophic levels (Frank et al., 2007). Tropical oceanic pelagic ecosystems, such as the Warm Pool province in the western Pacific Ocean, are generally oligotrophic and thought to be driven by bottom-up processes (Watters et al., 2003; Frank et al., 2007). Increasing global temperatures are likely to increase ocean surface temperatures and decrease the productivity of phytoplankton. In bottom-up-driven systems, this effect can propagate through the system causing parallel changes in the biomass

of higher trophic levels (Aebischer et al., 1990). Fisheries that target high trophic level predatory species are therefore likely to experience reduced catches, and ultimately a decline in value.

Ecosystem modelling contributes to the framework described above by facilitating the process from steps 2 to 7 by helping define indicators and setting target values, and, through simulations, analyse risks, assess management options, simulate monitoring and evaluate management measures (Tallis et al 2010, Levin 2009). In this paper, information is provided on recent changes observed in the pelagic ecosystem detected through bycatch catch rate trends based on observer and logsheet data and ecosystem indicators. In addition the most recent progress on a trophic mass-balance ecosystem model of the Warm Pool is presented, exploring the potential ecological effects of fishing and of climate change on the biomass of secondary production and forage species, and the subsequent flow-on effects on the catches of the mid-level predators and top predators including commercial tuna species skipjack, albacore, yellowfin and bigeye tuna.

Methods

Bycatch catch rate trends

Evolution of bycatch catch rate trends through time was estimated using observer and logsheet data from the Hawaii-based longline fishery and the New-Caledonia longline fishery.

Central north Pacific

In the central north Pacific, the Hawaii-based longline fishery operates over a large area from the equator to 40°N latitude and from 140°W longitude to the International Date Line; the core region of the fishing ground is bounded by 12-27°N latitude. Logsheets are completed by fishermen and provide data on the landed species. Observers onboard randomly selected vessels record all catches including non-commercial and between 1996 and 2006, approximately 16% of the effort in the core fishing ground had observer coverage. Catch rates were analysed for the deep-set longline fishery for the period 1996-2006 in the core region of the fishing ground. Temporally and spatially adjusted monthly catch rates (in number of fish per 1000 hooks) were calculated for 10 commercial target and bycatch species reported on logsheets and annual catch rates were calculated for 3 species of limited commercial value based on observer data. Details of the study and the methods are provided in Polovina et al 2009.

South-west Pacific

Supported by good observer and logsheet datasets, New Caledonia EEZ was used as an example to explore potential changes in bycatch catch rates in the southwest Pacific. Logsheets of longline fishing operations conducted in the New Caledonia EEZ are collected since the late 1970s and the number of logsheets increased greatly in 1997 when the local fleet developed. Provision of logsheets by fishermen is compulsory since 2002 and coverage rate is above 90% since 2004. Up to 1997 only the commercial species (tuna and billfish at the time) were reported and most of the bycatch was not landed. Since that date, the local market has opened to bycatch species such as mahi mahi, wahoo or opah, which are landed and reported on logsheets. Reporting rate of commercial bycatch on logsheet increased in the first five years of the marketing and logsheet data on common bycatch species are considered representative of the catch since 2003. In New Caledonia, the national programme observing the local longline fishery (there is no foreign fleet since 1998) was implemented in 2001 (however, observation data by SPC exist since 1992) and coverage rate has reached about 8% of number of hooks in recent years. Observer data provide information on all catches including, target, commercial bycatch and discards. Annual catch rates based on observer or logsheet data were

calculated (in number of fish per thousand of hooks). Time series were limited to 2002-2010 when observer coverage rate was above 2% in number of hooks (except for 2005 when it was 1.18%) and when bycatch was considered fully reported on logsheets. Annual catch rates were calculated for 13 species declared on logsheets (ALB, YFT, BET and MLS are not presented) and for the same species plus five more species of limited commercial value based on observer data.

Trends of catch rates and ecosystem indicators

Simple linear regressions were fitted to the annual CPUE data. Pearson's test were conducted to determine if the linear slope was statistically different from zero establishing if the trend observed was significant.

Following calculations are based on Polovina et al 2009 and are applied to New Caledonia; specificities on Hawaii data are detailed in Polovina et al 2009. Based on the linear regression, the annual percent change in CPUE of each species was computed as the slope divided by the intercept at the beginning of the time series, multiplied by 100 to convert to a percentage. From annual catch estimates based on logsheets for 13 species (Table 1) and estimates based on observer data for five species (blue shark, skipjack, lancetfish, escolar and snake mackerel), we computed time trends of 3 indicators. Indicators were the mean trophic level of the catch, the annual proportion of the catch composed of apex predators (with trophic level at least 4.0), and the annual proportion of the catch with moderate or high production to biomass (P/B) ratio (defined as at least 1.0). These indicators were computed as a mean weighted by the relative catch in numbers as follows:

$$M_j = \sum_{i=1}^{18} X_i \left(\frac{C_{ij}}{CC_j} \right)$$

where M_j = annual trophic level, annual percent of the catch with trophic level at least 4.0, or annual percent of catch with P/B ratio of at least 1.0 in year j ;

X_i =trophic level of species i or binomial variable with value 0 if trophic level < 4.0 or P/B < 1.0 and 100 otherwise;

C_{ij} = catch in number of species i in year j ; and

CC_j = combined catch of the 18 species in year j .

Estimates of trophic level and production to biomass ratio were available from the warm pool ecosystem EwE (Ecopath with Ecosim) model presented in this paper (Table 2) and from the central North Pacific ecosystem EwE model (Kitchell et al 2002) used in Polovina et al 2009 (Table 1). Calculations were conducted with both parameters, however the warm pool EwE model is still in development and some of the values are dubious; for this reason and to conduct a comparison with the analysis by Polovina et al (2009), it was decided to use the TL and P/B based on the Central North Pacific EwE model. Polovina et al (2009) detail how the TL and P/B of some species not present in the Central North Pacific EwE model were estimated. For the species not mentioned into Polovina et al (2009), values of similar species were used: striped marlin values for other billfish species, striped marlin TL and blue shark P/B for mako shark, wahoo TL and lancetfish P/B for opah.

Table 1. Estimates of trophic level (TL) and production to biomass ratio (P/B) for each of the species.

Species			Warm pool EwE		Central North Pacific EwE	
			TL	P/B	TL	P/B
SWO	Swordfish	<i>Xiphias gladius</i>	5.39	0.4	4.3	0.5
BLM	Black marlin	<i>Makaira indica</i>	5.69	0.24	4.3	0.5
MLS	Striped marlin	<i>Tetrapturus audax</i>	5.77	0.82	4.3	0.5
BUM	Blue marlin	<i>Makaira nigricans</i>	5.69	0.24	4.3	0.5
SSP	Shortbill spearfish	<i>Tetrapturus angustirostris</i>	5.31	0.82	4.3	0.5
SFA	Indo-Pacific Sailfish	<i>Istiophorus platypterus</i>	5.31	0.82	4.3	0.5
SMA	Short-finned mako shark	<i>Isurus oxyrinchus</i>	5.86	0.22	4.3	0.3
BSH	Blue shark	<i>Prionace glauca</i>	5.49	0.27	4	0.3
BET	Bigeye	<i>Thunnus obesus</i>	5.6	0.65	4	0.8
YFT	Yellowfin	<i>Thunnus albacares</i>	5.28	0.76	4	1.2
SKJ	Skipjack	<i>Katsuwonus pelamis</i>	4.91	0.9	3.9	1.9
ALB	Albacore	<i>Thunnus alalunga</i>	5.08	0.67	4	0.6
WAH	Wahoo	<i>Acanthocybium solandri</i>	4.86	1.24	3.9	2
DOL	Dolphinfish	<i>Coryphaena hippurus</i>	4.69	3.45	3.9	3
LEC	Escolar	<i>Lepidocybium flavobrunneum</i>	6.02	0.46	3.2	0.8
ALX	Lancetfish	<i>Alepisaurus ferox</i>	5.53	0.35	3.2	0.3
LAG	Opah	<i>Lampris guttatus</i>	5.51	0.41	3.9	0.3
GES	Snake mackerel	<i>Gempylus serpens</i>	6.02	0.46	3.2	1

Ecopath with Ecosim (EwE) modelling

We constructed a trophic mass-balance ecosystem model of the Warm Pool pelagic ecosystem using Ecopath with Ecosim software (www.Ecopath.org). Ecopath trophic models describe the static state of energy flows in a food web that balances a group's net production with all sources of mortality and migration (Polovina, 1984). Ecosim re-expresses the static Ecopath model in a dynamic form, whereby the dynamics and sensitivity of the model is largely controlled by the predator consumption rates and the proportion of the prey that exist in a vulnerable state. Detailed description and discussion of Ecopath and Ecosim can be found in Walters et al. (1997), Christensen and Pauly (1992) and Christensen and Walters (2004).

Model structure

The Warm Pool is defined oceanographically as the area of the western Pacific Ocean bounded by the 28°C sea surface temperature isotherm. Because the oceanography in this area is seasonally and annually dynamic, for the purposes of this work the model of the Warm Pool was geographically defined as 10°N-15°S and 110°E-165°E. This covered a total area of 12,555,000 km² (Figure 1).

The intended use of the model was to investigate effects of climate change on the primary target species of tuna fisheries in the Warm Pool, which are primarily large apex predators such as tunas and billfishes. Therefore, we disaggregated high trophic level functional groups (mostly into single species and even ontogenetic stages within species) in order to focus on the effects of climate change on the target species.

The biota of the Warm Pool were assigned to one of 44 functional biological groups based on their ecological similarity such as preferred habitat, feeding mode and diet, size, and rates of production and consumption (Table 2). Two of these were non-living groups including detritus and fishery discards. Each group in the model acts as a single biomass pool, or species, despite some groups being comprised of numerous species. The year 2005 was chosen to characterise the static description of the trophic flows in the Warm Pool.

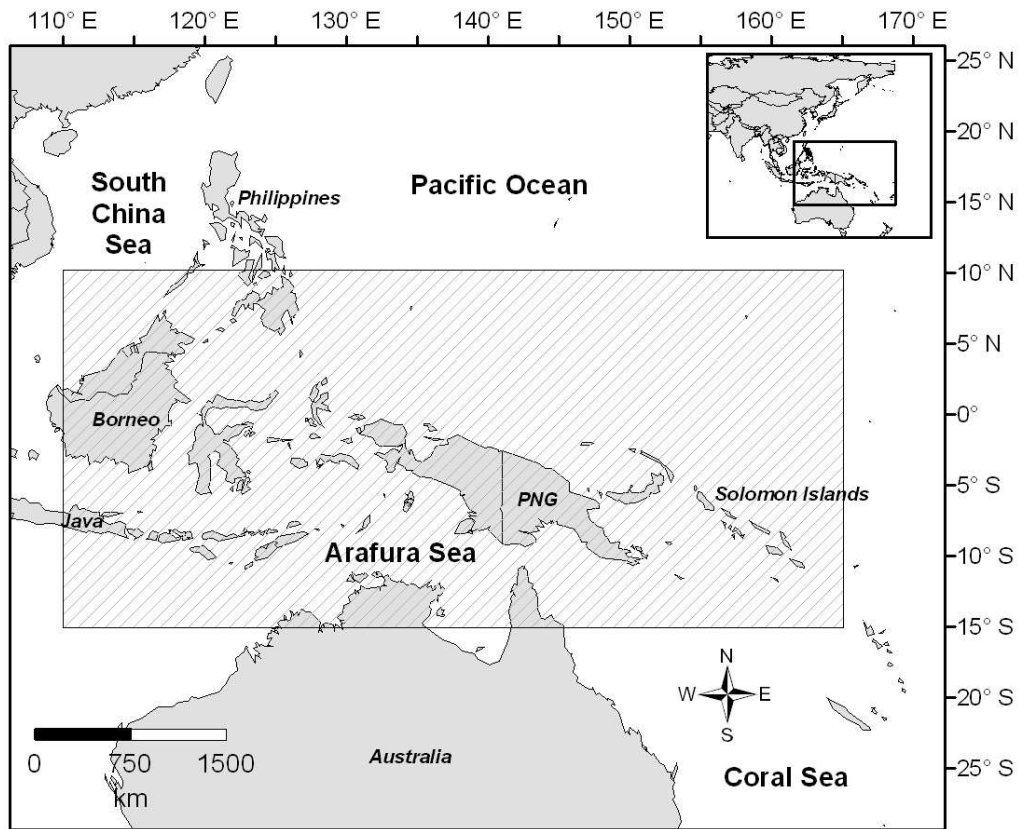


Figure 1. The geographic boundaries of the Warm Pool ecosystem model (hatched area).

Sources of biological and fishery data

The key biological parameters (biomass, production/biomass ratio, consumption/biomass ratio, ecotrophic efficiency, diet composition, and catch) for each functional group were derived from stock assessments, primary research data, fishery data recorded in logbooks or by scientific observers, or the literature. The diet matrix (Table 3) was primarily based upon stomach content analyses undertaken by the SPC ecosystems program (Allain et al 2012) and supplemented, where necessary, by dietary data from various studies undertaken in Australia and Papua New Guinea (e.g. Griffiths et al., 2009; Kloster et al., 2009; Young et al., 2009).

Quantitative biomass estimates of intermediate to lower trophic level groups is often a major weakness of pelagic ecosystem models (Olson and Watters, 2003), largely due to the difficulty of quantitatively sampling the standing biomass. Therefore, we used estimates of forage biomass from the SEAPODYM model (see Lehodey et al., 2008) characterised for bigeye tuna

Five fisheries were included in the model: longline, purse seine associated with floating objects, purse seine unassociated with floating objects, pole and line, and the Philippines/Indonesian miscellaneous fishery. The annual fishery landings and discards of each species in 2005 was estimated from logbook and scientific observer data for the model area.

Table 2. Biological parameters used in the Warm Pool Ecopath model. Biomass, fishery landings and discards is in tonnes wet weight km⁻²; P/B and Q/B are the ratios of production and consumption to biomass per year, respectively; ecotrophic efficiency (EE) is the proportion of production consumed within the system. Values in bold were estimated by Ecopath software.

Group No.	Group name	Trophic level	Biomass	P/B	Q/B	EE	Landings	Discards
1	Turtles	3.7535	0.0033	0.1900	3.5000	0.0730	0.0000080	0.0000377
2	Small swordfish (<90 cm OFL)	5.4911	0.0001	0.5030	9.9676	0.3057	0.0000025	
3	Large swordfish (>90 cm OFL)	5.3873	0.0001	0.4000	3.4310	0.3127	0.0000099	
4	Blue marlin	5.6858	0.0005	0.2400	4.6350	0.3872	0.0000220	
5	Striped marlin	5.7685	0.0001	0.8229	4.6350	0.4055	0.0000220	
6	Billfish other	5.3097	0.0006	0.8230	4.6350	0.5913	0.0001260	0.0000251
7	Mako shark	5.8594	0.0003	0.2210	11.6800	0.2898	0.0000064	0.0000128
8	Blue shark	5.4947	0.0104	0.2733	5.0000	0.2680	0.0007600	
9	Silky shark	5.1149	0.0025	0.5205	3.5000	0.4297	0.0003657	0.0002001
10	White tip shark	5.7771	0.0007	0.5205	3.2850	0.4291	0.0001464	0.0000204
11	Other sharks	5.3596	0.0010	0.3000	5.0000	0.3689	0.0000458	0.0000495
12	Small BET (<124 cm FL)	5.4667	0.0587	0.5414	24.4489	0.9675	0.0104042	
13	Large BET (>124 cm FL)	5.5967	0.0032	0.6530	15.0000	0.4650	0.0009309	
14	Small YFT (<120 cm FL)	4.4102	0.4242	0.8608	31.1055	0.8490	0.2585267	
15	Large YFT (>120 cm FL)	5.2783	0.0130	0.7647	16.1395	0.8915	0.0088161	
16	Baby SKJ (<24 cm FL)	4.2917	0.3400	0.9100	104.5810	0.9616	0.0239599	
17	Small SKJ (25-43 cm FL)	4.1990	0.2313	1.0323	32.3394	0.4430	0.0465262	
18	Large SKJ (>43 cm FL)	4.9122	0.1411	0.9011	25.0000	0.7649	0.0930739	
19	Albacore	5.0820	0.0072	0.6688	3.9420	0.9055	0.0019227	
20	Wahoo	4.8560	0.0002	1.2390	11.7000	0.8773	0.0000531	0.0000826
21	Dolphinfish	4.6911	0.0005	3.4540	20.4400	0.9500	0.0000778	0.0000549
22	Small tunas	4.0390	0.2982	1.5000	7.9570	0.9500	0.0001711	0.0001478
23	Escolar & Oilfish	6.0233	0.0209	0.4580	3.6000	0.9500	0.0000032	0.0000051
24	Lancetfish	5.5273	0.0489	0.3500	5.5000	0.9500	0.0000003	0.0000068
25	Opah	5.5062	0.0001	0.4140	3.5000	0.8146	0.0000228	0.0000045
26	Pomfret	5.6158	0.2787	0.8680	3.6000	0.9500	0.0000105	0.0000033
27	Rainbow runner	4.4549	0.5433	0.8678	7.9570	0.9500	0.0010754	0.0010701
28	Epipelagic crustaceans	2.5880	9.5067	4.0000	25.0000	0.9500		
29	Epipelagic fishes	3.9154	1.7548	3.6900	10.7000	0.9500	0.0010079	0.0009998
30	Epipelagic small fishes	2.9687	6.9819	6.0000	60.0000	0.9500		
31	Epipelagic molluscs	4.0829	2.0057	10.0000	14.6000	0.9500		
32	Migrating mesopelagic fish & crustaceans	3.7644	3.0800	2.4000	8.0000	0.9950		
33	Migrating mesopelagic molluscs	4.4024	1.4000	4.4500	14.6000	0.9760		
34	Mesopelagic fish & crustaceans	5.0865	1.7100	2.7000	8.0000	0.8610		
35	Mesopelagic molluscs	5.1016	0.4200	4.4500	14.6000	0.8665		
36	Highly migratory bathypelagic forage	3.8004	1.8400	1.9200	8.0000	0.9566		
37	Migratory bathypelagic forage	5.0643	0.7200	1.6200	8.0000	0.5647		
38	Bathypelagic forage	4.1936	1.3290	0.8448	8.0000	0.8894		
39	Mesozooplankton	2.2000	4.3580	33.0000	230.0000	0.8152		
40	Microzooplankton	2.0000	1.4610	120.0000	382.0000	0.9209		
41	Large phytoplankton	1.0000	1.8490	368.0000		0.2247		
42	Small phytoplankton	1.0000	10.4770	368.0000		0.1004		
43	Detritus	1.0000	200.0000			0.1056		
44	Fishery discards	1.0000	0.0027			0.0029		

Ecosim model fitting to time series data

To increase the reliability of predictions from the Ecosim scenarios, the model was fitted to time series of biomass, fishing mortality and catch data for twelve functional groups: juvenile bigeye tuna (ages 0-4 yrs), adult bigeye tuna (5-10 yrs), baby skipjack (0-4 months), juvenile skipjack (5-12 months), large skipjack (1-4 yrs), juvenile yellowfin tuna (0-2.25 yrs), adult yellowfin tuna (2.5-7 yrs), striped marlin (1-10 yrs), albacore tuna (1-5 yrs), blue marlin (0-21 yrs), juvenile swordfish (1-2 yrs) and adult swordfish (3-20 yrs). Data were derived from the relevant region in spatially-explicit age-structured stock assessment models for the period 1952-2008 (Kleiber et al., 2003; Langley et al., 2007; Hoyle et al., 2008; Langley et al., 2008).

Modelling climate change scenarios

Using the balanced calibrated Warm Pool ecosystem model we explored scenarios using climate change projections by the IPCC:

- i) A2 2035 involving a -6% change in net primary productivity from 2010 to 2100
- ii) A2 2100 involving a -9% change in net primary productivity from 2010 to 2100

These simulations were undertaken by introducing a linear decrease in the biomass of large phytoplankton and small phytoplankton (i.e. primary producers) from 2005 (the year for which the Ecopath model was characterised) to 2100. Results are presented as the percentage change biomass and catch for the primary commercial target and bycatch species, as well as epipelagic, mesopelagic and bathypelagic forage species.

Modelling fishing scenarios

We were interested in exploring the change in ecosystem dynamics after implementing a hypothetical management strategy whereby skipjack was permitted to be fished at maximum sustainable yield (MSY) indefinitely after 2012. According to Hoyle et al. (2011), MSY of skipjack is achieved at approximately 2.7 times the fishing mortality rate (F) in 2011. The existing fishing mortality rate in the Ecopath model (0.689 yr⁻¹) was increased by increasing fishing effort in the four skipjack sub-fisheries. Because the model has three ontogenetic stages of skipjack (baby, small and large) and each fishery has a disproportional impact on each group, it was not possible to exactly impose a 2.7 times increase to achieve the desired FMSY for the overall population of skipjack. We were able to approximately double the fishing mortality on each skipjack group by multiplying the fishing effort in 2007 – the last year in the balanced Ecopath model where effort data was available – by approximately 1.4. On top of this proposed management change to the fishery, we simulated the coupled effects of climate change – using the A2 2035 scenario – to investigate the overall effect on the biomass and catch of target and bycatch species, as well as epipelagic, mesopelagic and bathypelagic forage species.

Ecosystem indicators from Ecopath with Ecosim

A number of simple indicators were used to describe the structure and exploitation of the Warm Pool ecosystem in its balanced state in 2005. We describe the contribution of each trophic level to the total biomass and the system and the total catch of all fisheries. The productivity of groups is assessed against to production/biomass ratio (P/B), and specifically those groups included in the catch to ascertain the likely rebound potential of exploited groups.

Results

Bycatch catch rate trends and ecosystem indicators

Central north Pacific, the example of Hawaii

Results from logsheet and observer CPUE time series revealed statistically significant linear trends in slopes for 9 species: declining trends for albacore, bigeye, blue shark, shortbill spearfish and striped marlin, increasing trends for dolphinfish, sickle pomfret, escolar and snake mackerel and no significant trends for skipjack, yellowfin, wahoo and lancetfish (Figure 2, Figure 3). Changes were between 3% and 9% annually for species with decreasing trends, and were from 6% to 18% annually for species with increasing trends. The species with declining trends had trophic level of 4.0 or larger and the species with increasing trends had trophic levels of 3.9 or less (Table 1).

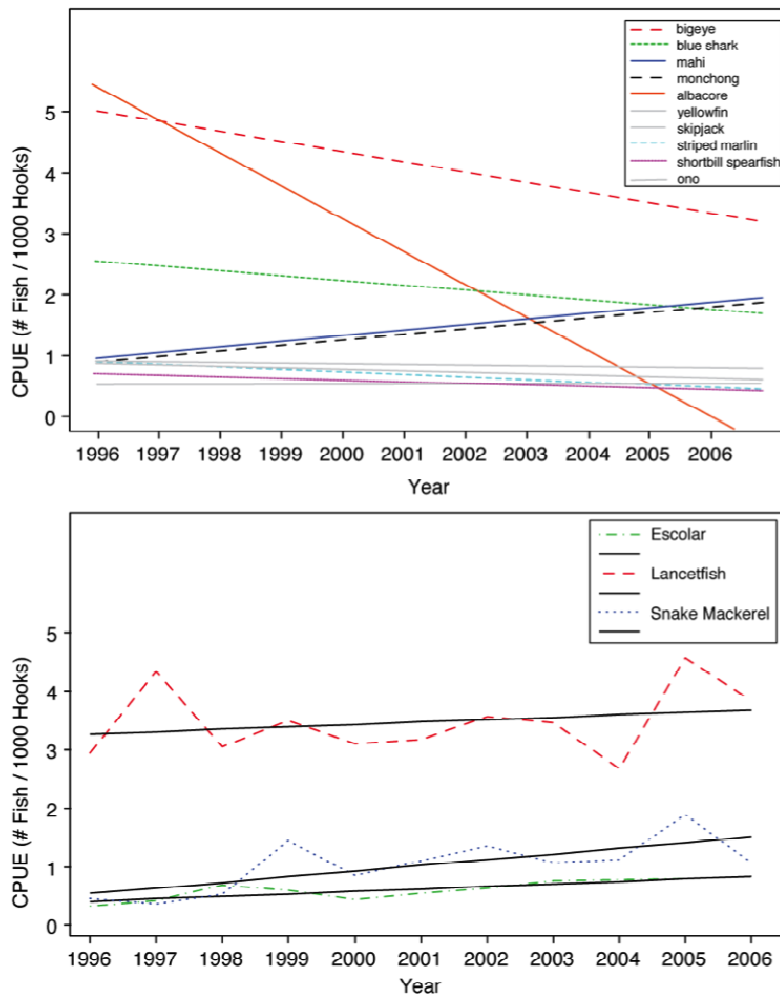


Figure 2. (Top) Linear catch per 1000hooks trends for the commercial species in the Hawaii based deep-set longline fishery from the generalized additive models, 1996-2006. (Bottom) Annual catch per 1000 hooks and linear regression line for the non-commercial species from the observer catch data in the Hawaii based deep-set longline fishery, 1996-2006. Species code and vernacular and scientific names are provided in Table 1. Mahi = dolphinfish, monchong= sickle pomfret= *Taractichthys steindachneri*, ono=wahoo. Figure from Polovina et al (2009).

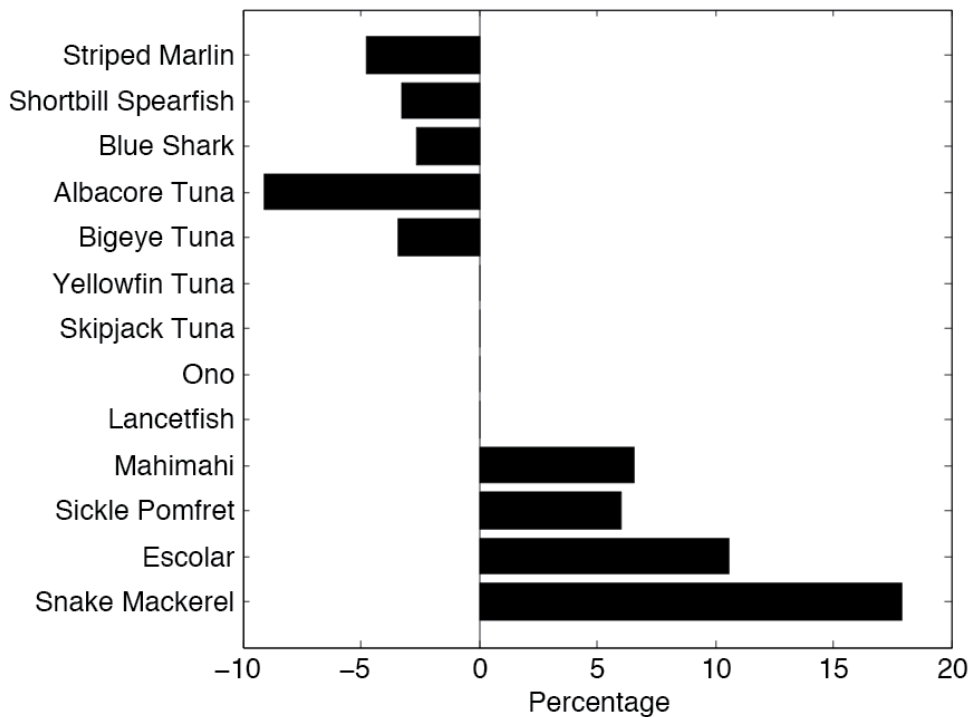


Figure 3. Annual percent change in catch per 1000 hooks from the Hawaii deep-set fishery, over the period 1996-2006, based on the linear trends Annual percent change in catch rate (number of fish per 1000 hooks) of the Hawaii deep-set fishery over the period 1996-2006 based on the linear trend presented in Polovina et al (2009). Negative values indicate decreasing trends, positive values indicate increasing trend. Non-zero values are statistically significant. Zero values indicate the non-significance of the trend which is not represented. Species code and vernacular and scientific names are provided in Table 1. Figure from Polovina et al (2009).

The mean annual trophic level of the top 13 species in the catch has declined over the time series by about 0.19 (or 5%) from about 3.85 to 3.66 (Figure 4). The percentage of the catch of the top 13 species composed of apex predators (TL \geq 4.0) has declined from about 70% to 40% (Figure 4). The percentage of the catch of the top 13 species with relatively high P/B (\geq 1.0) has approximately doubled from about 20% to 40% (Figure 4).

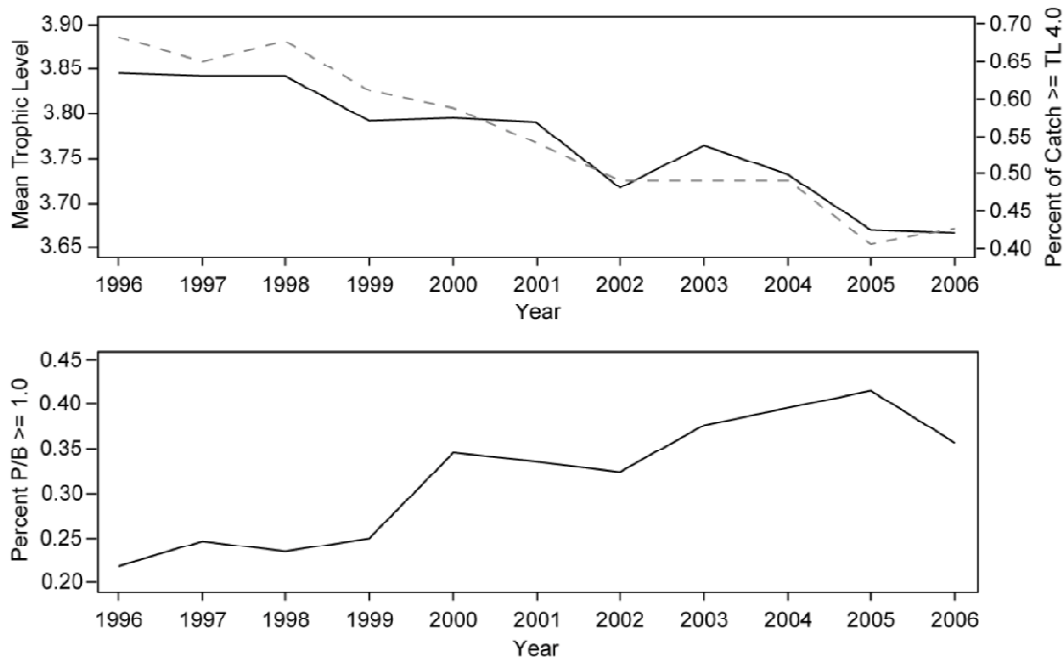


Figure 4. (Top) Weighted annual mean trophic level of the catch of the 13 most abundant species caught in the deep-set Hawaii-based longline fishery over the period 1996-2006 (solid line), and the percentage of the catch of the 13 species with trophic level greater than or equal 4.0 (dashed line). (Bottom) Percentage of the catch of the 13 species with production to biomass greater than or equal 1.0. Figure from Polovina et al (2009).

South west Pacific, the example of New Caledonia

When available, both logsheets and observer data estimates of catch rates were examined (Figure 5). The CPUE values estimated using each data source were very similar for the target species: albacore, yellowfin and bigeye, however they differ for bycatch species such as shortbill spearfish, striped marlin, wahoo, dolphinfish and in such cases observer values were always higher than logsheet values. Significant trends were observed for 6 species from the 14 species considered (excluding albacore, yellowfin, bigeye and striped marlin for confidentiality issues) (Figure 6): decreasing trends for mako shark and opah (logsheet data only) and for swordfish and sailfish (observer data only) and increasing trends for shortbill spearfish (logsheet data only) and dolphinfish (both logsheet and observer data). Over the studied period, (2002-2010) annual percent changes were about 10% for mako shark and shortbill spearfish and 5% for dolphinfish and opah according to logsheet data, and about 10% for swordfish and sailfish, and 29% for dolphinfish according to observer data (Figure 6). Annual percentage changes above 10% were non-significant for a number of species such as lancetfish, skipjack, escolar and black marlin due to the high variability of the annual CPUE. No major difference was noticed in the trophic level (Table 2) of species with increasing or decreasing trend.

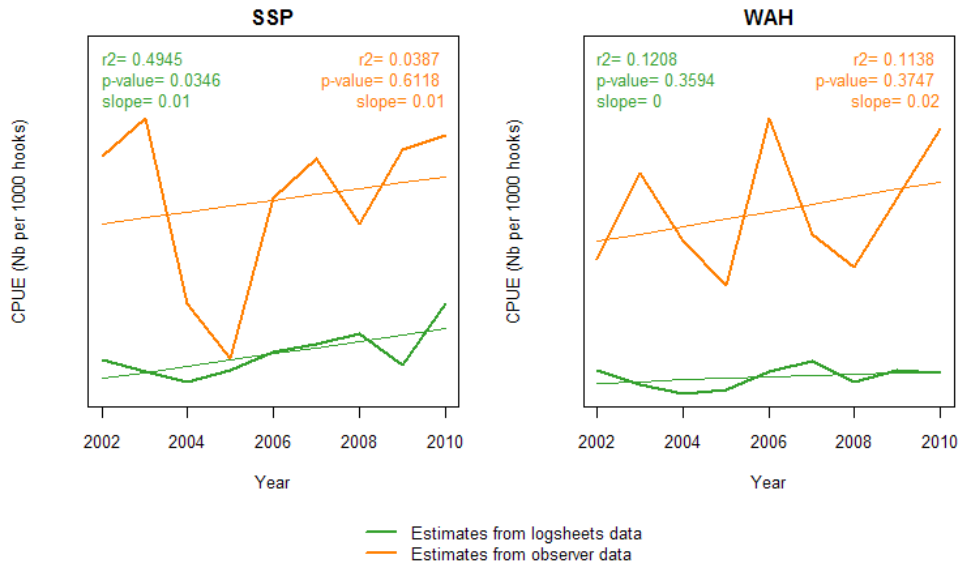


Figure 5. Annual catch rates (number of fish per 1000 hooks) and linear regression lines of New Caledonia catches over the period 2002-2010 based on observer (orange) or logsheet (green) data. Values of r^2 , p-value and slope respectively indicate the correlation coefficient, the statistical value indicating the significance of the relationship and the slope of the linear regression. Fourteen of the eighteen species are presented and the absence of y-axis is deliberate to preserve confidentiality of the data. Species code and vernacular and scientific names are provided in Table 1.

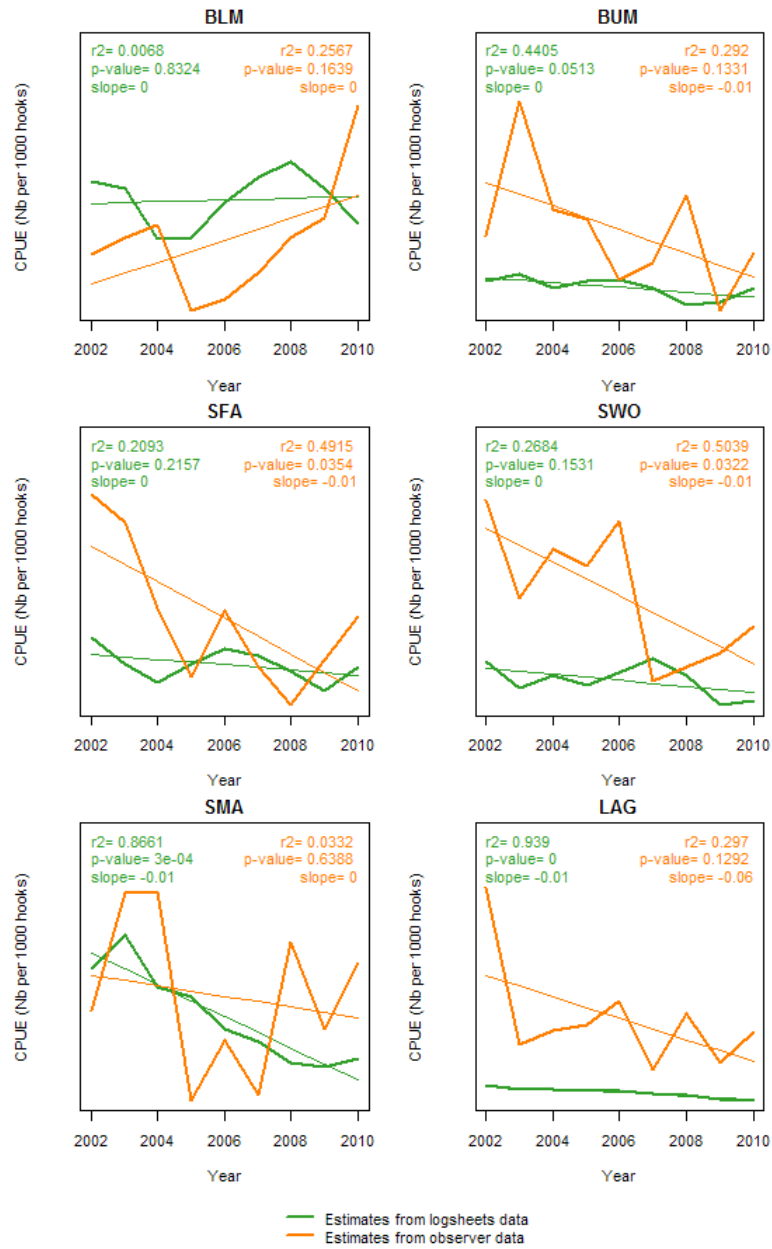


Figure 5. Continued

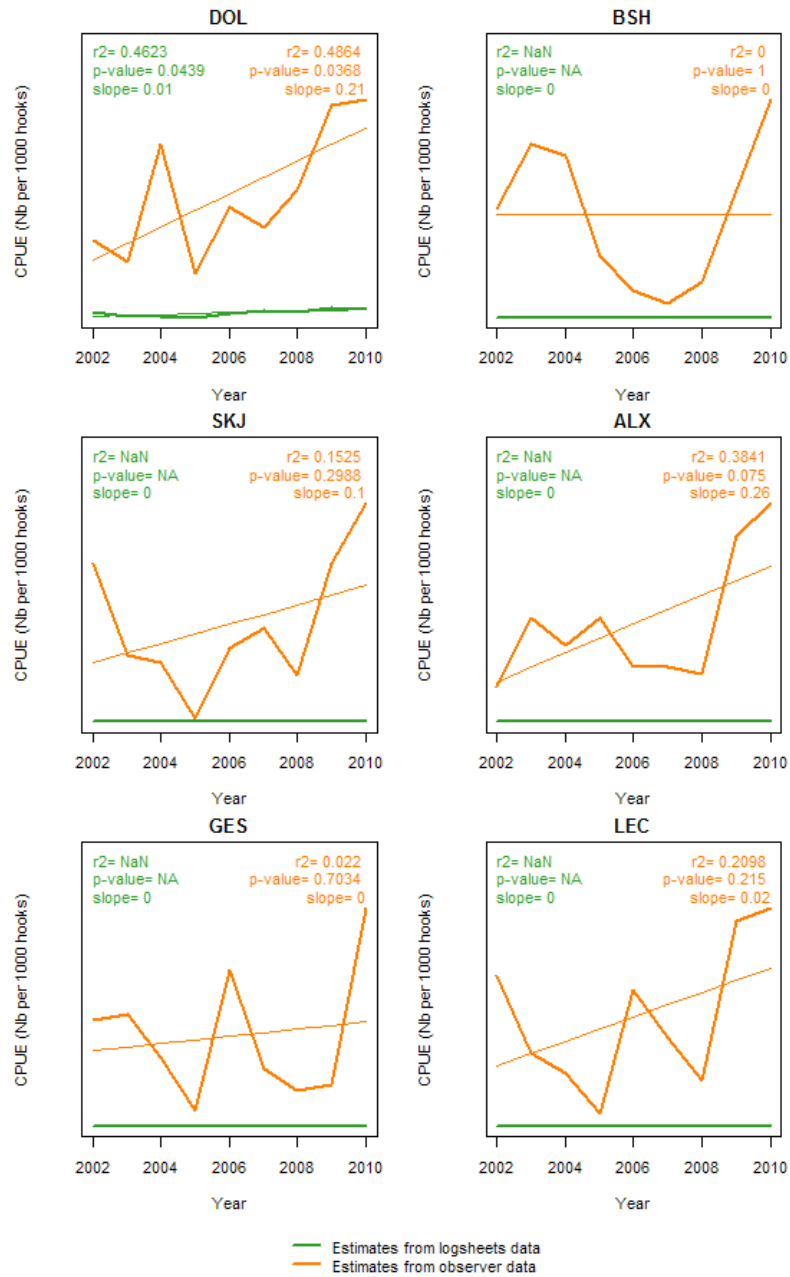


Figure 5. Finished

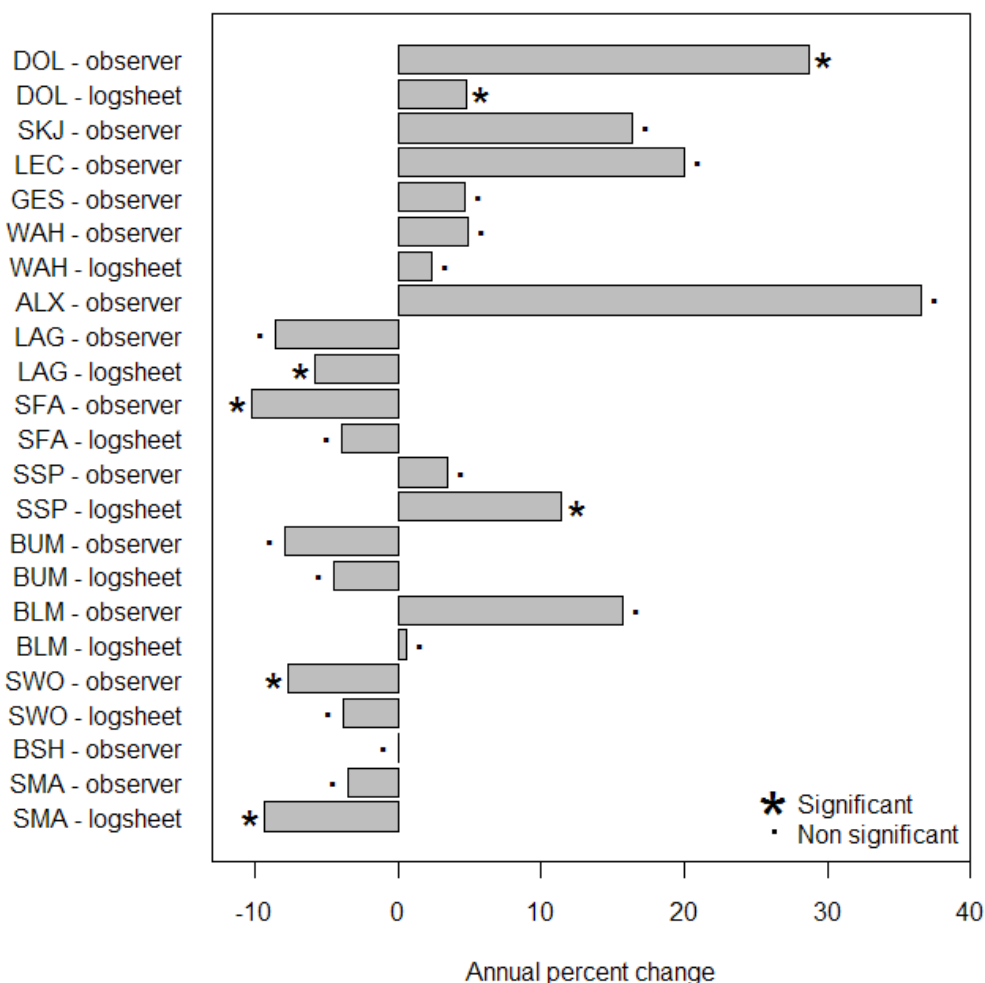


Figure 6. Annual percent change in catch rate (number of fish per 1000 hooks) of the New Caledonia catches over the period 2002-2010 based on the linear trend presented in Figure 5 and derived from observer or from logsheet data as indicated in the axis. Negative values indicate decreasing trends, positive values indicate increasing trend. Statistical significance of the trend at 95% is indicated by *. Species code and vernacular and scientific names are provided in Table 1.

The mean annual trophic level of the 18 species in the catch varied during the period studied and showed a decrease of about 0.06 (or 1.5%) from about 3.96 to 3.90 (Figure 7). The percentage of the catch of the 18 species composed of apex predators (TL \geq 4.0) has declined from about 80% to 75% (Figure 7). The percentage of the catch of the 18 species with relatively high P/B (\geq 1.0) has showed a slight decline from about 30% to 25% (Figure 7).

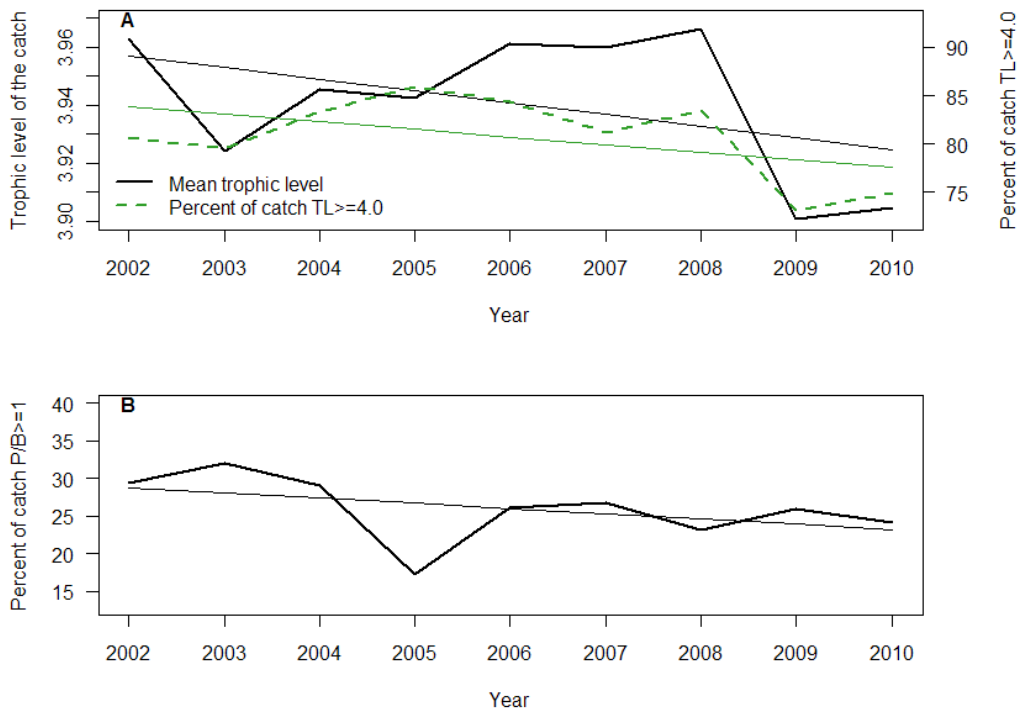


Figure 7. A) Weighted annual mean trophic level of the catch of the 18 most abundant species caught in New Caledonia over the period 2002-2010 (black solid line), and the percentage of the catch with trophic level (TL) greater than or equal 4.0 (green dashed line). B) Percentage of the catch with production to biomass (P/B) greater than or equal 1.0. Linear regression lines are added.

Ecopath modelling

Biomass changes

The balanced Ecopath model parameters for the 44 functional groups are shown in Table 2. The A2 2035 and A2 2100 scenarios involved a 6% and 9% reduction in net primary productivity in the Warm Pool model, which resulted in declines in the biomass of epipelagic forage (2.8 % and 16.8 %), mesopelagic forage (2.7 % and 15.5 %) and bathypelagic forage (2.6 % and 15.2 %) (Figure 8). Since these forage groups are important prey for large pelagic predators in the Warm Pool, the model predicted a bottom-up effect to cause a decline in the biomass of all mid trophic level predators such as wahoo (2.8 % and 14.7 %) and dolphinfish (2.4 % and 13.9 %), as well as high level predators including adult yellowfin (3.8 % and 22.3 %) and adult bigeye (3.7 % and 21.1 %) (Figure 8).

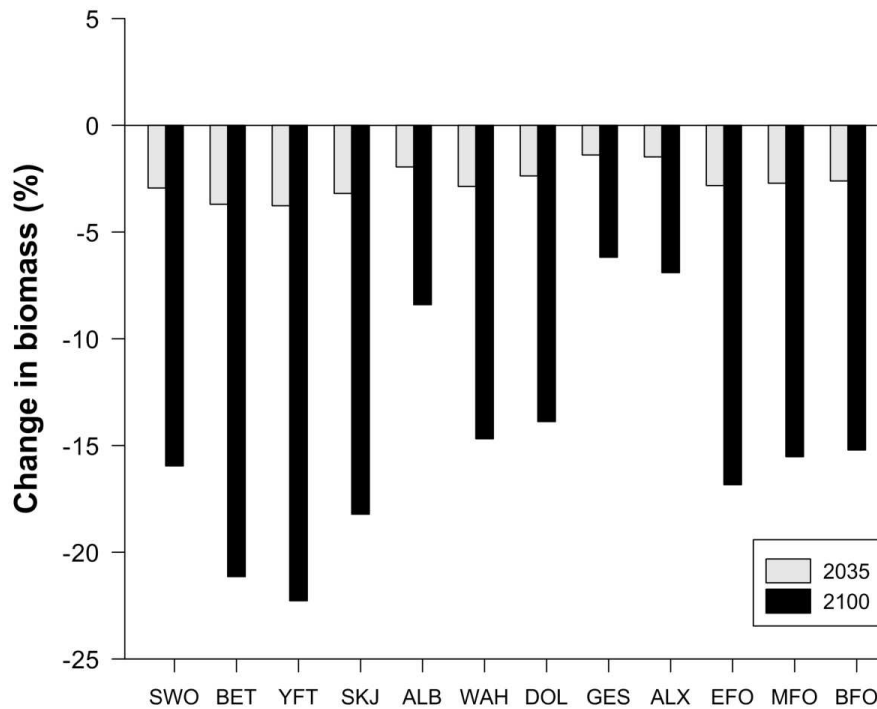


Figure 8. Predicted relative changes (%) in the biomass of key target and bycatch species, as well as forage groups in the Warm Pool ecosystem after imposing a linear decline of 6 % and 9 % in the biomass of phytoplankton from 2005 to 2035 and 2100 as predicted by the IPCC emissions scenarios. Species names are shown as FAO species codes, while additional miscellaneous species groups provided are: epipelagic forage (EFO), mesopelagic forage (MFO), and bathypelagic forage (BFO).

The skipjack fishery scenarios ran to 2035 applying the increased fishing mortality alone, and the coupled effect of increased fishing mortality and a 6% linear reduction in net primary productivity as defined in the A2 2035 climate change scenario. Both scenarios produce similar results in that the change in biomass of skipjack caused trophic cascades. In the absence of climate change, the largest change in biomass occurred for skipjack, declining by 86% (Figure 9), due to the large increase in fishing effort in combination with the high predation pressure exerted by high level predators including adult tunas, billfish and shark groups. Wahoo and bathypelagic forage were the only other two groups to decline in biomass, by 3.9 % and 27.6 %, respectively (Figure 9). All other target or bycatch species increased in biomass, most notably escolar (37.6 %), swordfish (28 %), bigeye (11.5 %), albacore (6.2 %) and lancetfish (6.3 %) (Figure 9).

The addition of climate change to the skipjack fishery effort increase primarily resulted in small changes (<5%) in the biomass of species groups changed in the scenario without climate change. However, the most obvious difference was the decrease in biomass of yellowfin (9.7 %), dolphinfish (9.5 %) and epipelagic forage (11.5 %) (Figure 9). These were also the groups that showed the greatest change in biomass under the A2 2035 scenario in the absence of fishing (Figure 8), indicating that the bottom-up effects caused by changes in primary productivity are stronger than the top-down forces by selectively fishing skipjack for these groups.

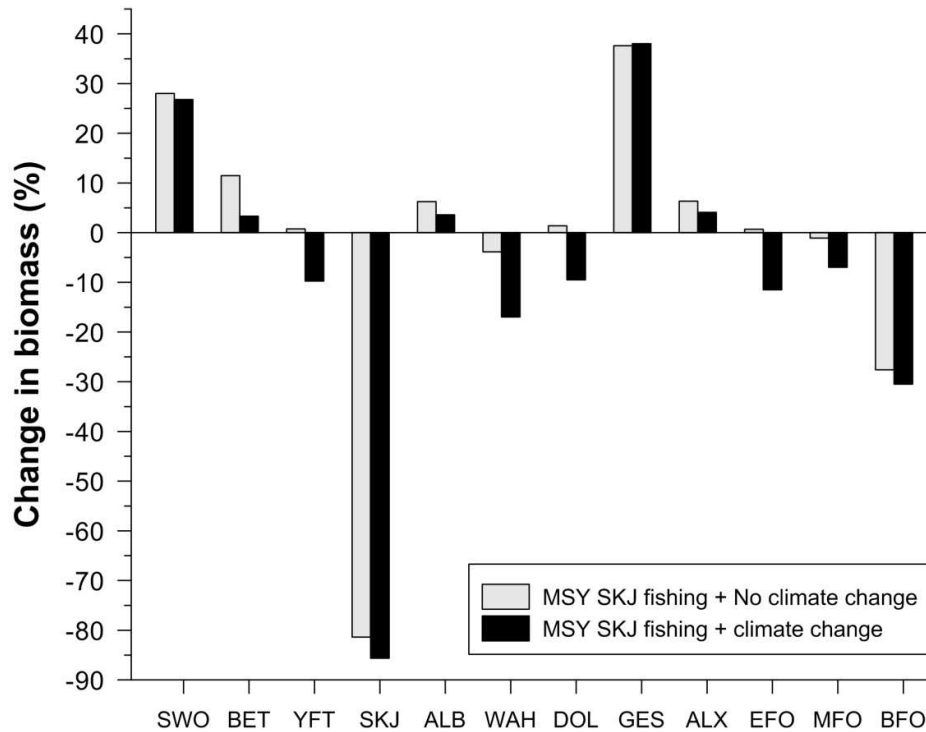


Figure 9. Predicted relative changes (%) in the biomass of key target and bycatch species, as well as forage groups in the Warm Pool ecosystem after i) increasing the fishing mortality rate to FMSY for skipjack and ii) increasing fishing mortality as well as imposing a linear decline of 6 % in the biomass of phytoplankton from 2005 to 2035 as predicted by the IPCC emissions scenarios. Species names are shown as FAO species codes, while additional miscellaneous species groups provided are: epipelagic forage (EFO), mesopelagic forage (MFO), and bathypelagic forage (BFO).

Ecosystem indicators derived from Ecopath/Ecosim

The Ecopath model showed that 83% of the total biomass in the Warm Pool is represented by trophic levels 1, 2 and 3 (Figure 10). In contrast, the total catch is comprised of trophic levels 3 and above, with trophic level 4 making the highest contribution to the catch (46%) (Figure 10). The production/biomass ratio (P/B) of the 26 groups comprising the catch ranged from 0.503 to 3.454, although only four groups (15%) had a P/B of greater than 1 and eight groups (31%) had a P/B less than 0.5.

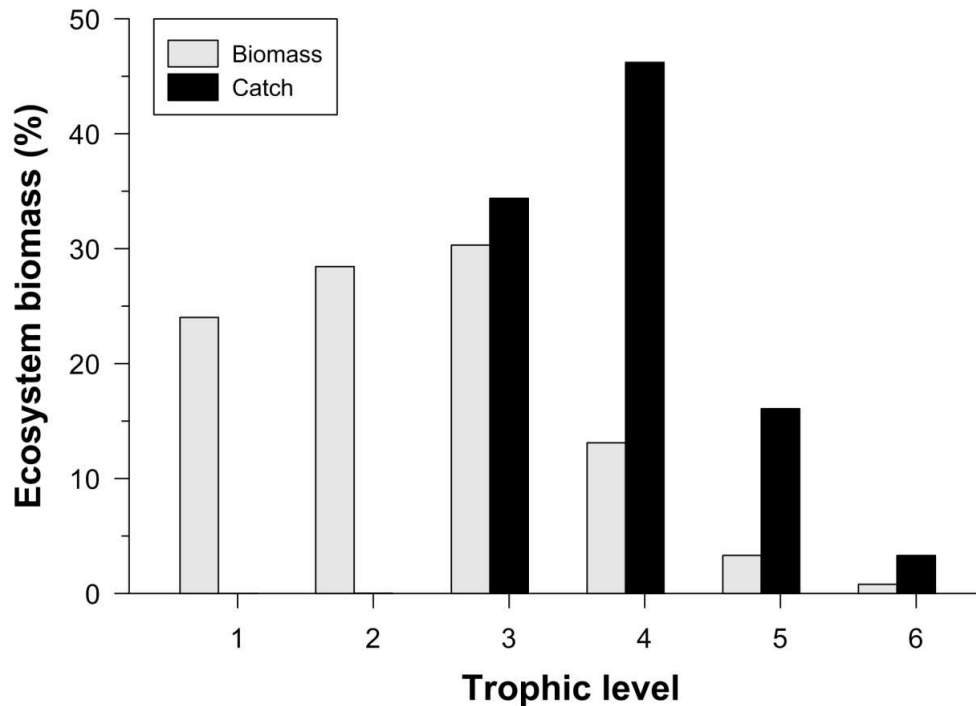


Figure 10. Contribution of each trophic level to the total biomass in the Warm Pool ecosystem and the total catch biomass in the Ecopath model’s balanced state characterized for 2005.

Discussion

Catch rate trends and ecosystem indicators

As highlighted by Polovina et al (2009), numerous factors influence catch rates such as changes in species targeting, gear changes, seasonal and spatial changes of the fishery and caution should be applied when analysing catch rate trends. Decline in albacore in Hawaii is partially explained by a shift of targeting (Polovina et al 2009); mako shark decrease in New Caledonia can be partially explained by a gear change (the use of wire trace has been abandoned in 2005 and new monofilament lines allow sharks to cut the line and escape).

Comparing Hawaii and New Caledonia catch rate trends and indicators show some similarities and also some differences. In both regions an increasing catch rate is observed for dolphinfish. However, shortbill spearfish show opposite trends and catch rate trends observed in Hawaii for blue shark, escolar and snake mackerel are non-significant in New Caledonia. For indicators, mean annual trophic level of the catch and percent catch with $TL \geq 4.0$ show decreasing trends in both areas but the changes are smaller in New Caledonia. For the percent catch with $P/B \geq 1.0$, the trends are opposite in the two regions.

In both areas some changes in the ecosystem are observed. In Hawaii Polovina et al (2009) explain the increase in catch rates of mid-trophic level predators concurrent with a decrease in catch rates of top predators by a top-down control as fishing has reduced the abundance of apex predators and mid-trophic level predators have increased in abundance in response to decreased predation. The hypothesis is in agreement with simulation conducted with the central north Pacific EwE model (Polovina et al 2009). In New Caledonia catch rate trends of mid-trophic and top predators do not

show the same consistency; the trend of all species together is similar to Hawaii but some top predators increase instead of decreasing and the reverse is true for mid-trophic predators. Effects are stronger in Hawaii and it could be explained by an important increase in the fishing effort in Hawaii. The number of hooks has more than doubled during the studied period (1996-2006) in the Hawaiian core fishing region (Figure 11), while it has been stable during the studied period (2002-2010) in New Caledonia. This increasing fishing pressure in Hawaii could have induced stronger changes in the ecosystem than in New Caledonia, with an important loss of top predators (from 70% to 40%) and a 5% decrease of the annual trophic level of the catch. On the other hand, in New Caledonia the stable fishing pressure could make the impact the ecosystem less detectable with a moderate decrease of top predators (from 80% to 75%) and annual trophic level of the catch (1.5%).

As shown by the data, the ecosystem may be changing in response to fishing and there is a need to expand the focus of monitoring beyond the few target species.

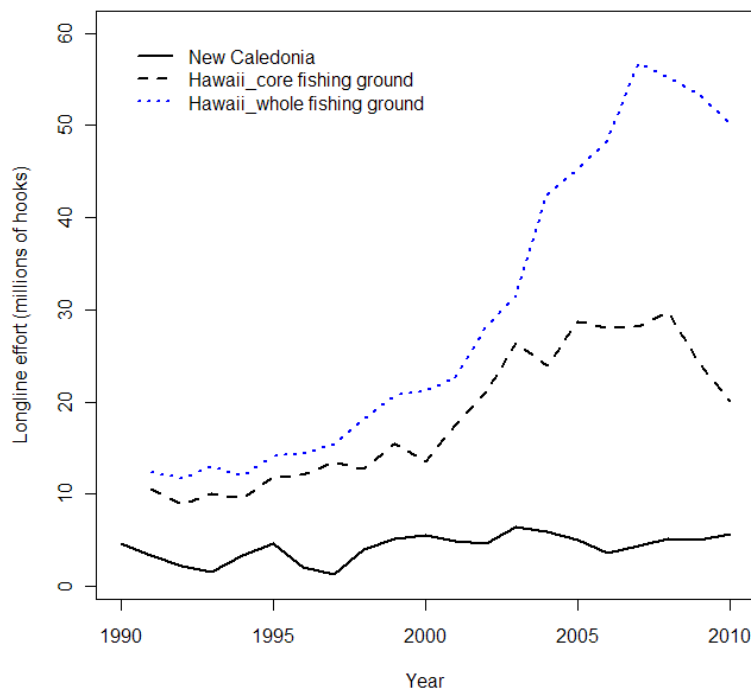


Figure 11. Annual longline effort (in millions of hooks) in New Caledonia and by the Hawaii longline fleet in the whole Hawaii fishing ground and in the core Hawaii fishing ground during the period 1990-2010.

Other ecosystem indicator in development

Many ecosystem indicators have been developed (Rochet and Trenkel 2003, Shin and Shannon 2010, Piet and Pranovi 2005, Rice 2000) but most of them still need to be tested with real data and uncertainty need to be included. Information provided in this paper shows that, in Hawaii, fishing results in a top-down ecosystem response where a decline in the abundance of the largest species results in an increase in the abundance of smaller exploited species. This suggests that size-based predation is a dominant factor in the central Pacific pelagic ecosystem and top-down and bottom-up impacts can be modelled with a relatively simple dynamic size-based model. However, the type of hook used also appears to modestly alter the composition of the catch. Polovina and collaborators are

exploring size-based indicators and whether hook type may be used as a management action to alter the ecosystem impact of longline fisheries.

Improving data to use catch rates and ecosystem indicators for ecosystem management

Differences observed between catch rates calculated based on logsheets and observer data raises the issue of the quality of the data used to determine these indicators. The fact that catch rates of bycatch based on observer data are higher than catch rates based on logsheets for New Caledonia suggests that bycatch catches might not be fully reported on logsheets. There is a need to encourage fishing companies to report as accurately as possible all the catches, not only the target species. It would be interesting to compare logsheet and observer records of the same trips to estimate the difference between the 2 sources and the confidence in the estimates.

Moreover the high variability of bycatch catch rates based on observer data in New Caledonia is an indication that the data collected are insufficient to be fully representative of the whole fishery. Exceptionally high or low catch rates by specific boats fishing in particular areas make the catch rate trends non significant and they do not appropriately represent the average situation. New Caledonia longline observer coverage was around 8% in number of hooks in the recent years, which is very high on Pacific standards. In comparison, annual bycatch catch rate are less variable in Hawaii where the observer coverage is about 16%. The targeted 5% observer coverage for longline fisheries in the WCPFC convention area is probably not sufficient to insure representativeness of the data and its use for the estimation of non-target species, and calculation of ecosystem indicators. It is difficult to identify an ideal observer coverage rate as it mainly depends on the goals of the subsequent analyses or the species of interest, but an observer coverage around 20% is probably a better target for longline fisheries and it should be encouraged to distribute observation over a large variety of vessels, areas and seasons to increase representativeness of the data.

Numerous factors influence catch rates such as changes in species targeting, gear, seasonal and spatial distribution of the fishery. To interpret catch rate trends as changes in abundance it is then necessary to consider the factors that could influence the catch rates and remove their effect. This was done for the catch rates issued from the logsheet data in Hawaii as the data considered was restricted to catches from deep sets to avoid gear disparity, and generalised additive models were used to take into consideration seasonal and spatial pattern (Polovina et al 2009). This standardisation was not conducted on Hawaii observer-based catch rates, due to limited sample size, or New Caledonia catch rates. Standardisation methods of catch rates should be widely used to take into consideration spatial distribution of the species as it has been done for sharks in the WCPO (Lawson 2011). There is also a need to better record any changes in gear or species targeting and to include these information into standardisation of catch rates.

Table 1 shows different values for biological parameters such as trophic level and P/B ratio according to the origin of the data and the calculation method. This variability and uncertainty in basic biological parameters compromises our confidence in the indicators based on these parameters. To illustrate this point, annual mean trophic level (Figure 7A) for New Caledonia was calculated with i) TL extracted from the central North Pacific ecosystem model and ii) from the warm pool model with all the species and iii) from the warm pool model with all the species except the lancetfish (ALX) (Figure 12). Lancetfish represents a high catch, and because it has a higher TL than tunas in the warm pool model compared to central north Pacific model, including ALX or not in the analysis induces important changes (Figure 12). A better knowledge on the trophic position and other biological

parameters of all the bycatch species should be acquired. Current diet studies by SPC and isotope and amino acid approaches developed by the University of Hawaii will increase our knowledge on these species; they need to be continued and spatial variation in the vast Pacific Ocean need to be explored.

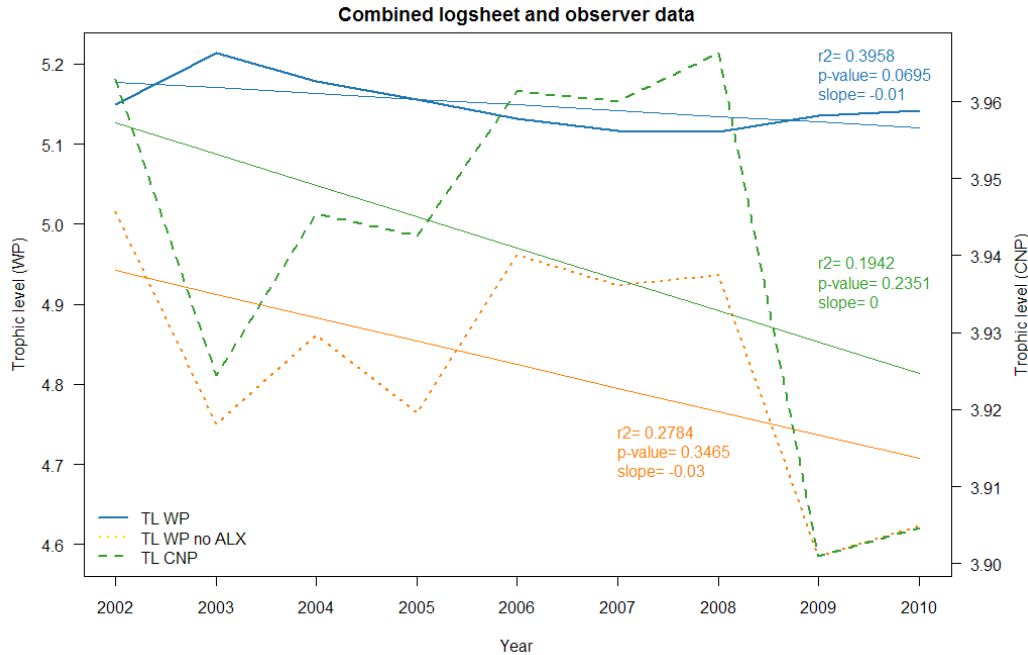


Figure 12. Weighted annual mean trophic level of the catch of the 18 or 17 most abundant species caught in New Caledonia over the period 2002-2010. The blue line represents the value calculated for the 18 species with TL determined by the warm pool ecosystem model (WP); the orange dashed line represents the value calculated for the 17 species (excluding lancetfish ALX) with TL determined by the warm pool ecosystem model; the green dashed line represents the value calculated for the 18 species with TL determined by the central North Pacific ecosystem model (CNP), identical to Figure 7A. Linear regression lines are added.

Ecopath with Ecosim modelling

The ecosystem model of the Warm Pool predicted that a decrease in the biomass of phytoplankton caused by increased sea surface temperatures would have a negative effect on the biomass of secondary producers and forage species. Because these forage species are the direct prey of many high trophic level predators, the biomass, and catches, of the primary commercial tuna species is likely to decline by up to 22 % by 2100.

These hypothesised simplified linear effects of bottom-up forcing on tuna catches have important implications for the value of tuna fisheries and their associated infrastructures. However, other indirect and more complex effects of climate change need to be considered before the full extent of the impact can be estimated. For example, increased surface temperature may change the stratification of epipelagic waters and alter the depth of the thermocline (Sarmiento et al., 2004), which defines the vertical distribution of several tuna species that support commercial fisheries in the Warm Pool (Musyl et al., 2003; Schaefer and Fuller, 2007; Schaefer et al., 2007). This stratification may therefore change the amount of available habitat and lead to a decline in abundance (Prince and Goodyear,

2006), and catches. Alternatively, this stratification may also contribute to the population becoming more vulnerable to fishing gears (Prince and Goodyear, 2006), and therefore lead to increase catches in the short-term.

In addition, changes to fisheries management strategies may complicate the process in forecasting ecosystem responses to perturbations. In this study, we simulated dramatic increases in the fishing effort for skipjack in the presence and absence of climate change. It was clear that fishing produced very different ecosystem responses than the A2 2035 and A2 2100 climate change scenarios alone. In particular, the fishery changes cause dramatic declines in skipjack, which resulted in trophic cascades as the imbalance of the release or increase in predation pressure propagated through the system. The addition of climate change to the change in skipjack fishing effort was not as simplistic as merely reducing the biomass of higher trophic level groups through the reduction of phytoplankton biomass as was seen in the A2 2035 scenario. The combination of these two perturbations produced a complex alteration of trophic flows that propagated to all trophic levels in the system.

The Warm Pool model is effective for investigating ‘what if’ hypothesis in a complex ecological system. However, further work is required to increase the confidence in model predictions to better understand the internal mechanisms that drive tropical pelagic ecosystems. By driving the Warm Pool model using primary productivity, we have made an implicit assumption that the system is controlled by bottom-up processes. However, with an increasing number of models being built for pelagic ecosystems worldwide (Kitchell et al., 2002; Watters et al., 2003; Rosas-Luis et al., 2008; Griffiths et al., 2010), it appears that these systems have characteristics of a complex form of ‘wasp-waist’ structure where the majority of the system’s biomass is comprised of mid-trophic level groups (Cury et al., 2000). The Warm Pool model appears to have a wasp-waist structure, which is evident by trophic level 3 comprising 30% of the total system biomass. Such mid trophic level groups are critical in the maintenance of ecosystem structure as they function as important predators of secondary producers and are prey of high trophic level predators such as tunas. A recent model of the pelagic ecosystem off eastern Australia demonstrated the importance of mid trophic level mesopelagic fishes and cephalopods for exerting top-down control on lower trophic levels, and bottom-up control as prey for large tunas, billfishes and sharks (Griffiths et al., 2010). Therefore, any significant change in their biomass – possibly from habitat compression from increasing a change in ocean stratification dynamics – can cause large and unpredictable changes to the biomasses of groups in higher and lower trophic levels, and thus change the overall integrity of the ecosystem structure.

Ecosystem models provide a useful theoretical framework in which the ecological effects of climate change can be explored. The enormous complexity of trophic interactions within pelagic ecosystems like the Warm Pool means that ecosystem models may be one of the few ways in which “what if” scenarios regarding the ecological effects of fishing may be explored. The Warm Pool model was based upon the highest quality datasets available that described the ecosystem structure, trophic ecology and biology of constituent species groups. However, the input parameters are by no means without error or uncertainty and there are several areas where the model can be improved. Basic studies on the feeding ecology, age and growth, and standing biomass of several functional groups, especially those of low commercial value that occupy low to intermediate trophic levels (e.g. bycatch or forage species), are required to improve estimates of key parameters in the model. Given the spatial variation that is often inherent in the diets and abundance of pelagic fishes, it is important to collect species-specific and regionally-specific data to maintain the realism of the model structure and dynamic outputs. This may be cost-effectively achieved by co-ordination of various fisheries agencies and RMFOs to undertake a fishery-dependent monitoring program.

Conclusion and future work

Examination of bycatch catch rate trends and of community indicators derived from catches and biological characteristics of the species (e.g. trophic level) show promises in providing ecosystem indicators of use for fisheries management. As demonstrated in this paper the variation in fishing pressure might have a top-down impact on the ecosystem. Further investigation of this hypothesis across the WCPO is clearly warranted. Other factors need to be accounted for as multiple parameters influence catch rate such as gear changes, fishery distribution, but also changes in the environment (climate variability) which could have a bottom-up impact on the ecosystem as shown by the Ecopath with Ecosim (EwE) modelling. More indicators also need to be explored as no single indicator provides a complete picture of the ecosystem state, a suite of indicators will be required (Fulton et al 2005).

Ecosystem modelling such as EwE provides a potential tool to explore simultaneously bottom-up and top-down impacts. While the uncertainty of ecosystem models presents serious challenges, this method holds great promise for ecosystem assessment and management (Levin 2009). It is however data demanding and this is an important pitfall of this type of approach. It requires multiple expertises and good data quality to obtain reliable models that can be used to define indicators and run simulations for EAFM. Insuring good quality and good reporting of target and non-target logsheet data, increasing the observer coverage rate in longline fisheries, implementing standardisation of catch rate, improving biological knowledge of bycatch species and improving the quality of the models is primordial to obtain accurate and trustable results for the development of ecosystem indicators to support management.

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