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Optimising fisheries management in relation to tuna catches in the western central Pacific Ocean: A review of research priorities and opportunities

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ABSTRACT

Some of the most important development goals for the countries and territories of the Western and Central Pacific Ocean (WCPO) involve the sustainable management of their fisheries in light of environmental, economic and social uncertainties. The responses of fish populations to variability in the marine environment have implications for decision making processes associated with resource management. There is still considerable uncertainty in estimating the responses of tuna populations to short-to-medium-term variability and longer-term change in the oceanic environment. A workshop was organised to examine how advances in oceanography, fisheries science and fisheries economics could be applied to the tuna fisheries of the WCPO and in doing so identify research priorities to improve understanding relevant to progressing management. Research priorities identified included: (i) improved parameterisation of end to end ecosystem model components, processes and feedbacks through expanded biological observations and incorporation of higher resolution climate models; (ii) development of seasonal and inter-annual forecasting tools enabling management responses to short-term variability in tuna distributions and abundances; (iii) improved understanding of the population dynamics of and the energy transfer efficiencies between food web components; (iv) assessment of the optimal value of access rights and overall fishery value under multiple scenarios of tuna distribution and abundance and influences on decision making by fisheries managers and fleets and (v) development of management strategy evaluation frameworks for utilisation in the implementing and testing of fishery management procedures and to help prioritise research directions and investment. Issues discussed and research priorities identified during the workshop have synergies with other internationally managed fisheries and therefore are applicable to many other fisheries.

1. Introduction

Many countries and territories in the Western and Central Pacific Ocean (WCPO) are reliant on fisheries resources for government revenue, food security and traditional culture [12,50]. Consequently, some of the most important development goals for these countries involve managing their fisheries resources to optimise these benefits, while maintaining future options given environmental, economic and social uncertainties. Information that allows the fisheries managers and governments of these countries to identify fishing levels that result in the best trade-off between conserving stocks for future generations and maximising present-day catch and benefits is therefore highly important [51].

Because of the cross-boundary distributions of many of the fisheries resources of importance to WCPO countries and territories,

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Regional Fishery Management Organisations (RFMOs) seek to regulate international fishing activity across these cross-jurisdictional regions. These organisations are increasingly aware of the need to coordinate with the national plans and aspirations of countries and territories. Fisheries managers are also increasingly required to balance short term tactical decisions (e.g. foreign fleet access rights, effort trading) and longer term strategic decisions (industrial investment in post capture processing and stakeholder trade-offs) to achieve desired outcomes.

Short-term tactical and longer term strategic decisions are complicated by the fact that fish populations underpinning the development benefits associated with their harvesting respond dynamically to the marine environment (e.g. [70,29,120]). The responses of fish populations to variability in the marine environment have implications for decision making processes. For improved stock assessments and planning, tools that quantify the links between fish populations, their ecosystems and major oceanographic features are needed [55]. These tools must provide information across a number of spatial (local to regional) and temporal (seasonal to decadal) scales, and additionally provide information of relevance to extreme events.

Of particular importance to countries and territories in the WCPO are fisheries for tuna and tuna-like species. Changes in water temperature, circulation and primary production (and flow-on changes to food webs) throughout the equatorial Pacific Ocean associated with the phases of El Niño Southern Oscillation (ENSO), result in changes to the distributions (and potentially abundances) of tuna species and in particular, skipjack tuna (*Katsuwonus pelamis*), which are then observed in fisheries catches [70,71,69]. The influence of ENSO on tuna populations, has resulted in considerable effort being put into better understanding how tuna populations might respond to projected changes to the WCPO environment with ongoing long-term climate change (e.g. [40,75]). A primary tool used to investigate these responses is a coupled dynamical ecosystem model, the Spatial Ecosystem and Population Dynamics Model (SEAPODYM; [74]). The framework for SEAPODYM allows the integration of tuna and tuna-like species biology and ecology within a description of the marine ecosystem and simulates the responses of focal species (e.g. skipjack tuna; [74]) to external forcing factors such as climate and fishing. This modelling framework has been useful for not only exploring the effects of climate variability, climate change and fishing on tuna population distributions and abundances, but also identifying key knowledge gaps and research priorities for improving understanding (e.g. [73]). Many of the key knowledge gaps identified via the use of SEAPODYM have also been highlighted elsewhere [52,118] and are associated with (i) modelling and forecasting of the climate system, particularly at spatial and temporal scales of relevance to fisheries; (ii) understanding of the physiology of tunas, particularly in relation to thermal, oxygen and pH preferences and thresholds; (iii) understanding of food webs in the WCPO; (iv) impacts of fisheries on tunas and their ecosystems and; (v) responses of fisheries to climate variability and longer-term change. Improving understanding in these five science areas will greatly benefit the identification and development of robust management strategies capable of ensuring the sustainability of resources and associated revenues. Further, readily accessible tools which allow fisheries managers and governments to easily evaluate both short term tactical decisions and longer term strategic decisions are currently lacking.

Recent advances in oceanography, fisheries science and fisheries economics have the capacity to progress efforts to address these uncertainties, thereby providing the information required for supporting and developing best management practices over varying time scales. As part of a multidisciplinary, multi-agency collaboration developed to address uncertainties in current understanding of tuna populations, their ecosystems and responses to environmental variability over multiple time scales [27], an international workshop, held in November 2013 in Hobart Australia, was organised to examine how these recent advances could be applied to the tuna fisheries of the WCPO. Importantly, it was identified that scientists from these separate fields of research need to work in close collaboration to appreciate and address the needs and uncertainties across disciplines (e.g. [40,30]). Here, we summarise emergent themes from the workshop, describe the status of current knowledge and identify major gaps and issues. We conclude with a list of research priorities, and potential areas for regional collaboration to advance understanding required for ensuring ongoing sustainability of tuna resources in the WCPO. Many of the issues discussed and priorities put forward are synergistic with the issues and research needs of regionally managed fisheries elsewhere and so are of broad application.

2. Current understanding

Participants spanned a range of disciplines, including physical, chemical and biological oceanography, ecology, economics, and fisheries assessments. Recent developments in each field were likely to provide new insights into important issues associated with uncertainties associated with tuna biology, fisheries and ecosystems of the WCPO. Thus, the workshop began with a series of talks outlining current understanding across the range of disciplines of relevance to the workshop.

2.1. Physical and biogeochemical ocean observations

The tropical Pacific Ocean (defined for these purposes as 20°N–20°S) is made up of distinct oceanic provinces that vary in regards to water temperature, salinity, mixing, nutrient availability, dissolved oxygen concentration and pH, resulting in very different habitats and ecosystems [80,68]. The region is also characterised by complex surface and subsurface currents that shape the physical and biogeochemical environment [101,39]. While the western Pacific Ocean experiences relatively low seasonal variability, it can change dramatically on inter-annual timescales in association with ENSO [86]. ENSO phenomena can induce major changes in wind regimes and current direction, influencing, in particular, the eastern extension of the western Pacific warm pool, an area in which substantial catches of tuna occur. During an El Niño event there is an eastward displacement of warm water associated with the warm pool. The thermocline deepens in the central and eastern Pacific Ocean, while shallowing in the western Pacific Ocean. In some extreme cases, this results in the relocation of the convergence zone to the east by more than 50° of longitude. During La Niña, the warm pool is displaced westwards and is typically confined to the extreme west of the equatorial Pacific, resulting in a deeper thermocline in this area [98].

Remote sensing and automated observing platforms (e.g. the ARGO float network and the TAO/TRITON tropical mooring array) have facilitated significant improvements in the observation of the physical and biogeochemical components of the region. Together with advances in understanding the underlying dynamics of the ocean and atmosphere, these observations have been key elements for the development of complex physical-biogeochemical models which operate at a range of spatial and temporal resolutions (see Section 2.2).

Supporting ocean modelling efforts in the WCPO region, particularly at higher spatial resolutions, is the international Southwest Pacific Ocean Circulation and Climate Experiment (SPICE) programme [39]. The main objective of this programme is to improve understanding of the southwest Pacific Ocean circulation and the South Pacific convergence zone as well as their local and remote influence. Over the past seven years, in-situ oceanic observations, modelling, as well as remote sensing and comprehensive analyses of historical data have been carried out. Monitoring of key parameters of the physical systems of the region is ongoing, with hydrographic cruises, ocean moorings, gliders and ships of opportunity continuously surveying several key areas of the Coral, Tasman and Solomon Seas. Currently the ARGO network, which has been central to the collection of physical observations on global scales, is being expanded to include measurements relevant for biogeochemical models such as oxygen (see www.ioccg.org/groups/argo). Together with the expansion of technologies such as gliders and miniaturisation of biogeochemical sensors, the future is likely to see a richer subsurface observational network and data availability.

2.2. Physical and biogeochemical models

Ocean and coupled ocean-atmosphere climate models can provide forecasts or scenario-based projections across a range of timescales, from daily to seasonal (4–5 months) through to multi-decadal and centennial climate change (e.g. [119,121,59]).

High spatial resolution forecasting of the ocean (1–10 km) to predict the evolution of mesoscale features such as eddies is largely limited to time scales on the order of days (~10 days). Like weather systems, these features are inherently chaotic, and so prediction on scales beyond a few weeks has limited skill. Forecasting on seasonal timescales (<1 yr.) generally occurs at lower spatial resolutions (100 km), and uses ensembles of simulations (i.e. multiple forecasts with small differences in their initial conditions). Seasonal-scale forecasts now support decision making around coral reef health, aquaculture and fisheries (e.g. [110,111]). The skill of these models varies in association with uncertainties associated with predicting the phase of ENSO. Prediction capability associated with forecasting an ENSO event is relatively high approximately six months prior to the event, but declines rapidly as the prediction moves further back in time [63].

Forecasts over longer time scales such as those made over decadal periods rely on the assumption that certain low-frequency variability in the ocean (e.g. the Pacific Decadal Oscillation; PDO) is predictable out to a number of years. Although considerable effort has gone into developing a framework for providing decadal predictions of the ocean and atmosphere, at present simulations over these time scales appear to offer little skill beyond 1–2 years in the tropical Pacific region [64]. This limits investigation of changes to modes of variability such as ENSO (e.g. [45]) and changes to the position of ocean provinces [14] via the use of climate models.

At longer time scales (>30 years), climate variability associated with features such as ENSO or the PDO is currently not predictable. The ocean state however, is strongly affected by trends in atmospheric greenhouse gas levels and processes associated with changes in atmospheric levels of these gases. The future trajectory of greenhouse gas emissions is inherently unpredictable and will depend on a variety of socioeconomic and technological factors. As part of the Intergovernmental Panel on Climate Change (IPCC) process, a number of future emissions scenarios (termed Representative Concentration Pathways, RCP) have been developed based on different assumed rates of population growth and energy consumption patterns [91]. Coupled ocean-atmosphere climate models are used to produce projections of the state of the ocean and atmosphere based on these scenarios. While early models generally only simulated the physical environment, many climate models (termed Earth System Models) now simulate chemical interactions and possess nutrient-phytoplankton-zooplankton components of varying complexity. Such models are being used widely to investigate the impacts of longer term environmental change on species, ecosystems and fisheries both in the WCPO and elsewhere (e.g. [87,48,72]).

2.3. Food webs

Skipjack tuna have an important role in the food web of the equatorial WCPO. The species constitutes a large biomass, has a relatively high turnover and contributes to the diet of most top predators throughout the region [2]. Because of their role in the equatorial ecosystem, removal of skipjack tuna from the ecosystem through commercial harvesting may impact the whole ecosystem through both a top-down and bottom-up process [44]. Also of importance to the food web are the small organisms that make-up the micronekton component of pelagic ecosystems [68]. These organisms occupy a central position in the pelagic ecosystem, linking the lower trophic levels through feeding on phytoplankton and zooplankton, and the upper trophic levels by comprising the forage of predators such as skipjack tuna.

Varying changes to food webs across the WCPO have been projected to occur over the coming decades [44,68,84]. While some uncertainties exist in climate model projections of the physical state of the ocean [15], projections suggest that surface intensified warming will result in a decrease in the salinity of western warm pool waters and an expansion of the warm waters associated with the western warm pool ([41,15]). Both the South Equatorial Current and the South Equatorial Counter Current are projected to decrease, while the Equatorial Counter Current is projected to increase. The thermocline is projected to shoal and increased stratification is projected to occur across most of the tropical Pacific Ocean [40]. Associated with projection of a shoaling of the thermocline is a shoaling of the nutricline into the photic zone. A decrease in nutrient upwelling is expected as a result of increased stratification, resulting in lower surface primary production. In most climate models, this results in an overall decrease in net primary productivity [112,84]. Recent examination of projections produced at high-resolution however, suggests that increased mixing due to changes in currents (which are not fully resolved in lower resolution models), results in increased subsurface primary production. This is expected to result in close to no change in overall net primary production [84].

Ecosystem modelling frameworks are increasingly being used to investigate the potential impacts of external forcing on the marine ecosystem such as climate variability and commercial fishing (see [36] for a review). The skill of these modelling frameworks in representing linkages and feedbacks within food webs, however, is reliant on limited observations of food webs [30]. Observer programs operating throughout the WCPO are now enabling the collection of large numbers of samples for assessment of the diet of predators throughout the pelagic ecosystem [92]. At the same time, at sea sampling under dedicated programs are also providing site specific observations via net sampling and acoustic observations (e.g. [66,2,88]), but information on ecosystem structure is still very sparse.

2.4. Movements and behaviour of tuna species

Understanding the movements and behaviour of wide ranging species is essential for understanding the vulnerability of species to fisheries, and in association, defining appropriate assessment and management frameworks to ensure sustainability [29]. A number of conventional tagging programmes in the WCPO spanning at least 40 years [77] have demonstrated that at least some individuals of tropical tuna species can move large distances in a short time period, which qualitatively supports the notion that tropical tuna species may form continuous spawning populations across the whole WCPO, or at least across vast regions [46].

Molecular analyses of populations throughout the Pacific Ocean have largely supported this assumption, reporting no compelling evidence of genetic differentiation within the WCPO [116,6,18]. More recently however, further analyses of conventional tagging data and detailed data on movements provided via the deployment of archival tags on individuals have revealed that the average horizontal displacements of both bigeye tuna (*Thunnus obesus*) and yellowfin tuna (*T. albacares*) are smaller than previously assumed and individuals may be semi-resident in particular regions [107,28,103]. This suggests that a complicated continuum of sub-populations may occur in these species across the WCPO. Preliminary investigations into the chemical structure of otoliths have also suggested some population structure in bigeye, yellowfin and albacore (*T. alalunga*) tuna associated with fidelity to distinct natal spawning regions [62,117,81]. Molecular investigations of population structure carried out to date may not be sufficient to pick up structure in populations as a small amount of gene flow (a few migrants per generation) may obscure genetic differentiation between conspecific stocks ([49]), even if important sub-populations exist at a scale that is relevant for management.

Acoustic and archival tags deployed on tropical tuna throughout the WCPO have resulted in high resolution observations which are being used to describe behaviour at a scale that is not possible with conventional tags [28,76]. Advances in statistical methods (e.g. [96]) and computing power are now facilitating quantitative descriptions of the interactions between individual behaviour, the environment [97], and fishing operations [105]. This is providing insights into drivers for behaviour and the impacts that fishing operations and in particular, the use of Fish Aggregating Devices (FADs), might have on the behaviour of individuals and the flow on influences these have on population vulnerability.

2.5. *Estimation of abundance and assessment of tuna stocks*

Fisheries stock assessments are routinely conducted for skipjack, yellowfin, bigeye and albacore tunas in the WCPO. The assessments report on the population status relative to standard reference points, quantify the relative effects of different fishing fleets, and provide managers with advice about the likely future effects of fishing on a range of time-scales (e.g. 1–3 years and long-term equilibrium). The main statistical model used to assess tuna populations in the WCPO is MULTIFAN-CL [33,46]. The model describes the temporal trajectory of a small number of spatially-linked, age-structured, single species fish populations, adding in young recruits and extracting losses due to natural and fishing mortality. Simultaneous estimates of many fishery-related (e.g. catchability, selectivity) and biological (e.g. numbers-at-age, natural mortality, migration and potentially growth) states and parameters are made within the model by fitting predictions in the model to fisheries observations (e.g. total catches, catch-at-size distributions, effort, and tag recoveries).

Despite what appears to be a large amount of available fisheries data, fisheries assessment problems are generally over-parameterized with more unknowns than informative observations, and tractable estimators can only be formulated with strong constraining assumptions in most cases (e.g. [104]). For example, it is typically assumed that large regions of the ocean where the fishery occurs are effectively homogeneous and many important model characteristics (e.g. growth, natural mortality, migration, fishery vulnerability) have limited inter-annual variability (although seasonal variability in some parameters can be estimated). It is well known that fisheries assessments are often sensitive to these assumptions. For example, the assessment for bigeye tuna across the WCPO is sensitive to the inclusion of a small tagging dataset in the numerically minor region of the Coral Sea [57]. Sensitivity to such a dataset may result in part, from inappropriate assumptions about tag mixing dynamics [55,67]. It seems unlikely that the estimators from these traditional statistical approaches can be improved substantially given the limitations of the available fisheries data. Useful improvements to stock assessment methods may however, be possible via incorporation of biogeochemical habitat descriptors and high resolution observations of fish and fishery behaviour, using innovative modelling approaches that are still in their infancy.

2.6. *Fisher behaviour and fleet dynamics*

Changes to the distributions and abundances of tuna populations, their availability to fishing fleets and any management decisions made in response have economic implications for fishing vessel operations, associated industries (e.g. fish processors, port operations) and national revenue [89,13]. Assessments of the economic implications of changes to those species that are the focus of fisheries over a range of time scales are required as part of evaluating short and long term management goals for fisheries.

A major challenge when projecting future fishing scenarios under environmental change is providing realistic simulations of where fishing effort is likely to occur and the characteristics of the fishing fleet that effort may be associated with. Many models used to evaluate the responses of harvested species to climate variability and longer term change currently do not include components that simulate the dynamic interactions between socio-economics, fishing fleets and associated effort on targeted species. Typically, fishing fleets and their effort are assumed to remain similar to recent levels, or a climatology of past fleet and effort distribution is used as a proxy for likely future distributions (e.g. [44,73]). Omitting socio-economics and fleet dynamics from models used for projections of future fishing scenarios limits the capability of frameworks evaluating potential management strategies that may be implemented in response to changes in population distributions and abundances [38,114]. Simulation of fishing effort across varying spatial and temporal scales is particularly necessary for evaluating the benefits of spatially explicit management of fisheries, the effects of extreme events (such as high intensity cyclones or tsunami's that may alter fleet or port availability) and optimising tactical decisions such as seasonal distribution of fishing effort or demand for access rights or resource allocations under relevant management frameworks.

Modelling the socio-economic and fleet components of tuna and tuna-related fisheries have included investigation of factors driving entry, stay and exit decisions made by fishers (e.g. [58,99]), the responses of fishers to various management measures (e.g. [23,95]) and decisions of fishers in response to various natural, social and endogenous risks associated with fishing operations (e.g. [100,24]). To date however, most models have been developed for single fleets operating in relatively restricted areas rather than across multi-species, multi-fleet fisheries operating across large regions such as those managed by RFMOs.

3. Key uncertainties

Discussion of current understanding led to the identification of following key uncertainties towards which research should be directed:

3.1. *Understanding seasonal and inter-annual variability of the biophysical ocean and the impacts of extremes*

Knowledge of climate and ocean systems is now at a point where exploration of the fidelity and value of seasonal and inter-annual forecasts of the ocean state and their influence on species distributions and abundances is possible. Use of high resolution ocean models that incorporate biogeochemistry (e.g. [93]) can greatly facilitate such investigations, providing information at smaller scales than previously. This is however, an emerging field and models developed still require extensive observations for validation.

The strength and characteristics of any particular ENSO event can vary considerably, with changes in the physical features of the WCPO observed under a particular El Niño or La Niña event demonstrating considerable variability from one decade to the next. Short term events associated with the extremes of ENSO events can have dramatic impacts on biological systems. Analyses of atmospheric extremes (e.g. droughts, floods, heatwaves etc.) are well developed with flow-on impacts on terrestrial systems extensively studied, contributing a major focus in the latest Inter-governmental Panel on Climate Change assessment [60]. Far less is known about the characteristics of extremes and their effects on marine ecosystems. Probably the most prominent example in the marine domain is the bleaching of coral reef systems associated with extreme water temperatures [22]. The sparse and sporadic nature of data on marine ecosystems means that the ability to evaluate predictions of these events is limited [22]. New regional and global datasets (including high resolution satellite and blended satellite/in situ products) are becoming available at resolutions that are sufficient to resolve mesoscale processes at sub-weekly timescales (e.g. [10]; www.ghrsst.org; see also Section 3.2). As some of these datasets now span multi-decadal periods, they can provide an opportunity to examine the impacts of oceanic extreme events (at least for temperature) on marine ecosystems. Further understanding of the many types of ENSO events and their influence on marine conditions and how these are changing as the ocean temperatures continue warming is needed. Hindcast analyses that describe how tuna biology is influenced by the strength of ENSO events would also be fruitful.

3.2. *Importance of mesoscale and sub-mesoscale ocean features*

Observational evidence suggests that species such as tunas can be influenced by mesoscale features such as ocean eddies, fronts or island boundary currents [9,32]. Relationships observed between these features and the distribution of species have been associated with the accumulation of elevated forage densities as a result of associated circulation convergence or through heightened biological productivity in regions of nutrient upwelling [43]. In addition, there is increasing evidence that submesoscale processes (features of 1–10 km in size) could play a significant role in vertical mixing and the supply of nutrients to the surface ocean [65,102]. High resolution models operating at eddy resolving scales (e.g. [93]) and regional investigations being carried out at sub-mesoscale resolutions (e.g. [83]) provide the opportunity to explore the responses of marine species such as tunas to mesoscale and submesoscale oceanic features. Exploring the relationships with and responses to such features by marine species such as tunas will be important for establishing whether a consideration of these scales is important for understanding the dynamics of tuna in the context of fisheries management.

3.3. *Trophic transfers*

A number of studies have investigated the diet of tuna species within the WCPO and of these, a proportion have investigated spatial and temporal variability in diet (e.g. Olson et al. [94,122]). Understanding of marine ecosystems supporting tuna however, is still limited. This is particularly true for observations of micronekton and other mid-trophic level organisms, and understanding of the linkages of these components of the ecosystem to regional oceanography. Recent research efforts have provided improvements to the understanding of the WCPO ecosystem (e.g. [56,88]), however, there is an urgent need to parameterise the role of physical (e.g. temperature, oxygen, stratification), chemical (e.g. nutrients) and biological (e.g. chlorophyll) drivers in determining the vertical distributions and migrations of forage (micronekton) components of the marine ecosystem. Estimation of the energy transfer efficiency between trophic levels within the ecosystem and an understanding of how changes in the marine environment will effect energy transfer is also required. Further, observational datasets that incorporate extended spatial and temporal assessments of trophic linkages are required in order to address uncertainties in ecosystem modelling frameworks being used to simulate marine ecosystems in the WCPO [92,30].

3.4. *Connectivity of tuna populations*

The degree of connectivity between tuna populations in the WCPO has important implications for fisheries management. If species mix rapidly over large distances and form a single panmictic spawning population, then for the purposes of overall population conservation, spatial variability in the distribution of fishing effort is not important. If, however, species do not mix rapidly and there is some geographic structure to the population, this spatial structure needs to be taken into account by management frameworks to ensure sustainability of populations [16,29]. If sub-populations are not managed at the appropriate scale, localised over-fishing could have long-lasting negative impacts on populations and this can further impact the viability of short-range national fishing fleets.

While the substantive tagging programs on tuna populations throughout the WCPO (see [108,28,77]) have been instrumental in establishing terms required for stock assessment such as estimates of broad scale dispersion, fishing mortality and growth rates, the degree of connectivity of populations across the region, mixing rates and overall movements of species are still not well known [55,67]. Most tagging programs have focused on deployments across equatorial regions resulting in limited understanding of the connectivity of individuals in higher latitude, low density fishing regions with equatorial regions where fishing density is the highest. There is therefore a requirement for better understanding of the movements and connectivity of each tuna species throughout both equatorial and higher latitude regions of the WCPO and with the eastern Pacific Ocean. Ideally, this should include a description of the seasonal and inter-annual movements of species across their life history stages, include tag deployments across both high and low fishing effort areas and also consider density dependent responses to removals via harvesting of the populations. New modelling frameworks capable of robustly investigating the effect of the environment on movement, including larval dispersal, fidelity to spawning areas and preferred habitats will need to be developed. At the same time, further work is required to identify the limitations of current assessment methods to help prioritise further research toward the most appropriate life history stages.

3.5. *The impact of fish aggregating devices on tuna behaviour and ecosystem structure*

Many pelagic species including tropical tunas are known to be attracted to and associate with floating objects such as logs, flotsam, marine observation buoys and whale sharks [34,78]. This behaviour has been exploited by fishing vessels for many years, with fishers searching for such objects and also constructing and releasing FADs both in inshore and offshore waters. Numbers of FADs deployed throughout the WCPO are estimated to be in the thousands, resulting in high densities of FADs across relatively small spatial areas [90,78]. Coupled with the high diversity of species attracted to floating objects such as FADs, fishing operations (largely purse seine operations) utilising FADs catch higher proportions of juvenile tuna and higher rates of bycatch than those conducted away from FADs [78]. Given the widespread use of FADs, there are concerns that increased utilisation of FADs might have negative impacts on the sustainability of tuna populations. There are also concerns for the many other species which comprise bycatch in such operations [42,78] and in association impacts on ecosystem functioning. There is some indication that FADs are not currently negatively impacting on populations and ecosystems, however comprehensive understanding of the impacts of FADs on tuna populations and on ecosystem structure and functioning is lacking [21]. Development of metrics for monitoring the behaviour of tuna populations and other species around FADs as well as the fisheries themselves is required. Utilisation of data from archival tagging and observer programs throughout the WCPO and innovative modelling techniques will enable investigation of the factors driving the behaviour of tunas around FADs, the extent of impacts on marine ecosystems and the impacts on bycatch species.

3.6. *Economic implications of climate variability on fisheries*

Shifts in the physical distribution of economically significant species are likely to result in flow on social and economic impacts [89,50]. Ascertaining these impacts will require an understanding of the social and economic dynamics of fishing communities and their fleets and their capacity to adapt to change [5]. Across the WCPO, these shifts are likely to result in significant variation in the contribution of fishing access fees to national economies, which for some island states can currently represent up to 63% of government revenue [11]. Shifts in the distributions of tuna species that occur in relation to ENSO are already reflected in the spatial distribution of purse seine fishing effort within the Exclusive Economic Zones (EEZs) of some countries in the WCPO (Table 1). This is particularly evident in those countries that dominate tuna catches such as Kiribati and Papua New Guinea where >60% of all tunas catches in the WCPO occur [11].

Within the framework of sustainable management, fisheries managers and policy makers require information to guide investments and adaption or mitigation strategies in response to potential change in fish distributions and abundances [5]. This will require an assessment of the exposure of national and international fishing fleets to changes in species distributions resulting from a changing climate, the sensitivity or dependence of those fleets to species undergoing changes in distributions, what management scenarios might be utilised to ensure ongoing sustainability and the degree to which fleets might adapt to changes in distributions and management scenarios [1,5]. Substantial opportunities will likely emerge for strategic behaviour in the way fisheries and access rights are managed, both between individual countries and territories and between fleets. Improved understanding of not only how these changes might affect the distribution of fishing fleets, but also how the incentives of individual nations will vary as a consequence is required. As an example, forecasts of fishing effort distribution could be used to direct the ‘cap and trade’ vessel day scheme used by member nations of the Parties to the Nauru Agreement (PNA) to manage purse-seine fishing effort across their EEZs and maximise the benefits from the scheme.

3.7. *Modelling future states of the marine ecosystem and fisheries*

Dynamic coupled ecosystem models are being developed at varying levels of complexity and increasingly utilised to explore the effects of external pressures such as fishing and environmental variability on components of marine ecosystems (see [36] for a review). The majority of simulations of the coupled WCPO system including physical oceanography, marine ecosystems, tuna populations and fisheries have been carried out using the SEAPODYM model ([74]; though also see [19,20,25] for additional modelling approaches in the WCPO). While this model has led to significant advances in understanding of how tuna populations might respond to changes to their environment, development of structurally independent models with distinct physical, biogeochemical and ecosystem components is required for assessing robustness of conclusions drawn from SEAPODYM alone. Utilisation of alternative models in the WCPO will not only broaden and diversify the scope of available models currently useful for investigating the impacts of environmental and commercial harvesting forcing on tuna populations, it will also facilitate increased skill, reliability and consistency in model forecasting [113]. An approach such as this has been very successful in the climate modelling community through the World Research Climate Program (WCRP) Coupled Model Intercomparison Project (CMIP; www.cmip-pcmdi.llnl.gov). This program provides for the ability to compare climate projections from a range of over 40 climate models. A similar effort is currently being developed under the ISI-MIP programme, which in its second phase will include model intercomparisons of marine ecosystems and fisheries (see www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/research/rd2-cross-cutting-activities/isi-mip). Development and utilisation of multiple modelling frameworks may also present new functionality; for example the use of frameworks such as individual-based models would facilitate easier comparison with tagging data and offer a simpler framework for including the behavioural characteristics of tuna populations.

4. Research opportunities and priorities

In identifying key uncertainties in understanding across the region, the following opportunities for targeted research were identified:

Table 1

Percentage of total fishing days spent by purse seine fishing fleets within the exclusive economic zones of countries that are members of the Parties to the Nauru Agreement during different phases of the El Niño-Southern Oscillation (ENSO) 2007–2013 (year represents July to June). Ocean Niño index 3.4 (ONI 3.4) and ENSO phase sourced from NOAA (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). ONI 3.4 values presented are the average for the year (July to June). FSM: Federated States of Micronesia; PNG: Papua New Guinea; *Provisional estimates.

Year	FSM	Kiribati	Marshall Islands	Nauru	PNG	Palau	Solomon Islands	Tuvalu	ONI 3.4 (lowest/highest monthly value)	ENSO phase
2007–08	13	13	0	6	54	1	10	4	−0.92 (−1.50/0.40)	La Niña
2008–09	9	17	2	5	50	1	10	4	−0.30 (−0.80/0.40)	La Niña
2009–10	13	27	1	7	41	0	6	4	0.85 (−0.40/1.60)	El Niño
2010–11	9	11	2	8	54	0	13	4	−1.05(−1.50/−0.20)	La Niña
2011–12	18	16	1	4	52	0	7	2	−0.54 (−1.00/0.00)	La Niña
2012–13*	16	23	2	5	45	0	5	4	−0.07 (−0.60/0.60)	Neutral
2013–14*	9	24	4	12	42	0	5	4	−0.28 (−0.60/0.10)	Neutral

4.1. *Spatially explicit simulations of ecosystem (trophic) dynamics*

Changes in the distribution and abundance of tuna which influence the accessibility of nations and fleets to resources is ultimately driven by variability in underlying ecosystems. Understanding of ecosystem structure and function, linkages and processes driving responses observed in tuna populations and variability in these is required for fisheries that rely on these populations to be adaptable and resilient to environmental variability and change (Table 2). Inherent in this requirement is an understanding of spatial and temporal variability in trophic linkages across life stages within species. Current knowledge on pelagic food web is so limited that even the first order of magnitude of the mesopelagic biomass, a key prey group of tuna, at the global scale is unknown. Current estimates of biomass (1000 million tons) have recently been suggested to be underestimated by one order of magnitude [61]. Because of a lack of direct observations, most relationships between tuna populations, their forage and regional oceanography have been inferred from modelling exercises (e.g. [3,44,74]). Such models require improved parameterisations involving expanded physical and biological observations in order to reduce uncertainty in model outputs. Improved estimates of energy transfer efficiency between trophic levels within ecosystems are also required [73]. Robust and efficient statistical methods (e.g. Maximum Likelihood Estimation approaches), need to be implemented in these models [106,72] to make the most of data collected at high cost.

Efforts to support large-scale observational programs and synthesis of individual datasets to form regional assessments of marine ecosystems have been initiated or are being proposed (e.g. [2,92]) and provide opportunities to address current limitations in models. National and international efforts such as the Australian Integrated Marine Observing System (http://imos.org.au) and the Global Ocean Observation System (http://www.ioc-goos.org) are collecting both physical and biological observations. Techniques to infer depth integrated primary productivity from satellite derived products, with varying degrees of skill are also now available (e.g. [35]). Regional fisheries observer programs are beginning to collect biological information from target and non-target species throughout tuna fisheries and investigations of these datasets are beginning to yield assessments of food webs throughout the WCPO (e.g. [4,56,88]). Direct observations of mid-trophic level organisms (i.e. zooplankton and micronekton) could be enhanced through dedicated ship based sampling, and augmented with indirect techniques such as acoustics that can be applied on both research vessels and vessels of opportunity. For example, the establishment of a network of echosounders on commercial vessels could substantially contribute to the monitoring of zooplankton and micronekton distributions and abundances [66] and the optimisation of ecosystem models [72].

Many FADs currently deployed by the purse-seine fishing industry in the WCPO are equipped with technology allowing for the tracking of those FADs via satellite and for measuring the biomass of tunas associated with the FAD. These measures are currently not available for scientific application, but if made available would potentially provide a fishery independent source of information on tuna biomass that could be integrated into population assessment models. They could also potentially provide information on prey biomass which could be integrated into ecosystem models. Further development of instrumented FADs could include equipping platforms with instruments that record the presence of and transfer information collected by electronically tagged tuna and measure key oceanographic and biogeochemical variables. This would also provide for realistic estimates of tunas movement to be integrated into modelling frameworks. Use of such infrastructure would further expand current observation systems throughout the WCPO and increase data available for improving ocean forecasting capabilities throughout the region.

As more extensive observations of oceanic ecosystems become available, the population dynamics of individual food web components will be better informed, improved between component energy transfer efficiencies will be calculated, and the relationship of these to environmental variability will be resolved (Table 2). The flow on benefits of these improvements have the potential to provide a range of stakeholders with the capacity to better assess stock resilience to climate and regional fisheries, the ecological impacts of fishing, balances between development associated with fishing and environmental and conservation goals and tools for mitigating impacts of fishing on the environment (Table 2). A reduction in uncertainty in model output will ensure that management planning and decisions made on the basis of projections of shifts in tuna distributions resulting from the models (such as the allocation of resources) are appropriately guided.

4.2. *Forecasts and projections of temporal and spatial variability in the distribution and population dynamics of target and non-target species*

Addressing the complexities of fisheries management in response to variable ocean conditions and extreme events, particularly at the national scale, requires robust forecasts of tuna distributions and abundance (Table 2). At the same time, in order to reduce interactions with non-target species, ensure conservation measures are met and ecosystem management objectives are upheld, robust forecasts of the distributions and abundance of non-target species are also required. Enhanced capacity through the provision of forecasting and evaluation tools to Pacific countries and territories is vital for short term tactical decisions (e.g. vessel day trading) and longer term strategic decisions (e.g. industrial investment in post capture processing) to help maximise economic returns within fisheries management frameworks (Table 2).

Biological responses to projected physical change in the ocean can be modelled based on the observed habitat preferences of species. These statistical patterns can be used to infer regional changes in distribution or abundance over short (e.g. [53]) or long time scales (e.g. [17]). To date, models used to forecast the distributions of species in this manner have been limited to linking species distributions directly to ocean physics (predominantly via thermal preferences). Intermediate relationships in the linkages between physics and fish such as trophic (e.g. prey availability) and life history components (e.g. spawning) are largely ignored. Dynamic coupled ecosystem models, in contrast, can incorporate intermediate steps such as ocean biochemistry, trophic components and population dynamics including abundance estimates derived from statistical assessments of the population (e.g. [37,72,85]). Including these intermediate levels is mechanistically more realistic, but there is a need for careful parameterisation [47] with robust data assimilation and parameter optimisation methods [106,26,72]. Current usage of dynamic coupled ecosystem models, in terms of assessing future states of populations, is also largely limited to investigating changes in the distributions and abundances of populations over temporal periods associated with climate change rather than those relevant to fisheries management (e.g. [72]).

Cross disciplinary approaches which operationalise capacity in physical and biological oceanography and incorporate climate models operating at meso- and submesoscales into ecosystem models have the capacity to progress current approaches to forecasting the distribution and abundance of tuna populations and populations of non-target species caught by fishing fleets. Improvements in the

Table 2
Summary table detailing the key requirements for building resilience in regional fisheries management in response to variable ocean conditions and extreme events, associated science approaches and benefits to primary stakeholders. Short: days to weeks; Medium: seasonal to year; Long: inter-annual to decade; FI: fishing industry; FM: fisheries management; G: government; C: conservation non-governmental organisations

Requirement (timeframe)	Benefit to stakeholder	Product	Science
Spatially explicit simulations of ecosystem dynamics (short, medium, long)	FI: improved assessments of stock resilience to climate and regional fisheries; improved assessments of monitoring required to ensure fish products meet public health standards FM: assessments of the ecological impacts of fishing and the monitoring required to ensure on-going capability in meeting ecosystem-based fishery management requirements G: improved assessment of the trade-off between industrial fishing and national aspirations; meeting of international and domestic conservation requirements and reporting on development goals C: tools to evaluate the effectiveness of by-catch mitigation schemes	Historical and medium to long-term predictions of the ecosystems that support target species in relation to environmental variability, fishing variability and management scenarios	Analyses that incorporate improved modelling of ecosystem structure and functioning (including trophic connectivity, the dynamics of ecosystem components and feedbacks within the ecosystem) and environmental influences (through improved physical and biogeochemical models) on ecosystem dynamics Analyses of the effectiveness of marine spatial planning using ecosystem models
Forecasts and projections of temporal and spatial variability in the distribution and population dynamics of target and non-target species (short, medium, long)	FI: improved assessments of stock resilience to climate and regional fisheries; optimisation of investment and effort deployment; optimisation of operational efficiencies FM: optimisation of Harvest Control Rules, conservation reference points and risk indicators to ensure sustainability; assessments of the interaction between fisheries and impacts on fisheries performance and viability; assessment of interactions between fisheries and non-target species; meeting of international and domestic conservation measure requirements G: improved assessment of food security goals; planning tools for negotiating domestic allocation and international access; meeting of international and domestic conservation requirements; improved guidance of marine spatial zoning; optimisation of food security C: tools to evaluate the effectiveness of by-catch mitigation schemes	Historical and medium to long-term predictions of the population dynamics of target and non-target species in relation to environmental variability, fishing variability and management scenarios	Analyses that incorporate improved population dynamics (including movement, behaviour, predator-prey relationships etc.) and environmental influences (through improved physical and biogeochemical models) on population dynamics into assessments of abundance Construction of species distribution/habitat models using ocean models and animal observation data Analyses of bycatch species behaviour to identify practical solutions for mitigating bycatch interactions with commercial fishing gear Analyses of the effectiveness of marine spatial planning Improved estimation of ENSO effects on the marine environment and associated expected variability using ocean models
Predictions of temporal and spatial fleet dynamics and associated socio-economics (short, medium)	FI: optimisation of fishing effort and investment FM: optimisation of catch/effort allocation and trading as well as surveillance for illegal, unreported and unregulated fishing G: optimisation of investment and returns from domestic and international fleets; planning tools for negotiating domestic allocation and international access; tools for improving insights into development investment C: improved assessment of fisheries overlap and bycatch risk	Historical and short to medium-term predictions of fleet size, effort and catches. Assessment of the carrying capacity of domestic and international fleets Economic assessments of domestic and international implications of changes to the fishery Feasibility assessments of development of fishery/fleet development	Analyses that model fishing effort distributions, operations and investment with oceanography and its effects on catchability/availability and associated fishing costs

reporting and spatial scales at which fishery catch and effort data are reported in conjunction with more comprehensive data describing the biology of these species will further improve the skill of forecasts provided by these models. Development of seasonal and inter-annual forecasting tools (6 months to 5 year time horizon) has the potential to provide fisheries management with the flexibility required for responding to short-term variability in tuna distributions and abundances and therefore in the distribution of resources. This will allow efficiencies in national fisheries operations and allocation of resources under management frameworks at the regional level to be maximised, whilst ensuring sustainability of populations. Such initiatives have recently been developed for the Indonesian Archipelago where the INDESO project (http://www.indeso.web.id/indeso_wp/) has been implemented to monitor changes in the distribution and abundance of marine resources in the Indonesian EEZ. This system includes real-time and forecast high resolution ($1/12^\circ \times$ day) modelling of tuna distributions by life stages (larvae, recruits, immature and adult fish) based on operational models and satellite monitoring. Once combined with real-time electronic catch reporting, which is currently under development, calibration of the model is expected to quickly improve. This will result in improvements to abundance estimates which will then be used to establish the optimal level of exploitation (total allowed catch) and the conservation measures (e.g., identification and protection of spawning grounds and nurseries) required for the sustainable exploitation of tuna resources within Indonesian waters. An initiative using a habitat preference model in conjunction with a seasonal climate forecasting model to forecast the distribution of southern bluefin tuna (*T. maccoyii*) has also been implemented in southern Australia allowing for increased efficiencies in the deployment of the commercial fishing fleet and associated ranching operations [31].

4.3. Simulations of temporal and spatial fleet dynamics and associated socio-economics

Changes in factors such as access agreements, demand, fleet efficiency and fuel costs modify the behaviour of fleets and associated fishing effort, affecting tuna catches. Understanding the behaviour of the tuna fishing fleet, the drivers influencing this behaviour, and their interactions with the effects of climatic variability and climate change on tuna distributions and abundances, are needed for fully effective management to ensure ongoing sustainability of harvested populations (Table 2). Further, understanding how fishing fleets might respond to environmental variability and longer term change and management measures implemented in association is key to the strategic decision making required by countries and territories in ensuring that economic returns from resources are maximised under such management frameworks.

Current economic approaches have the capacity to assess the optimal value of access rights and overall fishery value under multiple scenarios (of tuna distribution and abundance) and what influence these changes in value might have on decision making by fleets and fisheries managers. For example, fleet dynamics models could be developed to assess how vessels might aim to redistribute effort in response to changing fishery conditions and associated resource allocation. Incorporating game theoretic approaches (e.g. [7,8]) can provide insights into the likely outcomes of strategic behaviour by nations around the way fisheries and access rights are managed. Formal assessments of market linkages at different levels of the supply chain, and the possible substitutability of species within markets, would provide an empirical understanding of potential market effects and how these may ultimately influence fleet or management behaviour. Methodologies such as multi-criteria analysis (e.g. [82,79]) can be used to determine the relative priorities of alternative management objectives for different nations and thus how a changing environment will impact upon these. Such socio-economic approaches are required for providing guidance for planning at the national level, but also in identifying what management strategies that provide the best balance between population sustainability and the development goals of the countries and territories of the WCPO (Table 2).

4.4. Management strategy evaluation for robust fishery management

The workshop provided a multidisciplinary overview of research, knowledge gaps and opportunities related to understanding the bio-physical and socio-economic drivers of WCPO tuna and fishery dynamics. To the extent that improved fishery management is one of the main drivers of this research agenda, it is worth noting that there is a potentially valuable framework that was not discussed at this workshop. Specifically, Management Strategy Evaluation (MSE) has a potential role in helping to prioritise research investment by enabling the testing of fishery management procedures, simulations that include the key dynamic features of the system, including fish and fishery dynamics, data collection and harvest control rules ([109], see CCSBT 2013 for a RFMO application to a tuna fishery). Once fishery specific simulations have been developed, the MSE process can then be used to compare different management procedures under a range of conditions spanning the uncertainty in system dynamics, including functional relationship uncertainties and stochastic process and observation errors. Trade-offs among competing management objectives for the different candidate management procedures can then be quantified, as can the value of information (e.g. which data should be collected with what sampling intensity to achieve the desired management outcome with a certain probability). In particular, MSE could be used to guide the research agenda above allowing prioritisation of topics that are directly useful for improving fisheries management (e.g. *sensu* [115]) and should therefore be considered in parallel with the priorities for bio-physical and socio-economic research identified (which would in turn assist the MSE in quantifying uncertainties and management priorities). In doing so, this would also help guide efforts towards appropriate funding sources.

In concluding, continued discussion on these issues and the research required to address them is expected as part of on-going collaborations within the group and under wider discussions within organisations involved and the CLIOTOP program (http://www.imber.info/index.php/Science/Regional-Programmes/CLIOTOP).

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