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An ocean observation system for monitoring the affects of climate change on the ecology and sustainability of pelagic fisheries in the Pacific Ocean

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Abstract Climate change presents an emerging challenge to the sustainable management of tuna fisheries, and robust information is essential to ensure future sustainability. Climate and harvest affect tuna stocks, populations of non-target, dependent species and the ecosystem. To provide relevant advice we need an improved understanding of oceanic ecosystems and better data to parameterise the models that forecast the impacts of climate change. Currently ocean-wide data collection in the Pacific Ocean is primarily restricted to oceanographic data. However, the fisheries observer programs that operate in the region offer an opportunity to collect the additional information on the mid and upper trophic levels of the ecosystem that is necessary to complement this physical data, including time-series of distribution, abundance,

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size, composition and biological information on target and non-target species and mid trophic level organisms. These observer programs are in their infancy, with limited temporal and spatial distribution but recent international and national policy decisions have been made to expand their coverage. We identify a number of actions to initiate this monitoring including: consolidating collaborations to ensure the use of best quality data; developing consistency between sub-regional observer programmes to ensure that they meet the objectives of ecosystem monitoring; interrogating of existing time series to determine the most appropriate spatial template for monitoring; and exploring existing ecosystem models to identify suitable indicators of ecosystem status and change. The information obtained should improve capacity to develop fisheries management policies that are resilient and can be adapted to climate change.

1 Introduction

Tuna fisheries in the tropical Pacific Ocean are generally regarded as healthy by global standards, but are coming under pressure as fishing effort continues to increase (SPC 2012). Climate change may present an additional challenge to their sustainable management (Rice and Garcia 2011). Decision makers need robust science-based advice if tropical Pacific tuna stocks are to be sustained for future generations. This includes advice on how climate and harvest affect the target stocks, populations of non-target, associated and dependent species, and ecosystem structure and function (Garcia and Cochrane 2005; Hughes et al. 2005). The potential implications of alternative future climate scenarios for skipjack and bigeye tuna fisheries in the Western and Central Pacific Ocean (WCPO) have been recently examined (Lehodey et al. 2011; 2012). Increasing atmospheric CO_2 (a key driver of climate change) is expected to lead to a warmer and more acidic Pacific Ocean resulting in a change in the distribution and abundance for both species (Lehodey et al. 2010, 2011; 2012). However large gaps in our knowledge remain, particularly the implications of climate change for the large and complex food web that supports tuna populations and their fisheries (Le Borgne et al. 2011), and whether climate change may alter the interactions between tuna fishing and ecosystem structure and function in the tropical Pacific Ocean. Early modelling of the eastern tropical Pacific suggests that climate may dampen top-down effects of fishing on the pelagic ecosystem (Watters et al. 2003). Documenting how harvest affects ecosystem structure and function and how management measures are implemented to minimise any negative impacts is becoming a key requirement before some markets will accept fisheries products for sale. Such social and economic forces are particularly strong in ‘high return’ markets such as Europe and the USA, where purchasing fish from certified sustainable fisheries is increasingly promoted (Jacquet et al. 2009; Gulbrandsen 2009).

Here we discuss the need to better understand the food web, in order to forecast the impacts of climate change on tuna fisheries. We outline the opportunity to establish the first ocean basin scale system to monitor how climate change affects the interaction between physical oceanography and

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all trophic levels of pelagic ecosystems. Such a monitoring system would give Pacific Island countries and territories (PICTs) and the international community the information they need to design management measures and policies that are resilient and adaptable to a changing climate.

2 Why is it so important to understand how climate change affects the food web that supports tuna in the Pacific?

The abundances and distributions of species in nature are driven by dynamic interplay between species and the physical environment. These complex interactions define ecosystem structure and their effects diffuse throughout the ecological community. Species' interactions are both direct and indirect, and their positive and negative feedbacks help to stabilise ecosystem structures. However, perturbing these linkages (for example, through fishing or changes in environmental conditions) can alter these feedbacks and result in both intuitive and non-intuitive changes in ecosystem structures and species abundances (Frank et al. 2005; Casini et al. 2009). The development of policies that will ensure Pacific Ocean tuna fisheries are resilient to the impacts of climate change requires better knowledge of ecosystem structure and function and how perturbations propagate through the ecosystem.

3 What is currently known about the structure of the oceanic ecosystem in the Pacific Ocean?

Past analyses suggest that open-ocean pelagic ecosystems are mediated by both bottom-up and top-down feedbacks (Verity and Smetacek 1996; Baum and Worm 2009). Bottom-up feedbacks exert control through food abundance and imply the control of predators by their prey. These feedbacks are simply described as the interplay between the physical environment (ocean chemistry and physics) and primary production, which influences secondary production and higher trophic orders (Hays et al. 2005; Frederiksen et al. 2006). Top-down processes, which exert control through predation (including fishing), are described as the influence that species at higher trophic positions have on those at lower trophic levels (Paine 1980). Apex predators (e.g. tunas) may act as keystone species, which are species with relatively low biomass that disproportionately affect the food web (Power et al. 1996). They strongly control ecosystem structure and function in marine ecosystems (Libralato et al. 2006; Coll and Libralato 2012), and perturbing these species (e.g. harvest, habitat alterations) can cause trophic cascades that change the overall structure of the ecosystem. To build models that can forecast changes in ecosystem structure, we must understand the relative influence of top-down and bottom-up effects, and identify key species or groups (Watters et al. 2003).

Understanding of such interactions in the tropical Pacific Ocean is mounting from recent analyses. Bottom-up effects have been identified in association with ocean-basin wide oceanographic cycles such as the El Niño Southern Oscillation and the Pacific Decadal Oscillation. Species distributions tend to track preferred habitat e.g. skipjack tuna (Lehodey et al. 1997) and jumbo squid (Ichii et al. 2002), and ecosystem structures change with the oceanography e.g. anchoveta and sardine cycles (Chavez et al. 2003). In the central North Pacific subtropical pelagic ecosystem, the oligotrophic areas at the centres of the subtropical gyres have expanded by 2–4 % per year over the past decade (Polovina et al. 2008, 2011). In the Hawaii-based longline fishery for the same period, catch rates of mid-trophic predator fishes have increased and apex predators decreased (Polovina et al. 2009).

In several regions in the Pacific Ocean 'wasp-waist' feedbacks are evident in trophic models (Ecopath with Ecosim, EwE; Christensen and Walters 2004), in which the large biomass of key components at middle trophic levels gives them significant control over both upper and lower levels of the food web (Kitchell et al. 2002; Griffiths et al. 2010; Olson and Watters 2003). Organisms at mid-trophic levels (microneckton) are prey for many higher-level predators, but also function as important predators for a range of lower trophic groups. Changes in micronekton biomass quickly affect the upper and lower trophic levels (Griffiths et al. 2010). In these models the apex predators are somewhat redundant, because they share a diverse suite of prey and comprise only a small percentage of the biomass (Kitchell et al. 2002; Griffiths et al. 2010). Reducing the biomass of particular predators in these models significantly changed ecosystem structure but with few trophic cascades, which does not support the concept of apex predators acting as keystone species in these ecosystems (Kitchell et al. 2002; Griffiths et al. 2010). Trophic cascades occur in other oceanic ecosystems from reducing or removing top-down feedbacks (e.g. Benguela current; Bakun and Weeks 2006), but were more evident in Pacific Ocean models when the biomass of the mid-trophic level was manipulated. In models of the south western Pacific, climate-related changes to the biomass of the mid trophic level resulted in trophic cascades that significantly affected fished species (Griffiths et al. 2010). Species in the mid-trophic level are typically small and have fast life cycles, and a recent synthesis of information from the Atlantic Ocean concluded that species with these life history traits are susceptible to range shifts associated with sea temperatures (Perry et al. 2005). If these relationships hold for the Pacific Ocean then changes in ecosystem structures and animal distributions could be expected in response to climate change.

For single species, the ecosystem model SEAPODYM (Lehodey et al. 2008) has been used to forecast climate change impacts on distribution and abundance of skipjack and bigeye tuna (Lehodey et al. 2011). This model integrates oceanography and prey abundance to force the population dynamics of the target species. However, the model does not currently quantify interactions between species and trophic levels. Hence, it is not feasible to explore questions about how fishing may affect ecosystem structure and function or whether this interaction is likely to alter under climate change scenarios. To examine these questions, more complex multi-species ecosystem models are required such as ATLANTIS (Fulton et al. 2011) and EwE (Polovina 1984; Christensen and Pauly 1992; Christensen and Walters 2004), which require descriptions of the food web and preferably time-series of abundance data to tune the models to resemble reality (Watters et al. 2003; Griffiths et al. 2010). Four EwE models have been drafted for the Pacific Ocean; eastern (Olson and Watters 2003), central (Cox et al. 2002; Kitchell et al. 2002), western (Allain et al. 2007; Le Borgne et al. 2011), and south western (Griffiths et al. 2010). Based on long-term diet studies, qualitative signed digraph models for the eastern, western and south western Pacific Ocean have also been drafted, and are being used to examine how differences in foodweb structure lead to different responses to perturbations, such as climate change (Dambacher et al. 2010). The outputs of quantitative trophic models (e.g., EwE, ATLANTIS) are also strongly influenced by the underlying differences in foodweb structures and ecological processes that are explicitly or implicitly included by the model author(s) (Pascual et al. 1997; Dambacher et al. 2002). To understand these inherent biases requires structural and parameter sensitivity analyses, which is most effective when there are sufficient data and knowledge to construct competing models of the ecosystem.

4 Why are the fisheries observer programs so important? A basin-scale pelagic ecosystem ocean observing system

Large knowledge gaps limit confidence in existing ecosystem model predictions of how climate change will affect tuna fisheries. To fill these gaps, information is needed on the physical and biotic components of the ecosystem that occur across the Pacific. Global initiatives have commenced to provide some of these data. The Global Ocean Observing System (GOOS) is a collection of ocean observing and information delivery systems that provide near real time measurements of the state of the oceans. Currently GOOS relies almost entirely on physical measurements (e.g. temperature, salinity) from satellites, buoys, floating profilers, and ships. However we need to be able to link these data with those collected on the biotic components of the ecosystem. Direct experimentation to enhance our understanding of the ecological relationships within oceanic ecosystems is difficult and expensive to implement over large spatial domains and for the long time-series required for monitoring climate change. Bio-logging (Bograd et al. 2010), continuous plankton recorder (e.g. Hays et al. 2005) and ships of opportunity programs (e.g. Handegard et al. 2009) are providing some of this biotic data. An additional key that promises to help unlock access to this biological information is the fisheries operating throughout the region. Fishing vessels routinely collect detailed information on the volume of catch, together with corresponding data on time, location and effort.

More recently, fisheries observer programs have commenced in the Pacific Region. The observer programmes place trained staff on board licensed tuna fishing vessels (WCPFC 2007; IATTC 1992). The duties of these staff typically include verification of vessel catch documentation with fishing and/or trans-shipment activities; registering compliance with all fishing regulations; collection of catch, composition, gear interaction (i.e. not landed, released or escaped) and environmental/ecological data; and biological sampling of the catch (WCPFC 2007). Observation is the only reliable method to obtain information on bycatch and discards. Time series of the catch of target and non-target species provide the opportunity to monitor a number of ecosystem indices which could be changed by fishing, environmental variations and climate change: predator assemblages (Morato et al. 2010), species' distributions (Lawson 2011), abundance (Polovina et al. 2009), mean lengths of species (Clarke et al. 2011), as well as mean weight, and sex-ratio. The collection of biological samples can also be used to monitor a number of life-history traits, which could be impacted by climate change. For example, gonad sampling will detect any variation in spawning season and fecundity (Farley et al. 2011), collection of otoliths and spines can determine changes in growth and age composition (Kopf et al. 2009), and stable isotope samples can be used to describe any alterations in trophic level (Olson et al. 2010). Furthermore, the systematic collection of stomachs from a range of apex predators by observers provides the additional opportunity to monitor mid-trophic level communities (Young et al. 2010). Stomach content analyses of marine predators are well noted as reliable methods for documenting the distribution and ecology of prey species (Boyd et al. 2006). In short, fisheries observer programs can collect spatially explicit and long-term time-series of distribution, abundance, size, composition and biological information on target and non-target species and mid trophic level organisms.

At present, the limited number of fisheries observer programs in the Pacific Ocean, involving only a few fleets, has resulted in limited spatial and temporal coverage (Figs. 1 and 2; Supplementary Material 1). The observer programs for the tuna fisheries in the Pacific Ocean are undergoing a revolution in the quality and quantity of collected monitoring data, and promise to change this situation. The Regional Fisheries Management Organisations

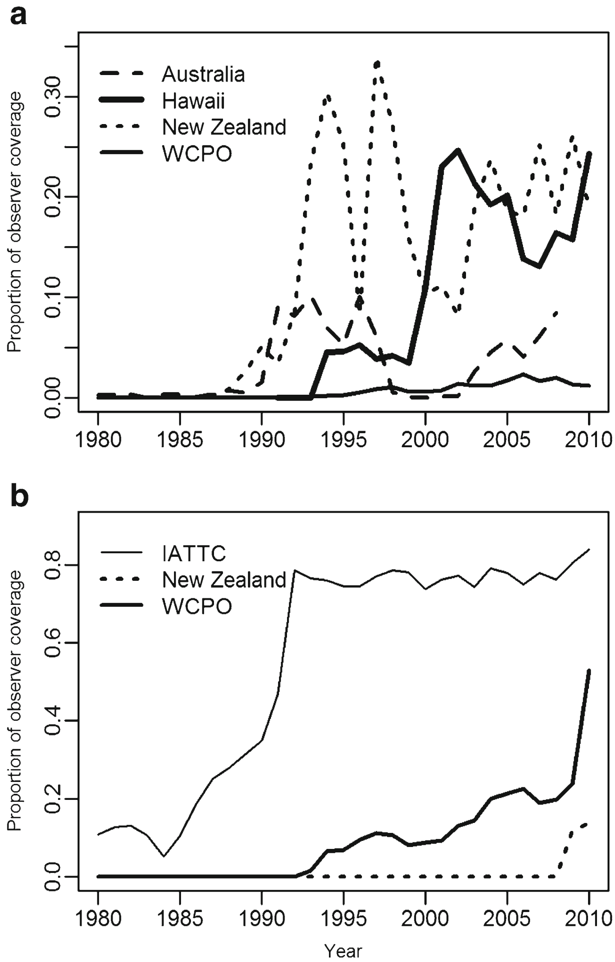

Fig. 1 Evolution of the observer coverage on tuna fishing vessels during the last three decades for different programmes in the Pacific for **a** longline in hundred of hooks (hhooks) and **b** purse seine in number of sets. WCPO: Western and central Pacific Ocean programmes including national and sub-regional programmes (Appendix 1), IATTC: Inter-American Tropical Tuna Commission programme. Note: estimate for 2010 is provisional as observer data entry for 2010 may be incomplete

(RFMOs) and other sub-regional tuna fisheries organisations which oversee governance at the regional scale have recently approved policies that will increase the spatial and temporal coverage of fisheries observers. There are currently 441 purse-seine and 2,025 longline fishing vessels registered to operate in the Pacific Ocean. Since 2011, 100 % observer coverage on all purse-seine vessels fishing in all fleets is a license requirement (excluding the domestic fleets fishing in archipelagic waters) and from 2013, 5 % observed coverage will be required on all large tuna longline fleets operating in the Pacific Ocean (WCPFC 2007, 2008, 2009; PNA 2010; IATTC 2009, 2011). In addition the recent proposal to create a marine reserve in the Coral Sea has seen Australia express interest in setting up a more robust collection strategy in the area to provide the biological data needed to interpret and inform ecosystem models (Young et al. 2012).

These new observer coverage policies will permit comprehensive spatial and temporal monitoring of top-down processes operating upon the ecosystems in the Pacific Ocean through the establishment of time series of distribution and abundance for many top predators. If we combine the data collected by the observers with the existing monitoring systems for bottom-up processes, and fisheries catch and effort data, we will establish a

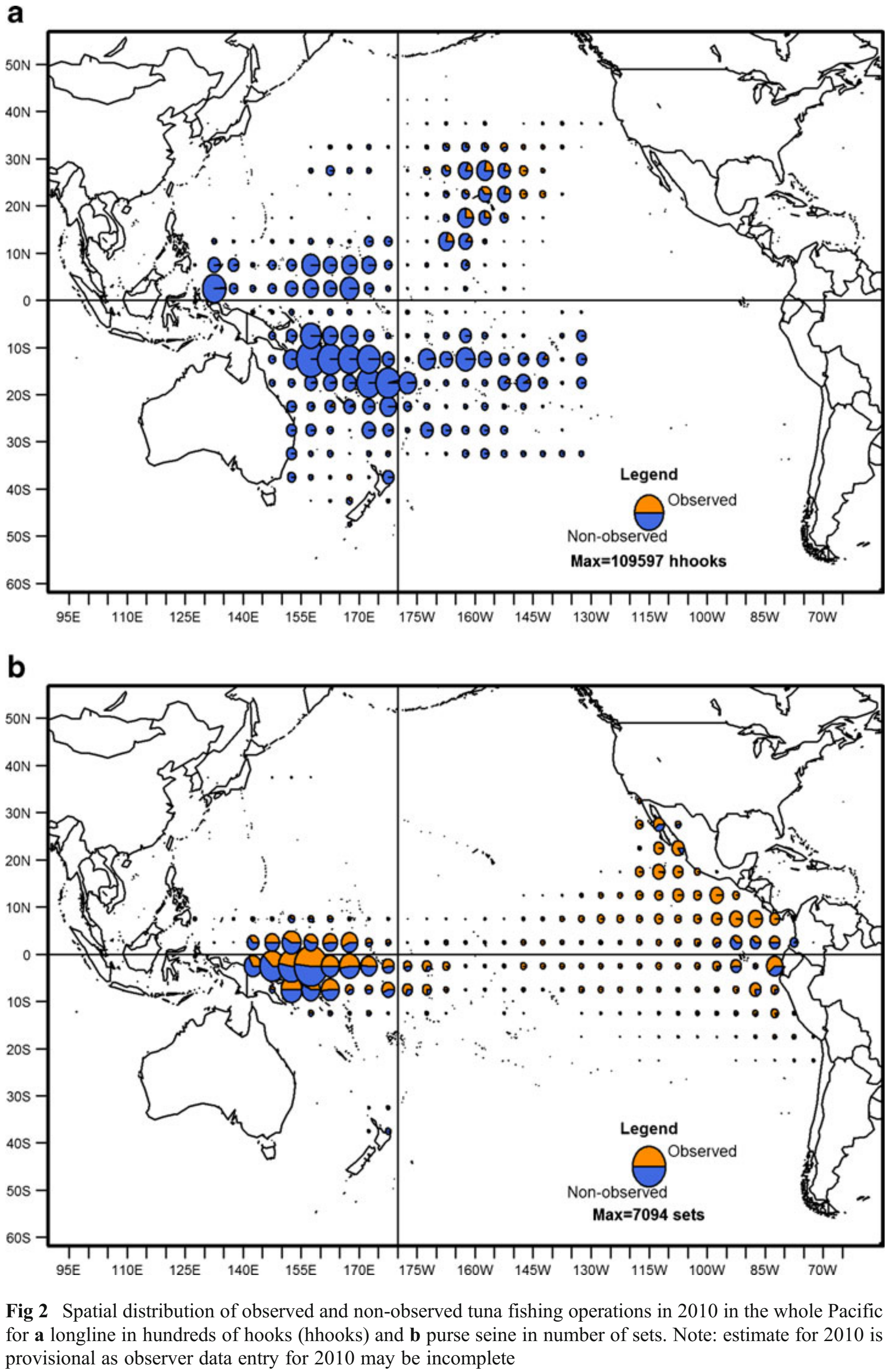

Fig 2 Spatial distribution of observed and non-observed tuna fishing operations in 2010 in the whole Pacific for **a** longline in hundreds of hooks (hhooks) and **b** purse seine in number of sets. Note: estimate for 2010 is provisional as observer data entry for 2010 may be incomplete

resource of crucial information on all trophic levels of the oceanic ecosystem at the ocean basin-scale for the first time. This also opens the door to creating a basin-scale pelagic ecosystem ocean observing system.

5 Immediate tasks

We identify a number of tasks that, if pursued immediately, will underpin and enhance the development of an ocean observation system for climate change impacts.

5.1 Consolidate collaborations

The RFMOs have been established in the Pacific Ocean to manage the open ocean tuna fisheries, including compiling standardised fisheries monitoring data. However, many fishing nations have data at higher spatial and temporal resolution than the aggregated data supplied to the RFMOs. These higher resolution data are particularly useful for removing biases associated with fishing behaviours and activities that may exist in lower resolution aggregated data (see Bigelow and Hoyle 2009; Chang et al. 2010). The RFMOs provide the mechanism for regional collaboration and increasing their attention upon the coordination of common approaches for data collection, curation, sharing and analyses is necessary to maximise monitoring and analyses opportunities. Developing reliable indices on abundance and spatio-temporal distribution are not trivial tasks and will require substantial scientific efforts including the integration of data from multiple sources (e.g. data from observer and bio-logging programs). The establishment of multi-national teams under the auspices of the RFMOs would not only facilitate data sharing to ensure the best information available is used in management models but also help ensure that samples and data are analysed routinely in a consistent way internationally. The two RFMOs in the Pacific currently share information on fishery catch and effort. Extending this exchange to include relevant data collected through observer programmes would be highly desirable.

5.2 Examine and develop consistency between sub-regional observer programmes

To ensure consistent regional collection of ecological and ecosystem data, a region-wide observer sampling protocol is required (e.g. Cotter and Pilling 2007). This protocol should meet the short and longer term objectives of national and regional fisheries management, and the monitoring of climate change effects. In developing this protocol consideration will need to be given to observer workloads. Observers already collect large amounts of information for multiple projects and purposes. Overburdening observers may mean that the data is not always collected or the quality of data collection is low. Analyses of existing information to determine if all data needs to be collected from all sets observed would assist the development of a practical sampling protocol. The specifications in the RFMO conservation measures for increased observer coverage in the Pacific Ocean are broad and consideration also needs to be given to how these measures are implemented. The management measure for longline vessels is limited to specifying 5 % effort coverage for all fleets, with no further detail about how this effort should be distributed across vessels, space and time. Fishing effort is not randomly distributed in space and time so will under-sample some areas, against the likely objective of maximising spatial coverage.

To explore the risk of under-sampling, we randomly allocated 5 % observer coverage to each year of longline effort over the period 1998–2008 and then aggregated the data to visualise the resulting coverage (Fig. 3). There were important areas where the effort observed was likely to be very low, particularly in the sub-equatorial regions. Extra attention may be required to ensure that these areas are adequately sampled. Obtaining the desired spatial coverage is also likely to be further complicated due to the targeting of different species by the various longline fleets and vessels (e.g. shallow versus deep deployment of longline hooks). Similar consideration may need to be given to the distribution of observer effort on purse seine vessels. Although the current observer coverage on purse seine vessels is nominally 100 %, this level cannot always be achieved due to logistical constraints. In Fig. 4, we illustrate the possible distribution of 80 % observer coverage of purse seine effort (days) and note that even high coverage gives an uneven spatial distribution. The areas of lower coverage expand further when the calculations were done by set type (unassociated vs. associated sets) (Fig. 5), which influences species composition (OFP 2010). Moreover, it is likely that observer placement is not random, which may result in further under-sampling of particular areas. These issues will therefore need consideration when refining observer protocols.

5.3 Interrogation of existing time series and identifying appropriate biomes to monitor

Detailed ecological analyses of existing observer data for the Pacific Ocean basin should be implemented to advance our understanding of the effects of the environment and fishing on the higher trophic levels at the Pacific Ocean scale. Furthermore, to evaluate the most efficient design for any future sampling regime, analyses of the dynamic oceanographic biomes (Hobday et al. 2011) are an immediate priority. These include analyses to associate these biomes with tuna size patterns, growth rates, bycatch composition, diet composition

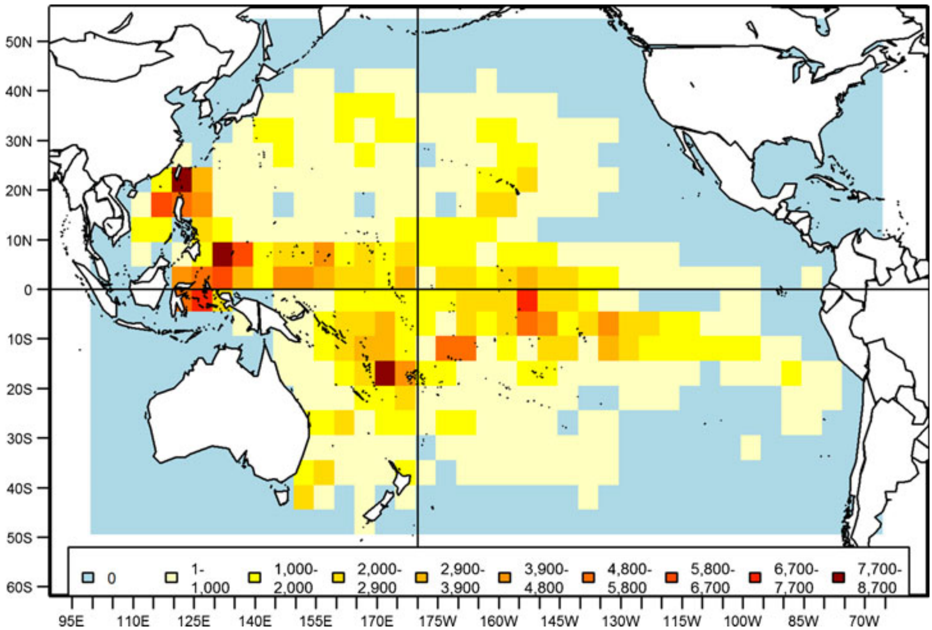

Fig 3 Plot of the distribution of longline observer coverage, based upon sampling 5 % of the total effort (sampling 5 % of the effort, hooks by fleet and year). Data for 1998–2008. Legend shows the resulting number of hooks (thousands of hooks) by 5° square

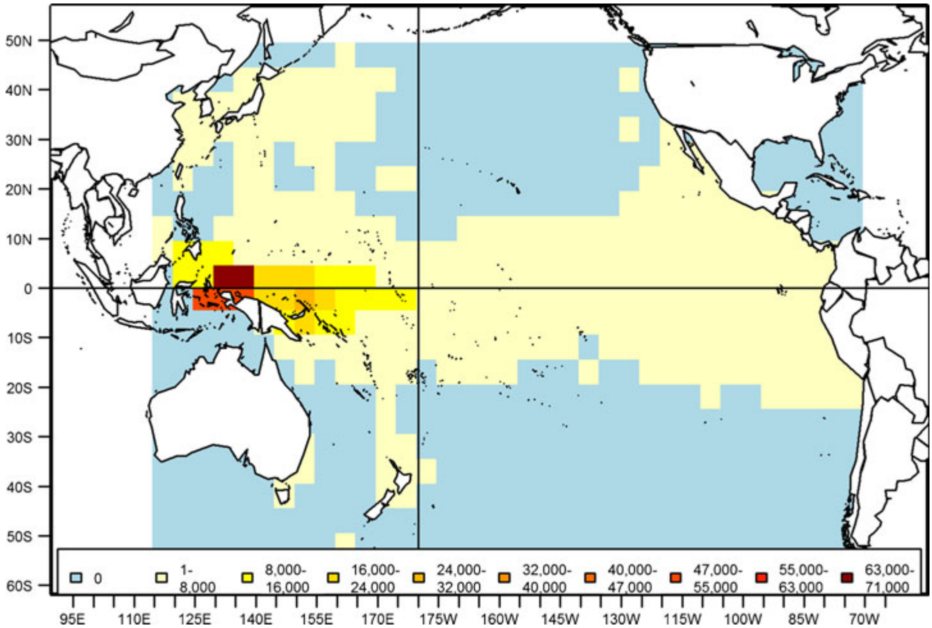

Fig 4 Plot of the distribution of purse seine observer coverage, based upon sampling 80 % of the total sets by fleet and year. Data for 2000–2010. Legend shows the resulting number of sets by 5° square

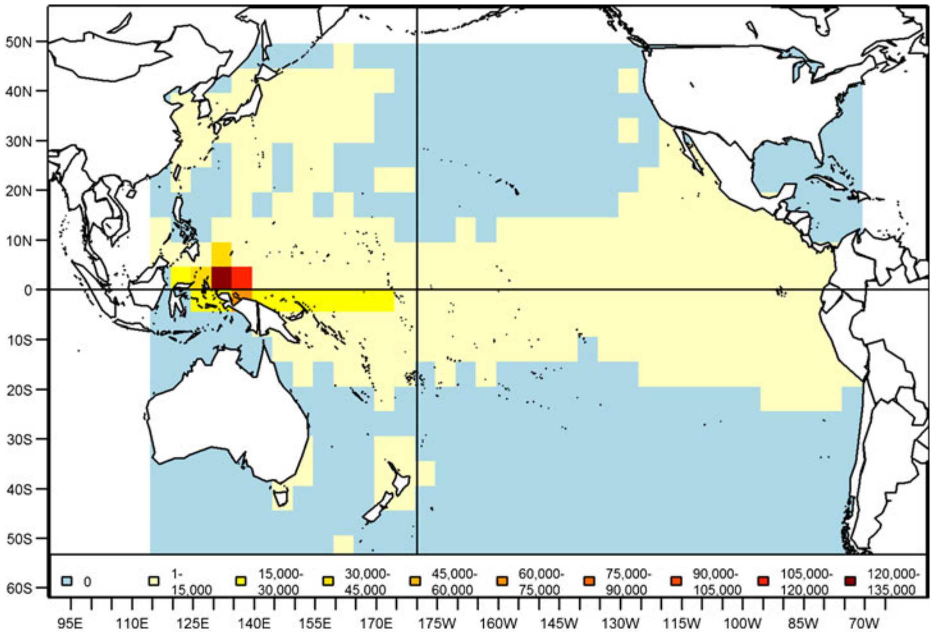

Fig 5 Plot of the distribution of purse seine observer coverage, based upon sampling 80 % of sets by set type (associated or unassociated sets), flag and year. Data for 2000–2010. Legend shows the resulting number of sets by 5° square

and stable isotope signatures. Such analyses will provide the spatial template necessary for future sampling programs. The efficacy of this biome approach has been demonstrated in eastern Australia using satellite-derived oceanographic information (Hobday et al. 2011). The approach effectively identified specific habitat types that are relevant to trophodynamics and species composition of pelagic communities and how the location and size of biomes can vary seasonally and annually. It has also been successfully applied to forecasting the impacts of climate change in the North Pacific. Three biomes (temperate, subtropical, and equatorial upwelling) were defined based on model-estimated depth-integrated phytoplankton. Over the twenty-first century, the model predicted a 30 % expansion of the subtropical biome and 34 and 28 % declines in the temperate and equatorial upwelling biomes, respectively (Polovina et al. 2011).

5.4 Mid trophic level observation

Comprehensive monitoring of mid-trophic level organisms is crucial for parameterising and constraining the numerical models of those communities that allow explicit linking of ocean circulation, biogeochemical interactions and higher trophic-levels (Le Borgne et al. 2011). Further validation of the sub-model describing the functional groups of micronektonic prey is an identified priority for SEAPODYM (Lehodey et al. 2012). Similar needs are also identified for the multi-species model for the Western Pacific Warm Pool (Allain et al. 2007). Acoustic surveys are increasingly showing that mid-trophic biomasses are generally higher than previously thought (Kloser et al. 2009). Combining acoustic data with taxonomic data from stomach analyses will produce more reliable inputs into regional ecosystem models (e.g. Griffiths et al. 2010). In addition, time series of distribution and abundance of mid-trophic level species are necessary to identify indicator species and monitor community-level changes associated with environmental variability, climate change, and/or fishing impact. Indicator species may act as sentinels for pending large-scale changes in pelagic ecosystems, thereby giving fisheries managers cues to rapidly implement adaptive strategies (e.g. adjustment of regional tuna fishing effort allocations; Bell et al. 2011).

5.5 Multiple models and candidate indicators

We encourage comparisons and standardizations of the pelagic ecosystem models already developed for the Pacific, to compare both the function and structure of the Eastern, Central, Western and Southern Pacific Ocean ecosystems, and the methods used to develop the models. This comparison would also help develop a candidate list of indicators of ecosystem status and change, including and beyond the sentinel species described above. This information is needed for managing marine resources to ensure ecosystem integrity and the maintenance of beneficial services and products for PICTs and other nations. Indicators could also serve to include Pacific Ocean ecosystems within existing international comparative initiatives that report and study marine ecosystem structures and functions thereby providing opportunity for global analyses (Shin et al. 2012).

6 Concluding remarks

The proposed actions identify areas of uncertainty in both our existing knowledge and the models we use to predict future conditions. The actions will also define the spatial and temporal scale of any biological data collection programme to address these areas of uncertainty and inform future management decisions, providing a foundation for a focused Pacific-wide observer-based biological data collection scheme.

The resulting time series of information at appropriate spatial and temporal scales can be combined with data on the physical characteristics of the Pacific ecosystem. The combined information can be used to examine uncertainties in our knowledge and the robustness of any management interventions to future climate change. It will provide biological and physical inputs for existing ecosystem models, and structuring information for new bio-physical models in addition to complementing existing ecosystem observing systems. These approaches should start to disentangle the effects of fishing and climate on pelagic ecosystems.

In a management context, combining physical information on ocean states with observer data on the pelagic ecosystem would provide PICTs with much of the information needed to incorporate climate change into ecosystem management. This will help them to build economic, food security and environmental policies that are resilient and adapt to climate change impacts. On a regional basis, monitoring enhances the capacity of the PICTs to contribute to international initiatives, including the United Nations Global Ocean Assessment being carried out under the auspices of the UN General Assembly (eg. Bernal 2011). These processes can give PICTs access to international expertise and ensure that Pacific Island issues are considered by global policy makers including development fund administrators.

An Ocean Observation System for the Pacific is now more feasible than ever. The developing observer programmes in the Pacific Ocean promise much and can help ensure that fishing does not interfere with the ecosystem's capacity to adapt to a changing tropical Pacific Ocean. They may also provide an important example of the benefits of individual countries and territories working together in a regional partnership. The Ocean Observation System now needs broad and long-term support from PICTs, Regional development agencies and management organisations. We call for the required scientific collaboration and implementation of policy measures to succeed in this important endeavour.

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