Operationalising access to oceanic fisheries resources by small-scale fishers to improve food security in the Pacific Islands

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Abstract

Maintaining high per capita fish consumption in Pacific Island countries as coral reefs are degraded by global warming and ocean acidification will depend on transferring some fishing effort from reef fish to tuna and other large pelagic fish. Nearshore fish aggregating devices (FADs) are recognised as a prime way of assisting small-scale fishers to make this transition. Several investments to optimise the use of nearshore FADs have already been identified and include, for example, pinpointing the locations where FADs are likely to make the greatest contributions to nutrition of coastal communities, integrating use of FADs with other livelihood activities, and improving the designs of FADs. However, additional investments are needed to help operationalise the regular use of nearshore FADs in many Pacific Island countries, particularly those prone to cyclones. These investments include: 1) training in safe and effective FAD-fishing methods, especially for small-scale fishers with limited experience in offshore fishing; 2) developing reliable ways for forecasting when tuna, and other large pelagic fish (e.g., mahi mahi and wahoo), are likely to come close to the coast and delivering this information to fishers; and 3) storing spare FAD materials, boats and fishing gear in cyclone-proof containers so that FADs lost during natural disasters or for other reasons can be replaced quickly. When combined with measures to sustain catches of coastal demersal fish, operationalising the use of nearshore FADs is expected to help several Pacific Island countries attain the food security goal of the Regional Roadmap for Sustainable Pacific Fisheries.

1. Introduction

In 2015, Pacific Island leaders signed the *Regional Roadmap for Sustainable Pacific Fisheries* to maintain or improve the contributions of the region's rich tuna resources and diverse coastal fisheries to the economies and societies of their countries [1]. An important goal of the *Roadmap* is to increase the availability of tuna for local consumption by 40,000 tonnes per year by 2024 to help maintain the food security of rapidly growing populations. Although there is much scope for increasing landings of tuna by industrial fleets in Pacific Island ports for use by urban populations, and improving the availability of canned tuna processed in the region, the most practical way to increase access to tuna for small-scale fishers in rural coastal communities is to expand the use of nearshore fish aggregating devices (FADs) [2-5]. Building national networks of nearshore FADs not only promises to increase the access to fish in the near term, it is also a key adaptation to climate change – increased use of FADs should enable communities to maintain the fish catches they need for good nutrition as the productivity of coastal demersal fisheries declines due to degradation of coral reefs caused by higher water temperatures and continued ocean acidification [6-8].

Several studies have demonstrated that catch rates of small-scale fishers improve when they fish around nearshore FADs [9-13]. Based on these encouraging results, considerable thought has already gone into identifying the actions needed to optimize the use of nearshore FADs for local food security. These actions include, for example, pinpointing locations where FADs are likely to make the greatest contributions to nutrition of coastal and island communities, integrating the use of FADs with other livelihood activities, and improving the designs and effectiveness of nearshore FADs [14-16]. As important as they are, however, these actions do not directly assist people to catch fish around FADs, or provide them with an effective way of replacing FADs lost during cyclones.

Three additional investments are needed to assist small-scale fishers to operationalize the use of FADs. The first involves training small-scale fishers in safe and effective FAD-fishing methods, especially where they have limited experience fishing offshore [16]. In particular, there is a need to raise awareness that more precautions are required when fishing around FADs, which are typically located 2-5 km beyond the fringing or lagoonal barrier reefs where most small-scale fishing operations have traditionally taken place. The lives lost at sea during the rapid development of the Alia longline fishery for albacore in Samoa in the 1990s [17] is a sobering reminder of what can happen when small-scale fishers are not accustomed to operating further offshore.

The second investment is the development of tools for forecasting favourable conditions for catching yellowfin and skipjack tuna, and other large pelagic fish (e.g., wahoo and mahi mahi), around nearshore FADs and delivering this information effectively to small-scale fishers. This is important because coastal and island communities have many competing demands on their time, e.g., production of subsistence food crops [18,19]. Forecasting when safe conditions for fishing around FADs also coincide with times when target fish species are expected to occur in coastal waters will assist communities to optimise their various livelihood activities.

The third investment centres around development of systems for provincial fisheries officers and communities to store spare FAD materials, boats and fishing gear in cyclone-proof containers so that FADs lost during natural disasters can be replaced quickly. In the aftermath of cyclones, the many demands for (limited and often damaged) national shipping can cause long delays in the replacement of FADs. Unless the materials needed to deploy FADs are stored within easy reach of communities, it is highly unlikely that lost or damaged FADs will be replaced in time to yield fish catches when they are needed most – during the months required for newly planted crops to be harvested following natural disasters.

Here, we describe the specific activities that will be needed for each of these investments. We use Vanuatu as a case study because it has a rapidly growing population, a need to increase access to tuna for food security [4], and is one of the Pacific Island countries affected most frequently by cyclones [20]. Vanuatu has also been an early adopter of FADs [21] and is well placed to benefit from the three proposed investments. The ideas presented here should also apply to other cyclone-prone countries and territories in the Pacific Island region where FADs are needed to help provide an important source of protein for coastal and island communities.

2. Training in safe and effective FAD-fishing methods

In Vanuatu, small-scale fishers who use FADs fall into two categories: 1) subsistence fishers operating from paddling canoes catching fish relatively close to shore (1-3 km from the coast and in depths of 200-500 m), principally for their own households; and 2) commercial (artisanal) fishers using motor boats who typically catch fish around FADs further offshore (5-7 km from the coast, and in depths of 500-1000 m) for sale at local markets or in Port Vila and Luganville.

It is estimated that there are ~16,000 small-scale fishers in Vanuatu (Supplementary Table 1) and that by the end of 2017 more than 50 nearshore FADs will be deployed at ~30 locations (Fig. 1, Supplementary Table 1).

To improve the safety and effectiveness of their fishing operations, both canoe and motor boat fishers need: 1) meteorological forecasts of wind speed, wind direction, atmospheric pressure, wave height and ocean current velocity to evaluate the risks associated with fishing offshore in small craft; 2) advice about safety procedures, which safety equipment to carry, and how and when to use it; and 3) training in the best ways to catch target fish species around FADs at different times of year.

2.1 Meteorological forecasts

The Vanuatu Meteorological Service (VMS) provides regular, short-term, forecasts of atmospheric conditions (e.g., wind speed, pressure) and related oceanic conditions (e.g., wave height)[1] essential for the marine weather bulletins needed to inform small-scale fishers about the safety of boating in coastal waters. VMS also issues bulletins and warnings for high winds, cyclones, and high seas. However, VMS needs support to 1) customise this information to the needs of canoe and motor boat fishers, 2) routinely transmit customised bulletins to each province on all types of mobile devices, and 3) ensure that communities know how to interpret the information correctly.

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[1] These forecasts are delivered by VMS via its web site (http://www.meteo.gov.vu/) and by radio several times each day.

2.2 Safety

Safety at sea for small-scale fishers centres on training in the relevant procedures, such as informing people where you are going, when you plan to return, who is on board, etc., and ensuring that fishers have appropriate safety equipment and the knowledge to use it. However, the relatively high cost of safety equipment means that it is likely to be beyond the reach of many small-scale fishers, especially subsistence fishers. Communities can usually overcome this problem by requesting funds from development agencies to purchase multiple sets of safety equipment and establishing custodian systems for issuing it to, and retrieving it from, small-scale fishers each day. Appropriate custodians of safety equipment are usually the community women's group or the local fishers' association. Although the type of safety equipment needed by subsistence canoe fishers differs from that required by commercial fishers in motor boats operating further offshore (Supplementary Table 2), use of safety equipment is always made easier when it is assembled into a 'safety grab bag'.

2.3 Training in efficient fishing methods

The most successful techniques for catching tuna around FADs from canoes involve handline fishing in mid water, e.g., drop-stone fishing, rod-spreader jigging and 'palu-ahi' fishing. Other efficient methods also include trolling at low speed, drift-line fishing for mahi-mahi, and 'sabiki' rig jigging for baitfish. Small-scale commercial fishers operating from motor boats have a greater range of fishing methods to choose from. In addition to those described above, they can use vertical longlining, small-scale horizontal longlining, 'ika-shibi' fishing, sub-surface or deep trolling, and Hawaiian-style hoop-net fishing [22,23].

Based on the experiences of Fisheries Development Officers at the Pacific Community (SPC), training in boating safety and effective FAD-fishing methods is most effective with a group of 10-15 fishers at a time. For both categories of small-scale fishers, the training usually takes 5-10 days and should be done once the FAD has accumulated enough fish (i.e., once it has been in the water for at least one month).

'Train the trainers' approaches, where regional or local technical experts train an initial group of trainers (national/provincial fisheries officers and key members of fishers' associations), are needed to increase the uptake of safe and effective FAD-fishing methods by coastal and island communities [16]. This places the onus on countries to allocate the financial resources needed to 1) arrange for a core set of fisheries officers and representatives of fishers' associations to be trained in safe and effective FAD-fishing operations; and 2) support this group of trainers to conduct similar training for fishing communities throughout their country.

3. Forecasting favourable conditions for catching large pelagic fish around FADs

Much of the information needed to develop reliable forecasts of the occurrence and abundance (hereafter 'distribution') of tuna and other large pelagic fish in the coastal waters of Pacific Island countries is now available in open-access, global databases (Supplementary Material). Below, we describe: the main types of information needed for building such fish distribution forecasting tools for Vanuatu; the suitability and availability of forecasting tools; the need to validate the reliability of forecasts; and feasible systems for disseminating forecasts to small-scale fishers. This discussion focuses on tuna because the information on habitat requirements and preferences for yellowfin and skipjack tuna [24,25] is more advanced than for other large pelagic fish expected to associate with nearshore FADs, e.g., mahi mahi and wahoo. Nevertheless, the forecasting approaches outlined here should also be applicable to other fish species targeted by small-scale fishers around nearshore FADs once the environmental conditions preferred by these species are understood more fully.

3.1 Information needed for forecasts

Identification of the environmental conditions preferred by tuna (and other large pelagic fish) is a key pre-requisite for development of tools for small-scale fishers that can forecast, and ‘nowcast’, conditions likely to attract tuna close to the coast. Both forecasting and nowcasting are important – forecasting allows fishing trips to be planned, whereas nowcasting confirms that forecasted conditions have eventuated.

Much information on the environmental preferences of skipjack and yellowfin tuna is already available from observations by industrial fisheries and research using electronic tags [24,25] (Supplementary Material) at a range of spatial scales. At the largest (ocean-basin) scale (1000’s of km), climate drivers such as the El Niño Southern Oscillation (ENSO) influence the distribution of tuna by modifying, for example, sea surface temperature (SST) [26-28]. Distributions of tuna are also affected by variation in ocean features at regional scales (100’s of km), such as shifts in currents [29,30], and at local scales (10’s of km), such as formation and movement of eddies and fronts [30-32]. In addition, tuna aggregate at small scales (100’s of metres) in response to bathymetric features like seamounts [33-35]. To forecast and nowcast conditions when tuna are likely to occur in nearshore waters where FADs are installed, information relating ocean features and the distributions of tuna species is needed at all these scales.

The most common variables used to identify environmental conditions preferred by tuna and predict the availability of suitable habitat are SST, chlorophyll-a concentration (a proxy measure for productivity/food supply for tuna), atmospheric pressure, and current speed and direction. Other useful variables, at least at regional and local scales, include mixed layer depth, eddy kinetic energy, presence of frontal systems, and prey distribution [31].

Sea surface temperature and chlorophyll-a have been used to describe historical distributions of tuna at regional and local scales [25,36,37]. More importantly, short-term changes in SST, atmospheric pressure, current speed and direction, eddy characteristics, and wind speed and direction have been applied to forecast local occurrence and abundance of tuna. For example, real-time (next day), short- (<7 days) and medium-term (up to 3 months) forecasts of distribution based on SST have been developed to: assist commercial fishers to catch southern bluefin tuna in South Australia [36]; manage bycatch in eastern Australia [38]; identify the best locations for recreational fishing for mahi mahi on the east coast of Australia [39]; provide commercial fishers targeting albacore in Spain’s Basque country with daily maps of habitat, re-parameterised each evening with the previous day’s catch [40]; and forecast the distribution of bigeye tuna in Indonesia [41]. Such forecasts are expected to improve further once predictions of changes in chlorophyll-a concentrations become routinely available at regional and local scales – at present, only experimental chlorophyll-a products based on biogeochemical and statistical models are available for limited areas, e.g., coastal bays [42,43] and coasts [37]. Forecasts are also expected to be improved by integrating knowledge (including traditional knowledge) about the distribution of tuna related to seasonal patterns of migration, and to moon and tidal phases.

3.2 Suitability and availability of forecasts

The short-term forecasts of atmospheric conditions (e.g., wind, pressure) and related oceanic conditions (e.g., wave height) described in Section 2.1 are typically issued at ocean-basin to local scales out to seven or 10 days. However, most physical features of the ocean, including SST, generally vary on longer time scales than atmospheric variables [44,45], permitting forecasts with longer lead times. For ocean features where forecasts are not presently available, like chlorophyll-a concentration, long-term average seasonal patterns (climatologies) and the anomaly from, and variability about, the average state of the ocean feature can be used to indicate how conditions are likely to vary in the near future. Nevertheless, care should be taken to consider how consistent such patterns are because they can vary substantially in space and time [46]. Typically, the reliability of forecasts of environmental variables decreases with increasing lead-time – nowcasts and short-term forecasts have greater accuracy than predictions for several weeks or months into the future.

Small-scale fishers in Vanuatu would benefit most from forecasts of ocean variables at relatively small spatial scales, and short temporal scales, that pinpoint suitable conditions for aggregation of tuna in coastal waters several days or a few weeks in advance.

Short-term SST forecasts (lead times up to seven days), such as those from OceanMaps[2] available on a 10-km grid for the Australian region, have much potential for identifying thermal conditions likely to attract tuna into coastal waters. Until these OceanMaps forecasts are available for Vanuatu, longer-term, global SST forecasts (several weeks to months), such as the coarse resolution modelling (~2° × 0.5–1.5°) from POAMA[3], could be used. However, a more promising option for SST forecasts for immediate application in Vanuatu is NOAA's Climate Forecast System Version 2 (CFSv2) (resolution: 0.5° × 0.5°) [47]. Since 2012, NOAA's Coral Reef Watch has been using CFSv2 forecasts for SST (Fig. 2a) to predict the risk of mass coral bleaching on a weekly basis up to four months in advance[4] [48,49], based on the magnitude and timing of stressful warm temperatures (Fig. 2b). Importantly, the spatial resolution and data grid layout of the SST forecasts from CFSv2 can distinguish SST patterns across the six provinces of Vanuatu (Fig. 2). Given that the deployed FADs define the location of fishing operations in each region, the primary guidance from the forecasts is to provide small-scale fishers with information on the timing of favourable conditions. The CFSv2 output can provide effective and timely information on ~~Therefore,~~ the likelihood of tuna occurring around FADs in the coastal waters of Vanuatu ~~at useful spatial scales could be assessed from CFSv2~~, based on known temperature preferences of yellowfin and skipjack tuna.

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[2] http://www.bom.gov.au/oceanography/forecasts/

[3] http://poama.bom.gov.au/

[4] http://coralreefwatch.noaa.gov/satellite/bleachingoutlook_cfs/outlook_cfs.php

The skill of the CFSv2 SST prediction varies seasonally and with the length of lead-time[5], however. For example, at a lead-time of up to one month, SST predictions around Vanuatu are more reliable for spring (September-November; correlation, r >0.8) than for summer (January-March; r <0.7) (Fig. 3). As lead-time increases, reliability of the predictions decreases, and is lowest from February to May. Overall, weekly forecasts of SST for Vanuatu are most reliable when made for periods no greater than two months in advance.

The addition of other important variables, like chlorophyll-a concentration, to produce an integrated tool has the potential to further enhance the skill of forecasts [50]. Any such improvement would depend on the accuracy of predicted variables, as well as how strongly they are correlated with tuna aggregation. For the example of chlorophyll-a concentration, development of forecasts based on coupled biogeochemical models for the Pacific Island region are likely in the next few years (R. Matear, pers. comm.). The development of stochastic prediction tools [46] can be undertaken immediately.

Investments are now needed to integrate the information outlined above to provide forecasts and nowcasts of tuna distribution in the coastal waters of Vanuatu (and other Pacific Island countries) based on predictions of ocean features expected to match the environmental conditions preferred by tuna.

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[5] http://www.cpc.ncep.noaa.gov/products/people/mchen/CFSv2HCST/metrics/rmseCorl.html

The skill of forecasts of tuna distribution in coastal waters can be assessed through hindcast performance. This involves correlating historical *forecasted* model values of environmental variables with historical *observed* values in both space and time, and assessing accuracy with several statistical techniques [51,52]. In the case of SST, satellite data or re-analysis products can be used [53]. In general, skill is higher for forecasts of fish presence based on physical conditions, such as SST, than for forecasts that integrate physical and biological data [38]. This is because the response of fish to physical conditions is mediated by physiological and behavioural factors, such as the size of the fish (e.g., larger tuna can tolerate cooler waters) or the reproductive life stage (e.g., spawning tuna may seek particular environmental conditions that are more limited than their usual range, or be willing to tolerate conditions that are unsuitable for feeding).

3.3. Validating forecasts

Ultimately, catch or other scientific data are needed to validate any tool designed to forecast the distribution of these large pelagic fish. In the absence of data needed for validation, full release of forecasts should be delayed until there is a high level of confidence that the information is useful and reliable. Limited release of forecasts may be appropriate, however, to help evaluate experimental products or to guide the collection of validation data. In such circumstances, communication among project partners and small-scale fishers regarding the experimental nature of forecasts is essential.

There are good prospects for obtaining catch data to validate forecasts of tuna distribution in the coastal waters of Vanuatu. During 2017, catch-per-unit-effort (CPUE) data are due to be collected from 10-15 FADs distributed throughout much of Vanuatu using the ‘Tails’ database developed by the Pacific Community[6] (Supplementary Material). Also, since August 2016, some CPUE data have been collected from artisanal fishers in several provinces (Tafea, Sanma, Penama, Tafea and Malampa) by Vanuatu Fisheries Department using Tails. A positive correlation between these catch data and forecasts of good fishing conditions would provide a first validation of a forecasting tool, which can be improved with formal skill assessment when a longer time series is available [38].

The rapid development and relatively low cost of acoustic buoys fitted to the drifting FADs used by industrial purse-seine vessels [54,55] provides another avenue for obtaining the data needed to validate a tool for forecasting tuna distribution for the benefit of small-scale fishers in Vanuatu. These acoustic buoys are equipped with echo sounders or sonar and transmit estimates of fish biomass associated with FADs to a depth 80 m [56]. Although these systems are not yet able to identify the fish species associated with FADs, purse-seine crew are now experienced at predicting the presence and relative abundance of tuna through interpreting signal strength and diurnal vertical behaviour. Therefore, attaching echo sounder buoys to representative nearshore FADs and transmitting the information to the Vanuatu Fisheries Department has considerable potential to validate a forecasting tool by correlating estimates of fish biomass associated with the FAD with conditions predicted to be favourable for tuna and other pelagic fish species.

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[6] Available online: https://play.google.com/store/apps/details?id=spc.ofp.tails&hl=en

3.4 Disseminating forecasts to small-scale fishers

Once the forecasting tool has been validated and placed on the web, either as part of the VMS suite of products or via the Vanuatu Meteorological and Geohazards Division, it can be accessed by users via mobile phone networks. Indeed, the stage is set for uptake of forecasts of tuna distribution in Vanuatu because the national 3G network provides reasonable coverage in five of the six provinces and more than 50% of the mobile phones in use are now smart phones.

4. Rapid replacement of lost FADs

A key lesson from Tropical Cyclone Pam (Category 5) that struck Vanuatu in March 2015 has been that it is very difficult for national governments to replace FADs quickly in the aftermath of devastating natural disasters – it took 18 months before FADs began to be replaced. New policies and practices are needed to ensure that FADs can be replaced within weeks of being lost during cyclones so that communities have access to nutritious fish before emergency food aid comes to an end and during the time it takes for new crops to mature.

A practical way to do this is to secure 40' shipping containers on all major islands in Vanuatu to provide cyclone-proof storage for spare FADs materials, and as a place where small-scale fishers can keep boats and fishing gear safe when a cyclone is approaching. Once the cyclone has passed, the boats can be used to deploy the FADs and to fish around them. The Vatuika FAD designed by the Vanuatu Fisheries Department [21] is ideal for this purpose because it can be deployed from small craft.

However, the logistics involved in installing and securing 40’ containers on remote islands can be difficult and costly in archipelagic nations like Vanuatu. To install such cyclone-proof storage in remote locations, Vanuatu and other Pacific Island countries prone to cyclones could request assistance from the Ministries of Defence in Australia or New Zealand. Both nations have naval vessels, such as HMAS Canberra (Australia) and HMNZS Canterbury (New Zealand), purpose-built for humanitarian assistance.

5. Discussion

The three investments described here are expected to create opportunities for small-scale fishers to increase their access to tuna and other large oceanic fish species in safe and effective ways. The investments will also make small-scale fishers more resilient to the devastating effects of cyclones and help them adapt to climate-related change. There are, however, a few factors that could temper the benefits to these investments.

The first is the possible effects of industrial fishing on the catches of small-scale fishers and the need to incorporate the proximity of industrial fishing operations into the forecasts of tuna distribution in coastal waters. Although the time needed for tuna to re-aggregate following localised depletion by industrial fishing is poorly understood, reduced catch rates have been reported in artisanal fisheries following nearby industrial purse-seine fishing operations [57]. Analyses of tagging data from areas where purse-seine fishing does and does not occur in the Pacific Island region also indicates that industrial fisheries may reduce local densities of tuna [58]. In addition, recreational fishing competition data infer that catch rates for striped marlin can be affected by industrial longline fishing [59].

Integrating industrial fishing activity with variation in key environmental variables to produce better short-term forecasts of local tuna abundance will necessitate near-real-time access to information on industrial fishing operations. In the case of Vanuatu, this may not be of such importance because industrial fishing for tuna is limited largely to longline operations outside a 12 nm industrial fishing exclusion zone. Analysis of the main locations of previous longline fishing within Vanuatu's exclusive economic zone (EEZ) shows that most activity occurred well east of the archipelago, between 50 and 100 km from the coast (Supplementary Material, Supplementary Figs. 2 and 3).

The second consideration is that recent modelling of the effects of climate change on the distribution and abundance of tuna shows that the biomass of yellowfin tuna is likely to decrease in the Vanuatu EEZ in 2035 and 2050, but that the biomass of skipjack tuna is likely to increase (Supplementary Fig. 5, Supplementary Materials). When the expected effects of increased fishing pressure over time are combined with those of climate change, the patterns are in the same direction, although the decreases in biomass for yellowfin tuna are projected to be greater, and the increases in biomass for skipjack tuna are projected to be lower (Supplementary Table 3).

Modelling the effects of climate change on the preferred habitats of two other large pelagic fish commonly caught by small-scale fishers around nearshore FADs in Vanuatu, mahi mahi and wahoo (Supplementary Fig. 6, Supplementary Material), indicates that both of these species are expected to decrease in abundance over time, with the effects expected to be greater for mahi mahi than for wahoo (Supplementary Table 3).

The implications of the climate change projections are that the relative abundances of the four species around nearshore FADs can be expected to change in the future, and that the focus for forecasting will eventually need to be on the species projected to increase in abundance, skipjack tuna.

Ultimately, effective forecasting will not only need to incorporate the projected effects of climate change but also local-scale effects of FADs on the behaviour of large pelagic fish species. Individual-based simulation models [60] (Supplementary Materials, Supplementary Fig. 7) provide an approach for exploring the possible interactions between FAD placement and fish behaviour.

The third factor is that expected decreases in the costs of acoustic equipment and using 3G networks should eventually enable an interface to be established for transmitting data from acoustic buoys attached to nearshore FADs directly to small-scale fishers, allowing them to assess the amount of fish associated with FADs on smart phones and tablets (Supplementary Material). Eventually, this innovation would be expected to supersede the need for a tool to nowcast tuna distribution for those Islands with good connectivity to the internet. However, nowcasts should continue to be useful for communities in more remote locations with limited connectivity. The benefits of short-term tuna distribution forecasts are expected to continue for communities at all locations.

Conclusions

Although planning is now well underway to establish nearshore FADs as part of the national infrastructure for food security in many Pacific Island countries, further investments are needed to train small-scale fishers and forecast suitable and productive fishing conditions to assist them to fish safely and effectively around FADs. Investments are also needed to develop systems for replacing lost FADs rapidly. Governments can support the vital role that nearshore FADs promise to play in providing nutritious food for rapidly-growing populations by implementing polices to ensure that deployment of nearshore FADs is accompanied by training in safe boating practices and effective FAD-fishing methods for the small-scale fishers expected to use them. Forecasting of wind and sea conditions to determine boat safety can be complemented by forecasting the conditions preferred by the target fish species so that communities can dovetail productive fishing periods with other important livelihood activities. In time, governments can also assist small-scale fishers to benefit from technological advances in acoustic ‘fish finding’ equipment so that they can directly assess how many fish are associated with nearshore FADs when planning fishing trips.

Communities that succeed in transferring some of their fishing effort from coral reefs to nearshore FADs are likely to be vulnerable if FADs lost during cyclones are not replaced quickly. Installation of cyclone-proof storage for spare FAD materials, and motor boats capable of deploying FADs, on all major islands in archipelagic countries (such as Vanuatu) will greatly reduce this vulnerability.

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References

[1] FFA and SPC. Future of fisheries: A regional roadmap for sustainable Pacific fisheries. Honiara and Noumea: Pacific Islands Forum Fisheries Agency and Pacific Community; 2015.

[2] SPC. Fish aggregating devices. Policy Brief 19/2012. Noumea: Secretariat of the Pacific Community; 2012.

[3] Bell JD, Andrew NL, Batty MJ, Chapman LB, Dambacher JM, Dawson B et al. Adapting tropical Pacific fisheries and aquaculture to climate change: management measures, policies and investments. In: Bell JD, Johnson JE, Hobday AJ, editors. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Noumea: Secretariat of the Pacific Community; 2011.

[4] Bell JD, Allain A, Allison EH, Andréfouët S, Andrew NL, Batty MJ, Blanc M et al. Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories. Mar Policy 2015;51:584–591.

[5] Bell JD, Cisneros-Montemayor A, Hanich Q, Johnson JE, Lehodey P, Moore B et al. Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands. Mar Policy (this volume).

[6] Pratchett MS, Munday PL, Graham NAJ, Kronen M, Pinca S, Friedman K et al. Vulnerability of coastal fisheries in the tropical Pacific to climate change. In: Bell JD, Johnson JE, Hobday AJ, editors. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Noumea: Secretariat of the Pacific Community; 2011.

[7] SPC. Coastal fisheries and climate change. Policy Brief 16/2012. Noumea: Secretariat of the Pacific Community; 2012.

[8] Bell JD, Ganachaud A, Gehrke PC, Griffiths SP, Hobday AJ, Hoegh-Guldberg O et al. Mixed responses of tropical Pacific fisheries and aquaculture to climate change. Nat Climate Change 2013;3:591–599.

[9] Chapman L, Pasisi B, Bertram I, Beverly S, Sokimi W. Manual on fish aggregating devices (FADs): Lower-cost moorings and programme management. Noumea: Secretariat of the Pacific Community; 2005.

[10] Sharp M. The benefits of fish aggregating devices in the Pacific. SPC Fish Newsl 2011;135:28–36.

[11] Sharp M. Investment profile for anchored nearshore fish aggregating device. SPC Fish Newsl 2012;136:46–48.

[12] Sharp M. Positive results of a FAD monitoring programme in Yap. SPC Fish Newsl 2014;143:34–38.

[14] Albert JA, Beare D, Schwarz A-M, Albert S, Warren R, Teri J. The contribution of nearshore fish aggregating devices (FADs) to food security and livelihoods in Solomon Islands. Plos One 2014;9(12):e115386

[15] Bell JD, Albert A, Andréfouët S, Andrew NL, Blanc M, Bright P, Brogan D, Campbell B, Govan H, Hampton J et al.· Optimising the use of nearshore fish aggregating devices for food security in the Pacific Islands. Mar Policy 2015;56:98–105.

[16] Anon. Sharing Pacific nearshore FAD expertise. SPC Fish Newsl 2016;150:37–41.

[17] Gillett R. Aspects of sea safety in the fisheries of Pacific Island countries. Rome: Food and Agriculture Organization of the United Nations; 2003.

[18] Bell J, Taylor M. Building climate-resilient food systems for Pacific Islands. Penang: WorldFish; 2015.

[19] Taylor M, McGregor A, Dawson B (editors). Vulnerability of Pacific Island agriculture and forestry to climate change. Noumea: Pacific Community; 2016.

[20] Lough JM, Meehl GA, Salinger MJ. Observed and projected changes in surface climate of the tropical Pacific. In: Bell JD, Johnson JE, Hobday AJ, editors. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Noumea: Secretariat of the Pacific Community; 2011.

[21] Amos G, Nimoho G, Fujii M, Seko A, Inuma M, Nishiyama K et al. New FAD development approach strengthens community-based fisheries management in Vanuatu. SPC Fish Newsl 2014;144:40–47.

[22] Preston GL, Chapman LB, Mead PD, Taumaia P. Trolling techniques for the Pacific Islands. Noumea: South Pacific Commission; 1987.

[23] Preston GL, Chapman LB, Watt PC. Vertical longlining and other methods of fishing around fish aggregating devices (FADs). Noumea: Secretariat of the Pacific Community; 1998.

[24] Lehodey P, Hampton J, Brill RW, Nicol S, Senina I, Calmettes B et al. Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In: Bell JD, Johnson JE, Hobday AJ, editors. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Noumea: Secretariat of the Pacific Community, 2011.

[25] Robinson L, Hobday AJ, Possingham HP, Richardson AJ. Trailing edges projected to move faster than leading edges for large pelagic fish under climate change. Deep Sea Res II 2015;113:225–234.

[26] Lehodey P, Bertignac M, Hampton J, Lewis A, Picaut, J. El Niño Southern Oscillation and tuna in the western Pacific. Nature 1997;389:715–718.

[27] Lan, KW, Evans K, Lee M-A. Effects of climate variability on the distribution and fishing conditions of yellowfin tuna (*Thunnus albacares*) in the western Indian Ocean. Climatic Change 2013;119:63–77.

[28] Fromentin J-M, Reygondeau G, Bonhomeau S, Beaugrand G. Oceanographic changes and exploitation drive the spatiotemporal dynamics of Atlantic bluefin tuna (*Thunnus thynnus*). Fish Oceanogr 2014;23:147–156.

[29] Hartog J, Hobday AJ, Matear R, Feng M. Habitat overlap of southern bluefin tuna and yellowfin tuna in the east coast longline fishery – implications for present and future spatial management. Deep Sea Res Part II 2011;58:746–752.

[30] Young JW, Hobday AJ, Campbell RA, Kloser RJ, Bonham PI, Clementson LA, Lansdell, MJ. The biological oceanography of the East Australian Current and surrounding waters in relation to tuna and billfish catches off eastern Australia. Deep Sea Res II 2011;58:720–733.

[31] Hobday AJ, Hartog JR. Dynamic ocean features for use in ocean management. Oceanography 2014;27(4):134–145.

[32] Morato T, Miller PI, Dunn DC, Nicol S, Bowcott J, Halpin, PN. Do oceanic fronts promote aggregation of visitors on seamounts? Fish Fish 2015; doi:10.1111/faf.12126.

[33] Dagorn L, Bach P, Josse, E. Movement patterns of large bigeye tuna (*Thunnus obesus*) in the open ocean, determined using ultrasonic telemetry. Mar Biol 2000;136:361–371.

[34] Hobday AJ, Campbell G. Topographic preferences and habitat partitioning by pelagic fishes in southern Western Australia. Fish Res 2009;95:332–340.

[35] Morato T, Hoyle SD, Allain V, Nicol, SJ. Seamounts are hotspots of pelagic biodiversity in the open ocean. Proc Nat Acad Sci 2010;107:9707–9711.

[36] Eveson JP, Hobday AJ, Hartog JR, Spillman CM, Rough KM. Seasonal forecasting of tuna habitat in the Great Australian Bight. Fish Res 2015;170:39–49.

[37] Dell JT, Wilcox C, Matear RJ, Chamberlain MA, Hobday AJ. Potential impacts of climate change on the distribution of longline catches of yellowfin tuna (*Thunnus albacares*) in the Tasman Sea. Deep Sea Res II 2015;113:235-245.

[38] Hobday AJ, Spillman CM, Eveson JP, Hartog JR. Seasonal forecasting for decision support in marine fisheries and aquaculture. Fish Oceanogr 2016;25(S1):45–56.

[39] Brodie S, Hobday AJ, Smith JA, Spillman CM, Hartog JR, Everett JD et al. Seasonal forecasting of dolphinfish distribution in eastern Australia to aid recreational fishers and managers. Deep Sea Res II (in press).

[40] Artetxe I, González de Zarate A, Ruiz J. Implantación en el País Vasco del plan de recuperación del atún rojo (Reglamento CE 643/07). Revista de Investigación Marina 5; 2008. http://www.azti.es/rim/wp-content/uploads/2014/01/revista_marina_05.pdf

[41] Lehodey P, Senina I, Wibawa TA, Titaud O, Calmettes B, Conchon A et al. Operational modeling of bigeye tuna (*Thunnus obesus*) in the Indian Ocean and the Indonesian region. Mar Pol Bull (in press).

[42] Lazzari P, Teruzzi P, Salon A. Pre-operational short-term forecasts for Mediterranean Sea biogeochemistry. Ocean Sci 2010;6:25–39.

[43] Rajaee T, Boroumand A. Forecasting of chlorophyll-a concentrations in South San Francisco Bay using five different models. Appl Ocean Res 2015;53:208–217.

[44] Linacre E, Geerts B. Climates and weather explained: an introduction from a southern perspective. New York: Taylor and Francis e-Library; 2003.

[45] Denman K, Hofmann E, Marchant H. Marine biotic responses to environmental change and feedbacks to climate. In: Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (editors). Climate change 1995. Cambridge: Cambridge University Press; 1996.

[46] Welch H, Pressey RL, Heron SF, Ceccarelli DM, Hobday AJ. Regimes of chlorophyll-a in the Coral Sea: implications for evaluating adequacy of marine protected areas. Ecography 2015; doi:10.1111/ecog.01450

[47] Saha S, Moorthi S, Wu X, Wang J, Nadiga S, Tripp P et al. The NCEP climate forecast system version 2. J Climate 2014;27:2185–2208.

[48] Eakin M, Liu G, Chen M, Kumar A. Ghost of bleaching future: Seasonal outlooks from NOAA's operational climate forecast system. Proc 12th Int Coral Reef Symp; 2012.

[49] Liu G, Eakin CM, Chen M, Kumar A, De La Cour JL, Heron SF et al. Predicting coral bleaching heat stress to inform reef management: NOAA Coral Reef Watch’s four-month outlook. Frontiers Mar Sci (in press).

[50] Tommasi D, Stock C, Hobday AJ, Methot R, Kaplan I, Eveson P et al. Managing living marine resources in a dynamic environment: the role of seasonal to decadal climate forecasts. Prog Oceanogr (in press).

[51] Spillman C, Alves O. Dynamical seasonal prediction of summer sea surface temperatures in the Great Barrier Reef. Coral Reefs 2009;28:197–206.

[52] Spillman CM, Hobday AJ. Dynamical seasonal forecasts aid salmon farm management in an ocean warming hotspot. Clim Risk Manage 2014;1:25–38.

[53] Yin Y, Alves O, Oke PR. An ensemble ocean data assimilation system for seasonal prediction. Monthly Weather Rev 2011;139:786–808.

[54] Fonteneau A, Chassot E, Bodin N. Global spatio-temporal patterns in tropical tuna purse-seine fisheries on drifting fish aggregating devices (DFADs): taking a historical perspective to inform current challenges. Aquat Living Resour 2013;26:37–48.

[55] Chassot E, Goujon M, Maufroy A, Cauquil P, Fonteneau A, Gaertner D. The use of artificial fish aggregating devices by the French tropical tuna purse seine fleet: historical perspective and current practice in the Indian Ocean. Indian Ocean Tuna Commission. Working Party on Tropical Tunas. IOTC-2014-WPTT16-20 Rev_1; 2014

[56] Lopez J, Moreno G, Sancristobal I, Murua J. Evolution and current state of the technology of echo-sounder buoys used by Spanish tropical tuna purse seiners in the Atlantic, Indian and Pacific Oceans. Fish Res 2014;155:127–137.

[57] Hampton J, Lawson T, Williams P, Sibert J. Interaction between small-scale fisheries in Kiribati and the industrial purse-seine fishery in the western and central Pacific Ocean. In: Shomura RS, Majkowski J, Harman RF, editors. Status of interactions of Pacific tuna fisheries in 1995. FAO Fisheries Technical Paper 365. Rome: Food and Agriculture Organization of the United Nations; 1996.

[58] Leroy B, Peatman T, Usu T, Kumasi B, Caillot S, Moore B et al. Interactions between artisanal and industrial tuna fisheries: insights from a decade of tagging experiments. Mar Policy 2016;65:11–19.

[59] Knight E, Park T, Bromhead D, Ward P, Barry S, Summerson R. Analyses of interactions between longline and recreational gamefish fisheries taking or tagging striped marlin off New South Wales. Canberra: Bureau of Rural Sciences; 2006.

[60] Scutt Phillips J, Sen Gupta A, van Sebille E, Senina I, Lehodey P, Nicol S. Individual-based methods for simulation of movement by WCPO skipjack and other species. Western and Central Pacific Fisheries Commission Scientific Committee 12; 2016.

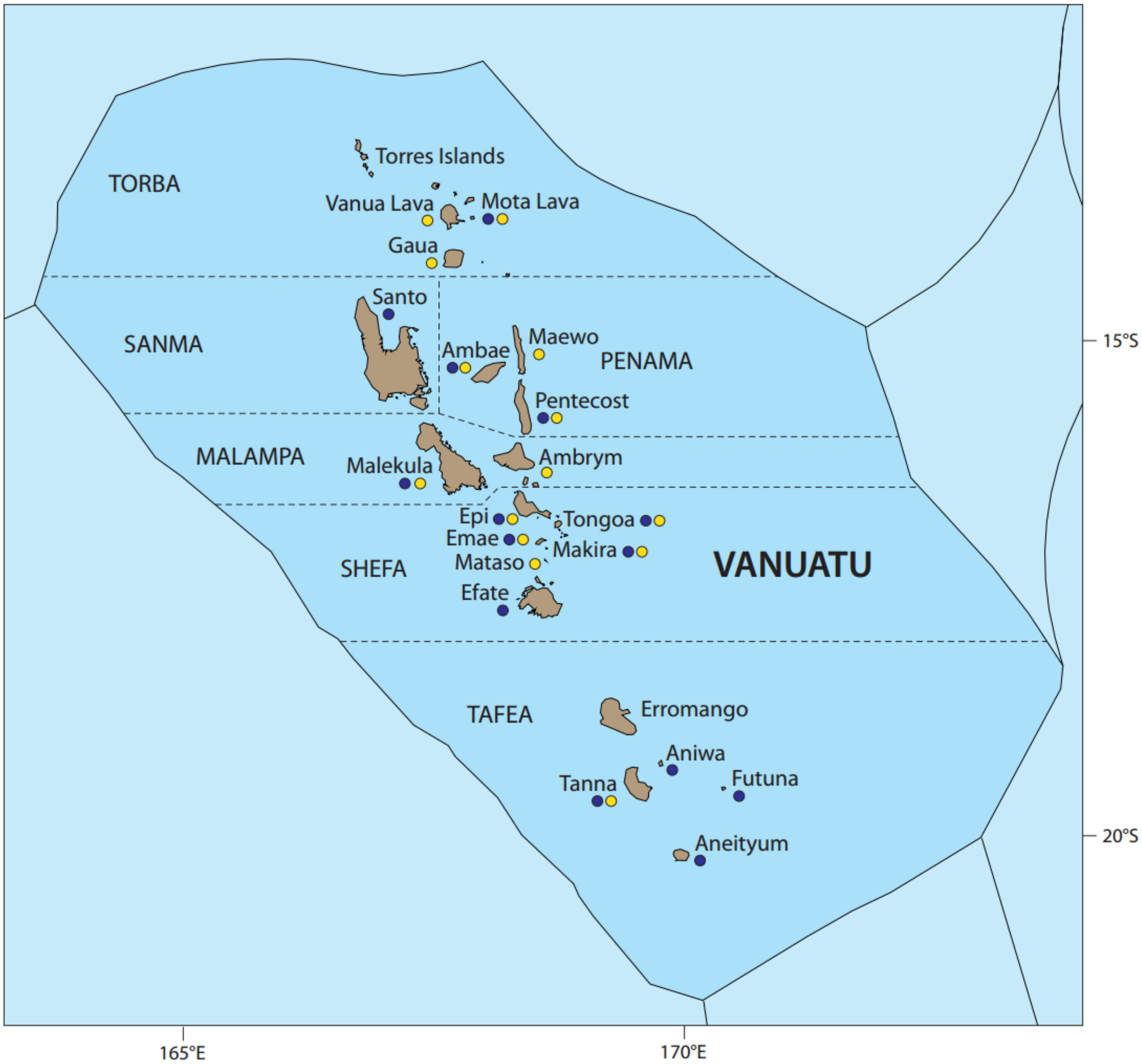


Fig. 1. Map of Vanuatu showing the exclusive economic zone, the six provinces, the locations where fish aggregating devices (FADs) have already been installed close to the coast for small-scale fishers (blue circles) and the locations where FADs will be installed during 2017 (yellow circles) (see also Supplementary Table 1).

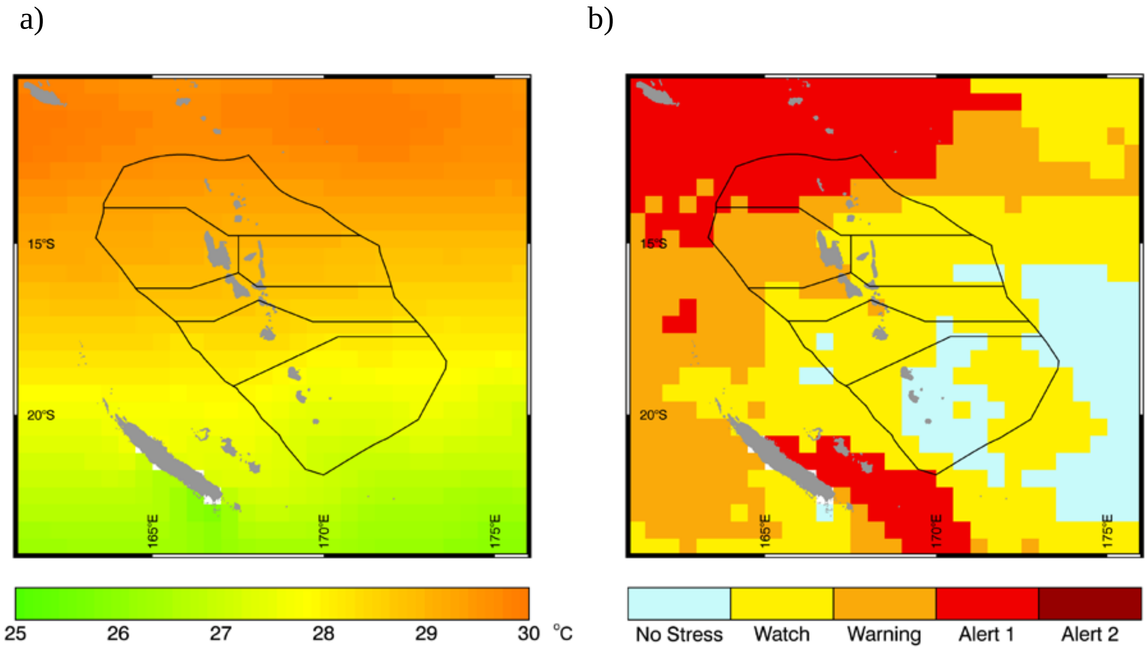


Fig. 2. a) NOAA Climate Forecast System v2 predicted sea surface temperature in the Vanuatu region for 13 March 2016 from the forecast issued on 24 January 2016; b) management product describing the highest predicted level of coral bleaching likelihood during the four-month period leading up to 13 March 2016, issued on 24 January 2016. The six provinces of Vanuatu are distinguished in both panels out to the boundary of the exclusive economic zone (black lines).

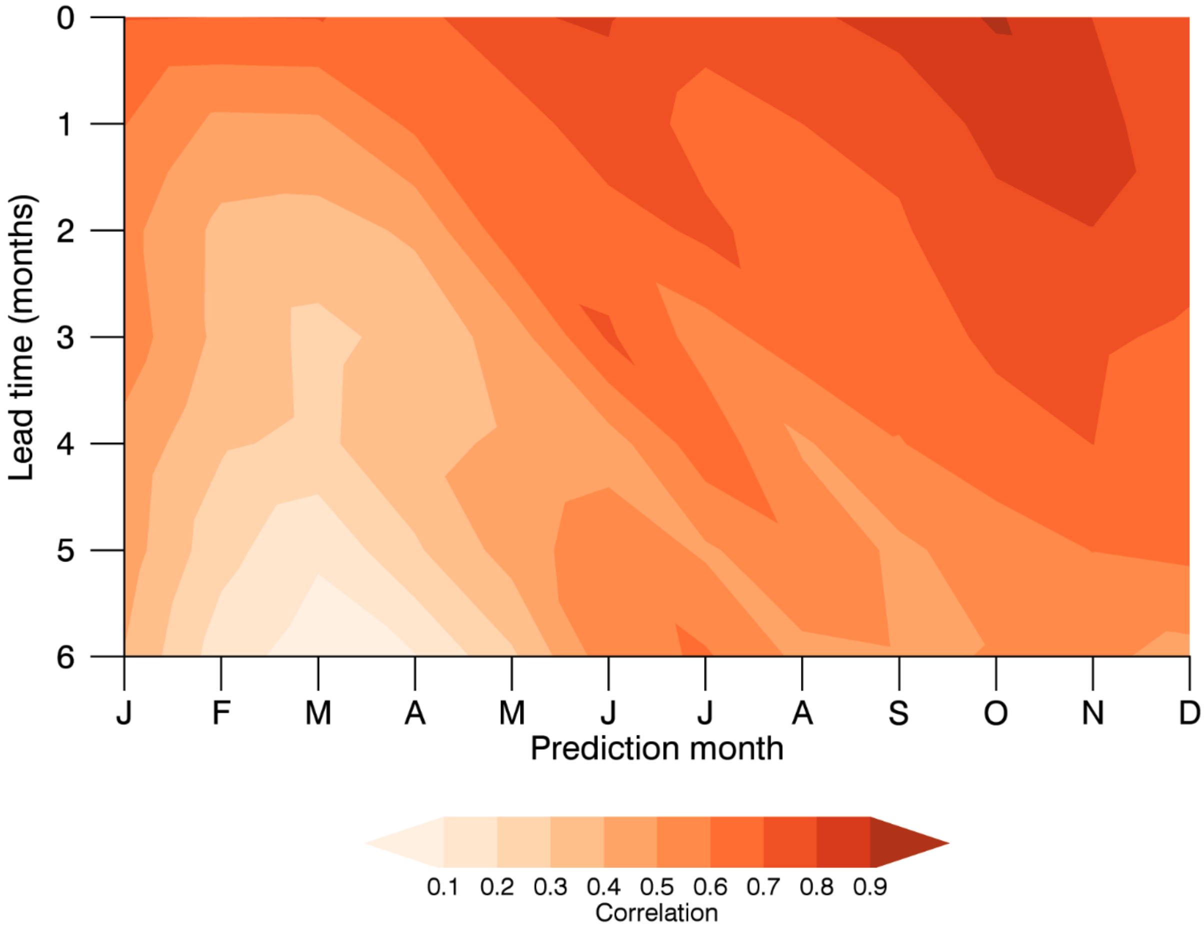


Fig. 3. Variation in the correlation coefficient of SST predictions by the NOAA Climate Forecast System v2 for the Vanuatu region with season and model lead-time.

Supplementary Material

Introduction

The information below supports several of the points made in the paper ‘Operationalising access to oceanic fisheries resources by small-scale fishers to improve food security in the Pacific Islands’ and has been arranged in the same general sequence as the main text.

The supplementary figures and tables referred to in the supplementary material, and/or in the main text, have been placed at the end of the document in numerical order.

The supplementary material contains several new references but also cites references listed in the main text. For completeness, the reference list at the end of the supplementary material includes the references from the main text as well as the new references.

Contents

Global databases useful for accessing information needed to forecast suitable environmental conditions for tuna and other large pelagic fish species

Examples of near real-time data on variables influencing the distribution of tuna are given below.

Variable	Example product	Source
Sea surface Temperature	Blended 5km OISST	coralreefwatch.noaa.gov www.ospo.noaa.gov/Products/ocean/
Chlorophyll-a	VIIRS MODIS	www.star.nesdis.noaa.gov/socd/mecb/color/ pifsc-oceanwatch.irc.noaa.gov/erddap/info/ www.ospo.noaa.gov/Products/ocean/
Sea surface height	AVISO HYCOM (model)	pifsc-oceanwatch.irc.noaa.gov/erddap/info/ hycom.org
Sea surface Salinity	Aquarius	pifsc-oceanwatch.irc.noaa.gov/erddap/info/
Surface wind speed	Blended Seawinds ASCATwinds	www.ncdc.noaa.gov/oa/rsad/air-sea/seawinds.html http://apdrc.soest.hawaii.edu/datadoc/ascat.php
Ocean currents	OSCAR HYCOM (model)	podaac.jpl.nasa.gov/dataset/OSCAR_L4_OC_third-deg hycom.org
Mixed Layer Depth	Ocean Heat Content HYCOM (model)	www.ospo.noaa.gov/Products/ocean/ hycom.org
All variables above (observation and model products)	Global Ocean 1/12° Physics Analysis and Forecast updated daily	http://marine.copernicus.eu/

Environmental conditions preferred by tuna

Water temperature

Each species of tuna has a range of sea surface temperature (SST) within which it occurs. The range of SST throughout the distributions (all occurrences) of skipjack and yellowfin tuna in the Pacific Ocean, together with the SST range where substantial commercial catches of these species are made (abundant occurrences), are shown in the table below.

Tuna species	All occurrences (°C)	Abundant occurrences (°C)
Skipjack	15–30	20–29
Yellowfin	15–31	20–30

Source: Robinson et al (2015) [25], Sund et al. (1981) [61].

The preferred thermal habitat of tuna also varies with size (age). Based on the statistical approach within the SEAPODYM maximum likelihood estimation framework, catch data, size frequency data and tagging data (Senina et al. 2015; 2016) [62,63], yellowfin tuna up to a size of 100 cm share the same range of optimal average temperature (27-29 °C) as skipjack tuna. However, when yellowfin tuna grow larger than 100 cm their preferred temperatures decrease rapidly (Supplementary Fig. 1), enabling them to inhabit deeper and colder oceanic waters.

Dissolved oxygen

Marine fish are highly sensitive to the availability of dissolved oxygen (O_2) – many species cannot maintain their metabolic rate and swim when O_2 decreases to 1 mg/l or less (Heath 1995) [64]. Skipjack and yellowfin tuna conform to this general pattern, although lower, lethal, O_2 levels vary considerably between these two species. In general, yellowfin tuna have slightly better tolerance of low ambient O_2 concentrations than skipjack tuna. For example, skipjack tuna increase their swimming speeds when O_2 levels fall below 4 mg/l, whereas yellowfin tuna show no such behaviour until O_2 concentration reaches 2.5 mg/l (Dizon 1977) [65]. Skipjack tuna spend less than 10% of their time at depths where O_2 levels are below about 5.0 mg/l (3.8 ml/l, 75% saturation), whereas yellowfin tuna spend less than 10% of their time at depths where ambient O_2 levels are below 4.3 mg/l (3.3 ml/l, 65% saturation) (Cayré 1991, and Cayré and Marsac 1993) [66,67].

The table below shows the lower lethal O_2 levels for skipjack and yellowfin tuna in the tropical Pacific, based on the ratio of the minimum hydrostatic equilibrium speeds of a skipjack tuna of 50 cm to those of other tuna species and other body sizes. The lower lethal

O_2 level for a 50 cm skipjack tuna has been estimated by converting mg O_2/l to ml O_2/l. Percentage saturation was calculated at a temperature of 25°C.

Species of tuna	Fork length (cm)	Lower lethal O_2 levels		
		mg/l	ml/l	% saturation
Skipjack	50	2.45	1.87	37
	75	2.83	2.16	43
Yellowfin	50	1.49	1.14	23
	75	2.32	1.77	35

Ocean currents

Skipjack and yellowfin tuna are sensitive to changes in oceanic circulation because currents determine: locations that have the temperatures required for successful reproduction (spawning grounds), the dispersal of larvae and juveniles and their retention in areas favourable for growth and survival; and the distributions of prey for adults. Also, eddies create favourable, smaller-scale, foraging areas for these species (Humston et al. 2000) [68], and circulation around islands and seamounts produces complex oceanographic features, including eddies, that appear to play an important role in the spawning strategies of tuna species.

Tuna are also affected by the stratification of the water column resulting from the effects of ocean circulation and water temperature. Each species swims and forages to a different depth, depending on optimal or threshold temperature and dissolved O_2 values. However, the area of suitable habitat for each species changes with seasons and inter-annual climatic variability. For example, the deepening of the thermocline in the eastern tropical Pacific and shoaling of the thermocline in the west during El Niño events, changes the area of habitat available for yellowfin tuna because this species occupies the entire mixed layer (Lehodey et al. 2011) [24].

Primary productivity (ocean colour)

Skipjack and yellowfin tuna are acutely sensitive to alterations in primary productivity. Any changes in nutrient supply in the photic zone cascade down the food web through their effects on productivity of phytoplankton, zooplankton and micronekton. This affects the abundance of larval and juvenile tuna and, ultimately, the number of adult tuna than can be harvested. Peaks of larval recruitment occur when ample food for larvae, and absence of predators, coincide. Such favourable events have been observed during transition from El Niño to La Niña phases in the equatorial Pacific (Lehodey 2001) [69].

Proposed monitoring of catches around FADs in Vanuatu during 2017

Catches of small-scale fishers will be monitored at locations identified as priority sites for deployment of nearshore FADs by Vanuatu Fisheries Department. Monitoring will be undertaken by trained village monitors to enable regular collection of data. The monitoring protocol is based on that developed by the Pacific Community (SPC), modified to suit the local situation in Vanuatu. In brief, fish catches will be monitored two to three days per week on typical fishing days. Representative fishing activities by small-scale fishers will be recorded, along with the total number of canoes and motor boats used for fishing during the recording period.

Importantly, data will be collected from fishing trips to FAD and non-FAD locations (including coral reefs and offshore areas) to enable a comparison of fish catches made with and without FADs. For each fishing event, the data recorded will include: location, number of fishers, departure and return date and time, time spent fishing, boat type, number and weight of fish by species and fishing method, financial expenditure (quantity of fuel used, fishing gear purchased) and the end use of the catch (household consumption, sale to markets, gift). Catch-per-unit-effort will be calculated. Data will be collected using computer tablets and the ‘Tails’ application developed by SPC (see below).

Description of the Tails database developed by the Pacific Community

The ‘Tails’ application developed by SPC for tablets and smart phones revolutionises electronic collection of artisanal tuna catch data. Tails allows national fisheries staff to easily collect information on the catch of tuna and bycatch species by small-scale fishers in remote locations, and to transfer these data to the main office for analysis, even when internet connectivity and bandwith are limited. This new technology eliminates costly and time consuming delays in sending paper-based data from outer islands to the central fisheries office, and enables fisheries officers to monitor and manage artisanal tuna catches based on real-time data. Tails can send data from ~500 fishing trips at a time.

Capabilities of acoustic devices attached to drifting FADs used by purse-seine vessels

The echo-sounder buoys attached to the drifting FADs used by the industrial purse-seine tuna fishery are normally single-frequency units with transducers operating somewhere between 38 and 200 KHz. These acoustic devices can be used to estimate the total biomass of tuna and associated bycatch species attracted to a FAD, but not the relative quantities of each species. Through trial and error, fishermen can become adept at estimating tuna biomass with this equipment but environmental and biotic factors can have a negative impact on these estimates.

Acoustic buoys that operate at different frequencies are better at discriminating the presence of skipjack tuna, which do not have a swim bladder, and yellowfin/bigeye tuna, which have well developed swim bladders. Experiments by the International Sustainable Seafood Foundation (ISSF) have shown better discrimination of skipjack tuna at high frequencies and better discrimination of bigeye/yellowfin at low frequencies (Restrepo et al. 2016) [70].

Accurate discrimination of skipjack, yellowfin and bigeye tuna, and the size of individual fish, will depend on the use of multi frequency, echo-sounder buoys. Progress is being made towards achieving this goal by a number of the more competitive acoustics companies.

Given that the most common large pelagic fish species caught by small-scale fishers in Vanuatu is yellowfin tuna (Supplementary Fig. 2), low-frequency acoustic buoys should be fitted to nearshore FADs in Vanuatu until effective multi-frequency buoys capable of discriminating between tuna species have been developed.

The cost of single-frequency acoustic buoys is relatively inexpensive (~USD 1000 per unit). The greater expense is for the antennae and interface box needed to transmit information on the amount of fish associated with a FAD detected by the acoustic buoy to a land-based computer (USD 5000 or more).

Important considerations for assessing the scope for using acoustic buoys to validate forecasts of tuna abundance around FADs in coastal waters are:

1) the occurrence of false images due to the presence of nekton and smaller fish species;
2) the fact that the acoustic signal is vertical and will mainly only detect fish that pass directly beneath the echo sounder buoy attached to the FAD; and
3) the effects of currents on the orientation of acoustic signals from a buoy attached to an anchored FAD.

The latter problem can be addressed to a reasonable extent by placing the acoustic buoy in a boat-shaped float tied to the FAD to eliminate drag and tilt.

Potential for interactions between industrial tuna fisheries and artisanal fisheries in Vanuatu

Based on data collected by the Vanuatu Fisheries Department and analysed by the Pacific Community, three species (wahoo, yellowfin tuna and skipjack tuna) dominate the catches of large pelagic fish by artisanal fishers in Vanuatu (Supplementary Fig. 2).

The only species that comprises a substantial percentage (>25%) of the catches of both the industrial longline fishery and the artisanal fishery is yellowfin tuna. However, the industrial and artisanal fisheries are separated spatially and there is estimated to be little scope for conflict between them for two reasons: 1) the industrial longline effort in the Vanuatu EEZ has been concentrated in waters east of the main archipelago (Supplementary Fig. 3); and 2) most of the industrial longline catch is taken between 50 and 100 km off the coast (Supplementary Fig. 4).

Modelling projected changes in distribution and abundance of yellowfin and skipjack tuna due to climate change

The projected effects of climate change on the distribution and abundance of yellowfin and skipjack tuna in Vanuatu's EEZ were made using the Spatial Ecosystem and Population Dynamics Model (SEAPODYM) (Lehodey et al. 2008) [71]. SEAPODYM incorporates information on fish physiology, the direct effects of physical and chemical changes to the ocean, and the indirect effects of changes to food webs, on the spatial distribution of tuna. It also includes a definition of habitat indices, spawning, local movements in response to habitat quality and basin-scale seasonal migrations, accessibility of prey within different vertical layers of the water column, predation, natural mortality and variation in this mortality due to environmental conditions. A data assimilation technique based on adjoint code and maximum likelihood approaches is used to parameterize the model (Senina et al 2008) [72] before forecasting the future of tuna populations with climate change projections (Lehodey et al. 2013; 2015; Senina et al. 2015) [62,73,74] .

The projections used here for yellowfin and skipjack tuna biomass were driven by the physical-biogeochemical fields predicted from three of the climate models used for the 5th IPCC Coupled Model Intercomparison Project (CMIP5), IPSL, GFDL and NorESM, coupled to the PISCES biogeochemical model (Aumont et al. 2015) [75] and forced by atmospheric CO_2 from historical records from 1860–2000, following the RCP8.5 IPCC emissions scenario. For the 2005 plots in Supplementary Fig. 5, total biomass (tonnes per km^2) was averaged over 2000–2010. Projections were made for the 10-year periods 2030–2040 (2035) and 2045–2055 (2050) to account for interannual variability. The projections for all three models were then averaged, and the differences between these averages and the average for 2000-2010 (2005) were calculated.

Modelling projected changes in habitat suitability for wahoo and mahi mahi due to climate change

The projected effects of climate change on the suitability of the Vanuatu EEZ for wahoo and mahi mahi were made using a multispecies distribution model approach to quantify the past and future distribution of these species. This modelling approach is based on the concept of ecological niche (Hutchinson 1957) [76]. Ecological niche theory states that a species can occur in a multidimensional environmental interval defined by the way that evolution has shaped its physiological characteristics and by its ability to compete for resources.

To identify the environmental niche of wahoo and mahi mahi, we gathered all occurrences of these species from the Ocean Biogeographic Information System (OBIS - www.iobis.org); the Intergovernmental Oceanographic Commission of UNESCO (IOC- ioc-unesco.org/); the Global Biodiversity Information Facility (GBIF - www.gbif.org), Fishbase (www.fishbase.org); and the International Union for the Conservation of Nature (IUCN - http://www.iucnredlist.org/technical-documents/spatial-data). From the initial dataset, we removed records with spatial location "Not Assigned" (NA) or null values and replicated among databases (i.e., records with the same species name, coordinates, and sampling details). We then used an environmental dataset based on the outputs of the Geophysical Fluid Dynamics Laboratory (GFDL) model assembled for the RCP 8.5 scenario. The environmental dataset (integrated from 0 to 100 m) comprised: temperature, salinity, oxygen, pH and primary production. Each parameter was spatially resolved on a 0.5°x 0.5° grid from 1950 to 2100. The climatological values (computed for the period 1970–2000) for each of these variables were interpolated to the position of each occurrence, in terms of latitude-longitude.

A multi-model approach was used to approximate the environmental tolerance of each species in the best possible way. This approach incorporated four environmental niche models (ENMs) dealing only with presence data: Bioclim from the Biomod package (Thuillier et al., 2008) [77], Maxent (Phillips et al., 2004) [78], NPPEN (Beaugrand et al., 2011) [79], and Boosted Regression Trees (Thuillier et al., 2008) [77]. The spatial distribution outputs for the two species from each of the four ENMs for each year were averaged from 1950 to 2100. The average spatial distribution approximated by the average habitat suitability index (HSI) for the period 1970–2000 was mapped for the Vanuatu EEZ as shown in Supplementary Fig. 6. The anomalies of HSI (expressed as percentage change) for the periods 2030-2039 (2035) and 2045–2054 (2050), compared to 1970–2000, were also computed for the Vanuatu EEZ (see Supplementary Table 3).

Individual particle-based modelling of projected changes in abundance and distribution of skipjack tuna in the Vanuatu EEZ

Another approach to projecting changes in the distribution of pelagic species within the Vanuatu EEZ is through individual-based simulation modelling (IBM). Given the fine-scale nature of the archipelagic waters of the EEZ, coupled with the current uncertainty in the attraction and aggregation process around coastal FADs, IBMs can provide a useful tool to examine emergent dynamics under a range of hypotheses regarding the nature of a system (Di Paolo et al. 2000) [80].

Such a model is being developed for skipjack tuna, the Individual-based Kinesis, Advection and Movement of Ocean Animals (IKAMOANA) model (Scutt Phillips et al. 2016) [60].

IKAMOANA simulates the movement of individual schools of tuna in continuous space, forced with the Lagrangian equivalent of advection-diffusion dynamics from ocean currents and movement parameters, which can be taken from SEAPODYM or other models (e.g., Supplementary Fig. 7, Supplementary Video 1). The true position of anchored FADs can be included alongside hypothesised aggregation behaviours to examine the likely presence of tuna around different coastal FADs (Dagorn et al. 2000) [81], including the rate at which FADs are recolonised by tuna following fishing events. These models are particularly suited to hypothesis testing of individual behaviour and characterising the connectivity of fish between regions at various scales.

References

[1] FFA and SPC. Future of fisheries: A regional roadmap for sustainable Pacific fisheries. Honiara and Noumea: Pacific Islands Forum Fisheries Agency and Pacific Community; 2015.

[2] SPC. Fish aggregating devices. Policy Brief 19/2012. Noumea: Secretariat of the Pacific Community; 2012.

[3] Bell JD, Andrew NL, Batty MJ, Chapman LB, Dambacher JM, Dawson B et al. Adapting tropical Pacific fisheries and aquaculture to climate change: management measures, policies and investments. In: Bell JD, Johnson JE, Hobday AJ, editors. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Noumea: Secretariat of the Pacific Community; 2011.

[4] Bell JD, Allain A, Allison EH, Andréfouët S, Andrew NL, Batty MJ, Blanc M et al. Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories. Mar Policy 2015;51:584–591.

[5] Bell JD, Cisneros-Montemayor A, Hanich Q, Johnson JE, Lehodey P, Moore B et al. Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands. Mar Policy (this volume).

[6] Pratchett MS, Munday PL, Graham NAJ, Kronen M, Pinca S, Friedman K et al. Vulnerability of coastal fisheries in the tropical Pacific to climate change. In: Bell JD, Johnson JE, Hobday AJ, editors. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Noumea: Secretariat of the Pacific Community; 2011.

[7] SPC. Coastal fisheries and climate change. Policy Brief 16/2012. Noumea: Secretariat of the Pacific Community; 2012.

[8] Bell JD, Ganachaud A, Gehrke PC, Griffiths SP, Hobday AJ, Hoegh-Guldberg O et al. Mixed responses of tropical Pacific fisheries and aquaculture to climate change. Nat Climate Change 2013;3:591–599.

[9] Chapman L, Pasisi B, Bertram I, Beverly S, Sokimi W. Manual on fish aggregating devices (FADs): Lower-cost moorings and programme management. Noumea: Secretariat of the Pacific Community; 2005.

[10] Sharp M. The benefits of fish aggregating devices in the Pacific. SPC Fish Newsl 2011;135:28–36.

[11] Sharp M. Investment profile for anchored nearshore fish aggregating device. SPC Fish Newsl 2012;136:46–48.

[12] Sharp M. Positive results of a FAD monitoring programme in Yap. SPC Fish Newsl 2014;143:34–38.

[14] Albert JA, Beare D, Schwarz A-M, Albert S, Warren R, Teri J. The contribution of nearshore fish aggregating devices (FADs) to food security and livelihoods in Solomon Islands. Plos One 2014;9(12):e115386

[15] Bell JD, Albert A, Andréfouët S, Andrew NL, Blanc M, Bright P, Brogan D, Campbell B, Govan H, Hampton J et al. Optimising the use of nearshore fish aggregating devices for food security in the Pacific Islands. Mar Policy 2015;56:98–105.

[16] Anon. Sharing Pacific nearshore FAD expertise. SPC Fish Newsl 2016;150:37–41.

[17] Gillett R. Aspects of sea safety in the fisheries of Pacific Island countries. Rome: Food and Agriculture Organization of the United Nations; 2003.

[18] Bell J, Taylor M. Building climate-resilient food systems for Pacific Islands. Penang: WorldFish; 2015.

[19] Taylor M, McGregor A, Dawson B (editors). Vulnerability of Pacific Island agriculture and forestry to climate change. Noumea: Pacific Community; 2016.

[20] Lough JM, Meehl GA, Salinger MJ. Observed and projected changes in surface climate of the tropical Pacific. In: Bell JD, Johnson JE, Hobday AJ, editors. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Noumea: Secretariat of the Pacific Community; 2011.

[21] Amos G, Nimoho G, Fujii M, Seko A, Inuma M, Nishiyama K et al. New FAD development approach strengthens community-based fisheries management in Vanuatu. SPC Fish Newsl 2014;144:40–47.

[22] Preston GL, Chapman LB, Mead PD, Taumaia P. Trolling techniques for the Pacific Islands. Noumea: South Pacific Commission; 1987.

[23] Preston GL, Chapman LB, Watt PC. Vertical longlining and other methods of fishing around fish aggregating devices (FADs). Noumea: Secretariat of the Pacific Community; 1998.

[24] Lehodey P, Hampton J, Brill RW, Nicol S, Senina I, Calmettes B et al. Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In: Bell JD, Johnson JE, Hobday AJ, editors. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Noumea: Secretariat of the Pacific Community, 2011.

[25] Robinson L, Hobday AJ, Possingham HP, Richardson AJ. Trailing edges projected to move faster than leading edges for large pelagic fish under climate change. Deep Sea Res II 2015;113:225–234.

[26] Lehodey P, Bertignac M, Hampton J, Lewis A, Picaut, J. El Niño Southern Oscillation and tuna in the western Pacific. Nature 1997;389:715–718.

[27] Lan, KW, Evans K, Lee M-A. Effects of climate variability on the distribution and fishing conditions of yellowfin tuna (*Thunnus albacares*) in the western Indian Ocean. Climatic Change 2013;119:63–77.

[28] Fromentin J-M, Reygondeau G, Bonhomeau S, Beaugrand G. Oceanographic changes and exploitation drive the spatiotemporal dynamics of Atlantic bluefin tuna (*Thunnus thynnus*). Fish Oceanogr 2014;23:147–156.

[29] Hartog J, Hobday AJ, Matear R, Feng M. Habitat overlap of southern bluefin tuna and yellowfin tuna in the east coast longline fishery – implications for present and future spatial management. Deep Sea Res Part II 2011;58:746–752.

[30] Young JW, Hobday AJ, Campbell RA, Kloser RJ, Bonham PI, Clementson LA, Lansdell, MJ. The biological oceanography of the East Australian Current and surrounding waters in relation to tuna and billfish catches off eastern Australia. Deep Sea Res II 2011;58:720–733.

[31] Hobday AJ, Hartog JR. Dynamic ocean features for use in ocean management. Oceanography 2014;27(4):134–145.

[32] Morato T, Miller PI, Dunn DC, Nicol S, Bowcott J, Halpin, PN. Do oceanic fronts promote aggregation of visitors on seamounts? Fish Fish 2015; doi:10.1111/faf.12126.

[33] Dagorn L, Bach P, Josse, E. Movement patterns of large bigeye tuna (*Thunnus obesus*) in the open ocean, determined using ultrasonic telemetry. Mar Biol 2000;136:361–371.

[34] Hobday AJ, Campbell G. Topographic preferences and habitat partitioning by pelagic fishes in southern Western Australia. Fish Res 2009;95:332–340.

[35] Morato T, Hoyle SD, Allain V, Nicol, SJ. Seamounts are hotspots of pelagic biodiversity in the open ocean. Proc Nat Acad Sci 2010;107:9707–9711.

[36] Eveson JP, Hobday AJ, Hartog JR, Spillman CM, Rough KM. Seasonal forecasting of tuna habitat in the Great Australian Bight. Fish Res 2015;170:39–49.

[37] Dell JT, Wilcox C, Matear RJ, Chamberlain MA, Hobday AJ. Potential impacts of climate change on the distribution of longline catches of yellowfin tuna (*Thunnus albacares*) in the Tasman Sea. Deep Sea Res II 2015;113:235-245.

[38] Hobday AJ, Spillman CM, Eveson JP, Hartog JR. Seasonal forecasting for decision support in marine fisheries and aquaculture. Fish Oceanogr 2016;25(S1):45–56.

[39] Brodie S, Hobday AJ, Smith JA, Spillman CM, Hartog JR, Everett JD et al. Seasonal forecasting of dolphinfish distribution in eastern Australia to aid recreational fishers and managers. Deep Sea Res II (in press).

[40] Artetxe I, González de Zarate A, Ruiz J. Implantación en el País Vasco del plan de recuperación del atún rojo (Reglamento CE 643/07). Revista de Investigación Marina 5; 2008. http://www.azti.es/rim/wp-content/uploads/2014/01/revista_marina_05.pdf

[41] Lehodey P, Senina I, Wibawa TA, Titaud O, Calmettes B, Conchon A et al. Operational modeling of bigeye tuna (*Thunnus obesus*) in the Indian Ocean and the Indonesian region. Mar Pol Bull (in press).

[42] Lazzari P, Teruzzi P, Salon A. Pre-operational short-term forecasts for Mediterranean Sea biogeochemistry. Ocean Sci 2010;6:25–39.

[43] Rajaee T, Boroumand A. Forecasting of chlorophyll-a concentrations in South San Francisco Bay using five different models. Appl Ocean Res 2015;53:208–217.

[44] Linacre E, Geerts B. Climates and weather explained: an introduction from a southern perspective. New York: Taylor and Francis e-Library; 2003.

[45] Denman K, Hofmann E, Marchant H. Marine biotic responses to environmental change and feedbacks to climate. In: Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (editors). Climate change 1995. Cambridge: Cambridge University Press; 1996.

[46] Welch H, Pressey RL, Heron SF, Ceccarelli DM, Hobday AJ. Regimes of chlorophyll-a in the Coral Sea: implications for evaluating adequacy of marine protected areas. Ecography 2015; doi:10.1111/ecog.01450

[47] Saha S, Moorthi S, Wu X, Wang J, Nadiga S, Tripp P et al. The NCEP climate forecast system version 2. J Climate 2014;27:2185–2208.

[48] Eakin M, Liu G, Chen M, Kumar A. Ghost of bleaching future: Seasonal outlooks from NOAA's operational climate forecast system. Proc 12th Int Coral Reef Symp; 2012.

[49] Liu G, Eakin CM, Chen M, Kumar A, De La Cour JL, Heron SF et al. Predicting coral bleaching heat stress to inform reef management: NOAA Coral Reef Watch’s four-month outlook. Frontiers Mar Sci (in press).

[50] Tommasi D, Stock C, Hobday AJ, Methot R, Kaplan I, Eveson P et al. Managing living marine resources in a dynamic environment: the role of seasonal to decadal climate forecasts. Prog Oceanogr (in press).

[51] Spillman C, Alves O. Dynamical seasonal prediction of summer sea surface temperatures in the Great Barrier Reef. Coral Reefs 2009;28:197–206.

[52] Spillman CM, Hobday AJ. Dynamical seasonal forecasts aid salmon farm management in an ocean warming hotspot. Clim Risk Manage 2014;1:25–38.

[53] Yin Y, Alves O, Oke PR. An ensemble ocean data assimilation system for seasonal prediction. Monthly Weather Rev 2011;139:786–808.

[54] Fonteneau A, Chassot E, Bodin N. Global spatio-temporal patterns in tropical tuna purse-seine fisheries on drifting fish aggregating devices (DFADs): taking a historical perspective to inform current challenges. Aquat Living Resour 2013;26:37–48.

[55] Chassot E, Goujon M, Maufroy A, Cauquil P, Fonteneau A, Gaertner D. The use of artificial fish aggregating devices by the French tropical tuna purse seine fleet: historical perspective and current practice in the Indian Ocean. Indian Ocean Tuna Commission. Working Party on Tropical Tunas. IOTC-2014-WPTT16-20 Rev_1; 2014

[56] Lopez J, Moreno G, Sancristobal I, Murua J. Evolution and current state of the technology of echo-sounder buoys used by Spanish tropical tuna purse seiners in the Atlantic, Indian and Pacific Oceans. Fish Res 2014;155:127–137.

[57] Hampton J, Lawson T, Williams P, Sibert J. Interaction between small-scale fisheries in Kiribati and the industrial purse-seine fishery in the western and central Pacific Ocean. In: Shomura RS, Majkowski J, Harman RF, editors. Status of interactions of Pacific tuna

fisheries in 1995. FAO Fisheries Technical Paper 365. Rome: Food and Agriculture Organization of the United Nations; 1996.

[58] Leroy B, Peatman T, Usu T, Kumasi B, Caillot S, Moore B et al. Interactions between artisanal and industrial tuna fisheries: insights from a decade of tagging experiments. Mar Policy 2016;65:11–19.

[59] Knight E, Park T, Bromhead D, Ward P, Barry S, Summerson R. Analyses of interactions between longline and recreational gamefish fisheries taking or tagging striped marlin off New South Wales. Canberra: Bureau of Rural Sciences; 2006.

[60] Scutt Phillips J, Sen Gupta A, van Sebille E, Senina I, Lehodey P, Nicol S. Individual-based methods for simulation of movement by WCPO skipjack and other species. Western and Central Pacific Fisheries Commission Scientific Committee 12; 2016.

[61] Sund PN, Blackburn M, Williams F. Tunas and their environment in the Pacific Ocean: A review. *Oceanogr Mar Biol: An Ann Rev* 1981;9:443–512.

[62] Senina I, Lehodey P, Calmettes B, Nicol S, Caillot S, Hampton J, Williams P. SEAPODYM application for yellowfin tuna in the Pacific Ocean. Western and Central Pacific Fisheries Commission Scientific Committee 12; WCPFC-SC11-2015/EB-IP-01; 2015.

[63] Senina I, Lehodey P, Calmettes B, Nicol S, Caillot S, Hampton J, Williams P. Predicting skipjack tuna dynamics and effects of climate change using SEAPODYM with fishing and tagging data. Western and Central Pacific Fisheries Commission Scientific Committee 12; WCPFC-SC12-2016/EB WP-01; 2016 http://www.wcpfc.int/node/27443

[64] Heath AG. Water pollution and fish physiology. Boca Ration: CRC Press; 1995.

[65] Dizon AE. Effect of dissolved oxygen concentrations and salinity on swimming speed of two species of tunas. Fish Bull US 1977;75:649–653.

[66] Cayré P. Behavior of yellowfin tuna (*Thunnus albacares*) and skipjack tuna (*Katsuwonus pelamis*) around fish aggregating devices (FADs) in the Comoros Island as determined by ultrasonic tagging. Aquat Living Res 1991;4:1–12.

[67] Cayré PF, Marsac F. Modelling the yellowfin tuna (*Thunnus albacares*) vertical distribution using sonic tagging results and local environmental parameters. Aquat Living Res 1993;6:1–14.

[68] Humston R, Ault JS, Lutcavage M, Olson DB. Schooling and migration of large pelagic fishes relative to environmental cues. Fish Oceanogr 2000;9:136–146.

[69] Lehodey P. The pelagic ecosystem of the tropical Pacific Ocean: dynamic spatial modelling and biological consequences of ENSO. Prog Oceanogr 2001;49:439–468.

[70] Restrepo V, Dagorn L, Moreno G, Forget F, K, Sancristobal I et al. Compendium of ISSF at-sea bycatch mitigation research activities as of July 2016. ISSF Technical Report 2016-13. Virginia: International Seafood Sustainability Foundation; 2016.

[71] Lehodey P, Senina I, Murtugudde R. A spatial ecosystem and population dynamics model (SEAPODYM) – modelling of tuna and tuna-like populations. Prog Oceanogr 2008;78:304–318.

[72] Senina I, Sibert J, Lehodey P. Parameter estimation for basin-scale ecosystem-linked population models of large pelagic predators: application to skipjack tuna. Prog Oceanogr 2008;78:319–335.

[73] Lehodey P, Senina S, Calemttes B, Hampton J, Nicol S. Modelling the impact of climate change on Pacific skipjack tuna population and fisheries. Climatic Change 2013;119:95–109.

[74] Lehodey P, Senina I, Nicol, Hampton J. Modelling the impact of climate change on South Pacific albacore tuna. Deep Sea Res 2015;113:246–259.

[75] Aumont O, Ethé C, Tagliabue A, Bopp L, Gehlen M. PISCES-v2: an ocean biogeochemical model for carbon and ecosystem studies. Geosci Model Dev 2015;8:2465–2513.

[76] Hutchinson GE. Concluding remarks. Cold Spring Harb Sym Quant Biol 1957;22:415–427.

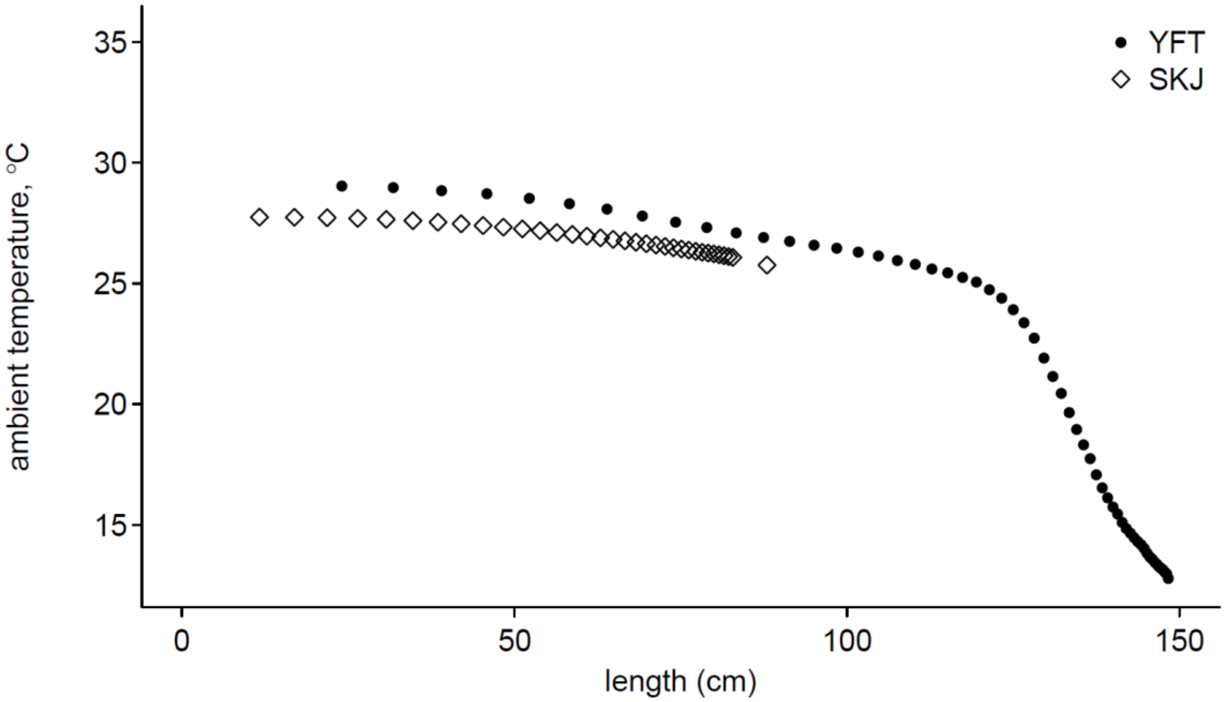
[77] Thuiller W, Lafourcade B, Engler R, Araújo MB. BIOMOD – a platform for ensemble forecasting of species distributions. Ecography 2009;32:369–373.

[78] Phillips SJ, Dudík M, Schapire RE. A maximum entropy approach to species distribution modeling. Proc 21st Int Conf Machine Learning ACM; 2004.

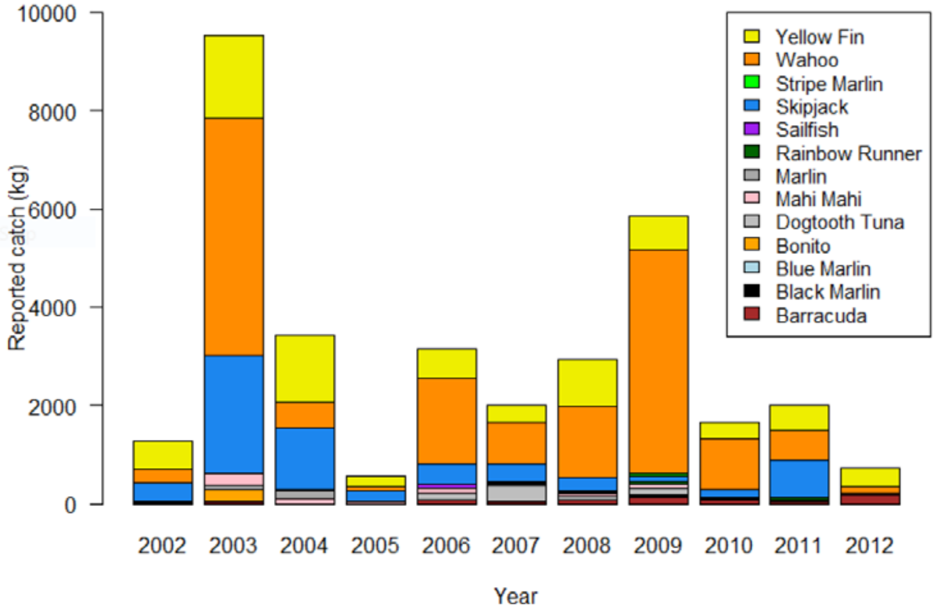
[79] Beaugrand G, Lenoir S, Ibañez F, Manté C. A new model to assess the probability of occurrence of a species, based on presence-only data. Mar Ecol Prog Ser 2011;424:175–190.

[80] Di Paolo EA, Noble J, Bullock S. Simulation models as opaque thought experiments. In: Bedau M, McCaskill JS, Packard NH, Rasmussen S, editors. Artificial life VII: The seventh international conference on the simulation and synthesis of living systems. Cambridge: MIT Press; 2000.

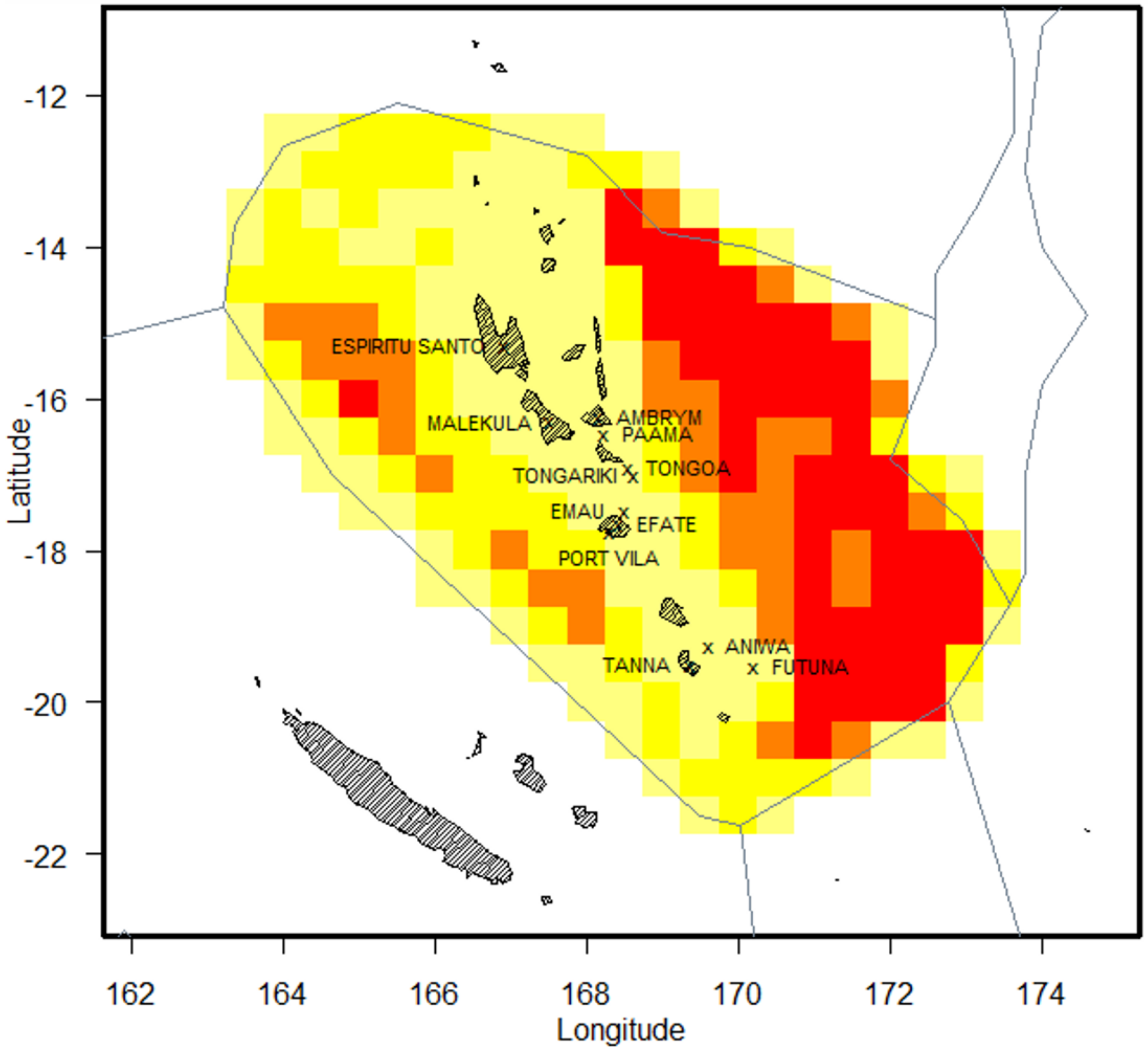
[81] Dagorn L, Josse E, Bach P, Bertrand A. Modeling tuna behaviour near floating objects: from individuals to aggregations. Aquat Living Res 2000;13(4):203-211.



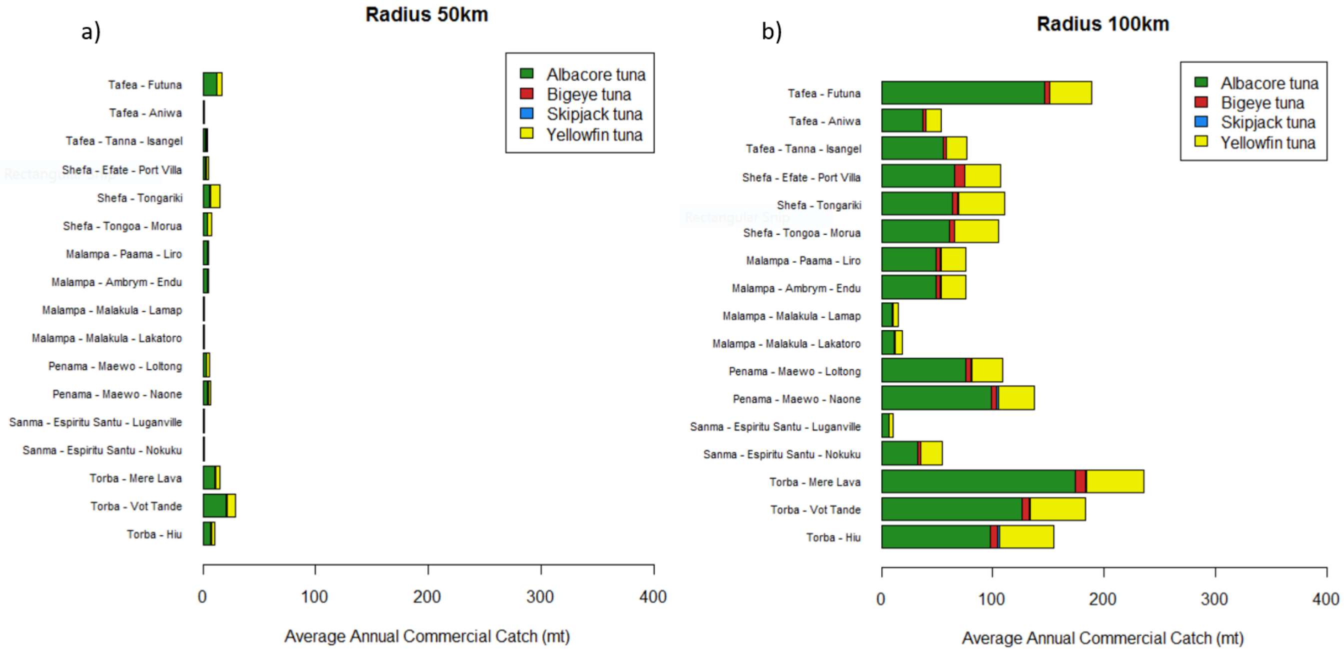
Supplementary Fig. 1. Optimal average temperature for yellowfin (YFT) and skipjack (SKJ) tuna of different sizes, estimated using a maximum likelihood estimation approach within SEAPODYM (Senina et al., 2015; 2016).



Supplementary Fig. 2. Reported catch by species and year for the artisanal troll fishery in Vanuatu for the period 2002 to 2012 (source: Vanuatu Fisheries Department and Pacific Community).



Supplementary Fig. 3. Distribution of longline hooks in the Vanuatu exclusive economic zone for all fleets combined for the period 1990–2010 (source: Vanuatu Fisheries Department and Pacific Community).



Supplementary Fig. 4. Annual average total industrial catch (mt) of yellowfin, skipjack, bigeye and albacore tuna between 2006 and 2012 within a) a 50 km radius, and b) a 100 km radius, of a subset of islands or coastal villages in Vanuatu. The y-axis names generally state the province first, island second, and if referenced, village third (source: Vanuatu Fisheries Department and Pacific Community).

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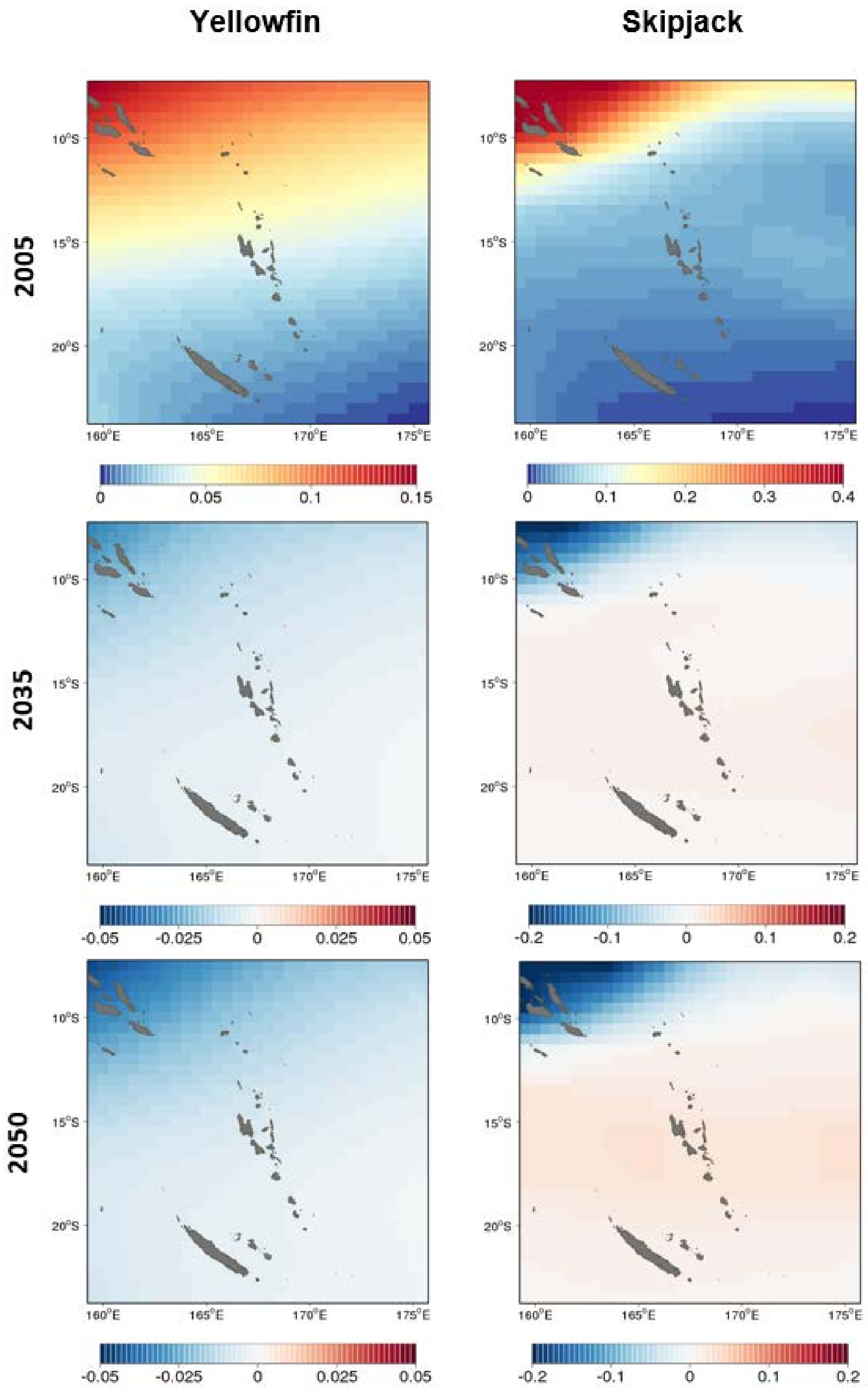
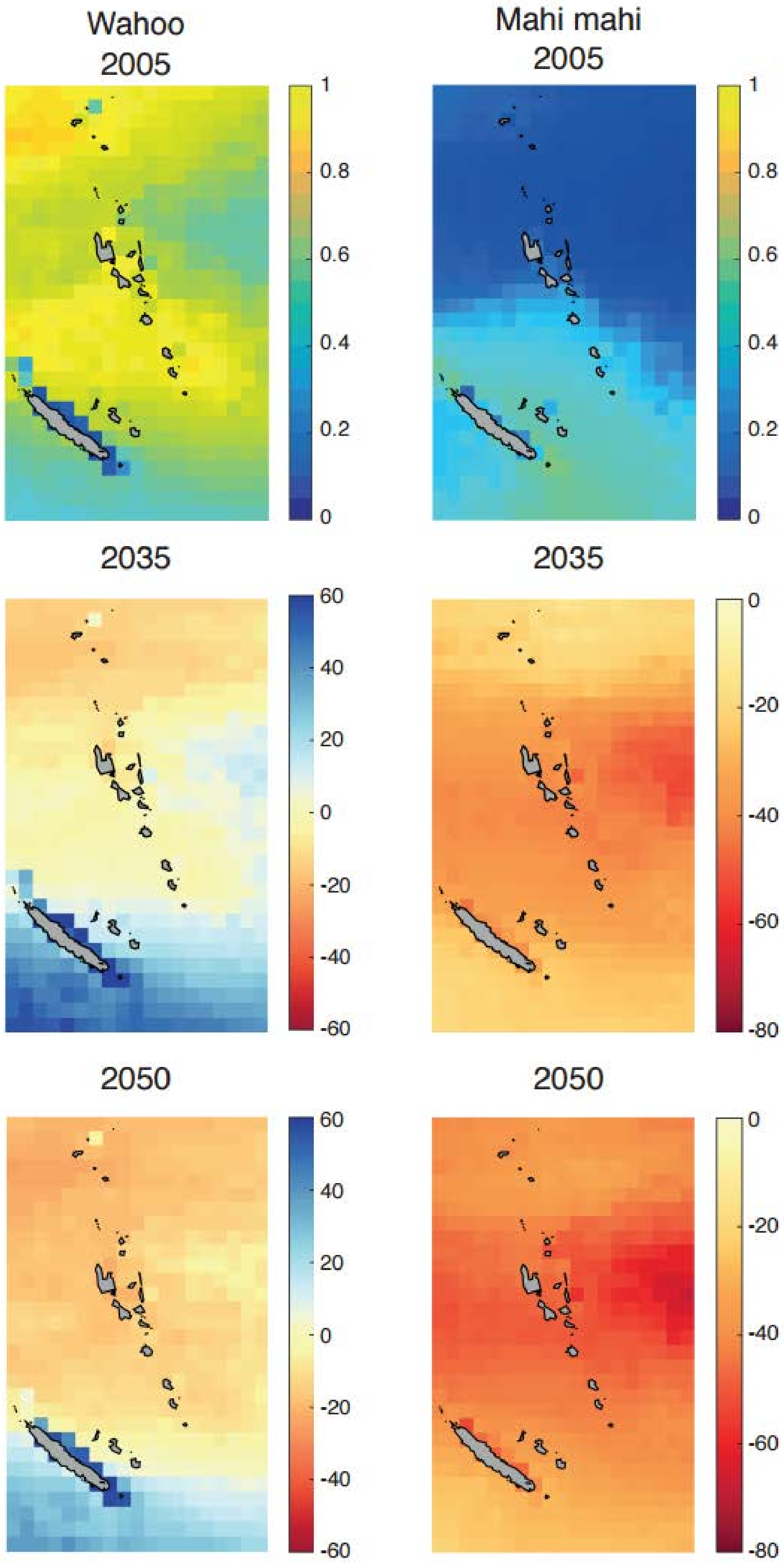
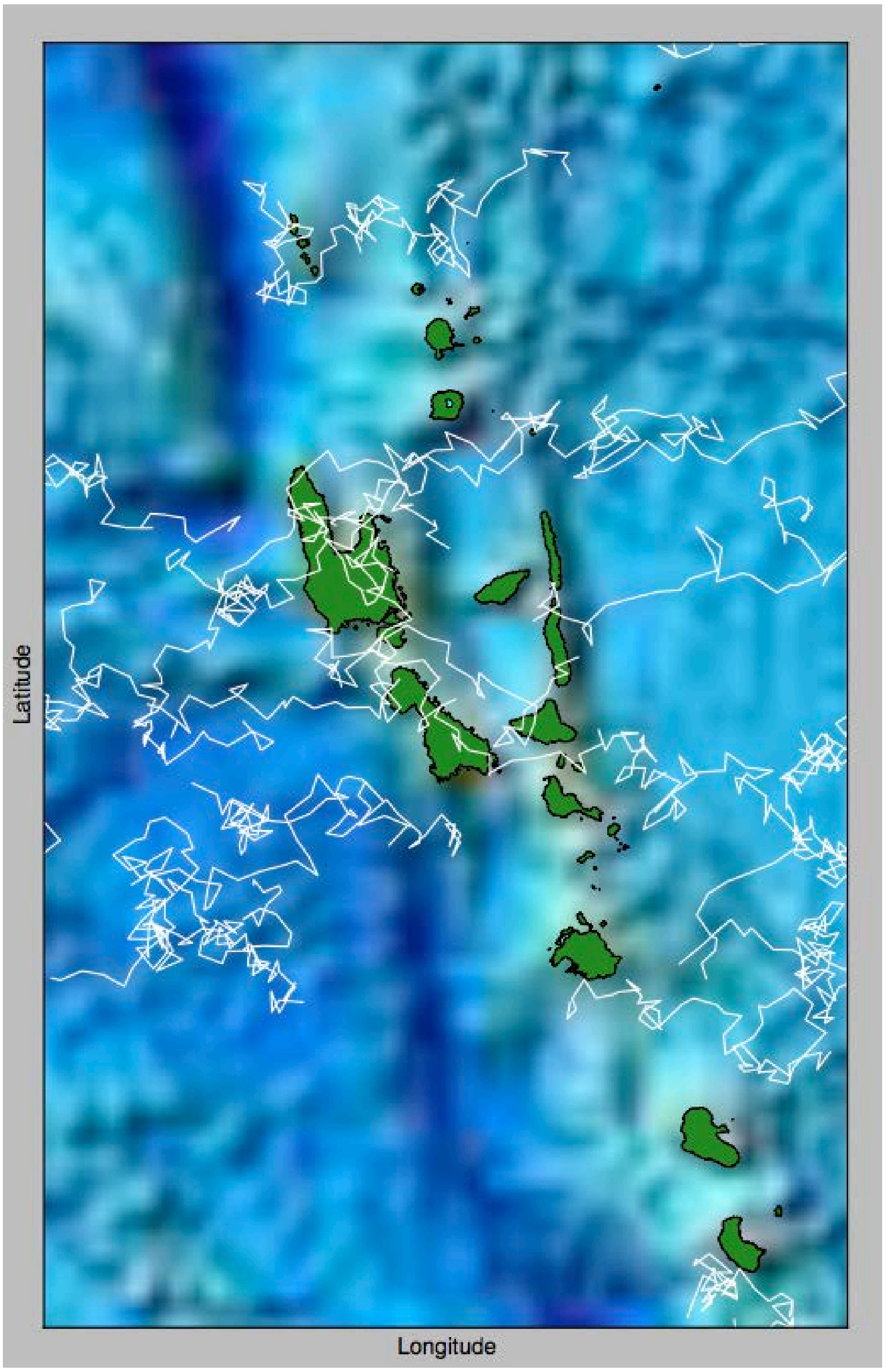


Supplementary Fig. 5. Maps of average distribution of unfished yellowfin (top-left) and skipjack (top-right) tuna biomass (in tonnes per km^2) predicted for the water surrounding Vanuatu by SEAPODYM in 2005. The maps for 2035 and 2050 show the biomass change for each species since 2005 (in tonnes per km^2) projected to occur under a high emissions scenario (see text above).



Supplementary Fig. 6. Maps of average habitat suitability indices (HSI) for wahoo and mahi mahi for waters surrounding Vanuatu for the period 1970–2000 (top panels), and HSI anomalies for both species for 2035 and 2050 under a high emissions scenario (see text above), relative to 1970–2000.



Supplementary Fig. 7. One month of example movement tracks of schools of adult skipjack tuna (white lines) around the Vanuatu exclusive economic zone simulated by the IKAMOANA model (Scutt Phillips et al. 2016). School movement is driven by the same assumptions and forcing as SEAPODYM (Senina et al. 2016) at a resolution of 1° by 1°, with a 3 hour time-step. A video of this simulation during a three month period Sept–Nov 2003 is available at www.drjscutt.com/IKAMOANA/VanuatuSim.mp4.

Supplementary Table 1. Total numbers of nearshore fish aggregating devices (FADs) due to be installed in each of the six Provinces of Vanuatu by the end of 2017, together with the estimated number of households engaged in fishing and the number of small-scale commercial fishers expected to be licenced by the end of 2017 (source: Government of Vanuatu).

Province	**Number of nearshore FADs**	**Number of rural households engaged in fishing**			**No. licenced small-scale commercial fishers**
		Total	**Fishing mainly for consumption**	**Fishing for consumption & occasional sale**	
Torba	6	1,300	720	575	-
Sanma	9	2,189	1,908	281	20
Penama	8	2,742	2,015	714	-
Malampa	9	4,413	3,699	691	63
Shefa	12	2,927	1,715	1,179	160
Tafea	8	2,188	1,500	688	11
Total	**52**	**15,759**	**11,557**	**4,128**	**254**

Supplementary Table 2. Safety equipment recommended for small-scale fishers operating around nearshore FADs from paddling canoes and motor boats.

Safety item	**Canoe**	**Motor boat**	**Comments**
Personal locator beacon with GPS		√	PLB transmits a signal with its position to the nearest search-and-rescue operation center
Solas strobe light		√	Waterproof, flashing light visible for km at night, lasts longer than flares
Medical kit		√	
Mirror	√	√	Signaling-device used during day-time to attract attention of nearby boats and aircraft
Whistle	√	√	Signaling-device used at night or in fog to attract the attention of nearby boats
Rescue laser flare	√	√	Long-range, laser device used at night to attract attention of boats and planes; replaces flares or parachute-rockets
Sea rescue streamer		√	Floating signaling-device used during day-time, visible by aircraft
Hand-held VHF radio (waterproof)		√	Multi-channel, 2-way radio enabling boat-to-boat and boat-to-land communication; the operating range is 5-10 nautical miles; distress signals should be sent on channel 16
Hand-held GPS		√	Navigation device giving exact geographic position of boat to rescuers (by VHF radio or mobile phone); increasing the safety of boat operators at night and in a distress situations
Mobile phone	√	√	Useful communication tool in areas with adequate mobile phone coverage; from a legal point of view, does not replace VHF radio
Sea anchor or drogue (125 cm)	√	√	Keeps boat heading into the wind and slows its drift
Manual inflatable lifejackets	√	√	Personal flotation device, inflated by either activating a self-contained CO2 cartridge or by exhaling through a blow-tube
Map compass		√	A device to determine direction, consisting of pivoting horizontally-mounted magnetic needle aligning with earth’s magnetic field
Batteries	√	√	AAA-size dry cell batteries for hand-held GPS, VHF radio, strobe light and rescue laser flare
Emergency blankets	√	√	First-aid, heat-reflective blanket to reduce heat loss in a person’s body. Can be used as improvised signaling device when sunny
Floating emergency grab bag	√	√	Water-proof bag used to store all items above; should be large enough to also store tinned food, water, knife and fishing tackle

Supplementary Table 3. a) Projected percentage changes in biomass of yellowfin and skipjack tuna in the Vanuatu exclusive economic zone (EEZ) due to the effects of climate change alone, and due to the combined effects of climate change and fishing effort 1.5 times greater than for the reference period 2006–2010; b) recent (1970–2000) habitat suitability indices (HIS) for wahoo and mahi mahi in the Vanuatu EEZ, and the average percentage change projected to occur in HIS relative to 1970–2000 in 2035 and 2050.

a)

Species	**2035**		**2050**	
	F_0	$F_{x1.5}$	F_0	$F_{x1.5}$
Yellowfin tuna	-8	-24	-10	-19
Skipjack tuna	16	8	44	33

b)

Species	**Recent HSI**	**% change 2035**	**% change 2050**
Wahoo	0.59	0.8	-12.2
Mahi mahi	0.25	-38.1	-45.5

Supplementary Video

www.drjscutt.com/IKAMOANA/VanuatuSim.mp4